HEAT TRANSFER TO SPHERES AND CYLINDERS
IN A CONFINED PLASMA JET

A
THESIS
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ABSTRACT

The operating characteristics of a direct-current nitrogen plasma jet confined in an 8.00-in. i.d. graphite chamber were obtained for twenty power levels and flow rates of up to 36 kw. and 250 s.c.f.h. respectively. Gas velocity and temperature profiles were measured at a test section 10.5 in. below the entry of the jet, and the recirculation phenomenon was examined.

The heat transfer rates were determined from the plasma jet to water-cooled 0.625 and 1.000-in. diameter spheres, and a 0.250-in. diameter transverse cylinder, at temperature differences of up to 5000 °F. and over the Reynolds number ranges of 600 to 4,300 and 300 to 1,100 respectively. The data were correlated in terms of the Nusselt and Reynolds numbers, with gas properties taken at bulk temperature. The high intensity of turbulence increased the heat transfer rates to above those previously reported, and Reynolds number exponents typical of turbulent systems were obtained.
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GENERAL INTRODUCTION

Electric arcs have been used for heating gases to high temperatures since the latter part of the last century. Within the past ten years, however, the technology of plasma generation and the development of new applications in the aerospace field, material preparation, and chemical processing have progressed at a considerably accelerated pace. Before they are able to make full use of this powerful new tool, however, chemical engineers must become familiar with concepts of high temperature operations developed in the main by scientists in other disciplines.

The transfer of energy to liquid droplets and solid surfaces exposed to a hot gaseous medium has received considerable attention in the literature. A better understanding of the mechanisms involved is of fundamental importance in the evolution of high-temperature solids-gas contacting techniques. The present study forms part of a continuing programme of investigation of transport phenomena at high temperatures which have been carried out in these laboratories in the past few years by Hoffman (1), Pei (2), Themelis (3), Brown (4), and Li (5). Many of the published works on particulate systems have involved the simultaneous transfer of heat and mass or, alternatively, if the transfer of heat alone was involved, the latter occurred under conditions of low temperature differences. In the present study, however, forced convection effects with large temperature gradients have been investigated. The results obtained will aid in
the development of high temperature systems in which particles are undergoing physical and chemical changes in such drastic environments as plasma jets, hot wind tunnels and reactors.

The first part of the thesis consists of a critical review of the literature. It is not intended as a historical survey of the whole field of high-temperature technology and heat transfer, but rather as a summary of the more recent literature of particular pertinence to the subject. The second part deals with the experimental aspects of the investigation, more specifically (i) the design, construction and development of the special equipment and measurement techniques required in this particular field, and (ii) the experimental results obtained during the study of forced-convection heat transfer to spheres and cylinders. Both of these latter sections have been made complete in themselves, in that they each have a separate Introduction, Nomenclature and Bibliography. This makes possible the publication of separate parts of the thesis with little modification and presents the work in a clearer light, facilitating its interpretation. Tables of experimental data are presented as an appendix.
SURVEY OF THE LITERATURE
SURVEY OF THE LITERATURE

INTRODUCTION

This survey is intended to review the multiple aspects of the field of high-temperature technology which have been involved in the prosecution of the experimental work. When working with a plasma jet, it is not only necessary to be familiar with its operation, but its characteristics and limitations must also be known. This also implies a knowledge of high temperature systems in general, such as the behaviour of matter under such conditions. All technologies also involve some kind of specialized measurement. In the case of high temperature systems, new and often non-conventional measuring techniques have had to be developed. These considerations were of great importance in the design and development stages of this project and are reviewed in the first part of this survey.

The second part is concerned with a summary of the physical aspects of the problem. Free and confined jets have been studied extensively in the literature and some of this work was very pertinent since a confined jet of hot gas has been used in the experimental investigation. The last part of the survey discusses the field of heat transfer to spheres and cylinders by forced convection and includes the effects of various complicating factors such as mass transfer and turbulence.
I. DEVELOPMENTS IN HIGH TEMPERATURE TECHNOLOGY

THE BEHAVIOUR OF MATTER AT HIGH TEMPERATURES

If a gas such as nitrogen is heated from room temperature up to extremely high energy levels, it undergoes many changes in behaviour (6a). The only important change up to about 3500°R. is an increase in the random thermal vibrations of the gas molecules. Around 12000°R., about one-third of the original nitrogen molecules have dissociated into atoms and the thermal excitation of the electron shells shows as an intense glow, even though only about 1 percent of the particles have ionized to the extent of losing one of their outer electrons. At 20000°R., virtually no molecules remain and primary ionization has increased to about 14 percent; the gas is thus electrically conducting. Double ionization (N\textsuperscript{++}) has started by about 35000°R., and at 50000°R., 60 percent of the particles have become free electrons. The remainder are singly (N\textsuperscript{+}) and doubly (N\textsuperscript{++}) ionized nitrogen atoms, with few neutral atoms left while molecules are now statistically extinct. The gas in this condition exhibits similarities to metals, semi-conductors, electrolytes and ordinary gases, and is described by the term "plasma". It is simply a mixture of electrons and gaseous ions with or without electrically-neutral atoms or molecules, formed when any substance is heated to very high temperatures. A plasma jet is merely a flowing stream of plasma. Since it is the predominant form of matter in the universe, it is regarded as the fourth state of matter. In the innermost regions of the hottest stars, the gas consists of a mixture of
bare nuclei and free electrons at temperatures in the range of $10^7$ °R., if the concept of temperature may still be regarded as valid.

In many apparently simple cases, it has been found that complex species are present in high temperature systems and that the situation becomes more complicated with increasing temperature. Margrave (7) has reviewed the current problems in high temperature chemistry and states that classical rules of valence and bonding no longer apply. Mass spectrograph and molecular beam techniques have provided the means for the study of sublimation products of elements such as carbon and germanium, and compounds such as silicon carbide. Polymeric species and unusual species of other kinds have been discovered in this way. Some of the techniques involved in the study of these gaseous molecules have also been covered by Margrave (8).

Thermodynamic and transport properties of plasmas are fundamentally different from those of the same material at low temperatures. The specific heat and enthalpy of a plasma not only differ numerically from those of ordinary gas by orders of magnitude, but also show a non-linear change with increasing temperature. In those ranges where thermal dissociation and ionization processes are taking place, each temperature increment requires a greater amount of energy and the specific heat shows sharply-peaked maxima. The density and mean molecular weight of a plasma are meanwhile lower by an order of magnitude or so from those of room temperature gases. The electrical conductivity rises very rapidly in the lower ionization range due to an increase in the charged particle concentration, and then it
levels off. The thermal conductivity, which is also influenced by the events occurring in the gas, is affected in a more complex way (9). Thermal diffusion of molecules and neutral atoms in the lower temperature ranges is supplanted by the electron kinetic contribution and both the ionization and recombination processes. As a result, the thermal conductivity undergoes maxima at temperatures where ionization predominates but not where dissociation is ascendant. It is the effect of diffusion of ionization energy rather than the electronic contribution that produces the maxima. Viscosity rises to a maximum during the primary ionization and then falls off drastically. Emmons (9) explains that this drop is caused by decrease in particle mobility due to long range coulomb forces which reduce the transport of momentum.

THE PHYSICAL MEANING OF HIGH TEMPERATURE

The concepts of heat and temperature, and scales of temperature have been reviewed by Wensel (10). The definition of temperature based on the efficiency of the Carnot Cycle is described, as well as the development of the Kelvin Thermodynamic Scale. Planck's law dealing with the intensity of blackbody radiation is also a classic definition of temperature and is described mathematically by

\[ J \lambda T = \frac{c_1}{\lambda \left[ e_{c_2/\lambda T} - 1 \right]} \]  

Wensel further describes the adoption of the International Temperature Scale in 1927, which assigns numbers to six basic fixed points, the highest being the gold point at 1063.0 °C.
The optical pyrometer is used to determine the ratio of radiant flux of monochromatic visible radiation at wavelength $\lambda$ at absolute temperature $T$ to that at the gold point, using the mathematical expression of Planck's law. The practical problems of obtaining blackbody conditions restrict the use of the International Scale to temperatures below which solids melt, i.e., below 7000 °F.

Ferguson and Phillips (11) have considered the properties of the molecules, atoms and charged particles in systems above 7000 °F, from the point of view of statistical mechanics. Thus follows a definition of temperature based on microscopic properties of a large number of particles in a plasma. They postulate that these particles have energies distributed in distinct levels ranging from a nearly continuous array of levels to levels that are well separated. According to the Maxwell-Boltzman (92) law, the relative number of particles ($N$) occupying levels $s$ and $j$ will be given by the equation:

$$
\frac{N_s}{N_j} = \frac{g_s}{g_j} e^{-\left[\left(\frac{\epsilon_s - \epsilon_j}{kT}\right)\right]}
$$

(2)

where $g$ and $\epsilon$ are the statistical weight (the number of ways the particle can form a given state) and the energy of the levels indicated, respectively. For this equation to hold, $\epsilon_s > \epsilon_j$ and $\frac{g_s}{g_j} \geq \frac{N_s}{N_j}$. This implies relatively large differences in energy levels between particles in equilibrium at high temperatures.
Next are considered the four energy modes available in a diatomic gas. The molecule first of all possesses translational, vibrational, rotational and electron-excitational modes. As the total energy content is increased, the vibrational and rotational energies exceed the strength of the bond and dissociation occurs. The neutral atom then possesses only the translational and electron-excitational energy modes. On further addition of energy, the electron-excitational energy exceeds the bond energy between the atom and the electrons, and ionization occurs. Further increases in the translational energies of the ions and electrons, as well as the broadening of the electron-excitational energy distribution will cause further ionizations and eventually the disintegration of the nucleus.

For thermal equilibrium to exist in a plasma, all of the defined temperatures must be equal. Any factors that tend to slow the energy transfer between the different energy modes create a non-equilibrium condition. Ferguson and Phillips also deal with this concept. Gases at low pressure, with a corresponding large mean free path, are likely to deviate from thermal equilibrium in electric arcs in which the energy is provided in the form of the electron translational mode. The rate at which thermal equilibrium is reached depends on the excited mode. It is the rotational and translational modes that are generally the fastest, since these are most affected by collisions which create the state of thermal equilibrium. Finkelburg (6b) states that for gases in arcs at atmospheric or higher pressure, deviations from equilibrium range "from one to possibly several percent". This low
deviation stems from the small voltage gradient present in the arcs and the correspondingly little gain in translational energy which an electron can make between collisions in the electric field. He further says that some deviation is also caused by photons leaving the arc without being reabsorbed appreciably.

At extremely high temperatures, when extensive ionization is present, an ionization temperature may be defined by the Saha equation in terms of the equilibrium between the species present. Because ionization equilibrium depends on other parameters as well as temperature, it finds as yet little use in high temperature measurements, though some astrophysical applications do occur (12).

GENERATION OF HIGH TEMPERATURES

High temperature phenomena dealt with in this section have included those occurring above 2000 °F., but somewhat lower than those in nuclear fission and fusion reactions where the temperatures exceed the million degree mark. The generation of temperatures in this range may be carried out by chemical reactions, electrical resistance and induction heating, arc techniques, exploding wires and mechanical shock tubes. Kennedy et al. (13) have compiled a bibliography of high temperature measurement and production published between 1958 and 1961 and refer to bibliographies covering earlier literature. There have also been symposia and conferences on high temperature technology which have dealt at least in part with their production. Reference will be made both to the Proceedings of the Symposium on "High Temperature - a Tool for the Future" held at Berkeley, California, in 1956, and to the
"Conference on Extremely High Temperatures" held at Boston in 1958. More recent conferences have been concerned with applications rather than generation of plasmas.

Altman (14), in reviewing chemical processes as methods of achieving high temperatures, refers to a "chemical barrier" which represents the temperature range where dissociation of molecular species destroys the energy source responsible for the chemical heat release. Because carbon monoxide and nitrogen dissociate at the highest temperature of the species involved in combustion, the choice of unstable reactants should involve only the elements C, O and N at a 1:1 atom ratio of C to O. He lists flame temperatures at one atmosphere, from the combustion of carbon at 2200 °F. to that of carbon-subnitride (C₄N₂) at 9000 °F. Grosse (15) deals with the vast amount of work with combustion of gases and metals which he has supervised at the Research Institute at Temple University. Suffice to say that metal vapours may be fed to a torch with oxygen and operated in much the same way as the oxy-acetylene torch. An oxy-aluminum flame, with its easily condensable combustion product, gives rise to a much more efficient heat transfer from flame to material than is the case with the oxy-acetylene flame, at comparable temperatures.

Resistance and Induction-heated furnaces have been frequently described in the literature (16, 17, 18, 20, 23, 24). With suitable heating elements and materials of construction such as tungsten or graphite, operation up to 5800 °F. has been made possible.

Arcs utilize the electrical conductivity of gases at
elevated temperatures and thus may be considered to be gaseous resistance heaters. They make available plasma jets at temperatures up to about 100,000 °F., depending on the gas used (11). Morris (21) has carried out an analysis of the direct current arc, based primarily upon interpretation of calorimetric data. Phenomena discussed include the cathode region, mechanism of power transfer to the anode and power dispersal in the arc. These phenomena, and the generation of plasma jets will be covered at length in another section of this literature survey.

Exploding wires, by passing large surges of electrical energy through them, cause their disintegration and create high temperatures for short times of up to several m sec. (22). Energy from a transformer or batteries is usually stored in a condenser bank.

Shock waves are formed when two gases at widely differing pressures are suddenly allowed to mix with one another. This is accomplished by separating two sections of a pipe by a diaphragm, charging one section with the high pressure "driver" gas and the other with the experimental "driven" gas at a lower pressure. The high-pressure section is separated from an evacuated tank by a second metal diaphragm. When the diaphragm between driver and reactants is ruptured, the driver gas rushes into the lower pressure section at supersonic velocity, generating the shock wave which compresses and heats the reactants very rapidly. Further increases in pressure and temperature occur when the shock wave reflects from the end of the reactor. A cooling wave is generated when the diaphragm between the driver
and the vacuum tank is ruptured, within a few milliseconds after the beginning of the process. The second diaphragm is thus optional and is used in the chemical shock tube when more control is required over the condition of the reactants (11, 19, 26). The gases may be heated up to temperatures in the order of $10^6 \, \text{O}_\text{R}$. Davydchenkov (25) has described an installation in which shock waves at a velocity of 1000 km./sec. heat gas to $10^8 \, \text{O}_\text{K}$. This plasma was retained for times up to several hundred thousandths of a microsecond. It is intended to use relatively slow electrons at a velocity of 150,000 km/sec. to obtain temperatures of $10^9 \, \text{O}_\text{K}$.

Many of the methods used to generate high temperatures are presently scientific curiosities with no apparent engineering utilization potential, but most of those described here are finding some application, albeit some only on the research laboratory development scale.

MATERIALS FOR CONTAINING HIGH TEMPERATURES

There are many types of failure observed in materials at high temperature other than melting and thermal shock. No materials now known possess the complete set of properties desired, and compromise efforts have led to the synthesis of cermets and the various refractory coatings. Kennedy et al. (13), in their bibliography of high temperature measurement and production, have included a section on metals, ceramics and graphite. The textbook "High-Temperature Technology" edited by Campbell (23) contains sections on metals and refractories as does that edited by Hehemann and Ault (27). The latter deals at length with cobalt and nickel - base alloys which are now finding
widespread use in reactors and engine parts up to 2000 °F. (28). Cermets were developed in an attempt to combine the desirable properties of ceramics, such as strength at high temperatures, and those of metals such as good thermal-shock resistance. Their applications have ranged from thermocouple protection tubes to gas-turbine blades at temperatures over 2000 °F., but their use has been superseded by other materials.

There are sixteen metals with melting points above 3000 °F., but the mechanical properties of most near melting are so inferior that they will barely support their own weight. Metals are not generally satisfactory for high temperature structural application, often because of high vapour pressure, low physical strength, lack of resistance to oxidation and difficulties in fabrication.

Norton (29) examined the known materials that have high melting points in relation to the kinds of atoms involved, the crystal structure and the types of bonding. Margrave (30) dealt with equilibrium considerations for interaction of high temperature materials with their environment. Laszlo (31) approached the material-container combination with thermodynamics by means of free energies, phase changes, crystalline properties, and vaporization and dissociation.

The need for new materials to withstand severe conditions has prompted the materials engineer to explore the possibility of utilizing such materials as oxides, carbides, borides, nitrides, aluminides, silicides and sulphides (23). The melting points of these refractory materials attain a maximum of 7100 °F.
Oxides are unexcelled in stability under oxidizing conditions but are lacking in mechanical strength. In vacuo, the high-melting metal borides and carbides are about the only refractories suited for use at temperatures over 4000 °F, because of their non-volatility. Commercial utilization of silicides is still in its infancy, but their properties are being extensively investigated. Nitrides are extremely brittle and possess low oxidation resistance, but their addition to other refractories appears promising. Sulphides are still laboratory curiosities but have been used experimentally as crucibles for melting high purity metals.

Many of these refractories are available only in powder form and thus are as yet unsuitable as materials of construction. Because of the viscous silica glass formed on its surface, silicon carbide is quite resistant to oxidation up to about 2700 °F, and is used as a resistor for electric furnaces. It is extremely hard, has very high strength and thermal conductivity and decomposes at about 4300 °F. Both silicon carbide and titanium carbide (melting point 5600 °F, ) are finding increasing use as structural materials in combustion chambers. Improvements in mechanical properties, thermal shock resistance, and oxidation resistance are being made by development of better bonding agents (23, 33, 34).

Carbon, and in particular graphite, its high-temperature stable allotropic form, possess a unique combination of properties which make it a most versatile material under these conditions (23, 35-39). Some of these properties, such as chemical inertness, refractoriness and thermal-shock resistance are characteristic of
the element and can hardly be varied, but others such as mechanical strength, thermal conductivity and gas permeability can be varied over a considerable range by changing the raw materials and processes used to prepare the various forms of graphite. The largest current use of carbon and graphite in processes involving high temperature is in the production of electric furnace electrodes, followed by use in furnace linings in the production of materials such as phosphorus, aluminum and even iron, the latter in blast-furnace hearths. Since graphite is very easily machined, graphite heat exchangers, tubes and shapes of all kinds are now produced. In the nuclear engineering field, it is not only useful as moderator to slow down fast neutrons, but also because of its thermal-neutron reflecting power and low capture cross-section. Because of its high sublimation temperature (6700 °F.), and its high tensile strength which increases with temperature up to 4500 °F., it has found use as a material of construction in an induction furnace operating up to 6150 °F. (40).

Pyrolytic graphite is a polycrystalline form of graphite deposited from a carbonaceous vapour on a suitable substrate under vacuum. This manner of formation produces a material with metallic characteristics in one planar direction and ceramic attributes normal to the plane. Thus its thermal and electrical conductivities and thermal expansion vary considerably depending upon direction. The strength-to-weight ratio of this material is higher than that of stainless steel at low temperatures; above 3500 °F., the ratio is five times that of other types of graphite. Its erosion and oxidation resistances are vastly improved also.
When materials used for structural parts do not possess the necessary properties to withstand severe environments, such as an oxidising atmosphere at high temperature, the surfaces may be coated with a suitable refractory to provide the desired resistance (32, 41). A coating is, however, potentially a limiting factor in the life of a component since its use may create problems in bonding and differences in thermal expansion, which, if not sufficiently understood and remedied, may lead to unexpected failure of not only the coating, but also of the base itself (42).

TRENDS IN HIGH TEMPERATURE CHEMICAL PROCESSING

Developments in high temperature are now almost beyond prediction. Thousands of new compounds will be prepared within the next few years (7). These will be largely endothermic compounds quenched to low temperatures which can then be maintained in a new useful form because of slow conversion to thermodynamically more stable systems. The determination of high-precision thermodynamic data such as heats of formation and heat capacities will aid in the prediction of chemical behaviour at high temperatures. The establishment of highly reliable standards for temperature measurement and the development of better techniques for deducing structures of high temperature gaseous species will also greatly advance plasma chemistry.

The fixation of atmospheric nitrogen as nitric oxide has received, and will continue to receive, a great deal of attention (11). Optimum yields of close to ten percent are possible at 9000 °F. and one atmosphere, but rapid quenching will be required to prevent the reaction products from reversing to
their low temperature equilibrium. Fluidized beds (43) offer quenching rates of $2 \times 10^7$ deg. F./sec. without diluting the products. These beds may, on the other hand, be heated by resistance elements or by high-frequency induction up to 7000 °F. In the Shawinigan process for hydrocyanic acid, ammonia and hydrocarbons react in a bed of carbon at about 2500 °F, with a residence time of 0.1 to 0.5 second.

Electrical energy is most suitable for heating materials to high temperature in controllable fashion. The plasma jet will continue to be investigated for pyrometallurgical and chemical processing as well as in material fabrication and in the aerospace field. These will be discussed at length in another section. One of the most promising methods for applying electrical energy is based on electromagnetic radiation, particularly microwaves (44). Their conversion efficiency has now been raised to 70 percent for continuous operation in the 400 kw. range. Plasmas generated by microwaves are sometimes more desirable than those created by other means, since high degrees of ionization and dissociation can be obtained without adding sensible heat to the gas. Chemical changes are initiated by electron collisions that lead to formation of ions and excited species.

Magnetohydrodynamics is concerned with the manner in which magnetic fields interact with electrically-conducting fluids. Active investigations in this field have been instigated by attempts to achieve controlled nuclear fusion reactions, by the study of high-speed vehicles and by recent progress in astrophysics. Mawardi (45) has made a survey of the literature. Further discussion of this topic is beyond the scope of this thesis.
II. MEASUREMENT TECHNIQUES IN HIGH TEMPERATURE GASES

INTRODUCTION

There are many techniques available for determining the operating characteristics of high temperature gaseous systems. New developments in thermocouples have extended their use to over 5000 °F., while the space race has resulted in the commercial availability of water-cooled thermodynamic probes. Optical pyrometers have been in common use for many years (46) and will not be discussed here. At temperatures above 5000 °F., spectroscopic measurements of the emitted radiation are often the only sensitive and practical means for determining the temperature. Other techniques, such as measurements of velocity, composition, heat flux, and ultrasonic methods will also be described.

There exist in the literature several up-to-date bibliographies on high temperature measurement (13, 47, 48). Kostkowski (49) has reviewed the accuracy and precision of measuring techniques above 1300 °F., including those of thermocouples, resistance thermometers, pyrometers, and spectroscopic methods. Hottel, Williams and Jensen (50) have presented an extensive literature survey of optical methods of measuring plasma jet temperatures and have included brief sections on others. Thermodynamic probe techniques have been reviewed by Grey (51) who has classified these into three types: pneumatic devices, heat-transfer gauges and calorimetric methods.
THERMOCOUPLES

High temperature thermocouples are generally of the same construction as conventional ones, but the sheath, insulation and wire materials must be chosen on the basis of environmental conditions (52). Steven (53) reviewed this field in 1956. At that time, metallic thermocouples such as those containing platinum, rhodium, iridium and, to a limited extent, tungsten, had been developed. Others, such as rhenium could not be fabricated into wires. Stability of calibration and exposure in oxidising and reducing atmospheres were also presenting trouble. Ceramic and metal-ceramic thermocouples were finding use where accuracy of the determination was not too important.

Donne (54) describes the development of a new "platinel" thermocouple to reduce the drift and low e.m.f. output of conventional types. Platinel, which is made up of alloys of gold, palladium and platinum, may be used only up to 2400 °F. Thermocouples containing tungsten, rhenium and other refractory metals have been developed for use up to 4500 °F. (55-59). Tungsten-rhenium wire is now readily available and calibrations can be reproduced consistently by means of wire-lot screening and matching procedures. These thermocouples are now stable under thermal cycling after annealing, and drift characteristics have been found to be insignificant. Because of the brittle nature of pure refractory metals, they are now being alloyed and the tungsten - 5% rhenium/tungsten - 26% rhenium thermocouple is finding increasing application in non-oxidizing atmospheres.
Ceramic thermocouples are also presently receiving a great deal of attention. Klein et al. (60) have investigated electrical galvanomagnetic effects along the layer planes of pyrolytic graphite and state that these systems are capable of operation up to 5000 °F. Panasyuk and Samsonov (61) describe the use of refractory carbides for use up to 5400 °F. Also from the Soviet Union comes news (62) of semiconductor thermocouples for use in oxidising, reducing or inert atmospheres up to 4200 °F. The first is one of molybdenum silicide and carbon saturated with boron. Other materials such as titanium boride and carbide have also been tried.

The range of a thermocouple may be extended above its melting point by shuttling it back and forth between a point in the gas stream and a water-cooled jacket. Temperature measurements of up to 6000 °F. by chromel-alumel thermocouples have thus been obtained (63, 64). The average temperature recorded depends upon the gas temperature, cycling time and uniformity of cooling, but this technique would seem unsuitable for measurements in large temperature gradients. The intermittency would also make difficult the calculation of conduction and radiation corrections which are appreciable at low velocities. Another transient method of high temperature measurement above the melting point of the thermocouple material is that disclosed by Giedt and Chambers (65). Temperatures up to 4800 °F. were calculated from simultaneous temperature-time measurements of two elements of chromel-alumel thermocouple of identical geometry but unequal thermal capacity. The radiation error is reduced by means of a single shield, but further shields would make the dual-element transducer
even more bulky and thus decrease the resolution possible in thermal gradients.

Srikantiah and Ramachandran (66) have investigated readings of thermocouples in the temperature range of 1600 to 2200 °F. in a low velocity gas stream with up to four radiation shields, a single heated shield, a double shield with nozzle and with the thermocouple inside a suction probe. The accuracy of the shielded probe increased with the number of shields while the suction probe yielded the lowest error at 2200 °F., only 30 F. deg.

Scadron and Warshawsky (67) have carried out an experimental determination of time constants and Nusselt numbers for bare-wire thermocouples in high velocity air streams and also an analytic approximation of conduction and radiation errors. Graphs and nomographs are presented for aid in computation of these errors and of the time constant.

**THERMODYNAMIC PROBE TECHNIQUES**

In many hot environments, temperatures are too high for thermocouples, and spectroscopic methods are not applicable due to lack of window facilities, opacity of the gases, or large thermal gradients. Such applications have led to the development of thermodynamic probe techniques.

The pneumatic probe depends on application of the continuity equation to a continuously-flowing sample of gas, for example a perfect gas expanding isentropically through two orifice nozzles (51). In heat transfer probes, the enthalpy or temperature determination is carried out by measurement of heat flux
across a calorimeter surface (at the front stagnation point) at a measured stagnation pressure and the subsequent use of known heat transfer correlations or of a theoretical analysis. The ablation rate of a suitable material may also be used, as a variation of this technique. Both methods have been well covered in the review by Grey (51).

Calorimetric methods have led to the development by Grey, Jacobs and Sherman (68) of a probe in which gas enthalpy is calculated from a heat balance. This probe consists of three concentric tubes joined at the tip in such a way that hot gas can be sampled through the innermost tube and cooling water flows in and out via the remaining two annular gaps. Thermocouples record the temperatures of the exit gas and coolant, in and out. Heat balances are carried out with gas flowing through the probe and then with the gas sample shut off. This method yields the enthalpy of the gas stream in terms of the difference in heat transfer between the outer and the inner tube. The effectiveness of this technique is dependent on the duplication of flow condition near the probe tip under the two conditions. Grey (69) has carried out a sensitivity analysis for the probe which has been termed "adequate to confirm the general approach", but is really quite inconclusive. Smith and Churchill (70) have found a large dependency of measured temperature with sampling rate. They postulate that in low velocity gas streams and at small sampling rates the probe takes in gas from the cool boundary layer. They obtained temperatures of 5000 °K. and lower with the probe compared to 9000 °K. with spectrographic techniques. It would appear that this technique is best suited to use with high velocity gas
Another type of calorimetric probe is the diluent type described by Haas and Vassallo (71). It utilizes direct injection of a coolant into the gas sample just inside the probe tip. The calorimetric probes offer great versatility in that they may be used to measure enthalpy by heat balance, composition by sampling and velocity from dynamic pressure.

Glawe et al. (72) have developed a simple heat transfer gauge whose primary sensing element consists of a water-cooled cylindrical tube in crossflow. The gas temperature is obtained from heat transfer relationships after determination of a constant of proportionality by calibration at a lower temperature. Cheng and Blackshear (73) have constructed and analysed the performance of a transpiration cooled probe, which sucks the hot gas through a convergent-divergent nozzle and mixes it turbulently with cold diluent gas. The necessity of a cooling water system, several thermocouples and tubes make the probe rather bulky.

Zsombor-Murray (74) has designed and constructed a heat-flux device which consists of a fine stainless steel tube heated by the hot gas and cooled internally by flowing water. From his extensive analysis and calibration, he has shown that the heat flux depends only on the coolant pressure drop and electrical resistance of the tube.

Fingerson and Blackshear (75) describe the characteristics of another heat flux meter which is basically a water-cooled constant-temperature hot film anemometer. This employs a thin platinum film deposited on a 0.006 in. o.d. glass tube which is
water-cooled. During operation in high-temperature gas streams, the surface is kept at essentially constant temperature by an electronic compensating circuit. The flow rate and temperature of the water entering the short platinized test section is also constant. Changes in heat transfer between the probe and environment are directly reflected by changes in power input from the compensating circuitry. The steady-state heat balance is:

\[ I^2R + h_b S_o (T_b - T_s) = U_i S_o (T_s - T_w) \]  

where the first term represents the electrical power input, the second the heat gain from the environment and the last the heat given up from the surface to the cooling water. It is claimed that heat fluxes of $2 \times 10^6$ Btu/hr-ft$^2$ can be withstood. The gas-film coefficient $h_b$ itself depends not only on the nature of the gas, but also its velocity, temperature according to heat transfer correlations to cylinders, as well as other factors such as scale and intensity of turbulence. If an aspirating probe, to provide constant gas velocity past the sensor, is used and if the sensor surface temperature $T_s$ and water temperature $T_w$ and flow rate are also kept constant, then $U_i$ - the inside heat transfer coefficient - is also constant. In such a case, the electrical power input may be directly calibrated to measure the temperature $T_b$.

If concentration is another variable, however, special techniques must be used to separate this effect. Fingerson (76) has developed and evaluated the method which measures heat flux at two different sensor temperatures. It was found that large errors are possible with present instrumentation because the calculations involve the difference between quantities of similar magnitude.
The probes described offer promising new techniques for the measurement of heat flux, enthalpy, temperature, concentration, and velocity from dynamic pressure measurements. At low velocities and sucking rates, however, cold boundary layer effects may well be a problem. Winkler and Griffin (77) warn that many of the techniques neglect the sizable fraction of the stream energy contained in molecular dissociation.

**SPECTROSCOPIC TEMPERATURE MEASUREMENTS**

The thermocouple and probe techniques that have been described measure a single temperature even when the various energy modes in a plasma are not in thermal equilibrium. Spectroscopic methods offer not only the means to obtain individual values for the vibrational, rotational, and the electron-excitational temperatures to check how closely the equilibrium is approached, but also allow the process of energy exchange to be studied. These temperatures can each be calculated from a knowledge of the Boltzmann distribution of energies in the mode involved. This distribution was described by Eq. (2), while the radiant energy emitted per unit volume and time, \( J \), in the transition between the states \((i_s, j)\) is given by:

\[
\frac{J}{h\nu} = N_s A_{s,j}
\]  

(4)

where \( h \) is Planck's constant, \( \nu \) is the frequency and \( A_{s,j} \) is the transition probability. Combination with Eq. (2) gives the intensity \( I \):

\[
I = c A_{s,j} e^{-[(E_s - E_j)/kT]}
\]  

(5)
Dicke (12) has discussed several applications of this equation. The spectrum of radiation from electronically-excited states of atoms appears as lines due to emission from different vibrational and rotational energy levels, while that from excited states of molecules appears as bands. Eq. (5) shows that the intensity of radiation from a line or band depends upon the temperature and concentration of the excited state, as well as the transition probability.

The measurement of spectroscopic temperatures below 7000 °F. has been described by Broida (78) who compared several techniques and found the spectrum line reversal method to be most precise in this range. In this method, the temperature of a source, such as a tungsten strip lamp or carbon arc, is varied until its radiant energy does not change when viewed through the hot gas, which should be in thermal equilibrium and at the same wavelength as the source.

The basic limitation of spectroscopic methods of the spectral line or band intensity is the lack of or inaccuracy of transition probability values (49). This has led to the use of relative intensity measurements within bands of narrow wavelengths, and the determination of temperature from the wavelength of maximum radiant energy. The latter is derived from Planck's equation, Eq. (1). Tourin (79) describes an infrared monochromatic radiation method in which the temperature alone is a function of the ratio of the infrared radiation emitted at a given wavelength to that absorbed at the same wavelength.

The use of spectroscopic techniques is usually expensive,
tedious and cumbersome. Great care must be taken in optical alignment and absolute intensity calibration. The presence of sharp temperature gradients, as in plasma jets, makes necessary observations through various regions of the gas. Since the value obtained is some average along the optical path, integral equations should be solved to yield the actual profile for the temperature distribution.

Details of the methods mentioned here, and of other spectroscopic techniques may be found in the reviews of Dieke (12), Hottel et al. (50), and Broida (78).

**VELOCITY MEASUREMENTS**

Several of the thermodynamic probes discussed earlier, such as the pneumatic probe and the aspirating or suction probe, may be used to obtain the total or stagnation pressure in a plasma jet. Smith and Churchill (70) used a calorimetric probe of the type developed by Grey et al. (68) to measure the total head in a confined plasma jet at atmospheric pressure. The free stream velocity was calculated by application of the Bernoulli equation:

\[
U^2 = -2g_c \int_{1}^{2} \frac{dp}{p}
\]

where \( \rho \) is the gas density, \( p \) the pressure, \( U \) the velocity, and \( dp \) corresponds to the change between free stream (\( \rho_1 \)) and tlp stagnation (\( \rho_2 \)) pressure. For an isothermal density change

\[
U^2 = 2g_c \frac{\Delta p}{\rho_1}
\]
For a water-cooled tip, however, this change is not isothermal and the use of an average density value gives a better approximation of the gas velocity:

$$u^2 = \frac{g_c \Delta p (T_1 + T_2)}{\rho_1 T_1} \tag{8}$$

Fingerson (76) has described a miniature total head probe made of a cluster of small (0.010 in. o.d.) tubes. The temperature correction in Eq. (8) can be neglected if an uncooled, rapid response probe of the type developed by Barkan and Whitman (80) is used. The tip of the probe is replaceable since it melts if over-exposed to the environment. Raelson and Dickerman (81) have employed a water-cooled copper pitot probe in an air plasma jet up to 10,000 °F., without any corrosion or ablation problems.

An interesting technique involving the measurement of the drag on a small plate swept across the arc was developed by Kimura and Kanzawa (82). This method also involves previous knowledge of the temperature profile and of the plasma density and viscosity. The error in measured velocity is estimated at less than 17.5 percent excluding that due to the distortion of flow caused by the insertion of the plate.

Cason (83) has reviewed methods for measuring velocities in a flowing plasma in which irregular bursts of plasma caused by instability in the arc process are followed by a high-speed camera or the signals from a pair of induction coils. He has also described the development of a technique based upon the polarization voltage induced when a plasma flows transversely to an applied magnetic field.
MISCELLANEOUS TECHNIQUES

There are several techniques available for the measurement of translational temperatures which are simply referred to as gas temperatures. For low-pressure electric arcs, the electron temperature is often much higher than the other translational modes. Mohler (84) has developed an electrode probe which measures the electron current reaching the probe at a known voltage. The electron temperature can then be determined from theoretical equations which have been confirmed by experiment. The velocity of a sound wave or small disturbance propagating through the plasma yields the gas temperature (85, 86), which is really in this case the translational mode of the molecules, atoms and ions. Carnevale et al. (87) have used an ultrasonic pulse technique in a plasma jet of air, argon and helium. Temperatures were calculated on the assumption that only the translational and rotational degrees of freedom were excited by the pulse.

Hoenig (88) has presented a technique for using a constant-current hot wire to measure temperatures above the melting point of the wire itself. A measurement of resistance of the wire, and hence its temperature, is made as a function of time until the wire is destroyed by erosion or melting. A simple mathematical treatment yields both the temperature of the gas and rate of heat transfer to the wire.

Any of the heat transfer gauges described in the earlier section on thermodynamic probe techniques may be used for the measurement of heat flux and determination of convective heat transfer correlations, if the velocity and temperature of the gas
stream are known. Radiative transfer must either be avoided or a correction factor estimated. Thermal radiation of high intensity may be measured by a modified thermopile of the type described by Simms et al. (89). This instrument is conventional in that it consists of a large number of thermocouple elements, but it has been fitted with a water jacket which serves to cool it and to house the cold junction. It has been calibrated for various water flow rates. Transducer techniques for measurement of heat flux by conduction and radiation in high temperature aerospace applications have been reviewed by Stempel and Rall (90).
III. ADVANCES IN PLASMA JET TECHNOLOGY

INTRODUCTION

Of all the means previously discussed for heating material to high temperatures, electrical energy appears to be the most suitable in that large amounts of material can continuously be heated in controlled fashion. The plasma jet, in particular, is establishing for itself a position not only in the aerospace field and the processing of refractory materials but is also finding increasing applications in chemical synthesis. Plasma generators operating in the megawatt power range are now commercially available but their widespread use by the chemical industry awaits improvements in efficiency and developments in generator design such as consumable electrodes and transpiration cooling.

In 1960, the Materials Advisory Board of the United States National Research Council prepared a comprehensive report on the development and possible applications of plasma and related high-temperature generating devices (91). In it were included sections on generation and uses of plasma as well as the status of research completed or in progress in the U.S.A. The report was intended to classify, for the first time, the types of plasma research being carried on, and to initiate contacts between groups working in the field who had up to then been unaware of each others' work. In the following year, John and Bade (92) made an exhaustive review of plasma generation technology and also included a large bibliography. Skrifstad (93) has outlined areas of research under investigation with particular emphasis on the
fundamentals of the arc process.

In the following sections, stress will be placed on the most recent developments, although some basics will, of necessity, also be covered.

**TYPES OF PLASMA GENERATORS**

Although several types of plasma generators have been developed in recent years, nearly all are rotationally symmetrical about a central axis. In the direct current types, coaxial electrodes are separated by an annular gap, across which the arc current passes and through which the gas flows. In this way, at least part of the gas flows through the arc column where the heating occurs. Alternating current generators and radio-frequency units are presently undergoing thorough investigation, but it is the D.C. types which presently find most use.

Conventional unconfined D.C. arcs employ a comparatively low current density, usually lower than 40 amp./cm². If the current density is increased above this value, the previously uniform voltage drop between the anode and cathode shifts to a drop concentrated at the anode surface. The transition is accompanied by an increase in brilliance and the arc path becomes distorted. This, the high intensity arc, was first described by Finkelnburg (94).

A constricted arc may be produced by confining the arc column in a nozzle into which gas is introduced under pressure and out of which the plasma jet issues. The cold gas may be introduced tangentially so as to produce a swirl or vortex.
The arc is thus forced to travel from the solid-tip electrode out of the nozzle and to strike back to the front face of the nozzle. In the gas-sheath stabilized plasma jet, the gas is fed axially into the zone between the solid cathode and nozzle anode. The arc remains within the nozzle and is prevented from striking the nearby wall by a gas sheath much thicker than the arc diameter. It is only after passing a considerable distance down the nozzle that the arc path is completed. The cathode which emits electrons is usually made of thoriated tungsten while the water-cooled copper nozzle constitutes the anode. The voltage drop varies from gas to gas (91), the highest being for hydrogen and ammonia (120-150 volts) and the lowest for argon (about 20 volts). Efficiencies of up to 80 percent have been reported by Browning (95), the main losses being those to the cooling water. More detailed descriptions of these commercially-available units are given by Thorpe (96), and Giannini et al. (97).

In the transferred-arc plasma jet, the current to the nozzle is limited to 20-100 amp, and the remaining current proceeds to a conductor located downstream from the nozzle. (96). This arrangement provides a longer arc path and hence more heating due to the higher inherent voltage.

In plasma jet generators, most of the voltage drop, and hence the highest temperature, occur in the vicinity of the anode surface. As a result, substantial amounts of heat may be carried away by the nozzle coolant and thus the efficiency is decreased. If, instead, the nozzle is transpiration-cooled by a flow of gas through its porous body, efficiencies of up to 90
percent may be obtained. Kinney et al. (98) have found that the 

The thermal and electrical characteristics of the transpiration-cooled plasma jets are now under thorough investigation (99-104).

The relatively high cost of rectifiers has generated interest in alternating current plasma jets, both with uncooled graphite and water-cooled copper electrodes. In three-phase units, the electrodes are coplanar concentric rings, and the arcs are made to revolve about the axis by means of an external magnetic field transverse to the arc path (92). The efficiencies, however, are low, from 15 to 40 percent (91). These low figures are due to the larger volume and greater area of electrode surface inherent in alternating current designs. The frequent breaking and re-ignition of the arc have also posed problems in their development and are still receiving attention (105, 106).

Radio-frequency or induction heating presents an electrodeless method for producing plasma jets. It thus diminishes contamination levels and allows the use of corrosive gases such as oxygen as working fluid. Reed (107) has successfully operated such a generator at 4 megacycles per sec. and at power levels up to 3 kw. The plasma jet was initiated by heating a graphite rod inductively and by its timely withdrawal. The heating of the gas by conduction lowered its breakdown potential sufficiently for the plasma to be established. The radio-frequency plasma jet has, in general, a lower velocity than its direct current counterpart. In spite of the fact that the power supply is very costly
and operating efficiency is low, this induction device is of sufficient importance to justify its further study. Marynowski and Monroe (108) have reviewed the operating characteristics and prospective applications of this technique.

OPERATING CHARACTERISTICS OF DIRECT CURRENT PLASMA JETS

Various aspects pertaining to the generation of direct current plasma jets are now being studied. These range all the way from fundamentals in the energy transfer process inside the generator itself to the temperature profiles and radiation losses outside. Other works deal with basics of operation such as the effect of gas flow rate on the voltage-current characteristics of these units.

John and Bade (92) have reviewed the voltage-current characteristics obtained with various gases and flow rates. At constant gas throughputs, the arc voltage is relatively insensitive to changes in current, but it increases significantly with flow rate at constant current. Okada et al. (109, 110) have studied the operation of an argon plasma jet with carbon, copper and tungsten cathodes. They found that it is the position of the arc striking the cathode and nozzle anode that affects the voltage. As the gas flow rate increases and pushes the arc further up the nozzle, the voltage is correspondingly increased. They also attempted to measure the pressure distribution inside the plasma torch with a view to estimating the temperature and velocity in the nozzle. The profiles obtained, under gross oversimplification of the electrical processes occurring in the nozzle,
were nevertheless helpful in the evaluation of their plasma jet as a metal-cutting device.

John et al. (111) have investigated a series of electric arc phenomena including the behaviour of a fully-developed laminar column, electrode materials behaviour and magnetic field-arc discharge interaction, both analytically and experimentally. They found that arc motion (to prevent electrode failure) can be maintained with an alternating current magnetic field and that the form of the arc is a sensitive function of the strength of the superimposed field. Skifstad (112) has carried out an analysis of the flow and transport phenomena, based on laminar flow assumptions, in a mutually interacting electric arc and a gas flow passing cocurrently through a cylindrical tube. An experimental study of the energy exchange with radial gas flow interaction was conducted by Elliott and Gomez (113). A simplified analysis for estimating the performance of a nozzle-confined arc for use in design of plasma generators was presented by Norton and Murphy (114). Sherman and Yos (115) worked out a dimensionless analysis of electric arcs subject to forced convection, which led to the following expression:

\[ V = \frac{1}{L} \frac{1}{\sigma} \left[ \frac{c_p \mu}{k}, \frac{\rho}{\mu U^2}, \frac{\rho U L}{\mu}, \frac{l^2}{\mu \sigma}, \frac{Q_{rg} L^2}{\mu i} \right] \tag{9} \]

where \( V \) is the arc voltage, \( I \) the current, \( L \) the characteristic dimension of electrode geometry, \( Q_{rg} \) the power radiated by the gas per unit volume, \( \rho \) the gas pressure, \( U \) its velocity, \( l \) its enthalpy, and \( \sigma, \rho, \mu, c_p, k \) its various properties.
The first three quantities in parentheses may be recognized as the Prandtl number, pressure coefficient, and the Reynolds number, respectively. Effects included in the analysis were those of viscous compressible flow, conductive, convective and radiative heat transfer, and ohmic heat dissipation. These scaling laws were verified with nitrogen and argon plasma jets at power levels up to 1 megawatt.

The region of the gas close to the anode surface has received much attention, since it is in this "anode sheath" that the large voltage drop occurs in high-intensity arcs. Dean (116) has investigated the heat transfer, flow and electrical phenomena near a cooled anode, while Shear (117) has worked with a transpiration-cooled anode. Winter (118) has measured the various heat losses in a commercial gas-sheath stabilized plasma torch and has found that the anode losses form 60 percent or more of the total losses. The influence of gas type, flow rate, arc current, anode material and geometry have been aptly demonstrated by McKee et al. (119).

An important feature of direct-current arcs is the intermittent nature of the arc process near the anode. The cool gas anode sheath may be bridged electrically by a moving concentrated arc, which leads to a cyclic variation of the voltage between cathode and anode at constant current. Re-ignition of the arc after each cycle of travel down the nozzle anode occurs by breakdown of the gas in the neighbourhood of the cathode. Wheaton and Dean (120) found that this cyclic process had a frequency of about 10,000 cycles per sec. in a nitrogen plasma
generator. Pfender and Cremers (121), using a similar system, measured voltage fluctuations of about 50 volts in nitrogen and 25 volts in argon at a frequency of about 5000 cycles per second. The latter figure was obtained from Fastax high-speed pictures. Jordan and King (122) have employed this technique to follow these fluctuations with a streak camera and thus obtained the arc column velocity.

Spectroscopic techniques for the measurement of plasma jet temperatures in air have been described by Hotte! et al. (50), Dickerman and Morris (123), and Pearce (124). Watson et al. (125), working with an argon plasma jet at Mach 2.5, measured axial electron and ionic translational temperatures along the jet using spectroscopic means and an electrode probe for the measurement of electron temperature and density. They found pockets of gas with a high electron temperature regularly leaving the plasma generator, probably due to the intermittency of the arc process. Since they were operating at a low pressure of about 2 mm. of mercury, thermal equilibrium conditions did not exist. Temperature determinations in nitrogen plasma jets have been carried out by Cremers and Pfender (126), Ryan et al. (127), and Brewer et al. (128). In general, the temperatures measured depended on the technique used due to the large temperature gradients present, and because the methods of measurement are based on a different averaging effect along the optical path. In some of the reported cases, the recorded intensities and temperatures may be too high because the arc column makes a hairpin turn upon leaving the nozzle and reattaches near the nozzle exit at high flow rates (121, 126).
Fishburne (129) found that thermal non-equilibrium is more likely to exist in such a case in regions near the nozzle than if the arc process takes place entirely inside the nozzle.

Garkavyi and Yasko (130), and Tikhomirov and Varlamov (131), in the U.S.S.R., have carried out semi-empirical analyses of the arc process to predict axial and radial temperature profiles, heat loss through the nozzle walls and the distribution of current over the nozzle lengths.

It has been found (92) that the efficiency of a plasma generator decreases with increasing pressure. Whereas the efficiency may be about 70 percent at 1 atm., it will decrease to about 15 percent at 100 atm. This is due both to increased convective and radiative heat losses, and may prove to be a fundamental limitation on the production of high pressure plasma jets.

Radiation losses in argon plasma jets at temperatures up to 20,000 °F. were found by Sherman et al. (132) to be about 12 percent of the net power input. Similar results were obtained by Tankin and Berry (133). Marlotte et al. (134) have related the radiation loss to the power loss to the wall. For argon, this ratio reaches 35 percent under typical operating conditions, but only 7 percent for nitrogen. The higher figure for argon is due to the fact that, for the same power input, its temperature is much higher than that of nitrogen due to the latter's greater specific heat. Whereas the heat causes dissociation of nitrogen before ionization, argon ionizes and, in that state, emits large amounts of heat by radiation. Simple analytic expressions and
similarity parameters were derived for describing this radiation loss. John et al. (111) tabulated the radiated power per unit volume of hydrogen, nitrogen, oxygen and air as a function of temperature and pressure. The value of this loss increases from hydrogen to air in the order given, by about four orders of magnitude at 5000 °K. and 1 atm.

AEROSPACE APPLICATIONS

The rapid development of plasma jet technology has been spurred primarily by the urgent need for experimental units capable of evaluating ablative materials under simulated atmosphere re-entry conditions of ballistic missiles. The plasma jet is well suited for such studies since it can provide sustained heat flux, pressure, composition and enthalpy conditions similar to those encountered in re-entry. Because of throat erosion problems and arc chamber pressure limitations, however, arc-heated wind tunnels are limited to operation at Mach numbers of less than 8 (92). The development of an arc-heated subsonic nitrogen wind tunnel for measurement of heat transfer in tubular test sections and nozzles has been described by Ghal and associates (135-137). Hypersonic tunnels designs and problems have been presented by Bunt and Olsen (138), and Stine (139).

It has been found in the course of plasma jet development that this device has potential as a low-thrust space engine. Its specific impulse, ranging from 1000 to 2000 sec. would make it suitable for missions being conducted outside the gravitational influence of planets (92). For such applications, however, electrode life must be extended, and less bulky cooling systems
developed (140). According to Hendel (141), specific impulses of 15,000 sec. are possible by using magnetic fields to minimize heat loss to the walls and also by accelerating the plasma jet. Of all the proposed electrical propulsion systems, the plasma jet appears to be closest to a workable rocket.

MATERIAL PROCESSING AND FABRICATION

The plasma jet has found an ever-increasing use in metal-working plants and in high temperature fabrication in recent years, due to its stable operation, ease of control, freedom from combustion products and, of course, its ability to achieve high temperatures.

It is now possible to cut five-inch thick aluminum plates, as well as four-inch thick stainless steel, copper, magnesium and other metal plates using a transferred-arc argon-hydrogen jet (142). The speed of cutting by this means is much greater than that obtained by any other method now in use, while the quality of cut surfaces equals that produced in the oxygen-cutting of mild steel (143). An additional advantage is that plasma-arc cutting can be used with metals such as aluminum and chromium without formation of refractory oxide surfaces, by shielding with an inert atmosphere of argon or nitrogen.

In welding applications, the transferred-arc moves along the joint and the plasma jet, shielded from the atmosphere, melts a seam which cools and solidifies as the torch moves away. Irons and Regan (144) have compared the high-speed welding techniques of transferred-arc, high-frequency heating, ultrasonic and electron-beam methods. They conclude that the transferred-arc
Involves the lowest capital investment, and is the most versatile of the methods considered, although it is not the fastest.

The plasma jet spraying process permits the rapid deposition of a refractory coating on a cold surface. Solid material may be introduced into the jet in either powder or wire form. When fine powder is used, the individual particles melt into spheres in the spheroidizing step (145) and are accelerated to a velocity nearly that of the gas stream. With a wire, molten droplets are sheared off by the high-velocity gas to form a fine spray. The molten particles then collide with the cold workpiece where they flatten out and solidify into a coating. The principal advantage of this technique lies in the ease with which temperature and atmosphere can be controlled. This feature is most important where the coating material is sensitive to oxidation or other chemical changes which occur in combustion or in air (146, 147). In plating with tungsten, for example, with its high melting point of over 6000 °F, and the ease with which it is oxidised, no problems exist during operation of the plasma jet with pure argon (148). Mash et al. (149) have reviewed some of the process variables involved in spraying, such as particle size and spraying rate, and plasma jet conditions. Engelke (150) and Meyer (151) have studied the heat transfer to, and melting of, fine particles in a plasma jet. They both found that melting is not directly related to the melting point of the material. Meyer ascribes this to the fact that the ion-to-atom and atom-to-molecule recombination processes, which release a large amount of energy, are catalysed by only some powders. Engelke, on the other hand, in his more analytical approach, considered the heat
conduction process through the boundary layer of gas around the particle. He found that the parameter \((L_m \rho^{-0.5})\), where \(L_m\) is the heat content per unit volume of the particle in its liquid state at its melting point and \(\rho\) is the density of the particles, may be used to determine the relative ease of melting of particles of similar size in the same plasma jet. For example, tantalum carbide, with the comparatively high melting point of about 7000°F., has a lower melting parameter than many powders with lesser melting points, and is thus sprayed with more success.

The plasma jet may be used also to test the effectiveness of these coatings deposited on various materials. Trout (152) reports an exploratory investigation of several coated and uncoated molybdenum, graphite and refractory models in a low-enthalpy air plasma jet at Mach 2, a stagnation temperature of 3800 °F., and for exposure times of up to 60 sec. Coatings of silicon carbide, zirconium boride and siliconized boron greatly increased the oxidation resistance. Peters and Rasnick (153), working with molybdenum and graphite, obtained similar results. Thus it is not only in the spraying of materials that the plasma jet is finding an important role, but it is also in the evaluation of materials that its unique capabilities are being exploited.

**CHEMICAL APPLICATIONS**

Shortly after the turn of the century, Birkeland and Eyde developed an industrial process for the synthesis of nitric oxide from air using an electric arc. This process was discussed in a paper by Edstrom (154) and was used in Norway, where electric
power was particularly cheap, until it was superceded by more efficient and economical processes such as the oxidation of ammonia. It was not until commercial plasma generators became available in the last ten years that interest in the possibilities of chemical processes utilizing this device grew to its present level.

Formation of compounds using a plasma jet may be considered to occur in two steps. The first of these is the dissociation, ionization, or the formation of free radicals and activated atoms in the jet and the attainment of the chemical equilibrium at the high temperature. The second step consists of the freezing of the reaction product composition by fast quenching methods. It is the formation of simple endothermic compounds that is favoured at high temperatures while exothermic compounds are decomposed. The plasma gas may itself take part in a reaction or act only as a heat source. Similarly, electrodes may be consumable, in which case they introduce reactants into the plasma stream, or non-consumable. Reactants may also be fed into the jet in the form of powders.

Phillips and Ferguson (155) have reviewed some of the factors involved in the synthesis of acetylene and nitric oxide in a plasma jet. Marynowski and his active group of workers (156) at the Stanford Research Institute have considered the thermodynamics of the hydrogen-carbon-nitrogen ternary system as a potential high temperature process for the production of hydrogen cyanide. The applicability of the data for evaluation of the three binary systems, C-H, N-H, and C-N is also discussed. Duff
and Bauer (157) have calculated the equilibrium composition of the C-H system at temperatures up to 5000 °K., and pressures of 0.1, 1.0 and 10.0 atmospheres. Cowperthwaite and Bauer (158) have listed experimental and estimated values for the heats of formation of the molecular fragments encountered in the high temperature pyrolysis of hydrocarbons. Shih et al. (159) have considered the species extant in the carbon-nitrogen vapour system and, using spectroscopic data, have computed the thermodynamic properties of the system. The availability of such thermodynamic properties and composition data will aid greatly in the synthesis of materials at high temperatures.

Grosse, as President of the Research Institute of Temple University in Philadelphia, has been in the forefront of high temperature chemical research. In the past, his main area of interest was the chemical production of high temperatures (15), but he has now turned his attention to the synthesis of gases such as acetylene and cyanogen, and solid materials such as refractory nitrides and carbides. Progress reports of these studies are available (160, 161). Stokes (162) has recently reviewed some of the reactions investigated.

Leutner and Stokes (163) have described several methods for the production of acetylene. These include the feeding of powdered carbon into a hydrogen plasma jet, the conversion of methane and the cracking of kerosene in an argon plasma jet. The first technique was fairly unsuccessful since most of the carbon was deposited as a fine soot. The conversion of methane to acetylene in argon was 80 percent, and 18 percent yields of acetylene were obtained from kerosene. Baddour, in collaboration
with Iwasyk (164) and Blanchet (165), has investigated reactions between carbon vapour, from a consumable graphite anode, and hydrogen and methane. With hydrogen, a maximum concentration of 26 percent acetylene was obtained. A methane feed raised this figure to 52 percent. Parent and Blanchet (166) have continued this study with ethane and propane. Bond et al. (167) have decomposed coal in a pure argon plasma jet, with a 20 percent conversion to acetylene. The addition of 10 percent of hydrogen increased this to 40 percent. Graves, Kawa and Hiteshue (168) conducted similar experiments with a highly volatile bituminous coal. A gas containing hydrogen, methane, carbon monoxide, 15 weight percent acetylene, and diacetylene was obtained.

Freeman and Skrivan (169) have shown that the cracking behaviour of ammonia and methane in a tube-confined plasma jet is diffusion-controlled. Anderson and Case (170) have used available thermodynamic and kinetic data to predict the reaction of methane with a hydrogen plasma jet. They have demonstrated that 90 percent conversion to acetylene is possible. This agrees with the figure obtained by Gulyaev et al. (171), in the U.S.S.R. Heaston (172) has investigated methane decomposition and methane-steam reactions in an argon plasma jet. In the first case, a 75 percent yield of acetylene occurred, and in the second, a 70 percent yield of carbon monoxide. Stokes et al. (173) have shown that the radio-frequency plasma jet may also be used in chemical synthesis. The decomposition of methane to acetylene yielded only a 28 percent conversion, compared to the 80 percent obtained with the direct current jet (163).
Tsentsiper et al. (174) have carried out a comparative study of reaction kinetics in the batch conversion of various hydrocarbons to acetylene in an electric arc. They found that ethane, propane, ethylene and propylene gave higher yields of acetylene than did methane. Asaba, Yoneda and Hikita (175) pyrolysed ethane in a shock tube. Ethylene was the main product at temperatures below 3000 °F. Above this temperature, the yield of acetylene increased to 35 percent and higher, while methane was formed to the extent of about 10 percent. Sennewald and Schallus (176) report the conversion of benzene vapour to a 75 percent yield of more or less equal amounts of acetylene and ethylene. Il'in and Eremin (177, 178) have investigated the pyrolysis of gasoline in a plasma jet. In the presence of hydrogen, volume percents of about 6, 9 and 9 percent of acetylene plus homologs, olefins and paraffins, respectively, were obtained. In a water-vapour plasma jet, volume percents of 11, 19 and 16 percent respectively were produced.

Leutner (179) has described the production of cyanogen in a direct current torch using a consumable graphite cathode and nitrogen feed gas. Conversions up to 15 percent were obtained, based on carbon input, at power levels from 9 to 12 kw. Unconverted carbon was collected as a fine soot, and it was found that fast quenching decreased the cyanogen yield drastically. It was felt that this was due to too short a reaction time or to the catalytic decomposition of cyanogen in the copper cooling funnel. The lowering of yield with a cooler was also noticed in the production of hydrogen cyanide (180). Using a consumable carbon cathode, a nitrogen plasma jet, and adding hydrogen, a conversion
of over 50 percent to hydrogen cyanide and 14 percent to acetylene was obtained, based on carbon input. By replacing the hydrogen with ammonia, the hydrogen cyanide and acetylene yields changed to 39 and 18 percent respectively. The reaction between methane, nitrogen and carbon yielded more acetylene and less hydrogen cyanide. When a mixture of methane and ammonia were fed into an argon plasma jet, there was still more acetylene formed than hydrogen cyanide. In a nitrogen plasma jet, however, yields of 50 and 20-30 percents were obtained, with hydrogen cyanide as the predominant product. Using the radio-frequency torch (173) with a feed of nitrogen and methane, lower yields occurred.

Stokes (162) has described attempts to improve the process for the fixation of nitrogen as nitric oxide. Typical conversions in previous processes including the radio-frequency torch have been around 2 percent. Increases have been accomplished by using a high concentration of reactants (i.e. using a nitrogen plasma jet), and by cooling very rapidly the reaction products in a large vacuum chamber. In this way, consistent conversions of 10 to 12 percent were obtained and Stokes is predicting a 20 percent fixation. Grosse et al. (160) produced traces of hydrazine (N₂H₄) when hydrogen was fed into a nitrogen plasma jet, but no ammonia since it is an exothermic compound. Stokes and Streng (181) have synthesized ozone by a technique involving a liquid oxygen-quenched helium plasma jet. Yields of 0.46 weight percent and production rates of 1.17 lb. per hr. of ozone have been obtained at power levels up to 10 kw.

Baddour and Bronfin (182) report the production of
tetrafluoroethylene by the reaction of carbon with carbon tetrafluoride in an electric arc. The high-intensity arc was struck between two graphite electrodes through one of which the tetrafluoride was fed. The other electrode was also hollow and had inserted through it a small sampling quench probe. At the pressure of 0.1 atmosphere and the power level of 17 kw., 69 mole percent of the feed was converted to tetrafluoroethylene. Additional fluoro-carbon gases were observed in small concentrations.

The plasma jet also provides very intense radiation whose spectra may be adjusted by choice of arc gases. Papp (183) has discussed some of the uses of plasma as a source in photochemical reactions. These include the polymerization of solid rocket propellant binders and the production of ozone. The potential of this technique in polymerization without catalysts certainly deserves close attention.

The activation of plastic surfaces in a non-equilibrium oxygen plasma jet is treated by Mantell and Ormand (184). The gas is partially dissociated by a glow discharge, expanded to high velocity through an orifice, and impinged on the surface. Parameters affected are surface-bonding characteristics and wettability.

Grosse and co-workers (185) have described the construction and operation of a furnace consisting of a centrifugally-rotated horizontal tube of liquid alumina or thoria in which materials can be heated to over 10,000 °F, by an argon or helium plasma jet. Such a furnace is suitable for the containment of liquids and study of chemical reactions at temperatures far higher than the melting points of conventional materials of construction, or of refractory materials. The central gas or vapour phase is
closed by layers of liquid metal such as aluminum, liquid oxide, solid oxide and high-porosity insulation. The authors suggest the development of a centrifugal nuclear reactor, consisting of a light uranium alloy floating on a crucible of liquid thorium. Hydrogen would be bubbled radially into the reaction zone, and would dissociate to form an exhaust of high energy for use as a rocket engine.

Warren and Shimizu (186) have made a review of some of the applications of plasma technology in extractive metallurgy, with particular reference to the spraying of powders in a plasma jet. They have also attempted to volatilize several minerals in a radio-frequency plasma jet but have found it is easily extinguished. This was due to the fact that the cooling of the plasma by the particles decreased the ion concentration and thus terminated the induction-heating process. They expressed the opinion that, if no way can be found to increase the utilizable enthalpy of the radio-frequency generated plasma, its value as a research and process tool will be very limited.

Stokes and Knipe (187) have prepared titanium nitride by injecting the metal powder into a nitrogen plasma jet. Refinements have increased yields to 100 percent. Harnisch et al. (188) have obtained similar yields by treating titanium tetrachloride gas with an ammonia or nitrogen-hydrogen arc-heated stream. The conversion of tungsten to its nitride in a nitrogen plasma jet has meanwhile only reached 25 percent (162). Correa and Stokes (189) have produced tantalum carbides by the treatment of tantalum pentoxide and tantalum powder with methane. Total yields of TaC
and Ta₂C obtained were up to 46 and 86 percent in the two cases respectively. In a similar study with tungsten trioxide (190), the best conversion to WC and W₂C occurred with tungsten powder in the sub-micron size range to the extent of 50 percent. In these investigations, tantalum pentoxide and tungsten trioxide were also reduced with hydrogen. Conversions to the metals of 43 and 95 percent respectively were obtained. Attempts to reduce aluminum oxide proved unfruitful (162) because the high heat of formation of alumina required the use of faster quenching methods than those available. Kursch (191) reports a promising technique, still in the development stage, of feeding pressed tablets of metal oxide and carbon into an electric arc through hollow electrodes for the production of metals such as magnesium, aluminum and iron.

Gibson and Weidman (192) have described the formation of uranium carbide spheres from a consumable uranium dioxide-carbon electrode. Jones et al. (193) have spheroidized particles of plutonium dioxide and mixtures of the dioxide of plutonium, uranium, thorium and zincconium in a radio-frequency plasma torch. Selover (194) has described the properties of nickel fume generated in a direct current plasma jet from nickel carbonyl, and has established the influence of the plasma in the creation of a high surface energy characteristics.

Papp (195) has discussed steam reforming with methane to carbon monoxide and hydrogen, and the reduction of phosphate rock with hydrogen to elemental phosphorus as potential plasma-arc processes. Among other reactions being considered are the
oxdation of propylene and ammonia to form acrylonitrile, and the direct oxidation of benzene to phenol.

It can thus be seen that the field of chemical synthesis in plasma jets is growing at a fast rate. Some reactions cannot as yet be successfully carried out and await the development of fast quenching techniques such as the fluidized bed (43, 196, 197). Much of the research in the field is being conducted by large industrial concerns without any publication of results. The next decade will see not only the synthesis of many new compounds using high temperature techniques, but will also herald a new era of miniaturization of existing processes and the putting into production of new ones by means of plasma generators.

MISCELLANEOUS RESEARCH

There are many investigations in the plasma jet field of interest to engineers which were not specific enough to fit into any of the previous sections. Of these, some of the most significant are studies of the heat transfer from a plasma jet to cold confining walls, which is of paramount importance in many of the chemical processes discussed. Heat transfer studies in hypersonic gas streams, however, will not be discussed since this review is more concerned with chemical processing at low velocities, which are far more prevalent. Rosner (196) has listed the papers presented and published by the Aero Chem Research Laboratories of the U.S.A.F. dealing with energy transport in supersonic, low-temperature, non-equilibrium plasma streams. Grey (51), in reviewing thermodynamic methods of high temperature measurement with probes quantifying heat flux across a calorimetric surface,
has dealt with the theory of stagnation-point heat transfer in hypersonic dissociated and ionized gas flows. Fay and Riddell (199) have developed the now-classical theory of stagnation-point heat transfer in dissociated air, and Fay and Kemp (200) have extended this to the case of a partially-ionized diatomic gas. The plasma jet has been used as a heat source to test the validity of the correlations developed (92).

Emmons (201) has summarized some recent developments in plasma heat transfer in an elongated section of the nozzle through which the arc is made to pass. Of particular interest are his discussions of helium gas properties at high temperature, and the measurement of pressure drop and heat transfer in the test section. From the voltage-current characteristics were obtained experimental mean kinematic viscosity and conductivity values for the system. An analytic treatment is also presented to predict quantitatively the arc behaviour, using several simplifying assumptions such as the existence of local equilibrium and simplification of gas property variations.

Churchill and co-workers (202) have compiled a report of progress in plasma engineering at the University of Michigan. Chludzinski (203) has studied heat transfer from a radio-frequency argon-nitrogen plasma jet to thermocouple introduced into it for short periods of time. Smith (70, 204) has investigated the simultaneous heat and material transport between a confined direct-current argon plasma jet and a nitrogen coolant stream by measurement of temperature spectrographically, and velocity and composition by means of a calorimetric sampling probe. Plans have been
made to study the photochemical effects of plasmas, and kinetics of chemical synthesis in a plasma jet.

Grey and his co-workers at Princeton University (205, 206, 207) are conducting a continuing programme of study into the fundamentals of the mixing process between a plasma jet and a dissimilar coolant gas stream, a study which is related to that of Smith at the University of Michigan.

There have been a number of studies involving the flow of a plasma jet through a cooled tube. Cassidy et al. (137) used nitrogen at temperatures up to about 2000 °F. and found a strong dependency of local heat transfer upon the distance from the entrance, or aspect ration (L/D). Bro and Steinberg (208) worked at about 6500 °F. and found that the standard correlation for fully-developed turbulent pipe flow predicted heat transfer rates within 20 percent eight diameters or more from the inlet, but upstream, heat transfer rates were as much as 45 percent higher than those predicted. Wethern and Brodkey (209) investigated heat and momentum from a laminar helium plasma jet inside water-cooled tubes. Although the Reynolds numbers were well below 2100, the assumption of laminar flow may not be valid due to the intermittency of the direct-current arc process and disturbances in the tube boundary layer in which large temperature gradients and hence convection currents exist. The heat transfer correlation obtained includes the effect of downstream distance:

\[ \text{Nu} = 0.049 \text{ (Re)}^{1/3} \text{ (Pr)}^{1/3} \text{ (L/D)}^{-1/2} \] (10)

Skrivan and von Jaskowsky (210) conducted their studies with
nitrogen, hydrogen and argon in the Reynolds number range of 400 to 3500, at inlet temperatures as high as 11,000 °F. and velocities up to 2000 ft/sec. The following correlation best fitted the data:

\[
Nu = 9.5 \times 10^{-3} (Re)^{1.25} [(L + L_n)/D]^{-1.67} (k/k_s)^{0.4}
\]  

(11)

where \( L_n \) is the torch nozzle length. The Reynolds number is evaluated at the mixed-mean temperature at the inlet, and the gas properties, other than \( k_s \), are based on the mixed mean temperature at the point where the local Nusselt number is being computed. The thermal conductivity ratio corrects for the large temperature gradients at the wall and brings about a single correlation for the various gases employed. The aspect ratio accounts for the boundary layer growth.

Raeison and Dickerman (81) found that the application of a magnetic field with the comparatively high field strength of 19500 gauss lowered the heat transfer rate from plasma jets at power levels of up to 1300 kw. by only about 15 percent. The authors feel that the gas flow-magnetic field interaction takes place in the region of steep thermal gradients near the wall.

It may be seen from the large number and vast range of investigations in the plasma jet field that, although experimental studies far outnumber analytic studies, much work remains to be done both in the fundamentals of plasma generation and on the applied side of this relatively new technology.
IV. PROPERTIES OF CONFINED JETS

INTRODUCTION

Formation of a jet occurs when one stream of fluid discharges into stagnant surroundings (free jet), or into a larger stream moving at a lower velocity (submerged jet). A jet discharging into an enclosure is called a confined jet. When the Reynolds number of the jet, based on its width and relative velocity, is sufficiently high, the jet becomes turbulent. Of the recent texts published in this field, the most noteworthy is that by Abramovich (211) on the theory of turbulent jets. Krzywoblocki (212), and Seddon and Dyke (213), have compiled extensive bibliographies on jets in 1956 and 1964 respectively and divided them into sections to facilitate their use.

Forstall and Shapiro (214) have discussed the principal types of analytical approaches to the jet-spreading problem, and have also included a bibliographical chart of analytical and experimental work performed with jets prior to 1950.

Since free jets issue into an atmosphere of constant pressure, and the viscous shear at the boundaries is zero, a total momentum balance may be used as a starting point in its analysis. Another widely-used method of describing mathematically the behaviour of a jet is the differential momentum balance by means of the time-averaged Navier-Stokes equation in the direction of flow, neglecting viscous forces. An alternative approach is to adopt the boundary layer form of the Navier-Stokes equation (243). Fluctuating components of velocities are then approximated in
terms of velocity gradients by the use of transport theories, such as the Prandtl mixing-length theory. An integral momentum balance offers another starting point in the prediction of velocity profiles in the jet. The differential energy and diffusion equations may be used if temperature and concentration profiles are being considered.

The analytical approach to the problem of a free turbulent jet has been described by Abramovich (211a), and Hinze (215) for the estimation of velocity, temperature and concentration profiles. Both quote experiments conducted with tracer gas at temperature differentials and concentrations sufficiently small to exclude density effects, to show that the spread of heat and mass are mutually identical, and much greater than that of momentum. Hinze (215) also reviews measurements of mean velocities and temperatures, and of turbulence parameters that have been reported in the literature.

Cleeves and Boelter (216) reviewed theoretical analyses of velocity and temperature distributions in free turbulent gas jets, and presented radial and axial temperature and velocity profiles for non-isothermal air jets with initial temperatures of 1200 °F. The radial profiles for distances of more than two diameters from the nozzle agreed well with the theoretical solution based on the point-source diffusion model. It was found that the same profile was obtained for velocity and temperature measured at different axial positions when the dimensionless quantities were plotted against the ratio of the local radius divided by the radius at which the dimensionless velocity or temperature were one-half the value at the jet axis, at the same
Coaxial isothermal gas jets have been investigated by Squire and Trouncer (217), Forstall and Shapiro (214), and Forstall and Gaylord (218). The last two papers also include mass transfer effects. Submerged jet analysis brings in an external boundary condition due to the presence of the secondary stream, and requires the assumption of an axial velocity profile. The general velocity profile is then dependent on the secondary stream velocity:

\[
\frac{u}{U_1} = f\left(\frac{x}{R_1}, \frac{r}{R_1}, \frac{U_2}{U_1}\right)
\]

(12)

where \( u \) is the local velocity, \( U_1 \) and \( U_2 \) the jet and secondary velocity respectively, \( r \) the local radius, \( x \) the axial distance, and \( R_1 \) the radius of the jet.

**THE CONFINED JET**

When a submerged jet is enclosed in a tubular region with a solid boundary at a distance \( R_2 \) from the axis, the system is called a confined jet. The flow near the source still approximates that of a submerged jet, but the presence of the wall in the developing region brings in a Reynolds number effect:

\[
\frac{u}{U_1} = f\left[\frac{x}{R_1}, \frac{r}{R_1}, \frac{R_2}{R_1}, \frac{U_2}{U_1}, \frac{U_2 \rho}{\mu}\right]
\]

(13)

The presence of the confining walls alters the flow from a constant momentum to a constant mass flow since the condition of constant pressure is no longer valid. The high velocity jet stream mixes with the secondary stream, transferring some of its kinetic energy to pressure energy in the mixture. The pressure term must thus be included in the equations of motion. In addition,
when the spreading jet reaches the wall, the system becomes one of complex shear flow and can no longer be considered a jet.

The confined jet is sometimes characterized by the phenomenon of recirculation. According to Abramovich (211b), mixing in a confined system of this type results in a pressure rise which retards the ambient flow and thus the momentum to zero, if large enough, and recirculation results.

Several attempts have been made to establish a criterion for the prediction of the presence of recirculation and to characterize the system with regard to rate of recirculation. Thring and Newby (219) developed a similarity parameter based on the premise that the primary jet spreads from a point source as if it were a free jet and obtained the following dimensionless group:

\[
\left[\frac{(\rho_1 Q_1)}{(\rho_1 Q_1 + \rho_2 Q_2)}\right]/(R_2/R_1)
\]

where \(Q\) is the volumetric flow rate.

Curtet and co-workers (220-223) have been studying isothermal confined jets for more than a decade, and have contributed significantly to the problem of recirculation. A model was developed, which was based on the simplifying assumptions that wall friction and radial pressure gradients are negligible, velocity profiles are similar before the jet spreads to the wall, and that the profile of the axial component of velocity is uniform and non-turbulent outside the mixing region. After integration of the equations of motion across the tube, the ratio \((R_2/R_1)\), and a momentum parameter \(m\) appeared, where:

\[
m = \left[\left(\frac{\gamma R_2^2}{Q_1^2}\right)\int_0^{R_2} (u^2 - U_2^2/2) 2\pi r \, dr\right]^{-1/2}
\]

(14)
It was found that this quantity $m$ was a constant of the flow, with initial value at the point of entry of the jet of

$$m_0 = \left[ \frac{R^2(U_1^2 - U_2^2) + U_2^2 R_2^2}{(Q_1/\pi^2 R_2^2)} \right]^{1/2}$$  \hspace{1cm} (15)$$

This parameter $m_0$ was useful not only in predicting the onset of recirculation, but also in characterizing flow patterns in a confined jet system.

Becker et al. (224) have carried out an intensive investigation into mixing and flow in ducted turbulent jets. In the analysis is derived a more useful form of $m_0$, which was given the name of Craya-Curtet number:

$$C_t = m_0^{-0.5} \hspace{1cm} (16)$$

Becker et al. found that recirculation exists for $C_t < 0.75$. The experimental part of the study consisted of the mapping and analysis of the mean velocities and concentrations of the turbulent confined jet. The properties of the recirculation eddy were characterized in terms of the Craya-Curtet number. The locations of the eye and the boundary of the eddy, the rate of circulation of fluid around the eddy, and the concentration patterns within the eddy were depicted in this way.

Peters and Wehofer (225) used a central supersonic jet of rocket exhaust gases initially at about 5000 °F., surrounded by a ducted secondary air stream at 1200 °F. A simplified theory predicted with fair accuracy the experimental axial static pressure and velocity distributions. Bouloucon (226) carried out measurements in the region of the confined jet upstream of the point where the jet had spread to the full duct width. The
experimental results for heat and momentum transfer were compared with theoretical predictions based on the simplified boundary layer equations using an exchange coefficient hypothesis. It extended the conclusions for free and submerged jets (211a, 214, 215) that the scalar transport of heat and mass are identical, and that both are greater than the momentum transport for small temperature and concentration gradients.

Dealy (227) describes an experimental study of the effects of turbulence in the jet source, at a relatively small ratio of duct-to-jet diameters, on the applicability of models which have been developed for simpler confined jets. He found that the flow near the source is very dependent on the jet Reynolds number, and that similar velocity profiles develop more rapidly than with the equivalent uniform jet source, because of the larger turbulent stresses involved. Dealy also confirmed the critical value of \( C_t = 0.75 \) for the case of the larger duct-to-jet diameter ratios, but noted that, with larger jet tubes \( (R_2/R_1 = 2) \), the jet did not develop similarity before reaching the wall and the \( C_t \) criterion no longer applied.

Hill (228) has predicted the behaviour of confined jets using empirical data on turbulent free jets. For flows in which the confining walls have significant effects, and before the jet spreads to the wall, the assumption of self-preservation of both velocity and turbulent shear stress is very useful. Downstream of this, only the shear stress is approximately self-preserving. He has also shown that the static pressure is fairly uniform through the recirculation region.
Stelmakh (229) has carried out an experimental investigation of the heat transfer between an axisymmetric gas jet and the walls of a cylindrical chamber. Recirculation occurred since there was no secondary stream, for which case the Craya-Curtet number reduces to:

\[
Ct = R_1 \left[ \frac{2}{(2R_2^2 - R_1^2)} \right]^{0.5}
\]  

For low temperature differences of about 100 °F., and a Reynolds number (based on the chamber diameter) range of 200 to 10,000, he obtained an empirical expression for the average heat transfer:

\[
Nu = 11.1 (Re)^{0.75} (Pr)(D_2/L)(D_1/D_2)^{0.25}
\]

The effect of different flow patterns on the gas temperature-field and wall-flux distribution in a cylindrical furnace has been examined by Hottel and Sarofim (230) for various flow models, including ducted-jet flow with recirculation rates of 0, 1 and 11 times the flue-gas rate. The study emphasizes the need to include allowance for gas temperature variation in furnace analysis.

**SUBMERGED AND CONFINED PLASMA JETS**

In the consideration of plasma jets, the effects of high kinematic viscosity and thermal conductivity must be taken into consideration. Thus, in the momentum and energy equations, those terms which reflect the influence of viscosity and thermal conductivity and were neglected at low temperature may become significant at high temperature. Fluctuations of these quantities may also have to be included, as well as the radiant heat term in the energy equation. In the core of the jet, molecular transport
predominates, while in the mixing region, where turbulence levels are large and the temperature is generally lower, it is the turbulent and not the molecular transport that is important.

Abramovich (211c) has derived the momentum and energy equations for high temperature systems which include the coefficients of molecular viscosity and thermal conductivity, and the radiant energy loss. If the variations of these quantities with temperature are substituted into the equations, along with some model of turbulence, it is possible to obtain the velocity and temperature profiles in the jet.

Grey and co-workers (205, 206) have carried out analytical and experimental studies of the axially-symmetrical turbulent mixing of a subsonic argon plasma jet with an annular cool helium stream. The system was confined in a large square duct, which configuration may have led to some recirculation effects. Concentration was found to spread more rapidly than temperature, and temperature more rapidly than momentum as predicted by the theory. A potential core, one jet diameter in length, was observed for all three of the above variables. The axial decay of concentration, velocity and temperature profiles was found to be much more rapid than that obtained in previous isenthalpic cases studied, probably due to the large concentration and enthalpy gradients and high turbulence levels present. Experimentally-determined profiles of concentration, velocity and temperature in the mixing region were similar, which supports the use of similarity assumptions in plasma jets. The Grey calorimeter probe (68, 69) was used extensively in this investigation, and should not cause errors due to cool boundary layer effects in the
temperature measurement in the jet core, but the results in the mixing region may be doubtful. The probe was also used in the velocity determination without the use of the density correction suggested by Smith (70), so that the velocity results are likely to be a little high. Grey et al. (207) have also investigated the mixing and heat transfer characteristics of a laminar subsonic argon plasma jet into a cool stagnant helium atmosphere. A cooled electrostatic probe was used to confirm the departure from thermal equilibrium in regions of the highest temperature gradient. Smith and Cambel (231) have presented the solution to the two-dimensional subsonic laminar jet of a compressible fluid with a Prandtl number of unity. In addition, a perturbation technique was used to solve the system of an electrically-conducting fluid with an applied transverse magnetic field.

Smith (70, 202), at the University of Michigan, has studied the mass and energy transfer between a confined, 3 kw. direct-current, argon plasma jet and a cool annular nitrogen stream. The temperature profiles in the mixing region were determined by spectroscopic means, specifically the argon electron-excitational and nitrogen rotational temperatures. The compositions and axial velocities (corrected for density effects) were obtained with a calorimetric probe, but its measurements of enthalpy were found to be unreliable. The measured nitrogen temperatures were found to be much lower than the argon temperatures present at the same point in the flow. Smith feels that this is because the argon atoms are unable to give up their translational energy directly to the rotational modes of the nitrogen
molecules. The Craya-Curtet numbers were calculated for the system. To allow for the large temperature gradients involved, the velocity terms were multiplied in equation (15) by the related density. For the range of $0.43 \leq C_t \leq 0.52$ investigated, the recirculation phenomenon was found to be important. It was also found that the turbulent diffusion process controlled the mixing of the plasma and coolant streams.

In applying the results of these studies to the behaviour of reactants injected into a plasma jet, it must be concluded that the mixing process is very rapid but that the internal energy modes of the reactant molecules may not be able to utilize the full energy available from the plasma due to the short residence times in the comparatively high velocity flow, characteristic of the core region of direct-current plasma jets.
V. FORCED-CONVECTION HEAT TRANSFER TO SPHERES AND CYLINDERS

INTRODUCTION

Convection is a process by which heat is transferred between a surface and a fluid, and may be regarded as conduction within parts of the fluid in relative motion. Convection may be natural or forced. When a temperature difference exists between a solid surface and a fluid, natural convection effects arise by virtue of the density difference which creates a buoyancy force on the fluid within the boundary layer. In forced convection, the fluid motion is generated by forces independent of the temperature of the fluid, such as externally-imposed pressure differences or agitation. Buoyancy forces are often neglected in forced convection since they are usually of much smaller magnitude than the external forces.

To provide a complete survey of the vast topic of heat transfer would be extremely tedious, and for diverse reasons many studies which are only superficially pertinent have been omitted from consideration. In particular, the extensive literature available on simultaneous heat and mass transfer is discussed only where the two processes cannot be separated and where inclusion serves to elucidate the specific aspects of heat transfer being described. The reader is referred to some excellent texts on the earlier work performed in this field (232, 233, 234).
GENERAL CONCEPTS

Theoretical predictions of the conduction heat transfer rate to a sphere immersed in an infinite stagnant fluid, at zero Grashof number, requires that the Nusselt number for heat transfer, or the Sherwood number for mass transfer be equal to 2.0 (235). This, the Langmuir conduction model, has been verified extensively (236, 237). Most of the transfer data for spheres and cylinders that have been reported in the literature are correlated in the form of the Nusselt number (Nu), corresponding to the overall heat transfer coefficient, Prandtl number (Pr) and Reynolds number (Re) of the stream. For relatively low Re, with negligible natural convection effects, these take the following form (238-241):

\[ \text{Nu} = a + b(\text{Re})^p(\text{Pr})^q \]  \hspace{1cm} (19)

The values of a for a sphere and cylinder are 2.0 and 0.32 respectively, while the exponent p for laminar boundary layer flows about a sphere is 0.5; McAdams (241) lists values of p for cylinders, and shows that p increases with Reynolds number, but has a value of 0.52 for \( \text{Re} < 1000 \). From a theoretical analysis of mass transfer, Froessling (239) has shown that q has the value of 1/3 for large Prandtl numbers. The corresponding equation for mass transfer replaces Pr by the Schmidt number (Sc):

\[ \text{Sh} = a + b(\text{Re})^p(\text{Sc})^q \]  \hspace{1cm} (20)

The use of the 1/3 exponent on \( \text{Pr} \) and \( \text{Sc} \) has been confirmed by Linton and Sherwood (242), for tubes, cylinders, spheres and plates.

During the past century, developments in analytical
approaches and mathematical techniques have made possible innumerable investigations in the fields of momentum, heat and mass transfer, by means of the fundamental equations of motion, energy and continuity. The Navier-Stokes equation describing the motion of an element of fluid in space can be stated precisely in a vectorial form for incompressible flow at constant viscosity as follows:

\[
\frac{DU}{D\theta} = F - \left(\frac{1}{\rho}\right)\nabla p + \nu \nabla^2 U
\]  

(21)

where \(\frac{DU}{D\theta}\) is the total derivative of the velocity vector \(U\) with respect to time and \(F\) represents any body force such as gravity, buoyancy or centrifugal force. The continuity equation associated with equation (21) may be written:

\[
\nabla \cdot U = 0
\]

(22)

The corresponding energy equation for constant thermal conductivity and pressure is given by:

\[
\frac{DT}{D\theta} = \dot{\chi} \nabla^2 T + \left(\frac{\nu}{c_p}\right) \dot{\phi} - Q_{\text{rg}}/\rho c_p
\]

(23)

where \(\dot{\phi}\) is the dissipation function, \(\dot{\chi}\) the thermal diffusivity and \(Q_{\text{rg}}\) the volumetric radiation loss whose contribution is appreciable only at high temperature. Finally, when material transport is involved, an additional equation results from the material balance on the diffusing component. This diffusion equation, neglecting thermal diffusion effects, is written:

\[
\frac{DC}{D\theta} = D_v \nabla^2 C
\]

(24)

Solutions for these equations are not available due to their non-linearity, except in cases where extensive simplifying assumptions are made.
One of the most useful concepts in fluid mechanics is
the boundary layer theory, which has been treated in the text by
Schlichting (243). By referring the variables, viz., \( x, y, z, u, v \) and \( p \), to scale factors such as the characteristic length
of the body, \( L \), and the free-stream velocity, \( U_\infty \), and by making
an order of magnitude analysis on the above equations of motion
(21) and continuity (22), the following are obtained for the two-
dimensional case:

Motion, x-direction:

\[
\frac{u}{u^+} \left( \frac{\partial u^+}{\partial x^+} \right) + \frac{v}{v^+} \left( \frac{\partial u^+}{\partial y^+} \right) = \left( \frac{1}{\rho} \right) \left( \frac{\partial p^+}{\partial x^+} \right)
+ \left( \frac{1}{Re} \right) \left( \frac{\partial^2 u^+}{\partial y^2} \right)
\] (25)

y-direction:

\[
\frac{v}{v^+} = 0
\] (26)

Continuity:

\[
\left( \frac{\partial u^+}{\partial x^+} \right) + \left( \frac{\partial v^+}{\partial y^+} \right) = 0
\] (27)

where \( x^+ = (x/L) \), \( y^+ = (y/L) \)

\( u^+ = (u/U_\infty) \), \( v^+ = (v/U_\infty) \)

\( p^+ = (p/\rho U_\infty^2) \)

These equations are known as the Prandtl boundary layer equations
and, as written, are applicable to incompressible flow in laminar
motion with constant fluid properties. The energy equation (23)
and the diffusion equation (24) may be similarly non-
dimensionalized:

Energy:

\[
\frac{u}{u^+} \left( \frac{\partial T^+}{\partial x^+} \right) + \frac{v}{v^+} \left( \frac{\partial T^+}{\partial y^+} \right) = \frac{1}{(Re)(Pr)} \left( \frac{\partial^2 T^+}{\partial y^2} \right)
\] (28)
Diffusion:

\[ u^+(\frac{\partial c^+}{\partial x^+}) + v^+(\frac{\partial c^+}{\partial y^+}) = \frac{1}{(Re)(Sc)} \left( \frac{\partial^2 c^+}{\partial y^+} \right) \]  

(29)

where \( T^+ = (T_\infty - T)/(T_\infty - T_s) \) and \( C^+ = (C - C_\infty)/(C_s - C_\infty) \)

In the derivation of the above equations, buoyancy forces are neglected, and the equations are thus applicable to forced convection only. In addition, it is assumed that the thickness of the boundary layer is small compared to the linear dimensions of the body.

The boundary conditions associated with these equations are as follows:

At the wall \( y^+ = 0, \ u^+ = 0, \ T^+ = 1, \ C^+ = 1, \) and \( v^+ = 0, \) or

\[ v^+ = v_s^+ (x^+) \]  

(30)

In the free stream \( y^+ = \infty, \ u^+ = U^+, \ T^+ = 0, \ C^+ = 0 \)

(31)

where \( U^+ = (U/U_\infty) \) and \( U = \) external flow velocity in the vicinity of the particle. The wall compatibility conditions which are always satisfied by exact solutions of equation (25) are given by:

\[ \left( \frac{\partial^2 u^+}{\partial y^+} \right) = \left( \frac{\partial p^+}{\partial x^+} \right) = -U^+(dU^+/dx^+) \]  

(32)

or \[ \left( \frac{\partial^2 u^+}{\partial y^+} \right) = v_s^+ (\frac{\partial u^+}{\partial y^+}) - U^+(dU^+/dx^+) \]  

(33)

Although theoretical solutions to the boundary layer equations are well established for simple cases, there is still much that can be done to analyse the flow phenomena around complex shapes such as spheres and cylinders at high transfer rates. Nevertheless, the solutions to two-dimensional cases have been used to derive dynamic similarity relations between different
systems, and the dimensionless groups thus involved have proved useful in correlating and interpreting experimental data for complex shapes.

There has been considerable divergence of opinion as to how best to account for variations in fluid properties - particularly viscosity and thermal conductivity. A few workers recommend that the Reynolds, Nusselt, and Prandtl numbers be evaluated at the ambient or bulk fluid temperature (244, 245, 246, 273, 274). Occasionally, a viscosity or temperature ratio correction such as \( \frac{T_b}{T_s} \) is used (247). Douglas and Churchill (248) made an extensive study of cylinder convective heat transfer and concluded that the best correlation of the data available was obtained when the fluid properties are evaluated at the arithmetic average of the free-stream and surface temperatures, or the mean film temperature \( T_f \). Unless otherwise stated, this basis will be assumed in the following discussions. Many of the investigations were, however, carried out at very small temperature differences, in which cases the temperature basis used was of no importance and was thus not even mentioned.

For high-speed flow, experiments have verified that the heat transfer at the surface of a body does not depend on the difference between the wall temperature and the free-stream temperature, but rather on the difference between the wall temperature and the adiabatic wall temperature (51, 72, 24le) which is related to the bulk temperature of the free stream \( T_b \) by the expression:

\[
T_{aw} = T_b + \left( \frac{N_r f U^2}{2 \rho g c_p} \right)
\]  

(34)
where $N_r$ is the temperature recovery factor. Its values are always less than one and are listed for various shapes and types of boundary layer by McAdams (241e).

It has also been shown (51, 72, 199, 249, 250, 251, 252) that, when the temperature range is such that the specific heat varies considerably within the boundary layer, best results are obtained when the temperature difference is replaced as the driving force in the heat transfer equation by the enthalpy difference. In supersonic, high temperature flows, thermal equilibrium does not usually exist and thus a single temperature cannot properly describe the state of the gas. Enthalpy, which is based on the heat content itself is thus a more logical and useful parameter in such a case. Eckert's survey (252) of boundary layer heat transfer at high velocities and temperatures is recommended as an excellent review of this field.

The catalytic activity of the wall surface has been shown to be important in determining heat transfer rates when the boundary layer is not close to thermal equilibrium. Differences in such activity may be responsible for some of the wide variations in reported data in the supersonic, high temperature stagnation point heat transfer field (51, 77, 253, 254, 255). It is the catalytic activity of the surface which determines how much the gas composition changes with respect to ionization or dissociation, and thus how much heat is given up at the surface by recombination of the various species present.
CORRELATIONS FOR SPHERES

Many theoretical and experimental investigations have been made on the phenomenon of heat transfer by natural convection (233, 241b). Suffice it to say that most correlations are generalized in terms of the Grashof and Prandtl numbers:

\[ Nu = f(Gr, Pr) \]  

(35)

Acrivos (256), and Eichhorn et al. (257) have treated the problem of combined natural and forced convection, and have found that the transition from one to the other is very gradual, particularly at high Prandtl numbers. They showed that the parameter \( \frac{Gr}{Re^2} \) was important not only in predicting whether natural or forced convection was predominant, but also in estimating the position of the separation point in, and stability of the boundary layer for aiding and opposing flow, i.e. buoyancy and flow acting in the same and opposite directions, respectively.

Kudryashev and Berezanskii (258) studied heat transfer from stationary copper spheres in air at Reynolds numbers from 8 to 120 in both aiding and opposing flows. Assuming that natural and forced convective effects were additive, contrary to the postulation of Acrivos (256), they presented an empirical correlation for pure forced convection in aiding flow.

\[ Nu = 2 + 0.33 (Re)^{1/2} \]  

(36)

Kudryashev and Ipatenko (259) have carried out analytical and experimental studies on heat transfer by combined natural and forced convection from a sphere, also assuming the effects to be additive, but agreement between experiment and theory was not
satisfactory. Using the Prandtl boundary layer equations, they obtained approximate solutions for a constant-property fluid in laminar compressible flow. For aiding flow:

\[
\text{Nu} = \left[2 + 0.383(Re)^{1/2}(Pr)^{1/2}\right] \left[1 + (3/92)(Gr/Re)\right]
\]

(37)

and for opposing flow:

\[
\text{Nu} = \left[2 + 0.383(Re)^{1/2}(Pr)^{1/2}\right] \left[(3/92)(Gr/Re) - 1\right]
\]

(38)

where all dimensionless groups are estimated with average properties.

In 1960, Yuge (260) reported experiments on sphere heat transfer for the Reynolds number range of 3.5 to \(1.44 \times 10^5\) and Grashof numbers from 1 to \(10^5\). He compiled an empirical and tedious graphical procedure for the prediction of heat transfer rates based on his experimental results. The asymptotic values for the Nusselt number at \(Pr = 0.7\) may be expressed by:

\[
\text{Nu} = 2 + 0.493(Re)^{1/2}
\]

(39)

for pure forced convection, and

\[
\text{Nu} = 2 + 0.392(Gr)^{1/4}
\]

(40)

for pure free convection. Tsubouchi and Sato (261) used small near-spherical thermistors cooling in air and obtained almost identical correlations to equations (39) and (40). The only discrepancy was in the latter equation where a coefficient of 0.45 replaced the figure of 0.392.

Pei (262) recently reported an experimental investigation on heat transfer rates to spheres under combined natural and forced convection. He concluded that:

(i) the mechanisms of the combined convection processes are non-
additive, and the transition between them is gradual,

(ii) for pure heat transfer from spheres, natural convection is negligible for \((Gr/Re^2) \leq 0.05\), and less than 10 percent of the total convection for \((Gr/Re^2) \leq 0.3\), and

(iii) for values of \((Gr/Re^2) > 100\), forced convection has no influence, except for fluids of high Prandtl number.

One of the most important pieces of analytic work in the field of particulate forced-convection heat and mass transfer was that carried out by Froessling (239). He calculated the temperature distribution in the laminar boundary layer of a body of arbitrary shape for the two-dimensional and axially-symmetrical case. Simplifying assumptions included incompressibility of the fluid and constancy of fluid properties. He proposed the following correlation for the overall Nusselt and Sherwood numbers:

\[
\begin{align*}
\text{Nu} &= 2 + 0.552(Re)^{1/2}(Pr)^{1/3} \\
\text{Sh} &= 2 + 0.552(Re)^{1/2}(Sc)^{1/3}
\end{align*}
\]

The experimental study of Ranz and Marshall (238) on the rate of evaporation from stationary liquid drops under natural and forced convection confirmed the validity of equations (41) and (42), except that these authors proposed a coefficient of 0.60 instead of 0.552:

\[
\begin{align*}
\text{Nu} &= 2 + 0.6(Re)^{1/2}(Pr)^{1/3} \\
\text{Sh} &= 2 + 0.6(Re)^{1/2}(Sc)^{1/3}
\end{align*}
\]

During the experimental investigation on the evaporation rates of acetone from single particles of various shapes accelerating freely in a downward cocurrent air stream, Pasternak and Gauvin (263)
found that the Nusselt numbers, corrected for mass transfer effects, were consistently higher beyond \( \text{Re} = 400 \) for larger particles than those predicted by the Ranz-Marshall equation. Downing (264) studied the evaporation of water, acetone, n-hexane and benzene in air at temperatures up to 350 °F, and at Reynolds number up to 325. The Nusselt number, again corrected for mass transfer effects was found to correlate with an average deviation of over 8 percent. This, however, was considered unsatisfactory due to an unusual scatter in the results on the basis of precision of replicate runs.

McAdams (241c) has reported data for heat transfer between spheres and air, correlated by Williams (265) in 1942. In the Reynolds number range of 17 to 70000, Williams recommended the use of properties at the mean film temperature and the following equation:

\[
\text{Nu} = 0.37(\text{Re})^{0.6}(\text{Pr})^{0.33}
\]  
(45)

Kramers (266) suspended steel spheres, which were heated by a high-frequency coil, by a pair of fine thermocouple wires with their junction at the centre of the sphere in a narrow vertical tube. A correlation was obtained for heat transfer in streams of air, water and oil:

\[
\text{Nu} = 2 + 1.3(\text{Pr})^{0.15} + 0.66(\text{Re})^{0.5}(\text{Pr})^{0.31}
\]  
(46)

For air, this reduces to

\[
\text{Nu} = 3.2 + 0.6(\text{Re})^{0.5}
\]  
(47)

Equation (46) was recommended for \( 0.7 < \text{Pr} < 400 \) and \( 0.4 < \text{Re} < 2000 \). The second term in equation (46) was required to allow for
the large variation in Prandtl number. It may actually be due to the increase in heat transfer caused by the disturbance of the thick liquid oils by the high-frequency field (267), or be due to the strong effect of the hot spheres on the viscosity of the oils. Tang et al. (268) carried out experiments similar to those of Kramers and, for $50 \leq Re \leq 1000$, proposed the following correlation:

$$Nu = 3.1(Pr) + 0.55(Re)^{0.5}(Pr)$$ \hspace{1cm} (48)

For air, this reduces to:

$$Nu = 2.2 + 0.39(Re)^{0.5}$$ \hspace{1cm} (49)

Yuge (269-272) plunged preheated spheres into an air stream and plotted cooling curves from readings by a centre thermocouple at Reynolds numbers up to 110. Above this range, steady-state measurements were made with electrically-heated spheres. Two correlations were proposed:

for $10 \leq Re \leq 1.8 \times 10^3$,

$$Nu = 2 + 0.493(Re)^{0.5}$$ \hspace{1cm} (50)

for $1.8 \times 10^3 \leq Re \leq 1.5 \times 10^5$

$$Nu = 2 + 0.300 \ Re^{0.5664}$$ \hspace{1cm} (51)

The break at $Re = 1.8 \times 10^3$ coincides with the change to the largest of three wind tunnels (267) which makes the above correlations suspect. Yuge also proposed (270) a local Nusselt number correlation in terms of the angle $\theta$ radians, measured from the front stagnation point, from a theoretical treatment of the laminar boundary layer:
\[ Nu_1 = 1.672 \left( 0.6773 - 0.105 \theta^2 - 0.0368 \theta^4 \right) (Re)^{0.5} \]  
for \( Pr = 0.733 \).

Leppert and associates \((273, 274)\) heated a copper sphere inductively in a narrow tube up which water was flowing. The plot of \( Nu \) against \( Re \) obtained included the data of Kramers \((266)\) and was correlated by means of the equation:

\[ Nu = 2.7(Pr)^{0.5} + 0.12(Re)^{0.66}(Pr)^{0.5} \]  
for \( 50 \leq Re \leq 5 \times 10^4 \) and for low temperatures differences. For temperature differences of up to 130 deg. F. a viscosity correction factor was included:

\[ Nu_b \left( \frac{\mu_s}{\mu_b} \right)^{0.25} = 1.2(Pr_b)^{0.3} + 0.53(Re_b)^{0.54}(Pr_b)^{0.3} \]  
for \( 2 \leq Pr \leq 380 \) and \( 1 \leq Re \leq 300000 \), with liquid properties other than \( \mu_s \) evaluated at bulk conditions. In a discussion following the paper \((273)\), Richardson strongly criticised the effect of tunnel blockage and the presence of a thick supporting stem on the sphere. A correlation similar to equation (54) was obtained in the further study by Brown, Pitts and Leppert \((274)\):

\[ Nu_b \left( \frac{\mu_s}{\mu_b} \right)^{0.25} = 0.14(Re_b)^{0.65}(Pr_b)^{0.5} \]  
for \( 5000 \leq Re \leq 480000 \) and for larger duct-to-sphere ratios of 2, 2.67 and 4.

Rowe et al. \((267)\) recently described heat and mass transfer experiments to air and water for \( 20 \leq Re \leq 2000 \). A correlation of the Ranz-Marshall type was obtained:
\[ \text{Nu} = 2 + b(\text{Re})^{0.5}(\text{Pr})^{0.33} \]  

(56)

where \( b = 0.69 \) for air and 0.79 for water. The Reynolds number exponent was found to increase from 0.4 at \( \text{Re} = 1 \) to about 0.6 at \( \text{Re} = 10^4 \).

**CORRELATIONS FOR CYLINDERS**

Most of the heat transfer data for cylinders have been obtained without the additional complication of mass transfer since heating and cooling processes outside tubes have been of great interest in heat exchange equipment. The relatively new techniques of hot-wire anemometry have also instigated research into the fundamentals of heat transfer to and fluid flow past cylinders. This is in contrast to the work done with spheres, where evaporation processes were of prime interest and pure heat transfer investigations were comparatively rare.

McAdams (24Ja) has reported on the work carried out prior to 1950 on heat transfer to cylinders transverse to fluid streams. Local distributions of heat flux are described, and it is noted that the maximum local transfer rate occurs at the front and rear stagnation points while the minimum rate, approximately 40 percent of the maximum, occurs at the sides. McAdams has plotted the data obtained in air by a large number of investigations in the Reynolds number range of 0.02 to 235,000 and for Nusselt numbers from 0.5 to 500, with the properties evaluated at the film temperature except for density which was taken at bulk temperature. Since the \( \text{Nu} \) versus \( \text{Re} \) line was curved for the large range of data employed, several straight-line correlations of the same form were proposed for different ranges of \( \text{Re} \):
0.1 \leq \text{Re} \leq 1,000 \quad \text{Nu} = 0.32 + 0.43(\text{Re})^{0.52} \quad (57)

1,000 \leq \text{Re} \leq 50,000 \quad \text{Nu} = 0.24(\text{Re})^{0.60} \quad (58)

\text{up to Re} = 250,000 \quad \text{Nu} = 0.0239(\text{Re})^{0.805} \quad (59)

Eckert and Drake (232) have listed the coefficients for use with cylinders of square and hexagonal cross-sections in equations of the same form as (57).

For liquids flowing past cylinders, McAdams (241a) suggests the following correlation:

\[ \text{Nu} = 0.35(\text{Pr})^{0.3} + 0.56(\text{Re})^{0.52}(\text{Pr})^{0.3} \quad (60) \]

for \( 1 \leq \text{Re} \leq 10^3 \). Perkins and Leppert (244, 245) have measured local and overall heat transfer coefficients from a uniformly-heated cylinder with water and ethylene glycol in crossflow. Local values were obtained by means of a thermocouple welded to the inner surface. Corrections were made for the influence of channel blockage due to the presence of the test cylinder and the following correlations were obtained for \( 2,000 \leq \text{Re}_b \leq 120,000 \), for \( 1 \leq \text{Pr}_b \leq 7 \) and temperature differences of up to 120 deg. F.:

\[ \text{Nu}_b \left( \frac{\mu_s}{\mu_b} \right)^{0.25} \text{Re}_b^{0.50} \text{Pr}_b^{0.40} + 0.11 \text{Re}_b^{0.67} \text{Pr}_b^{0.40} \quad (61) \]

\[ \text{Nu}_b \left( \frac{\mu_s}{\mu_b} \right)^{0.25} = 0.57 \text{Re}_b^{0.50} \text{Pr}_b^{0.40} + 0.0022 \text{Re}_b \text{Pr}_b^{0.40} \quad (62) \]

In equation (61), the first term on the right-hand side accounts for the laminar boundary layer heat transfer contribution and the second term, \( \text{Re}_b^{0.67} \), accounts for the separated region transfer. Equation (62) was included by the author to show the good comparison
with the correlation by Douglas and Churchill (248) for gases. Fand (275) recently presented new data for water in the Reynolds number range of $10^4$ to $10^5$. His experimental data were in close agreement with the McAdams equation (60), but Fand chose to represent the data by means of the laminar boundary layer and separated flow (this time $Re^{0.58}$) contributions:

$$Nu = \left[0.35 + 0.34(Re)^{0.50} + 0.15(Re)^{0.58}\right](Pr)^{0.30} \quad (63)$$

Van der Hegge Zijnen (276) has reviewed heat transfer to cylinders by natural and forced convection. For the range $(Gr.Pr) < 10^8$, he suggests the following correlation:

$$Nu = 0.35 + 0.25(Gr.Pr)^{1/8} + 0.45(Gr.Pr.)^{1/4} \quad (64)$$

and for $0.01 < Re < 5 \times 10^5$ in the forced convection regime:

$$Nu = 0.35 \Pr^{0.2} + (0.56 Re^{0.5} + 0.001Re)\Pr^{1/3} \quad (65)$$

The properties in each case are taken at the mean film temperature. His attempt to link combined natural and forced convection vectorially using equations (64) and (65) compared fairly well with his experimental data. He found that, in air, forced convection was predominant for $Re > 1,000$, and was negligible for $Re < 4$. Collis and Williams (277), in their work with electrically-heated wires in air at low Reynolds numbers (0.01 to 140), have obtained a correlation of the form:

$$Nu \left(\frac{T_f}{T_b}\right)^{-0.17} = a + b(Re)^p \quad (66)$$

The exponent value $p$ varies from 0.45 to 0.51, $a$ from 0.24 to 0, and $b$ from 0.56 to 0.48 with increasing $Re$.

Yuge (278) has carried out an analytic treatment of the
laminar boundary layer of a cylinder and has successfully predicted local Nusselt numbers, pressures and temperature distributions on the front surface with the assumption that kinematic viscosity and thermal conductivity vary linearly with temperature.

Heat transfer to cylinders making up thermocouples has been the topic of interest in the determinations of conduction and radiation corrections in hot air streams. Over the ranges $250 < \text{Re}_t < 30,000$ and $0.1 < \text{M} < 0.9$, Scadron and Warshawsky (67) recommend the use of the following relation, with gas properties evaluated at the total temperature $T_t$:

$$\text{Nu}_t = 0.478 (\text{Re}_t)^{0.5} (\text{Pr}_t)^{0.3}$$  (67)

This relationship has been verified by Glawe and Johnson (279) at temperatures up to 3,000 °F.

Churchill and Brier (247) studied the overall rate and angular variation of the rate of convective heat transfer to a water-cooled instrumented cylinder from nitrogen at temperatures up to 1,800 °F. and $300 < \text{Re}_b < 2,300$. The overall heat transfer rate was about 30 percent higher than that predicted by McAdam's equations (57) and (58) for low temperature differences, or $(T_b/T_s)$ of approximately one. In an attempt to allow for the large variations in gas properties across the boundary layer, the parameter $(T_b/T_s)$ was included in the proposed correlation:

$$\text{Nu}_b = 0.60 (\text{Re}_b)^{0.5} (\text{Pr}_b)^{0.33} (T_b/T_s)^{0.12}$$  (68)

In 1956, Douglas and Churchill (248) recorrelated all the data available at that time for convective heat transfer between gases and single transverse cylinders with large temperature differences.
It was found that the data for hot cylinders in cold streams and
cold cylinders in hot streams generally fell into separate lines
when plotted on McAdam's basis (241a), in which \( \text{Re} = (\text{DU}_b/\text{U}_f) \).
When the Reynolds number was changed to \( \text{Re}_f = (\text{DU}_f/\text{U}_f) \), much
of the scatter was eliminated and the following relationship was
proposed for \( 500 < \text{Re}_f < 300,000 \):

\[
\text{Nu} = 0.46(\text{Re})^{0.5} + 0.00128(\text{Re})
\]

The first and second terms were meant to represent the laminar
boundary layer and wake region contributions respectively.

Heat transfer to fine wires from rarified airstreams
where slip-flow conditions exist has been studied by Baldwin
(280). In such cases, the Knudsen number \( \text{Kn} \) (The ratio of the
mean free path of the gas \( \lambda \) to the cylinder diameter \( D \)) and the
Mach number \( M \) are important parameters. Baldwin found that slip
flow exists for \( \text{Kn} > 0.01 \), and that under these conditions there
is a shift from half to first-power dependence on \( \text{Re} \) as well as
large separation of constant Mach number parametric curves due to.rarified gas-flow phenomena. Further discussions of this topic,
including the effect of cylinder yaw, are available to the inter-
ested reader (252, 281, 282, 283).

Kimura and Kanzawa (284) recently reported experiments
on transient heat transfer to wires in a partially ionized argon
plasma jet. It was shown by means of probe measurements that the
boundary layers were near a frozen-composition state (i.e. the
plasma composition remained unchanged through the boundary layer
due to very slow recombination rates even though there was a
drastic drop in enthalpy. It was also considered that the gas
was not in thermal equilibrium in that the electron temperature
was higher than the ionic or atomic translational temperature, since the wire was placed very close to the jet exit and there was thus insufficient time for the argon to reach thermal equilibrium. The recombination heat transfer contribution was assumed to make up the difference between the total heat input to the wire and the convective transfer which was calculated from the McAdam's equation (60) for liquids. It was found that the recombination heat transfer in this case formed about 10 percent of the total.

Chludzinski, Kadlec and Churchill (285) have reported an investigation of the heat transfer from 5 kw. radio-frequency argon-nitrogen plasma jets to thermocouples immersed in the plasma for time periods of less than 0.1 sec. Gas film heat transfer coefficients were calculated from the dynamic response of the thermocouples, and the temperature of the gas up to 20,000 °F., was measured by spectrographic means. The film heat transfer coefficients obtained in pure argon (about 100 Btu./hr.ft.²°F.) were more than twice as large as those calculated from a conventional forced convection correlation of the form of equation (67), and the rate of heat transfer was found to double by the addition of 5 mole percent or more of nitrogen. Energy transfer contributions due to ion-electron and atom-atom recombination occurring near the solid were separated from the overall heat transfer, and it was found that contributions due to the ion-electron reactions were lower by a factor of three than the nitrogen atom reactions. The following relationship was proposed for calculation of heat transfer coefficients in argon and argon-nitrogen plasma jets to hemispherical probes with the tip pointing into the stream:
where \( C_{A^+}, C_{N^+}, C_N \) are the particle concentrations (number of particles per \( \text{ft}^3 \)) of argon ions, and nitrogen ions and atoms respectively, obtained from thermodynamic charts at the temperature of the gas. Gas properties were evaluated at bulk temperature conditions. The first term in the above equation is the forced convection contribution and the second is the effect of the various recombination processes. The gas velocity was not actually measured, and an average value was used, based on the total flow through the system, in the evaluation of \( Re \) which ranged in value from 2 to 10. Although the velocity profile in radio-frequency streams is more uniform than that in a corresponding direct-current plasma jet, the uniformity assumption is a source of possible error in the derivation of equation (70). Other sources of error would include the transient nature of the measurements, effects of cool boundary layer around the probe out of which the thermocouple was projecting, the general difficulties encountered in the measurements in high temperature environments, and the lack of availability of reliable physical properties of plasmas. The studies by Kimura and Kanzawa (284) and Chludzinski et al. (203, 285), however, represent the extension of conventional heat transfer investigations into regions in which difficulties are expected to abound and this fact should not be overlooked in discussions of such studies.
SEPARATED FLOW PHENOMENA AND EFFECTS OF TURBULENCE

At very low Reynolds numbers (Re < 0.1), the flow of fluid around a sphere in an isothermal system is such that the elements of the fluid meeting in front of the particle are slowly accelerated sideways, and the inertia effects are too small to cause a time lag in the closing-up of the flow behind the body. This phenomenon occurs in what is known as the Stoke's law region. A separation process in the boundary layer first begins to appear at a Reynolds number of approximately one. It is then that the streamline patterns become deformed and curl up to form a stationary vortex ring imbedded in the boundary layer of the sphere. This ring resembles a smoke ring and grows in size with increases in Reynolds number. As the latter is further increased in this transition region, the velocity gradients in the boundary layer become more severe, and the increase in sideways-acceleration is accompanied by a decrease in static pressure. In the region beyond the equator, the boundary layer is acted upon by the downstream viscous action of the adjacent stream, is retarded by friction at the sphere surface, and is further retarded by the adverse pressure gradient. Eventually, a slow back-flow occurs in the direction of the pressure gradient, and the boundary layer leaves the sphere surface at the point of separation. At 50 < Re < 500, in a turbulence-free stream, the vortex system begins to break away from the particle and feeds into a flow regime at the rear of the sphere which is bounded by a free shear layer. The separated boundary layer is called the wake. This vortex-separation phenomenon occurs at what is referred to as the lower
critical Reynolds number. This instability does not correspond to that occurring at laminar-turbulent transition which is associated with the free shear layer drawing closer to the separation point. The transition region for a sphere extends to a Reynolds number of approximately $2 \times 10^4$, during which there is a periodicity in the wake movement. Random turbulence gradually overcomes this effect as $\text{Re}$ increases further. In the vicinity of $\text{Re} = 2 \times 10^5$, the forward part of the boundary layer attached to the sphere becomes unstable and tends to become turbulent, producing an unsymmetrical unstable turbulent wake. At the higher critical Reynolds number (about $3 \times 10^5$), the point of separation moves suddenly to the rear causing a large drop in drag coefficient. At still higher $\text{Re}$, the whole boundary layer flow becomes turbulent and the wake, now relatively narrow, is also turbulent. The reader is referred to pertinent reviews on this topic by Torobin and Gauvin (286, 287, 288). Flow patterns around cylinders are similar to those around spheres, and the lower and higher critical Reynolds numbers occur at about 40 and $5 \times 10^5$ respectively (287).

At low Reynolds numbers, the heat transfer on the front side is much greater than that on the rear. As $\text{Re}$ increases, the rear heat transfer increases at a faster rate than that from the front. Richardson (289) has considered the topic of heat and mass transfer in turbulent separated flows and suggests that the total transfer from a bluff body can be expressed as the sum of the transfer from the regions of attached and separated flows, and that the transfer from each region is independent of the other. The contributions from the front laminar boundary region and the rear wake region were assumed proportional to $\text{Re}^{0.5}$ and $\text{Re}^{0.67}$ respec-
tively. Richardson then represented the results of Yuge (260) for a sphere by:

\[ \text{Nu} = 0.32 \text{Re}^{0.5} + 0.043 \text{Re}^{0.67} \]  \hspace{1cm} (71)

and found that correlations for cylinders in air at \( 10^2 \lesssim \text{Re} \lesssim 10^5 \) normally fell between the limits of:

\[ \text{Nu} = 0.37 \text{Re}^{0.5} + 0.057 \text{Re}^{0.67} \]  \hspace{1cm} (72)

and

\[ \text{Nu} = 0.55 \text{Re}^{0.5} + 0.084 \text{Re}^{0.67} \]  \hspace{1cm} (73)

Richardson (289, 290) also brought up the question of sphere support which can interfere with the flow. In particular, a rear support may cause reattachment of the separated flow, which would reduce the heat transfer in the rear due to a less-mobile wake. The complexities involved in the understanding of the transfer mechanism from bluff bodies necessitates extensive experimental investigation of factors affecting separated flow such as turbulence, shape effects, tunnel blockage effects, evaporation and large temperature gradients.

Acrivos et al. (291) have shown that the local heat transfer to the front half of a cylinder exceeds by far the rear contribution at Reynolds numbers up to 225 and that the rear Nusselt number is independent of \( \text{Re} \) in this range. Churchill and Brier (247), in their work with nitrogen at temperatures up to 1,800 °F., and \( 300 \lesssim \text{Re}_b \lesssim 2,300 \), found that the local Nusselt number at the rear was not independent of \( \text{Re}_b \) and was in fact increasing at a much greater rate than the front Nusselt number. Extrapolation of their data indicates that the two contributions
would be equal at about $Re_b = 3 \times 10^4$. When the Reynolds number exponent was plotted against angular position, it was seen that, up to $80^\circ$ from the front, the exponent was about 0.53, that it dipped at the equator and rose to a value of 0.9 at the rear.

The free-stream turbulence intensity does not appear to have a major effect upon heat transfer at the rear stagnation point of a bluff body in distinct contrast with the effect at the forward stagnation point (243). The findings of Seban (292) also indicate that this effect is the greatest at the front (up to 30 percent) and that it becomes proportionally less as the local pressure gradient upon the boundary layer increases. This increase in heat transfer may have occurred through a direct change in heat transfer to the laminar boundary layer because of an earlier transition to turbulence, or through an alteration in the character of the separated flow. A comparison of the data reported in the literature, however, on the effect of turbulence on heat transfer shows little agreement and is often inconclusive.

Van der Hegge Zijnen (293) has systematically studied the rate of heat transfer from cylinders to a turbulent flow of air for $600 \leq Re \leq 26,000$, with an intensity range of 2 to 13 percent and with the ratio of Eulerian scale ($L_x$), to the cylinder diameter varying from 0.31 to 240. He reported that the rate of heat transfer was a function of the intensity of turbulence and the scale ratio ($L_x/D$), in addition to the Reynolds number. He came to the following conclusions:

(i) at constant $Re$, the heat transfer increases continuously with the intensity of turbulence;
(ii) at constant intensity of turbulence, the Nusselt number increases with Reynolds number;

(iii) at constant Reynolds number and intensity of turbulence, the heat transfer rate may either increase or decrease with increasing scale ratio and a maximum is reached at \((L_x/D)\) of about 1.6.

These results conflict with those of Maisel and Sherwood (294) who found very little influence of scale ratio in their evaporation studies, which tends to indicate that mass transfer is another important effect.

Torobin and Gauvin (295), in their work on momentum transfer from freely-moving spheres at high relative turbulence levels, presented a plausible explanation for the higher rates of heat and mass transfer observed under turbulent conditions and in separated flow. They established conclusively that a laminar-turbulent transition would occur in the attached boundary layer of a sphere if, at a given \(Re\), the relative intensity of turbulence is high enough. Such transition would undoubtedly increase the rates of heat and mass transfer appreciably when it occurs. This transition theory led to the following mathematical expression:

\[
\left( \frac{I_R}{\sqrt{Re}} \right)^2 = \text{constant} \quad (74)
\]

where \(I_R\), the relative intensity of turbulence is given by:

\[
I_R = \left( \frac{u'^2}{U_r} \right)^{0.5} \quad (75)
\]

Here \(U_r\) represents the velocity of the particle relative to that of the fluid. They reported a value of 45 for the constant in
their momentum studies on spheres.

Sage and his associates at the California Institute of Technology have been carrying out a continuing programme of research on the effect of turbulence on the local and total heat and mass transfer from stationary spheres (296-300). The apparent levels of turbulence intensity reached 15 percent and the Reynolds number range was from 1,500 to 7,300. The data indicated a substantial increase due to the presence of turbulence, and they found that the local heat transfer rate varied by a factor of as much as eight around the sphere. Venezian, Crespo and Sage (300) made a comparison of heat transfer from a 1-in. diameter silver sphere and a porous sphere of the same diameter, from which n-octane was evaporating. The results showed that the overall Nusselt number for simultaneous heat and mass transfer was substantially higher than that for pure heat transfer at the same turbulence level.

In the investigations discussed, it has been found that an increase in turbulence intensity is more effective in increasing the transfer rates at the higher values of $Re$, a behaviour which could be explained by the onset of transition under these conditions. This may account for the marked increases in heat transfer which may occur due to the triggering effects of evaporation, large temperature gradients and various types of oscillations on transition from a laminar to turbulent boundary layers. Fand and Cheng (301) have shown that sound waves of frequency 1100 to 1500 c.p.s. increase the overall heat transfer rates from cylinders to air by as much as 25 percent due to acoustic effects in both the wake and forward boundary layer. Feiler (302) employed flows
parallel to a cylinder with flow oscillations of 100 c.p.s. and induced transition to a turbulent boundary layer. He found that the Nusselt number was proportional to $\text{Re}^{0.8}$. Parnas (303) used both flow pulsations and cylinder vibrations in his study of heat transfer between an air stream and transverse cylinder, and showed that the heat transfer increase was dependent on the frequency and amplitude of the oscillations.

Johnson and Rubesin (304) reported in 1949 that the Nusselt number, for flat plates in pure heat transfer with a turbulent boundary layer, was proportional to $\text{Re}^{0.8}$, as postulated also by Schlichting (243). A similar dependence occurs for the case of turbulent flow inside pipes (241d, 305). Iskachenko and Vzorov (306) have concluded from their studies of mass transfer from a wetted porous surface in a current of air that mass transfer is analogous to heat transfer under the same conditions of turbulence, and that the average mass transfer rate is proportional to $\text{Re}^{0.8}$.

Smolsky and Sergeyev (307), in 1962, conducted experiments in heat and mass transfer during evaporation in a gas stream, as well as heat transfer to metallic and dry porous flat plates. They found that the heat transfer rates with evaporation were higher than for pure heat transfer, for which the following correlation was obtained:

$$\text{Nu} = 0.037 \text{Re}^{0.8} \text{Pr}^{0.33}$$  \hspace{1cm} (76)

Their heat and mass transfer were found to correlate by the addition of a temperature factor, the Gukhman number:

$$\text{Nu} = 0.083 \text{Re}^{0.67} \text{Pr}^{0.33} \text{Gu}^{0.1}$$  \hspace{1cm} (77)
where \( G_u = \left( T_b - T_s / T_b \right) \). Sergeyev and Sergeyeva (308) extended this study to the cases of spheres, cones and discs. The data for the sphere were generalized by a dependence of the form of equation (76) in the range \( 10^3 < \text{Re} < 10^5 \).

Pasternak and Gauvin (309) have measured convective heat and mass transfer rates for 20 shapes of particles suspended in various orientations in hot turbulent air streams at turbulent intensities between 9 and 10 percent and at \( 500 < \text{Re} < 5,000 \). They correlated their data with a single equation by means of a new characteristic dimension \( L'' \), which was defined as the total surface area divided by the maximum perimeter perpendicular to the flow. This dimension was qualitatively explained from boundary layer considerations and was found to correlate successfully the data for different shapes available in the literature. It is thus possible to compare heat and mass transfer data for different shapes on single graphs.

The effect of turbulence is also present in heat transfer to objects exposed to impinging jets. Schuh and Persson (310) have investigated heat transfer to cylinders placed transverse to a two-dimensional jet, and at various distances from the source. The cylinder Reynolds number range was \( 2 \times 10^4 \) to \( 5 \times 10^4 \), and the jet velocity profile was assumed to be fully-developed and turbulent. Maximum heat transfer to the cylinder was found to occur with a jet width one-eighth of the cylinder diameter and with the cylinder at a distance from the nozzle of 2 to 8 times the jet width, where there exists a high intensity of turbulence. 

Gardon and Akfirat (311) have shown that heat-transfer characteristics of impinging jets cannot be explained in terms of velocity-
and position-dependent boundary layer thicknesses alone. These characteristics must take into account the influence of turbulence which may manifest itself by a transition from a laminar to a turbulent boundary layer.
NOMENCLATURE

ROMAN SYMBOLS

a - constant
A_{s,j} - transition probability between states \( s \) and \( j \)
b - constant
c - constant
c_1, c_2 - constants in Planck's law, \( 0.885 \times 10^{-20} \) cal. \( \text{cm}^2/\text{sec.} \) and \( 1.438 \) cm.\(^0\)K. respectively
c_p - specific heat at constant pressure, Btu/lb. \(^\circ\)F.
C - concentration of diffusing component, lb./ft\(^3\)
C^+ - \((C - C_\infty)/(C_\infty - C_s)\), dimensionless
C_{A^+}, C_{N^+}, C_N - concentration of \( A^+ \) ions, \( N^+ \) ions, \( N \) atoms respectively, particles ft.\(^{-3}\)
D - diameter, ft.
D_M - molal diffusivity, lb. mole./hr. ft.
D_V - mass diffusivity, ft\(^2\)/hr.
F - body force, lb./hr\(^2\) ft\(^2\)
g - statistical weight factor, dimensionless
g_c - gravitational constant, 32.17 ft. lb./lb. force sec\(^2\)
G - mass velocity, lb./ft\(^2\) hr.
h - heat transfer coefficient, Btu/hr. ft\(^2\) \(^\circ\)F.; Planck's constant, \( 6.624 \times 10^{-27} \) erg. sec.
i - enthalpy, Btu/lb.
l - electrical current, amp.; intensity of radiation, photons/sec.
l_R - relative intensity of turbulence, dimensionless
J - radiant flux, joules/sec.; mechanical equivalent of heat, 778 ft. lb. force/Btu.
J_{\lambda T} - monochromatic radiant energy with source at temperature \( T \), erg./cm. sec. ster.
\[ k \] - thermal conductivity, Btu/hr.ft. °F.; Boltzmann's constant, \( 1.38 \times 10^{-16} \text{ erg}/\text{°K} \).

\[ k_G \] - mass transfer coefficient, lb.mole./hr.ft.²

\[ L \] - length, characteristic dimension, ft.

\[ L_x \] - Eulerian macroscale of turbulence, ft.

\[ L'' \] - characteristic dimension equal to total surface area divided by maximum perimeter perpendicular to the flow, ft.

\[ m \] - momentum parameter, dimensionless

\[ m_0 \] - initial value of momentum parameter, dimensionless

\[ N \] - number of particles

\[ N_{rf} \] - temperature recovery factor, dimensionless

\[ p \] - constant; pressure, lb./ft.²

\[ p^+ \] - \( (p/\rho U_{\infty}^2) \), dimensionless

\[ q \] - constant

\[ Q \] - volumetric flow rate, ft.³/hr.

\[ Q_{rg} \] - volumetric radiation loss, Btu/hr.ft.³

\[ r \] - radial distance, ft.

\[ R \] - radius, ft.; resistance, ohm.

\[ S_o \] - outside surface area, ft.²

\[ t \] - time, hr.

\[ T \] - temperature, °F., °R., °C. or °K.

\[ T^+ \] - \( (T_{\infty} - T)/(T_{\infty} - T_S) \), dimensionless

\[ T_{aw} \] - adiabatic wall or recovery temperature

\[ T_f \] - mean film temperature

\[ T_t \] - total temperature

\[ u \] - component of velocity in x-direction, ft/hr.

\[ u^+ \] - \( (u/U_{\infty}) \), dimensionless

\[ u' \] - fluctuation of the component velocity in x-direction, ft./hr.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>velocity, ft./hr.; overall heat transfer coefficient, Btu/hr.ft$^2$ OF.</td>
</tr>
<tr>
<td>$U^+$</td>
<td>$(U/U_\infty)$, dimensionless</td>
</tr>
<tr>
<td>$U_r$</td>
<td>relative velocity, ft./hr.</td>
</tr>
<tr>
<td>$v$</td>
<td>component of velocity in y-direction, ft./hr.</td>
</tr>
<tr>
<td>$v^+$</td>
<td>$(v/U_\infty)$, dimensionless</td>
</tr>
<tr>
<td>$V$</td>
<td>arc voltage, volts</td>
</tr>
<tr>
<td>$x, y$</td>
<td>distances in cartesian co-ordinate system, ft.</td>
</tr>
<tr>
<td>$x^+$</td>
<td>$(x/L)$, dimensionless</td>
</tr>
<tr>
<td>$y^+$</td>
<td>$(y/L)$, dimensionless</td>
</tr>
</tbody>
</table>

**GREEK SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>thermal diffusivity $(k/\rho c_p)$, ft$^2$/hr.</td>
</tr>
<tr>
<td>$\beta$</td>
<td>coefficient of volume expansion, $(^\circ R.)^{-1}$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>energy of quantum state, electron-volts</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle, radians</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>time, hr.</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength, cm.; mean-free path of gas, ft.</td>
</tr>
<tr>
<td>$\mu$</td>
<td>viscosity, lb./ft. hr.</td>
</tr>
<tr>
<td>$\nu$</td>
<td>frequency of electromagnetic radiation, hr.$^{-1}$; kinematic viscosity, ft$^2$/hr.</td>
</tr>
<tr>
<td>$\pi$</td>
<td>3.14159</td>
</tr>
<tr>
<td>$\rho$</td>
<td>fluid or particle density, lb./ft$^3$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>electrical conductivity, ft.$^{-1}$ ohm.$^{-1}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>viscous dissipation function, hr.$^{-2}$</td>
</tr>
</tbody>
</table>
**DIMENSIONLESS GROUPS**

- **Ct** - Craya-Curtet number, \((m_o^{0.5})\)
- **Gr** - Grashof number, \([D^3 \beta (\Delta T)/\nu^2]\)
- **Gu** - Gukhman number, \([T_b - T_s/T_b]\)
- **Kn** - Knudsen number, \((\lambda/D)\)
- **M** - Mach number
- **Nu** - Nusselt number \((hD/k)\)
- **Pr** - Prandtl number \((c_p\mu/k)\)
- **Re** - Reynolds number \((DU_\infty \rho/\mu)\)
- **Re_c** - higher critical Reynolds number
- **Sc** - Schmidt number \((\mu/\rho D_v)\)
- **Sh** - Sherwood number \((k_GD/D_M)\)

**SUBSCRIPTS**

- **b** - bulk or free-stream
- **f** - film
- **i** - inside
- **j** - \(j\)th energy level
- **l** - local
- **n** - nozzle
- **o** - outside
- **s** - \(s\)th energy level; surface
- **t** - total
- **w** - water
- **1** - primary stream; free stream
- **2** - secondary stream; stagnation point
- **∞** - at infinite distance
BIBLIOGRAPHY


22. Conn, W. M., in ibid, pp. 29-44.
32. Bradstreet, S. W., in ibid, pp. 84-85.
47. Lier, R. H., Los Alamos Scientific Laboratory, University of California, Report LAMS-2325 (1959).


116. Dean, R. C., Jr., in Aerospace Research Laboratories,
Report ARL63-151, pp. 1-17, Office of Aerospace Research,

117. Shear, C., in ibid., pp. 18-89.


120. Wheaton, J. R., and Dean, R. C., Jr., Thayer School of
Engineering Tech. Rep., Dartmouth College, Hanover,


431 (1965).

123. Dickerman, P. J., and Morris, J. C., in Dickerman, P. J.
(ed.) "Optical Spectrometric Measurements of High

124. Pearce, W. J., Wright Air Development Division, WADC Tech.

125. Watson, M. D., Ferguson, H. I. S., and Nicholls, R. W.,

126. Cremers, C. J., and Pfender, E., Aerospace Research
Laboratories Report ARL 64-191, Office of Aerospace


129. Fishburne III, E. S., Ph.D. Thesis, Ohio State University,
Columbus, Ohio (1963).

130. Garkavyi, E. V., and Yasko, O. I., Int. Chem. Eng. 4 : 271
(1964).

131. Tikhomirov, V. B., and Varlamov, I. V., Int. Chem. Eng. 5 :
16 (1965).

Research Laboratories Report ARL 64-132, Office of Aero­


172. Heaston, R. J., Ph.D. Thesis, Ohio State University, Columbus, Ohio (1964).


209. Wethern, R. J., and Brodkey, R. S., AIChE Jour. 9 : 45 (1963).


EXPERIMENTAL SECTION
PART I.

THE PLASMA JET RESEARCH FACILITY

INTRODUCTION

DEVELOPMENT OF THE PROJECT

The study of the rate of energy exchange in the form of heat in various systems is motivated, in many cases, by the need for fundamental data which is required for design of equipment and for the development of new processing techniques. The present investigation owes its origin to the development of the atomized suspension technique described by Gauvin and Gravel (1). In this process, a spray of droplets or suspension of fine particles is passed rapidly through a sequence of physical and chemical operations such as evaporation or drying, and reduction, oxidation or pyrolysis, in a single piece of equipment which consists basically of a vertical cylindrical column whose walls are maintained at a high temperature (up to about 1800 °F).

In the present investigation, the heat source consisted of a plasma torch capable of providing continuous gas streams of nitrogen and hydrogen at temperatures up to 10,000 °F., and argon up to about 30,000 °F. The plasma jet was fed vertically downward through an insulated cylindrical graphite chamber which was designed and constructed for the study of heat and mass transfer, and kinetics in solids-gas systems at high temperatures. Provision was made to feed fine powders into the plasma jet in a process similar to the atomized suspension technique, and to
follow their physical and chemical changes by optical or probe means through ports. The apparatus was also suitable for the study of high temperature gaseous reactions.

After the plasma jet system had been assembled and the graphite chamber and cooling system had been set up, the operating characteristics of the apparatus were determined at various power levels and flow rates. It had originally been planned that both nitrogen and hydrogen gases and their mixtures would be used, but the operation with hydrogen turned out to be hazardous due to small leakages, and thus only nitrogen was employed. A test section was selected at a position of about 1 ft. below the entry of the plasma jet into the graphite chamber, and velocity and temperature profiles of the gas flow were obtained at this level by means of a modified water-cooled total-head probe and tungsten-5 percent rhenium/tungsten-26 percent rhenium thermocouples, respectively. Heat transfer measurements to stationary water-cooled spheres and cylinders were also carried out at this test-section in the second part of this investigation, which will be described in a later section.

**CONFINED JETS**

When a fluid jet is enclosed by a solid boundary such as a coaxial cylindrical tube, the system created is called a confined jet. It is sometimes characterized by the phenomenon of recirculation, since the mixing process results in a pressure rise which may be sufficient to retard the ambient flow to zero, and thus cause recirculation of the flow. Several attempts have been made to establish a criterion for the prediction of recircu-
lation, and to characterize the system in the presence of a secondary coaxial fluid stream.

Curtet and co-workers (2-5) have contributed significantly to the knowledge of isothermal confined jets. A model was developed, which was based on the simplifying assumptions that wall friction and radial pressure gradients are negligible, velocity profiles are similar before the jet spreads to the wall, and that the profile of the axial component of velocity is uniform and non-turbulent outside the mixing region. After integration of the equations of motion across the tube, the ratio \( \frac{R_2}{R_1} \) and a momentum parameter \( m \) appeared, where:

\[
m = \left[ \frac{\pi R_2^2}{Q_t} \right] \int_0^{R_2} (u^2 - \frac{U_2^2}{2}) 2\pi r \, dr - \left( \frac{1}{2} \right)
\]

and \( u \) is the axial velocity at radius \( r \), \( U_2 \) is the axial velocity component of the secondary stream, \( R_2 \) is the radius of the confining tube and \( Q_t \) is the total volumetric flow rate. It was found that this quantity \( m \) was a constant of the flow, with an initial value at the point of entry of

\[
m_0 = \left[ R_1^2(U_1^2 - U_2^2) + U_2^2R_2^2/2 \right]/(Q_t^2/\pi R_2^2) - \left( \frac{1}{2} \right)
\]

where \( U_1 \) is the initial axial velocity of the jet of radius \( R_1 \).

The parameter \( m_0 \) has found application in predicting the onset of recirculation, and was changed into a more useful form by Becker et al. (6), called the Craya-Curtet number:

\[
Ct = m_0^{-0.5}
\]

It has been shown (6, 8) that recirculation exists for \( Ct < 0.75 \).
Becker et al. have used the Craya-Curtet number in characterizing the properties of the recirculation eddy and the velocity profiles of the turbulent confined jet. The locations of the eye and boundary of the eddy, the rate of fluid circulation about, and the concentration patterns within it were depicted in the form of graphs, in terms of \( C_t \) as a parameter of the system. When there is no secondary stream present, the Craya-Curtet number reduces to:

\[
C_t = R_1 \left[ \frac{2}{(2R_2^2 - R_1^2)} \right]^{0.5}
\]  

For \( R_2 \gg R_1 \),

\[
C_t = \left( \frac{R_1}{R_2} \right)
\]

In this case, recirculation always occurs, since \( C_t \ll 0.75 \). The recirculation rate is given by the following equation, as derived by Curtet and described by Becker (7):

\[
Q^+ = \frac{Q_r}{Q_t} = \frac{(0.61)}{(C_t)} - (0.7)
\]

where \( Q_r \) is the volumetric recirculation rate about the eye of the eddy, and \( Q^+ \) is the non-dimensional recirculation rate.

Smith and Churchill (9) have studied the mass and energy transfer between a confined 3 kw. direct-current argon plasma jet and a cool annular nitrogen stream. The temperature profiles in the mixing region were determined by spectroscopic means, specifically the argon electron-excitational and nitrogen rotational temperatures. The measured nitrogen temperatures were found to be much lower than the argon temperatures present at the same point in the flow. The authors showed that this was caused by
the inability of the argon atoms to give up their translational energy directly to the rotational modes of the nitrogen molecules. Smith and Churchill also calculated the Craya-Curtet numbers for their system. To allow for the large temperature gradients involved, the velocity terms were multiplied in equation (2) by the related density. For the range of $0.43 \leq Ct \leq 0.52$ investigated, the recirculation phenomenon was found to be important.

**MEASUREMENT TECHNIQUES AT HIGH TEMPERATURES**

The need for measurements in high temperature systems has resulted in the development of several important new techniques. At temperatures above 5000 °F., spectroscopic measurements of the emitted radiation are often the only sensitive and practical means for determining the temperature. An up-to-date review of this topic has been presented by Hottel, Williams and Jensen (10).

In many hot gaseous environments, temperatures are too high for thermocouples, and spectroscopic methods are not applicable due to lack of window facilities, opacity of the gases, or large thermal gradients. Such applications have led to the development of various cooled thermodynamic probes (11). The pneumatic probe depends on the application of the continuity equation to a continuously-flowing sample of gas, for example a perfect gas expanding isentropically through two orifice nozzles. In heat transfer probes, the enthalpy or temperature determination is carried out by measuring the heat flux across a calorimeter surface, usually at the front stagnation point, and by the subsequent use of known heat transfer correlations. The calorimetric
probe developed by Grey, Jacobs and Sherman (12) consists of three concentric tubes joined at the tip in such a way that hot gas can be sampled through the innermost tube, and cooling water flows in and out via the remaining two annular gaps. Thermocouples record the temperatures of the exit gas and coolant, in and out. Heat balances with gas flowing through the probe, and then with the gas sample shut off, yield the enthalpy of the gas stream in terms of the difference in heat transfer between the outer and the inner tubes. The effectiveness of this technique is dependent on the duplication of flow conditions near the probe tip under the two conditions. Smith and Churchill (9) have found a large dependency of measured temperature on the sampling rate. They postulated that, in low velocity gas streams and at small sampling rates, the probe sucks in gas from the cool boundary layer surrounding the tip, which results in low values. They obtained temperatures of 9,000 °F. and lower with the probe, compared to 16,000 °F. with spectrographic techniques.

Fingerson and Blackshear (13) have described the characteristics of a heat flux probe, which is basically a water-cooled constant-temperature hot film anemometer. This employs a thin platinum film deposited on a 0.006-in. o.d. glass tube which is water-cooled. During operation in high-temperature gas streams, the surface is kept at essentially constant temperature by means of an electronic compensating circuit. The water flow rate and temperature entering the short platinized section are also kept constant. Changes in heat transfer between the film and gas are directly reflected by changes in power input from the compensating circuitry. The steady-state heat balance
is given by

\[ I^2R + h_b S_o (T_b - T_s) = U_i S_o (T_s - T_w) \]  

(7)

where the first term represents the electrical power input, the second the heat gain from the environment, while the term on the right represents the heat given up by the film to the cooling water. The gas-film heat transfer coefficient \( h_b \) itself depends not only on the nature of the gas, but also its velocity and temperature according to cylinder heat transfer correlations, as well as other factors such as scale and intensity of turbulence.

If an aspirating probe is used, in order to provide constant gas velocity past the sensor, and if the film temperature \( T_s \) is kept constant, then \( U_i \) - the inside heat transfer coefficient - is also constant. The electric power input may thus be directly calibrated to measure the temperature \( T_b \). If concentration is another variable, however, special techniques must be used to separate this effect, such as analysis of the sample gas, or measuring the heat flux at two sensor temperatures.

Thermodynamic probes offer promising new techniques for the measurement of heat flux, enthalpy, temperature, concentration, and velocity, the latter from dynamic pressure measurements. Smith and Churchill (9) used a calorimetric probe of the type developed by Grey et al. (12) to measure the total pressure in a confined plasma jet at atmospheric pressure. The free-stream velocity was calculated by application of the Bernoulli equation:

\[ u^2 = -2g_c \int_{1}^{2} \frac{(dp)}{\rho} \]  

(8)
where $\rho$ is the gas density, $p$ the pressure, $U$ the velocity, and $\Delta p$ corresponds to the change between free stream ($p_1$) and tip ($p_2$) stagnation pressures. For an isothermal density change, 

$$U^2 = \frac{2g_c \Delta p}{\rho_1}$$  \hspace{1cm} (9)

If the tip is water-cooled, however, this change is not isothermal, and the use of an average density gives a better approximation of the gas velocity:

$$U^2 = g_c \Delta p (T_1 + T_2) \rho_1 T_1$$ \hspace{1cm} (10)

The use of Pitot tubes in steady and unsteady flows has been well covered in the literature (7, 14-19). Suffice it to say that the velocity measurement obtained in turbulent flows is not the mean value, but is rather intermediate in value between the mean and root-mean-square velocity.

High temperature thermocouples are generally of the same construction as conventional ones, but the sheath, insulation, and wire materials must be chosen on the basis of environment conditions. Thermocouples containing tungsten, rhenium, and other refractory metals have been developed for use up to 4500 °F. (20-24). Tungsten-rhenium wire is now readily available, and calibrations can be reproduced consistently by means of wire-lot screening and matching procedures. These thermocouples are now stable under thermal cycling after annealing, and drift characteristics have been found to be insignificant. Because of the brittle nature of pure refractory metals, they are now being alloyed, and the tungsten-5 percent rhenium/tungsten-26 percent rhenium thermocouple is finding increasing application in non-oxidizing atmospheres.
Srikantiah and Ramachandran (25) have investigated readings of thermocouples in the temperature range of 1600 to 2200 °F., in a low velocity gas stream with up to four radiation shields, a single heated shield, a double shield with nozzle, and with the thermocouple located inside a suction probe. The accuracy of the shielded probes increased with the number of shields, while the suction probe yielded the lowest error at 2200 °F., only 30 deg. F.

A method of avoiding the use of such bulky probes is to calculate the radiation and conduction corrections from the characteristics of the system. Scadron and Warshawsky (26) have carried out an experimental determination of time constants and Nusselt numbers for bare-wire thermocouples in high velocity air streams, and also an analytical approximation of conduction and radiation corrections. Graphs and nomographs were presented as an aid in the computation of these errors and of the time constants. Their heat transfer correlation, over the range $250 < \text{Re}_T < 30,000$, and $0.1 < M < 0.9$, with gas temperatures evaluated at the total temperature $T_t$, is as follows:

$$\text{Nu}_t = 0.478 \left( \text{Re}_t \right)^{0.5} \left( \text{Pr}_t \right)^{0.3}$$

This relationship has been verified by Glawe and Johnson (27) at temperatures up to 3000 °F.

**HIGH TEMPERATURE GAS PROPERTIES**

When a gas such as nitrogen is heated from room temperature up to extremely high energy levels, it undergoes many changes in behaviour. The only important change up to about 3500 °F. is
an increase in the random thermal vibrations of the molecules. Around 12,000 °R., about one-third of the original nitrogen molecules have dissociated into atoms (28), and the thermal excitation of the electron shell shows as an intense glow, even though only about one percent of the particles have ionized to the extent of losing one of their outer electrons. At 20,000 °R., virtually no molecules remain, and primary ionization has increased to about 14 percent (29); the gas is thus electrically-conducting. Double ionization (N++) has started by about 35,000 °R., and at 50,000 °R., 60 percent of the particles have become free electrons. The gas in this condition exhibits similarities to metals, semi-conductors, electrolytes, and ordinary gases, and is described by the term "plasma". It is simply a mixture of electrons and gaseous ions, with or without electrically-neutral atoms or molecules, formed when any substance is heated to very high temperature.

Thermodynamic and transport properties of plasmas are fundamentally different from those of the same material at low temperatures. The specific heat and enthalpy of a plasma not only differ numerically from those of ordinary gas by orders of magnitude, but also show a non-linear change with increasing temperature. In those ranges where thermal dissociation and ionization processes are taking place, each increment of temperature requires a greater amount of energy, and the specific heat shows sharply-peaked maxima. The density and mean molecular weight are meanwhile much lower in value than those of room temperature gases. Thermal conductivity is determined by the thermal diffusion of molecules and neutral atoms in the lower temperature ranges, while it is supplanted by the electron kinetic contribution, and
both the ionization and recombination processes at higher temperatures. Viscosity rises steadily with temperature to a maximum during the primary ionization and then falls off. Emmons (30) explains that this drop is caused by decrease in particle mobility due to long-range coulomb forces which reduce the transport of momentum.

In high temperature gas dynamics, thermodynamic properties of gases are computed from statistical mechanics using spectrally-measured energy levels. Transport properties are obtained from the kinetic theory of gases using collision cross-section data. Svehla (31) has estimated the viscosities and thermal conductivities of 200 gases at temperatures of up to 9000 °R. Allowances were made for the presence of free radicals, but not for excited states and ions. Amdur and Mason (32) have employed molecular beam scattering techniques to derive intermolecular force laws for the calculation of transport properties up to 27,000 °R. for several gases, including nitrogen. Yun, Weissman and Mason (33) have extended the data to allow for the effect of dissociation, but have neglected ionization. Their viscosity data for nitrogen are approached closely by those of Mathur and Thodos (34). Westenberg and deHaas (35) have measured the thermal conductivities of nitrogen, carbon dioxide, and their mixtures from the thermal-wake widths of a steady line heat source in laminar flow up to 1500 °F., and have extrapolated the data up to 3200 °F. Skrivan and von Jaskowski (36) have calculated the viscosity and thermal conductivities of nitrogen and hydrogen from fundamental kinetic theory equations. John et al. (37) in
carrying out an intensive investigation into arc plasma-generation technology, have estimated that the overall accuracy of calculated transport properties is only about 10 to 20 percent. Their nitrogen viscosity data up to 6000 °F. are essentially in agreement with those of several other workers (32, 33, 34, 36, 38), and are shown in Fig. 1, for a pressure of one atmosphere. The graph of nitrogen thermal conductivity may be seen in Fig. 2, as calculated in references (32, 33, 37). The lines of Westenberg and deHaas (35), and Skrivan and von Jaskowski (36) lie slightly below that shown, and that of Svehla (31) slightly above.

Thermodynamic properties of argon, nitrogen and oxygen have been computed and compiled by Drellishak et al. (39). Nitrogen density at atmospheric pressure is shown in Fig. 3, and its specific heat at constant pressure in Fig. 4. Agreement with other authors is good in each case. Ionization effects are negligible below about 15,000 °F. (38), while dissociation exists to the extent of only about 0.1 percent at 6000 °F. (34), and thus its effect is not felt below this temperature.
FIGURE 1

VISCOITY OF NITROGEN AT 1 ATMOSPHERE
FIGURE 2

THERMAL CONDUCTIVITY OF NITROGEN AT 1 ATMOSPHERE
FIGURE 3

DENSITY OF NITROGEN AT 1 ATMOSPHERE
FIGURE 4

SPECIFIC HEAT AT CONSTANT PRESSURE OF NITROGEN AT 1 ATMOSPHERE
APPARATUS

THE PLASMA-GENERATING SYSTEM

The plasma generator employed in this study was of the direct-current type. The overall system, as purchased from Thermal Dynamics Corporation in Lebanon, New Hampshire, consisted of four units: the power supply, the control console, the cooling system, and the plasma torch. The power was supplied from a Model TDC1A-40 rectifier whose power rating was 57 kw. at 75 kva. The input voltage was 3-phase, 60 c.p.s., 575 volt, while the output open circuit could be connected at 80, 160, or 320 volt. The output D.C. current could be adjusted during operation with a variable rheostat up to 1000 amp. The control console contained all the necessary control and operating components for the plasma torch, power supply, and cooling system. Rotameters were provided for the direct reading of flow rates of argon, nitrogen, hydrogen, and carrier gas (for use with powders) at 50 p.s.i.g., in standard cubic feet per hour (s.c.f.h.). The power input to the plasma torch could be obtained from the readings of an ammeter and voltmeter. The cooling system, Model H-20, was made up of a non-ferrous pump-motor-heat exchanger unit for circulating distilled water at 80 p.s.i.g. and a flow rate of about 50 lb./hr. The heat exchanger employed city water as coolant. The use of distilled water for cooling the plasma torch is often necessitated by presence of minerals in ordinary water supplies, which may form deposits inside the torch over a period of time. In addition, the conductance of the water must be sufficiently low to
prevent short-circuiting of current inside the torch cooling channels.

Fig. 5 shows the configuration of the Model F-40 plasma torch and Fig. 6 its photograph. Table 1 is a list of parts for the torch to supplement Fig. 5. The body of the torch was about 10-in. long and had a diameter of 2.75 in. The central, water-cooled tungsten cathode (containing 2% thorium to improve its electron-emitting properties) was located at the entrance of the water-cooled copper anode nozzle. The distance between the anode and the cathode could be varied by means of the electrode knob. The electrode was positioned by turning until it hit the nozzle, and by retracting one full turn. The shoulder of the electrode was then 1/16-in. away from the nozzle, which was sufficient to prevent a short circuit through the gas at that point. The gas was fed axially through the annulus between the two electrodes, and thus through the arc whose path was between the cathode tip and a circular region down the nozzle, and whose shape was similar to an inverted umbrella.

An important feature of the direct-current arc is the intermittent nature of the arc process near the anode. The sheath of cool gas is bridged electrically by a moving concentrated arc, which leads to a cyclic variation of the voltage between cathode and anode at essentially constant current. Re-ignition of the arc after each cycle of travel down the nozzle occurs by breakdown of the gas in the neighbourhood of the cathode. Wheaton and Dean (40) have reported that this cyclic process has a frequency of about 10,000 c.p.s. in an F-40 torch operating with nitrogen.
FIGURE 5

CONFIGURATION OF THERMAL DYNAMICS MODEL F-40

PLASMA TORCH
**TABLE 1**

**LIST OF PARTS FOR F-40 PLASMA TORCH**

<table>
<thead>
<tr>
<th>Item Number in Fig. 5</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electrode Knob</td>
</tr>
<tr>
<td>2</td>
<td>Plastic Insulator</td>
</tr>
<tr>
<td>3</td>
<td>'O' Rings</td>
</tr>
<tr>
<td>4</td>
<td>Insulated Main Body</td>
</tr>
<tr>
<td>5</td>
<td>Water Tube</td>
</tr>
<tr>
<td>6</td>
<td>Main Body Shell</td>
</tr>
<tr>
<td>7</td>
<td>Ceramic Gas Ring</td>
</tr>
<tr>
<td>8</td>
<td>Nozzle Seating Plate</td>
</tr>
<tr>
<td>9</td>
<td>Nozzle Retaining Nut</td>
</tr>
<tr>
<td>10</td>
<td>Water-Tube Stud</td>
</tr>
<tr>
<td>11</td>
<td>Tungsten Cathode</td>
</tr>
<tr>
<td>12</td>
<td>Nozzle Anode</td>
</tr>
<tr>
<td>13</td>
<td>Gas Inlet Fitting</td>
</tr>
<tr>
<td>14</td>
<td>Water-Cooled Lead</td>
</tr>
<tr>
<td>15</td>
<td>Nozzle-Adjusting Nut</td>
</tr>
</tbody>
</table>
FIGURE 6

PHOTOGRAPH OF THERMAL DYNAMICS MODEL F-40

PLASMA TORCH
On Figures 5 and 6 may be seen three leads. The central lead was for the gas; while the two larger leads carried cooling water and electrical cables. Both electrodes were replaceable since they tended to wear out during operation due to gouging of the nozzle and cathode by the arc, the presence of air or water, or because of too high a power level, or too low a gas flow rate. Such deterioration could be observed since molten specks of tungsten, and green copper vapour issued from the nozzle. Gouging also occurred during the ignition process if the cathode and nozzle were not perfectly coaxial. This alignment could be checked by using a high frequency spark which struck from the tungsten electrode shoulder to the nozzle while a gas purge flowed through the torch. Corrections were made by means of the adjusting studs, shown in Fig. 5, which allowed movement of the nozzle relative to the cathode. The high-frequency spark could be seen by looking up the nozzle with a mirror, or when wearing a transparent face-shield. Alignment was correct when the arc was evenly distributed around the annulus. A high-purity grade of nitrogen gas, with an oxygen content of less than 20 parts per million and a dew-point of less than -76 °F., was employed.

Ignition was accomplished with a contact button which energized the high frequency and high voltage arc starter at a current of about 90 amp. This low a value was necessary if the initial surge, which struck across the shortest distance between the cathode and nozzle, was not to gouge the latter. Once ignition had occurred, the gas flow was adequate to blow the arc into the nozzle and to distribute it over a wider area. After completion
of this starting sequence, the current and gas flow rate could be adjusted to values within the capacity of the particular electrode and nozzle being used.

THE GRAPHITE CHAMBER AND COOLING SYSTEM

A schematic diagram of the apparatus in which the plasma jet was confined is shown in Fig. 7. It consisted essentially of an 8.00-in. inside diameter and 10.0-in. outside diameter, type AGR graphite tube, 71.75-in. long at room temperature. The operating pressure inside the graphite reactor was slightly above atmospheric, about 6-in. water gauge, and it varied only slightly with the nitrogen flow rate. Six graphite ports were mounted in three diametrically-opposed pairs with their centres at distances of 12.0, 36.0 and 60.0 in. from the top of the chamber. Each port had an inside diameter of 1.25 in. and a wall thickness of 0.625 in. The ports were press-fitted into the graphite chamber, with the ends matching the inside curvature of the chamber, and were sealed into place with electrode joint cement. They were 19-in. long and were provided with threads so that graphite flanges fitted with pyrex discs for observation could be screwed on them. Another type of port flange allowed for the insertion of probes by a press-fit through it. Fig. 8 is a photograph of the graphite chamber with holes for three ports. In the background is the control console of the plasma generating system. The top of the chamber was closed with a press-fitted, sealed 1.0-in. thick graphite lid which rested in a groove in the tube. A central hole, 1.375-in. diameter, was provided for the plasma torch whose nozzle face rested flush with the inside of the lid,
FIGURE 7

SCHEMATIC DIAGRAM OF GRAPHITE
CHAMBER AND COOLING SYSTEM
A - PLASMA TORCH
B - REACTOR NITROGEN PURGE
C - COOLING PLATE
D - GRAPHITE REACTOR
E - INSULATION
F - STEEL SHELL
G - SUPPORTING FLANGE
H - SHELL NITROGEN PURGE
K - I-BEAM SUPPORTS
L - RELIEF LINE
M - COOLING CONE
N - DOUBLE-PIPE COOLER
P - CYCLONE SEPARATOR
Q - NITROGEN INJECTOR
R - DOUBLE-PIPE COOLER
S - SAMPLING LINE
T - FLAME ARRESTER
FIGURE 8

PHOTOGRAPH OF GRAPHITE CHAMBER WITH TOP COOLING PLATE AND PLASMA TORCH IN POSITION
and a 0.50-in. i.d. graphite purge line entered the lid 3.0-in. from the centre. On top of the lid rested a cooling plate which protected the torch and its leads from the heat of the reactor. Internal vanes ensured the even distribution of cooling water, and holes were provided for the torch and purge line (Fig. 9).

The reactor was insulated with a 12-in. thickness of "Fiberfrax", which is made of alumina-silica fibres of high porosity and low thermal conductivity. The system was enclosed in a steel shell as shown in Fig. 10. A purge was provided to flush the enclosed space between the shell and reactor clear of oxygen which would burn the hot graphite if present.

The graphite tube had a 3-in. thick graphite flange screwed to its base which was connected by bolts to a hollow, water-cooled supporting flange. This, in turn, was provided with 4 pins which rested on a support (Fig. 8). The assembly was held up by two 4-in. x 4-in. I-beams shown in Fig. 11. The cooling cone (item M, Fig. 7) was made of type 316 stainless steel, as were the cooling plate and supporting flange. The cone was provided with a pipe leading to a relief valve set at 2 p.s.i.g. It was 13.5-in. long and connected the 8.0-in. i.d. reactor to the 2.0-in. i.d. copper double-pipe cooler. A cyclone separator was provided for the removal of fine particles during operation of the apparatus with pneumatically-conveyed solids. Fig. 11 shows the cooling cone, double pipe cooler, and the various water connections located below the reactor. A nitrogen injector was provided (item Q, Fig. 7) for use as a diluent when hydrogen was employed as the plasma gas. Before this gas was allowed into the
FIGURE 9

CLOSE-UP OF THE TOP COOLING PLATE WITH THE PLASMA TORCH INSERTED
FIGURE 10

PHOTOGRAPH OF THE GRAPHITE CHAMBER SYSTEM
FIGURE 11

PHOTOGRAPH OF COOLING SYSTEM AND I-BEAM SUPPORTS
atmosphere, it was made to pass through a check valve and flame arrestor.

The top of the reactor was located about 13 ft. above the level of the floor, and the equipment was made accessible with a steel platform and stairs. The apparatus was constructed in such a way as to facilitate modifications and to allow for easy disassembly.

**MEASUREMENT TECHNIQUES**

The graphite chamber wall temperature was measured at various distances down its length by nine chromel-alumel thermocouples in a 1/16-in., type 310 stainless steel sheath, pressed externally on the wall. The thermocouples were connected to a Minneapolis-Honeywell 12-point strip chart recorder which monitored each point every 24 sec. The remaining three points on the recorder were connected to bare chromel-alumel thermocouples measuring the gas temperature below the first double-pipe cooler, before entry to the atmosphere, and inside the reactor at the level of ports 2 or 3, or any other desired location.

The nitrogen temperature at port 1 was measured by means of bare-wire, 0.005-in. diameter tungsten-5 percent rhenium/tungsten-26 percent rhenium thermocouples, supplied by the Aero Research Instrument Department of American-Standard Products in Chicago. The sheath and insulation materials were inconel and magnesia respectively, with an outside diameter of 0.040-in. The thermocouple was enclosed inside a water-cooled 1/4-in. i.d. brass tube with a conical end, out of which the bare tip was made
to protrude from 1/8 to 1/4-in. while temperature measurements were being obtained. Extension wire connected the thermocouple to an ice bath, and to a Minneapolis-Honeywell variable-zero and variable-span strip chart recorder, whose range could be adjusted from 0-5 m volt. to 0-55 m volt. The thermocouple characteristics were provided by the manufacturer, and confirmed in reference (41).

The velocity at port 1 was obtained by means of a modified, water-cooled aspirating probe provided by Thermo-Systems Inc. in Minneapolis. This probe was of the type described by Fingerson and Blackshear (13). Fig. 12 is a photograph of the probe inserted into port 1, and shows the cooling water and electrical connections as used with the heat flux probe, which was described in an earlier section. The modifications, which converted the aspirating probe to a total-head probe, were made by soldering a 0.064-in. o.d., 0.023-in. i.d. and 3/8 in. long type 316 stainless steel tube to the opening. This tip may be seen, in Fig. 13, exposed at the level of port 1 to a gas temperature of about 5000 °F., and graphite wall temperatures of 1200 °F. (top), and 1850 °F. (bottom). The water-cooled tube-bundle to which the tip was joined prevented it from melting, although a surface layer of scale was sometimes formed, as the end glowed white-hot. A water-cooled 0.75-in. o.d. sleeve, extending to within 6 in. of the tip, provided additional cooling for the probe. A reference pressure, close to the static pressure in value, was measured inside port 1, and the uncorrected dynamic pressure was obtained from an inclined manometer, with methanol as working fluid. Inclinations of 1/10, and 1/25 were used. Fluctuations
FIGURE 12

PHOTOGRAPH OF HEAT FLUX PROBE INSERTED INTO PORT
FIGURE 13

PHOTOGRAPH OF TOTAL-HEAD PROBE IN GRAPHITE CHAMBER AT WALL TEMPERATURES OF 1200 °F., (TOP), AND 1850 °F. (BOTTOM)
in the pressures were damped out by means of short lengths of 0.010-in. i.d. capillary tubing. Because of the recirculation present in the region of the chamber near the wall at port 1, the probe had to be inverted to obtain the total pressure of this upward flow. It was found that the pressure measured by the probe pointing upwards with the flow near the wall was very slightly lower than the reference pressure in value, so this was taken as the static pressure and a correction was applied to the dynamic pressure readings. The difference in manometer reading between the static pressure and the reference pressure was less than 5 percent of the dynamic pressure obtained at the centre of the reactor. It was felt that the reference pressure was a little high because of a small radial component of velocity towards the wall, and that the static pressure was more closely approximated in the wake of the probe in the low velocities prevalent near the wall.
RESULTS

OPERATING CHARACTERISTICS OF SYSTEM

The F-40 plasma torch was operated using two sizes of nozzle: the No. 1, with a diameter of 0.219 in., and the No. 3 with a diameter of 0.312 in. In Table II are listed the operating ranges of the torch for nitrogen and hydrogen.

<table>
<thead>
<tr>
<th>Nozzle No.</th>
<th>Gas</th>
<th>Flow Range (s.c.f.h.)</th>
<th>Operating Voltage (volt)</th>
<th>Current Range (amp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nitrogen</td>
<td>40-150</td>
<td>50-75</td>
<td>70-450</td>
</tr>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>200-1000</td>
<td>90-120</td>
<td>70-350</td>
</tr>
<tr>
<td>3</td>
<td>Nitrogen</td>
<td>50-250</td>
<td>50-75</td>
<td>70-750</td>
</tr>
</tbody>
</table>

It was found that operation was unstable at low currents, and that the arc had a tendency to extinguish. At high currents, and particularly low flow rates, the plasma jet often showed traces of green copper vapour and molten specks of tungsten, which led to failure of the nozzle on several occasions. Thus, for prolonged operation with the plasma jet inside the reactor, when measurements were being obtained, the highest total power input to the torch was about 36 kw.

According to Thermal Dynamics Corporation, the efficiency of the energy transfer to the gas in the torch increased with voltage, and varied typically from about 60 to 70 percent.
during operation with nitrogen. In order to duplicate the net power input from run to run, the current was adjusted according to the value of the voltage (and hence efficiency), which were not amenable to alteration. Account was also taken of the power losses in the electrical cables.

Twenty sets of operating conditions were chosen, based on nozzle size, net power input to the gas, gas flow rate, and time of measurement, such as temperature and velocity in the reactor. These conditions are listed in Table III for ease of identification in later tables.

### Table III
DESIGNATION OF CONDITIONS FOR REACTOR RUNS

<table>
<thead>
<tr>
<th>Nozzle No.</th>
<th>Power Input to Gas (kw.)</th>
<th>Nitrogen Flow (s.c.f.h.)</th>
<th>Time (min.)</th>
<th>Run Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5</td>
<td>50</td>
<td>18</td>
<td>1-3.5-50</td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>100</td>
<td>7</td>
<td>1-3.5-100</td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>150</td>
<td>2</td>
<td>1-3.5-150</td>
</tr>
<tr>
<td>1</td>
<td>7.0</td>
<td>100</td>
<td>27</td>
<td>1-7.0-100</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>100</td>
<td>1</td>
<td>3-7.0-100</td>
</tr>
<tr>
<td>1</td>
<td>7.0</td>
<td>150</td>
<td>1</td>
<td>1-7.0-150</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>150</td>
<td>10</td>
<td>3-7.0-150</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>200</td>
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<td>3-7.0-200</td>
</tr>
<tr>
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<td>7.0</td>
<td>250</td>
<td>5</td>
<td>3-7.0-250</td>
</tr>
<tr>
<td>1</td>
<td>11.0</td>
<td>100</td>
<td>9</td>
<td>1-11.0-100</td>
</tr>
<tr>
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<td>11.0</td>
<td>150</td>
<td>4</td>
<td>1-11.0-150</td>
</tr>
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<td>150</td>
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<td>14.0</td>
<td>100</td>
<td>2</td>
<td>3-14.0-100</td>
</tr>
<tr>
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<td>14.0</td>
<td>150</td>
<td>2</td>
<td>3-14.0-150</td>
</tr>
<tr>
<td>3</td>
<td>14.0</td>
<td>200</td>
<td>1</td>
<td>3-14.0-200</td>
</tr>
<tr>
<td>3</td>
<td>19.5</td>
<td>150</td>
<td>2</td>
<td>3-19.5-150</td>
</tr>
<tr>
<td>3</td>
<td>19.5</td>
<td>200</td>
<td>2</td>
<td>3-19.5-200</td>
</tr>
<tr>
<td>3</td>
<td>23.4</td>
<td>150</td>
<td>2</td>
<td>3-23.4-150</td>
</tr>
<tr>
<td>3</td>
<td>23.4</td>
<td>200</td>
<td>2</td>
<td>3-23.4-200</td>
</tr>
</tbody>
</table>
The time is listed since conditions, such as gas and wall temperatures, and velocity slowly increased with time. Hence the thermocouple and total-head readings listed in later tables were obtained at the time indicated in Table III.

Fig. 14 shows a plot of the graphite reactor wall temperature as a function of time, in intervals of 30 minutes starting with the reactor at room temperature. The power input was 11.0 kw. at a net nitrogen flow rate of 100 s.c.f.h. through a No. 1 nozzle. For these conditions, the value of the gas enthalpy leaving the nozzle was about 5180 Btu/lb., while the temperature levels at ports 1 and 2 were found to be radially uniform at about 1500 and 400 °F. respectively at the start of the run. After 120 minutes, these values had increased to up to 2300 and 700 °F., respectively. The temperature and velocity profiles at port 1 may be seen in Fig. 15 for the same conditions, 9 minutes from the start of run. In Table IV are listed the enthalpy levels of the gas at ports 1, 2 and 3.

<table>
<thead>
<tr>
<th>Time (min.)</th>
<th>Enthalpy of Plasma Jet (Btu/lb.)</th>
<th>Enthalpy at Port 1 (Btu/lb.)</th>
<th>Enthalpy at Port 2 (Btu/lb.)</th>
<th>Enthalpy at Port 3 (Btu/lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5180</td>
<td>700</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>120</td>
<td>5180</td>
<td>1000</td>
<td>650</td>
<td>200</td>
</tr>
</tbody>
</table>

TABLE IV

MEAN NITROGEN GAS ENTHALPIES FOR RUN 1-11-100
FIGURE 14

GRAPHITE WALL TEMPERATURE VARIATION WITH TIME FOR RUN 1-11.0-100
Because of the high gas temperatures involved, the use of bare-wire thermocouples necessitated the calculation of radiation and conduction corrections. The method of Scadron and Warshawsky (26) was used. The radiation correction is given by:

\[ \Delta T_r = \frac{\sigma \varepsilon_{tc} D_{tc} T_b^4 \left[ 1 - (T_d/T_{tc})^4 \right]}{Nu_b k_b \left[ 1 + \left( 4 \sigma \varepsilon_{tc} D_{tc} T_b^4 \right) / (Nu_b k_b T_b) \right]} \]  (12)

where \( T_b, T_d \) and \( T_{tc} \) are the absolute temperatures of the bulk gas, enclosing duct, and the thermocouple junction, respectively; \( D_{tc} \) is the thermocouple wire diameter; \( \sigma \) is the Stefan-Boltzmann constant; \( \varepsilon_{tc} \) is the thermocouple wire emissivity from reference (42), and

\[ Nu_b = 0.32 + 0.478(Re_b)^{0.5} (Pr_b)^{0.33} \]  (13)

The figure 0.32 in equation (13) is the natural convection contribution for the low Reynolds number range, \( 0 \lesssim Re \lesssim 25 \), obtained from McAdams (43). The gas properties were estimated at the bulk gas temperature \( T_b \). The velocity was calculated from the equation:

\[ U = \left[ 2g_c \Delta_p / \rho_b \right]^{0.5} \]  (14)

Since the tip of the total head probe was glowing at red and white heat (1400-2000 °F.), and because of the high-frequency turbulent fluctuations in the gas, it was felt that the gas at the stagnation point was at a temperature close to the free-stream value, and no density correction of the type shown in equation (10) was deemed necessary. The conduction correction is given by:

\[ \Delta T_c = \Psi (T_{tc} - T_{sh}) / (1 - \Psi) \]  (15)
where

\[ \psi = \text{sech} \left( \eta \frac{L_{tc}}{2} \right) \]  (16)

and

\[ \eta = \left[ 4 \frac{Nubk_b}{D^2k_{tc}} \right]^{0.5} \]  (17)

Here, \( T_{sh} \) is the absolute temperature of the wire at the sheath, \( L_{tc} \) is the length of thermocouple wire outside the sheath, and \( k_{tc} \) is the thermocouple wire thermal conductivity.

The procedure for calculating the radiation and conduction corrections was iterative, in that the gas temperature \( T_b \) had first to be estimated, using the thermocouple reading as a first estimate. These corrections ranged in value from 15 to as much as 800 °F. at the highest temperatures measured. Tables V and VI list the temperature and velocity profiles at the level of port 1 for the 20 runs, whose results were found to be reproducible within five percent in the central region of the reactor. Near the wall, the gas temperature increased at a much faster rate than at the centre as the wall heated up and reproducibility was thus only about 10 percent, while the low dynamic pressures in this region were prone to a much larger scatter. Figures 15 to 18 show some typical profiles obtained. The enthalpy values shown in Table V were estimated from an approximate energy balance on the torch using the efficiency values provided by the manufacturer to calculate the heat loss to the cooling water.

The recirculation phenomenon was of sufficient interest and importance to warrant its calculation. The non-dimensional nitrogen recirculation rate \( Q^+ \) (mass recirculation rate divided by net mass input rate) is also shown in Table VI. It was calculated from a graphical integration of the downward flow using an average value for the density.
<table>
<thead>
<tr>
<th>Run</th>
<th>Radial Distance from Centre (r/R₂)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Enthalpy of Plasma Jet (Btu/lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.25</td>
<td>0.50</td>
<td>0.75</td>
<td>0.94</td>
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<tr>
<td>1-3.5-50</td>
<td>1680</td>
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<td>1300</td>
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<td>1260</td>
<td>1050</td>
<td>960</td>
<td>860</td>
<td>1650</td>
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<td>660</td>
<td>1080</td>
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<td>1330</td>
<td>3290</td>
</tr>
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<td>2250</td>
<td>2060</td>
<td>1840</td>
<td>1600</td>
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<td>1000</td>
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<td>2310</td>
<td>2120</td>
<td>1970</td>
<td>1740</td>
<td>1560</td>
<td>2210</td>
</tr>
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<td>3-7.0-200</td>
<td>1960</td>
<td>1820</td>
<td>1650</td>
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<td>1395</td>
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<td>2870</td>
<td>2610</td>
<td>2310</td>
<td>2020</td>
<td>1660</td>
<td>5180</td>
</tr>
<tr>
<td>1-11.0-150</td>
<td>2200</td>
<td>1990</td>
<td>1830</td>
<td>1580</td>
<td>1450</td>
<td>3440</td>
</tr>
<tr>
<td>3-11.0-150</td>
<td>3220</td>
<td>2850</td>
<td>2560</td>
<td>2090</td>
<td>1870</td>
<td>3440</td>
</tr>
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<td>2420</td>
<td>2210</td>
<td>2110</td>
<td>1820</td>
<td>1670</td>
<td>2590</td>
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<td>3-14.0-100</td>
<td>4110</td>
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<td>3160</td>
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<td>2580</td>
<td>6600</td>
</tr>
<tr>
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<td>2710</td>
<td>2440</td>
<td>2270</td>
<td>2000</td>
<td>4380</td>
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<td>4590</td>
</tr>
<tr>
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<td>4490</td>
<td>3930</td>
<td>3700</td>
<td>3450</td>
<td>7350</td>
</tr>
<tr>
<td>3-23.4-200</td>
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<td>4290</td>
<td>3860</td>
<td>3400</td>
<td>3250</td>
<td>5510</td>
</tr>
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</table>
TABLE VI.

VELOCITY PROFILES AT PORT 1 (ft/sec.)

<table>
<thead>
<tr>
<th>Run</th>
<th>Radial Distance from Centre (r/R_2)</th>
<th>Recirculation Rate Q^+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
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<td>1-3.5-50</td>
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<td>1-3.5-100</td>
<td>47</td>
<td>29</td>
</tr>
<tr>
<td>1-3.5-150</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>1-7.0-100</td>
<td>68</td>
<td>35</td>
</tr>
<tr>
<td>3-7.0-100</td>
<td>49</td>
<td>32</td>
</tr>
<tr>
<td>1-7.0-150</td>
<td>74</td>
<td>49</td>
</tr>
<tr>
<td>3-7.0-150</td>
<td>61</td>
<td>39</td>
</tr>
<tr>
<td>3-7.0-200</td>
<td>64</td>
<td>42</td>
</tr>
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<td>3-7.0-250</td>
<td>71</td>
<td>49</td>
</tr>
<tr>
<td>1-11.0-100</td>
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<td>84</td>
<td>46</td>
</tr>
<tr>
<td>3-14.0-100</td>
<td>72</td>
<td>43</td>
</tr>
<tr>
<td>3-14.0-150</td>
<td>81</td>
<td>47</td>
</tr>
<tr>
<td>3-14.0-200</td>
<td>96</td>
<td>63</td>
</tr>
<tr>
<td>3-19.5-150</td>
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</tr>
<tr>
<td>3-19.5-200</td>
<td>124</td>
<td>74</td>
</tr>
<tr>
<td>3-23.4-150</td>
<td>128</td>
<td>68</td>
</tr>
<tr>
<td>3-23.4-200</td>
<td>147</td>
<td>103</td>
</tr>
</tbody>
</table>

* upward flow
FIGURE 15

TEMPERATURE AND VELOCITY PROFILES AT PORT 1
FOR RUN 1-11,0-100
NOZZLE DIA. 0.219 in
NET POWER 11.0 Kw.
NET FLOW RATE 100 s.c.f.h.
TIME 9 min.
FIGURE 16

TEMPERATURE AND VELOCITY PROFILES AT PORT 1
FOR RUN 3-7.0-150
NOZZLE DIA. 0.312 in.
NET POWER 7.0 Kw.
NET FLOW RATE 150 s.c.f.h.
TIME 10 min.
FIGURE 17

TEMPERATURE AND VELOCITY PROFILES AT PORT 1
FOR RUN 3-14.0-150
NOZZLE DIA. 0.312 in
NET POWER 14.0 Kw.
NET FLOW RATE 150 s.c.f.h.
TIME 2 min.
FIGURE 18

TEMPERATURE AND VELOCITY PROFILES AT PORT 1 FOR RUN 3-23.4-150
NOZZLE DIA. 0.312 in.
NET POWER 23.4 Kw.
NET FLOW RATE 150 s.c.f.h.
TIME 2 min.
Plasma jets generated by means of direct current are characterized by high gas velocities at the nozzle exit. For the F-40 torch used in this investigation, this velocity ranged in value from about 1000 to 2500 ft/sec., which corresponded to a Mach number range of 0.2 to 0.5. The velocity at the centre of the test section (port 1) was much lower in value, from 40 to 150 ft./sec., as a result of both the mixing process and a decrease in temperature. The time taken for the gas leaving the plasma torch to reach the level of port 1 was thus of the order of milliseconds.

The species of particles present in the plasma jet at the nozzle exit were electrons, nitrogen molecules, nitrogen atoms, and nitrogen ions. The possible types of energy modes and temperatures possessed by the particles were translational, rotational, vibrational, and electron-excitational. For thermal equilibrium to exist, all of the above temperatures must be equal. Any factor which tends to slow the energy transfer between the different energy modes can create a non-equilibrium condition. Gases at low pressure, with a correspondingly large mean free path, are likely to deviate from thermal equilibrium in plasma jets in which the energy is provided in the form of the electron translational mode (44). It has been generally concluded, however, that for plasma jets at atmospheric pressure and above, the system is close to equilibrium, and that approximately the same temperature can be assigned to the various
modes (29, 45, 46, 47). Finkelnburg (29) has expressed the opinion that this is due to the small voltage gradient present in the arcs, and the correspondingly little gain in translational energy which an electron can make between collisions in the electric field.

The rate at which thermal equilibrium is reached depends on the nature of the excited mode. It is the rotational and translational modes that are generally the fastest, since these are most affected by collisions which bring about the state of thermal equilibrium. For the highest enthalpy level reached in this investigation, in Run 3-23.4-150, the equilibrium composition, as given by Drellishak et al. (39) is shown in Table VII for the gas in the plasma jet and in the centre of the reactor at port 1:

**TABLE VII**

**EQUILIBRIUM COMPOSITION OF GAS IN PLASMA JET AND AT CENTRE OF REACTOR AT PORT 1 FOR RUN 3-23.4-150**

<table>
<thead>
<tr>
<th>Species</th>
<th>Plasma Jet Composition</th>
<th>Port 1 Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecules (N(_2)) cm(^{-3})</td>
<td>6.8 (\times) 10(^{17})</td>
<td>2.4 (\times) 10(^{18})</td>
</tr>
<tr>
<td>Ionized Molecules (N(_2^+)) cm(^{-3})</td>
<td>3.3 (\times) 10(^{13})</td>
<td>1.5 (\times) 10(^{7})</td>
</tr>
<tr>
<td>Atoms (N) cm(^{-3})</td>
<td>4.5 (\times) 10(^{17})</td>
<td>6.1 (\times) 10(^{13})</td>
</tr>
<tr>
<td>Ionized Atoms (N(^+)) cm(^{-3})</td>
<td>1.0 (\times) 10(^{14})</td>
<td>1.7 (\times) 10(^{4})</td>
</tr>
<tr>
<td>Electrons cm(^{-3})</td>
<td>1.3 (\times) 10(^{14})</td>
<td>1.5 (\times) 10(^{7})</td>
</tr>
<tr>
<td>Total Particles cm(^{-3})</td>
<td>1.1 (\times) 10(^{18})</td>
<td>2.4 (\times) 10(^{18})</td>
</tr>
</tbody>
</table>

Extremely rapid temperature changes, 10\(^6\) °F./sec. and
higher, also give rise to non-equilibrium systems (44). In the present study, the maximum rate of temperature change was of the order of $10^6$ °F./sec., so it would seem that some deviation from equilibrium would have existed during operation at the highest power levels. Using the equations of Benson (48) for calculating the collision frequency between molecules with a Maxwellian velocity distribution, it was found that the particles would undergo about $10^6$ collisions before reaching the level of port 1. From a comparison of the particle concentrations in Table VII, it may be seen that it is only the ionized molecules ($N_2^+$), ionized atoms ($N^+$), and electrons whose concentrations would have deviated from the equilibrium composition at port 1. Nevertheless, any such deviations would be slight when compared to the total number of particles present, about $10^{18}$ cm$^{-3}$, since the concentration of the charged particles would be only of the order of $10^{10}$ cm$^{-3}$, and thus statistically unimportant. In addition, since the recirculation rate for Run 3-23.4-150 was about 12 times the input nitrogen flow rate, a further decrease in the charged particle concentration would have occurred. Greene et al. (49) have reported that nitrogen requires about 20 collisions for rotational relaxation, while Blackman (50) has stated that vibrational relaxation occurs after $10^4$-$10^5$ collisions. It seems probable then that a state of thermal equilibrium is closely approximated at the level of port 1.

Inside the torch itself, the gas was at a pressure above that in the reactor, so that the rate of collision was enhanced. Some deviation from thermal equilibrium in electric
arcs is caused by the escape of photons, which result from transitions between the excited electronic states, without appreciable reabsorption by the plasma (29). This effect becomes important only at temperature levels above and pressure levels below those encountered in this investigation. It has been found that the radiation loss in a direct-current torch, similar to the F-40 torch, operating with nitrogen is only about 1.5 percent of the power input to the torch (51).

Although the Reynolds numbers of the plasma leaving the nozzle were low in value, between 900 and 4900 (because of the high kinematic viscosity of nitrogen at high temperature), the jet possessed a high degree of turbulence. On the other hand, the intermittent nature of the arc process in the nozzle cannot be classed as turbulence because of its cyclic nature, with a frequency of about 10,000 c.p.s. (40). For this frequency and the velocity range of 1000 to 2500 ft./sec. corresponding to that of the plasma jet at the nozzle exit, pockets of plasma about one inch in length would have been superimposed on the turbulence generated by the jet mixing process. Such pockets of plasma, representing regions of high local temperature, have been observed in an argon plasma jet by Watson et al. (52).

In Table V are shown the gas temperature profiles at port 1 measured by the tungsten-5 percent rhenium/tungsten-26 percent rhenium thermocouple, and corrected for radiation and conduction losses. Using the results of Chludzinski et al. (53) for calculating the recombination heat transfer contribution to thermocouples immersed in argon-nitrogen plasmas, it was found
that the contribution of nitrogen ions ($N_2^+$ and $N^+$), and nitrogen atoms was negligible in comparison with the convective contribution. The equation for the heat transfer coefficient was given by:

$$h = 1.05(k_b/0)(Re_b)^{0.5}(Pr_b)^{0.3} + (0.20/12D)^{0.5} \left[ 1.72 \times 10^{-20} C_{A^+} + 1.11 \times 10^{-20} C_{N^+} + 7.5 \times 10^{-20} C_N \right]$$  \hspace{1cm} (18)$$

where $C_{A^+}$, $C_{N^+}$, $C_N$ are the particle concentrations (number per ft$^3$) of argon ions, nitrogen ions and nitrogen atoms respectively.

The temperatures of the plasma jet, obtained from the enthalpy values at the nozzle exit (right-hand column), ranged in value from about 4000 to 11,000 °F. for Runs 1-3.5-150 and 3-23.4-150 respectively, assuming that thermal equilibrium conditions were approached. The gas temperature drop from the nozzle to the centre of the reactor at the level of port 1 thus varied from 3000 to 6000 °F. In Table IV are listed the enthalpies of the gas at all three ports for Run 1-11-100. It may be seen that a drop in enthalpy of about 80 percent occurred between the top of the reactor and port 1, and that the enthalpy of the gas at all levels increased only slightly as the reactor heated up.

Fig. 14 shows the variation of the graphite wall temperature with time for the same run. The hottest region of the wall was just below the level of port 1, about 1.25 ft. under the entry of the jet into the chamber. This must then have been the region of greatest heat flux to the wall. According to the isothermal confined jet data of Becker et al. (6), the downstream limit of the recirculation eddy in the present study was located at exactly
this level. It was therefore the hot gas from the centre of the reactor which changed its direction of flow in rounding the eye of the recirculation eddy that caused the high heat flux to the confining wall at this level. As the gas travelled further up the wall, its temperature level had dropped with the result that the heat flux and wall temperature also decreased. The graphite wall further up the reactor was thus shielded from the hot jet by the cooler upward recirculatory flow.

The velocity profiles at the level of port 1 are shown in Table VI, and Fig. 15-18. The values of the upward flow velocities at the radial distance \( r/R_2 \) of 0.75 and 0.94 have a large possible error of as much as \( \pm 50 \) percent since they depended on small differences between the total and static pressure (1 to 7 mm. of alcohol at a manometer inclination of 1/25, as compared with readings from 30 to 400 obtained at locations closer to the axis). Thus velocity measurements nearer the centre of the reactor were very much more accurate, and had a possible error of less than 5 percent.

The mass balance between the downward flow in the jet and the upward recirculatory flow were in agreement within the possible error of the latter. The radial position of zero velocity was found to be at about \( r/R_2 = 0.6 \), as predicted for this system by Becker et al. (6). The recirculation rate was calculated from the downward velocity profile of the jet, and was found to be from 16 to 28, and 9 to 12 times the net nitrogen flow rate using the No. 1 and 3 nozzle sizes respectively. The recirculation rate \( Q^+ \), given earlier in equation (6) of this section,
\[ Q^+ = \left(\frac{0.61}{Ct}\right) - (0.7) \]

where \( Ct = R_1/R_2 \)

predicted values of 22 and 15 respectively for the two nozzle sizes. The value of \( Q^+ \) was fairly constant for runs performed with the No. 3 nozzle, about 30 percent below that predicted by the above equation, while the runs performed with the smaller nozzle showed more scatter and an even deviation of ±30 percent from the predicted value of \( Q^+ = 22 \). Although the recirculation rate expression was derived for an isothermal system, it may be seen that the predicted recirculation rates were in fair agreement with those obtained under conditions in which the absolute temperatures varied by as much as a factor of three.
CONCLUSIONS

It is believed that a reliable assessment of the operating characteristics of a plasma jet reactor system have been obtained. In particular, gas velocity and temperature profiles have been determined at a selected test section for twenty plasma jet power levels and flow rates, together with the measurement of wall temperature at various locations.

Consideration of the species present in the nitrogen plasma jet led to the conclusion that both thermal and composition equilibrium conditions were closely approached.

It is interesting to note that calculations of the recirculation rate, and estimates of both the radial and axial positions of the eye of the recirculation eddy agreed well with published analyses of isothermal confined jets.

The plasma jet system, as designed and constructed, is suitable for high temperature investigations such as pure heat transfer, simultaneous heat and mass transfer, and chemical kinetics with fixed bodies of various shapes, and also for multiparticle solids-gas reactions in conveyed systems in high temperature surroundings.
**Nomencature**

**Roman Symbols**

- $c_p$: specific heat at constant pressure, Btu/lb. °F.
- $C_{A^+, N^+, N}$: concentration of $A^+$ ions, $N^+$ ions and $N$ atoms respectively, $ft^{-3}$
- $D$: diameter, ft.
- $g_c$: gravitational constant, 32.17 ft.lb./lb. force sec$^2$
- $h$: heat transfer coefficient, Btu/hr.ft$^2$ °F.
- $i$: enthalpy, Btu/lb.
- $l$: electrical current, amp.
- $k$: thermal conductivity, Btu/hr.ft °F.
- $L$: length, ft.
- $m$: momentum parameter, dimensionless
- $m_0$: initial value of momentum parameter, dimensionless
- $p$: pressure, lb./ft$^2$
- $Q$: volumetric flow rate, $ft^3$/hr.
- $Q^+$: $(Qr/Qt)$ for equal densities, dimensionless
- $r$: radial distance, ft.
- $R$: radius, ft.; resistance, ohm.
- $S_o$: outside surface area, $ft^2$
- $T$: temperature, °F., °R., °C. or °K.
- $\Delta T_r$: radiation correction, deg. F.
- $\Delta T_c$: conduction correction, deg. F.
- $u$: component of velocity in axial direction, ft./hr.
- $U$: velocity, ft./hr.; heat transfer coefficient, Btu/hr.ft$^2$ °F.
GREEK SYMBOLS

\( \varepsilon \) - emissivity, dimensionless
\( \eta \) - thermocouple correction factor \([4 \frac{Nu_b k_b}{D^2 k_c}]^{0.5}\), ft
\( \lambda \) - mean free path of gas, ft.
\( \mu \) - viscosity, lb/ft.hr.
\( \Pi \) - 3.14159
\( \rho \) - density, lb./ft\(^3\)
\( \sigma \) - Stefan-Boltzmann constant, \(0.1714 \times 10^{-8}\) Btu/ft\(^2\) hr. °R\(^4\)
\( \psi \) - thermocouple correction factor, sech \((\eta | L/2)\), dimensionless

DIMENSIONLESS GROUPS

\( Ct \) - Craya-Curtet number, \((m_o^{-0.5})\)
\( Kn \) - Knudsen number, \((\lambda / D)\)
\( M \) - Mach number
\( Nu \) - Nusselt number, \((hD/k)\)
\( Pr \) - Prandtl number, \((c_p \mu / k)\)
\( Re \) - Reynolds number, \((DU \rho / \mu)\)

SUBSCRIPTS

\( b \) - bulk or free stream
\( d \) - duct
\( f \) - film
\( i \) - inside
\( o \) - outside
\( r \) - recirculatory; radiation
\( s \) - surface
sh  - sheath

t  - total; total input

tc - thermocouple

w  - water

l  - primary or jet stream; free stream

2  - secondary stream; stagnation point
BIBLIOGRAPHY


PART II

HEAT TRANSFER TO SPHERES AND CYLINDERS

INTRODUCTION

Investigations involving pure heat transfer to spheres have been comparatively rare in the literature, while combined heat and mass transfer - such as that encountered in evaporation or drying processes - has received much greater attention. Most of the heat transfer data for cylinders, on the other hand, have been obtained without the complication of mass transfer, because heating and cooling processes outside tubes in heat exchange equipment present problems of considerable practical interest. The relatively new techniques of hot-wire anemometry have also instigated research into the fundamentals of heat transfer to and of fluid flow past cylinders.

The development of the plasma jet research facility and determination of its operating characteristics, described in Part I of this thesis, provided the means for the study of pure heat transfer under conditions of high temperature gradients and turbulence levels which are typical of confined plasma jet systems. The latter are also characterized by the phenomenon of recirculation which is caused by the retardation of the expanding flow down to zero velocity, due to the pressure rise in the mixing process. A test section was selected in the cylindrical graphite chamber at a position of about one foot below the entry of the plasma jet, and velocity and temperature profiles were
measured at this level as a function of the radius. The central velocities and temperatures ranged in value from 40 to 150 ft./sec., and from 1100 to 5100 °F. respectively. Heat transfer measurements to water-cooled spheres and cylinders could thus be carried out at this position under predetermined conditions.

HEAT TRANSFER RELATIONS FOR SPHERES AND CYLINDERS

Most of the forced-convection heat transfer data for spheres and cylinders that have been reported in the literature are correlated in the form of the Nusselt number (Nu), based on the heat transfer coefficient, the Prandtl number (Pr), and the Reynolds number (Re) of the stream. For relatively low Re, the equations take the following form:

$$\text{Nu} = a + b \ (\text{Re})^p \ (\text{Pr})^q$$  \hspace{1cm} (1)

The values of a for a sphere and cylinder are 2.0 and 0.32 respectively, and correspond to the value of the Nusselt number in an infinite stagnant fluid. From a theoretical analysis of mass transfer, Froessling (1) has shown that q has the value of 1/3 for large Prandtl numbers. The analogous equation for mass transfer is

$$\text{Sh} = a + b \ (\text{Re})^p \ (\text{Sc})^q$$  \hspace{1cm} (2)

where Sh and Sc are the Sherwood and Schmidt numbers, respectively. The use of the 1/3 exponent on Pr and Sc has been confirmed by Linton and Sherwood (2), for tubes, cylinders, spheres, and plates.

There has been considerable divergence of opinion as to how best to account for variations in fluid properties. A few
workers, mainly those using liquids, have recommended the use of a viscosity correction factor, and that properties be evaluated at the free-stream or bulk fluid temperature $T_b$ (3-6). Churchill and Brier (7) followed this procedure in their heat transfer studies to water-cooled cylinders from nitrogen at temperatures up to 1800 °F., and applied a temperature correction factor $(T_b/T_s)$. On the other hand, Douglas and Churchill (8) made an extensive survey of cylinder convective heat transfer, and concluded that the best correlation of all the data available was obtained when the fluid properties were taken at the arithmetic average of the bulk and surface temperatures, or the mean film temperature $T_f$. Unless otherwise stated, this basis will be assumed in the following discussions. Most of the investigations, however, were carried out at very small temperature differences between the surface and fluid, in which cases the temperature basis employed was of no importance.

For the cases in which the temperature range is such that the specific heat varies considerably within the boundary layer, it has been shown that the temperature difference should be replaced by the enthalpy difference (9, 10). This is particularly important under conditions in which thermal equilibrium does not exist and a single temperature cannot properly describe the state of the gas.

One of the most important pieces of analytical work in the field of particulate forced-convection heat and mass transfer was that carried out by Froessling (1). He calculated the temperature distribution in the laminar boundary layer of a body of
arbitrary shape for the two-dimensional and axially-symmetrical case. Simplifying assumptions included incompressibility of the fluid, and constancy of fluid properties. He proposed the following expression for the overall Nusselt number for spheres:

$$\text{Nu} = 2.0 + 0.552 \, (\text{Re})^{0.5} \, (\text{Pr})^{0.33}$$  \hspace{1cm} (3)

The experimental study of Ranz and Marshall (11) on the rate of evaporation from stationary droplets confirmed the validity of equation (3), except that these authors proposed a coefficient of 0.60 instead of 0.552:

$$\text{Nu} = 2.0 + 0.60 \, (\text{Re})^{0.5} \, (\text{Pr})^{0.33}$$  \hspace{1cm} (4)

Analogous equations were obtained for the mass transfer case.

During the experimental investigation on the evaporation rates of acetone from single particles of various shapes accelerating freely in a downward cocurrent air stream, Pasternak and Gauvin (12) found that the Nusselt numbers, corrected for mass transfer effects, were consistently higher for the larger particles beyond Re = 400 than those predicted by the Ranz-Marshall equation. Downing (13) studied the evaporation of several liquids in air at temperatures up to 350 °F., at Re ≤ 325. The Nusselt number, again corrected for mass transfer effects, was found to correlate with an average deviation of over 8 percent. This, however, was considered unsatisfactory due to an unusual scatter in the results on the basis of the precision in replicate runs.

McAdams (14) has reported data for heat transfer between spheres and air, correlated by Williams (15) in 1942.
For $17 \leq \text{Re} \leq 70,000$, Williams recommended the use of properties at the mean film temperature, and the following equation:

$$\text{Nu} = 0.37 (\text{Re})^{0.6} (\text{Pr})^{0.33}$$  \hspace{1cm} (5)

Kramers (16) suspended steel spheres, which were heated with a high frequency coil, by a pair of fine thermocouple wires with their junction at the centre of the sphere in a narrow vertical tube. A correlation was obtained for heat transfer to streams of air, water, and oil. For gases at $0.4 \leq \text{Re} \leq 2,000$, this reduced to

$$\text{Nu} = 3.2 + 0.68 (\text{Re})^{0.5} (\text{Pr})^{0.33}$$  \hspace{1cm} (6)

Tang et al. (17) carried out experiments similar to those of Kramers, and for the range $50 \leq \text{Re} \leq 1000$, his correlation for air became

$$\text{Nu} = 2.2 + 0.44 (\text{Re})^{0.5} (\text{Pr})^{0.33}$$  \hspace{1cm} (7)

The large discrepancy between the two above equations may be due to a difference in the effect on the heat transfer of the high-frequency field in the two investigations.

The local Nusselt number has been correlated in terms of the angle $\theta$ radians measured from the front stagnation point, by Yuge (18), from a theoretical treatment of the laminar boundary layer and for $\text{Pr} = 0.733$:

$$\text{Nu}_l = 1.672 (0.6773 - 0.105 \theta^2 - 0.036 \theta^4) (\text{Re})^{0.5}$$  \hspace{1cm} (8)

Yuge (19) also obtained the following relationship for the overall Nusselt number in the range of $3.5 \leq \text{Re} \leq 1.44 \times 10^5$ for forced convection:
Rowe et al. (20) recently described heat and mass transfer experiments from spheres to air and water for $20 \leq \text{Re} \leq 2000$. A correlation of the Ranz-Marshall type was obtained:

$$\text{Nu} = 2.0 + b \text{Re}^{\frac{1}{4}} \text{Pr}^{0.33}$$  \hspace{1cm} (9)

where $b = 0.69$ for air and $0.79$ for water. The exponent $p$ was found to increase from $0.4$ at $\text{Re} = 1$ to about $0.6$ at $\text{Re} = 10^4$.

McAdams (14) has reported on the work carried out prior to 1950 on heat transfer to cylinders transverse to fluid streams. He plotted the data obtained in air by a large number of investigators in the Reynolds number range of $0.02$ to $235,000$, with the fluid properties taken at the film temperature, except for the density which was evaluated at $T_b$. Since the $\text{Nu} - \text{Re}$ line was curved, several straight-line correlations were proposed for different ranges of $\text{Re}$:

$$\begin{align*}
0.1 \leq \text{Re} \leq 1,000 & \quad \text{Nu} = 0.32 + 0.48 \text{Re}^{0.52} \text{Pr}^{0.33} \hspace{1cm} (11) \\
1,000 \leq \text{Re} \leq 50,000 & \quad \text{Nu} = 0.27 \text{Re}^{0.60} \text{Pr}^{0.33} \hspace{1cm} (12) \\
50,000 \leq \text{Re} \leq 250,000 & \quad \text{Nu} = 0.027 \text{Re}^{0.805} \text{Pr}^{0.33} \hspace{1cm} (13)
\end{align*}$$

Heat transfer to cylinders by natural and forced convection has been reviewed by Van der Hegge Zijnen (21). For $\text{Gr. Pr} < 10^8$, he suggested the following natural convection correlation:

$$\text{Nu} = 0.35 + 0.25 (\text{Gr. Pr})^{0.125} + 0.45 (\text{Gr. Pr})^{0.25} \hspace{1cm} (14)$$

and, for $0.01 \leq \text{Re} \leq 5 \times 10^5$, in forced convection:
Nu = 0.38 (Pr)0.2 + (0.56 Re0.5 + 0.001 Re)(Pr)0.33  \quad (15)

He found that, in air, forced convection was predominant for Re > 1000, and was negligible for Re < 4.

Heat transfer to thermocouples in the form of cylinders has been the topic of interest in the determination of conduction and radiation corrections in hot gas streams. Over the ranges 250 < Re < 30,000 and 0.1 < M < 0.9, Scadron and Warshawsky (22) recommended the use of the following relation, with gas properties evaluated at the total temperature $T_t$:

$$\text{Nu}_t = 0.478 (Re_t)^{0.5} (Pr_t)^{0.3}$$  \quad (16)

This correlation has been verified by Glawe and Johnson (23) at temperatures up to 3000 °F.

Churchill and Brier (7) studied the overall rate and angular variation of the rate of convective heat transfer to a 1-in. o.d. water-cooled instrumented cylinder from nitrogen at temperatures up to 1800 °F., and for 300 < Re < 2300. The overall heat transfer rate was about 30 percent higher than that predicted by McAdams' equations (11) and (12) for low temperature difference data. In an attempt to allow for the large variations in gas properties across the boundary layer, the parameter $(T_b/T_s)$ was included in the proposed correlation:

$$\text{Nu}_b = 0.60 (Re_b)^{0.5} (Pr_b)^{0.33} (T_b/T_s)^{0.12}$$  \quad (17)

In 1956, Douglas and Churchill (8) recorrelated all the data available at that time for cylinders transverse to gas streams, since it had been found that the data for hot cylinders in cold streams, and cold cylinders in hot streams generally fell into
separate lines when plotted on McAdams' basis (14) in which \( Re = \frac{D \rho_b \nu}{\mu_f} \). When the Reynolds number was changed to \( Re_f = \frac{D \rho_f \nu}{\mu_f} \), much of the scatter was eliminated, and the following relationship was suggested for \( 500 < Re_f < 300,000 \):

\[
Nu = 0.46 \left( Re \right)^{0.5} + 0.00128 \left( Re \right)
\]  

(18)

The first and second terms were meant to represent the attached laminar boundary layer and wake region contributions, respectively.

Heat transfer to fine wires from rarified airstreams in which slip-flow conditions exist has been studied by Baldwin (24). In such cases, the Knudsen number \( Kn \) (the ratio of the mean free path of the gas \( \lambda \) to the cylinder diameter \( D \)) and the Mach number \( M \) are important parameters. Baldwin found that slip flow exists for \( Kn > 0.01 \), and that under such conditions there is a shift in the Reynolds number exponent from 0.5 to 1.0, as well as a large separation of constant Mach number parametric curves due to rarified gas-flow phenomena. Further discussions of this topic, including the effect of cylinder yaw, are available (10, 25, 26, 27).

Kimura and Kanzawa (28) recently reported experiments on transient heat transfer to wires in an argon plasma jet. It was shown by means of probe measurements that the boundary layer was near a frozen-composition state (i.e. the plasma composition remained unchanged due to very slow recombination rates). It was also felt that the gas may not have been in thermal equilibrium since the wire was placed very close to the jet nozzle. The recombination heat transfer contribution was assumed to make
up the difference between the total heat input and the convective transfer, and formed about 10 percent of the total.

Chludzinski, Kadlec and Churchill (29) investigated the heat transfer rate from a 5 kw. radio-frequency argon-nitrogen plasma jet to thermocouples immersed in the plasma for time periods of less than 0.1 sec. Gas film heat transfer coefficients were calculated from the dynamic response of the thermocouples, and the gas temperature (up to 20,000 °F.) was measured by spectrographic means. The coefficients obtained in argon (about 100 Btu/hr.ft² °F.) were more than twice as high as those calculated from the Scadron and Warshawsky equation (16), and the rate of heat transfer was found to double by the addition of 5 mole percent or more of nitrogen. Energy transfer contributions due to ion-electron and atom-atom recombination occurring near the solid were separated from the overall heat transfer, and it was found that contributions due to the ion-electron reactions were lower by a factor of three than the nitrogen atom reactions. The following relationship was proposed

\[ h = 1.05 \left( \frac{k_b}{D} \right) \left( \frac{Re_b}{D} \right)^{0.5} \left( \frac{Pr_b}{D} \right)^{0.3} + \left( \frac{0.20}{12D} \right)^{0.5} \left[ 1.72 \times 10^{-20} C_{A^+} + 1.11 \times 10^{-20} C_{N^+} + 7.5 \times 10^{-20} C_N \right] \] (19)

where \( C_{A^+}, C_{N^+} \) and \( C_N \) are the particle concentrations (number per \( \text{ft}^3 \)) of argon ions, nitrogen ions and nitrogen atoms, respectively. The first term in equation (19) is the convective contribution, and the second is the effect of the various recombination processes. The gas velocity was not measured, and an average value, based on the total flow rate, was used for calculating the
Reynolds number which ranged in value from 2 to 10.

**SEPARATED FLOW PHENOMENA AND EFFECTS OF TURBULENCE**

At low Reynolds numbers, the heat transfer on the front of a sphere or cylinder is much greater than that at the rear. As Re increases, the rear contribution increases at a faster rate than that from the front. The data of Churchill and Brier (7) indicate that their Nusselt numbers at the front and rear stagnation points would be equal at about \( \text{Re}_b = 3 \times 10^4 \).

When the Reynolds number exponent was plotted against angular position, it ranged in value from about 0.53 to 0.9 at the front and rear respectively, and dipped at the equator.

Richardson (30) has considered the topic of heat and mass transfer in turbulent separated flows, and has suggested that the total transfer from a bluff body can be expressed as the sum of the transfers from the regions of the attached and separated flows, thus assuming that the transfer from each region is independent of the other. The contributions from the front laminar boundary layer region and the rear wake region were assumed proportional to \( \text{Re}^{0.5} \) and \( \text{Re}^{0.67} \), respectively.

Richardson then represented the results of Yuge (19) for a sphere in air by:

\[
\text{Nu} = 0.32 \left( \text{Re} \right)^{0.5} + 0.043 \left( \text{Re} \right)^{0.67}
\]  

(20)

and found that correlations for cylinders in air at \( 10^2 \leq \text{Re} \leq 10^5 \) normally fell between the limits of

\[
\text{Nu} = 0.37 \left( \text{Re} \right)^{0.5} + 0.057 \left( \text{Re} \right)^{0.67}
\]

(21)
and \[ \text{Nu} = 0.55 \left( \text{Re} \right)^{0.5} + 0.084 \left( \text{Re} \right)^{0.67} \] (22)

Richardson (30, 31) has also brought up the question of sphere supports which may interfere with the flow patterns. In particular, rear supports may decrease heat transfer by changing the wake structure.

The free-stream turbulence intensity does not appear to have a major effect upon the heat transfer at the rear stagnation point of a bluff body, in distinct contrast with the effect at the front stagnation point (32). The findings of Seban (33) also indicate that this effect is greatest at the front stagnation point (up to 30 percent), and that it becomes proportionately less as the local pressure gradient in the boundary layer increases. The rise in heat transfer may occur through an earlier transition to a turbulent boundary layer, or through an alteration in the character of the separated flow. A comparison of the data reported in the literature, however, on the effect of turbulence on heat transfer shows little agreement, and is often inconclusive.

Van der Hegge Zijnen (34) has systematically studied the rate of heat transfer from cylinders to a turbulent flow of air for \(600 < \text{Re} < 26,000\), with an intensity range of 2 to 13 percent, and with the ratio of the Eulerian scale \((L_x)\) to the cylinder diameter \(D\) varying from 0.31 to 240. He came to the following conclusions:

(i) at constant \(\text{Re}\), the Nusselt number increases continuously with the intensity of turbulence;
(ii) at constant intensity of turbulence, $\text{Nu}$ increases with $\text{Re}$;

(iii) at constant $\text{Re}$ and intensity of turbulence, $\text{Nu}$ may either increase or decrease with increasing scale ratio, and a maximum is reached at $(L_x/D)$ of about 1.6.

Torobir and Gauvin (35), in their work on momentum transfer from freely-moving spheres at high relative intensity of turbulence levels, presented a plausible explanation for the higher rates of heat and mass transfer observed under turbulent conditions and in separated flow. They established conclusively that a laminar-turbulent transition would occur in the attached boundary layer of a sphere if, at a given $\text{Re}$, the relative intensity $l_r$ is high enough. Such transition would undoubtedly increase the rates of heat and mass transfer appreciably. This transition theory led to the following expression:

$$\left[ (l_r)^2 \left( \frac{\text{Re}}{C} \right) \right] = 45 \quad (23)$$

where $l_r$, the relative intensity of turbulence is given by

$$l_r = \left[ \left( \frac{u}{U_r} \right)^{0.5} / U_r \right] \quad (24)$$

Here, $U_r$ represents the velocity of the particle relative to that of the fluid.

It has been generally found that turbulence is more effective in increasing the transfer rates at higher values of $\text{Re}$, a behaviour which could be explained by transition to a turbulent boundary layer. This could also account for the marked increases in heat transfer which may be caused by the triggering
effects of evaporation (36, 42), large temperature gradients (7), and various types of oscillations, such as sound waves (37), flow pulsations (38, 39), and particle vibrations (39).

Johnson and Rubesin (40) reported that the Nusselt number, for flat plates in pure heat transfer with a turbulent boundary layer, was proportional to $Re^{0.8}$, as postulated also by Schlichting (32). A similar dependence occurs for the case of turbulent flow inside pipes (14). Iskachenko and Vzorov (41) concluded in their studies of mass transfer from a wetted porous surface in a current of air, that mass transfer was analogous to heat transfer under the same conditions of turbulence, and that the average mass transfer rate was proportional to $Re^{0.8}$.

Smolsky and Sergeyev (42) conducted heat transfer and evaporation experiments with metallic and dry porous flat plates. For pure heat transfer, the following expression was obtained:

$$Nu = 0.037 (Re)^{0.8} (Pr)^{0.33}$$

(25)

Sergeyev and Sergeyeva (43) extended this study to spheres, cones, and discs. The sphere data were correlated by a dependence of the form of equation (25) in the range $10^3 \leq Re \leq 10^5$.

The effect of turbulence is also present in heat transfer with objects exposed to impinging jets. Schuh and Persson (44) have investigated heat transfer to cylinders placed transverse to a two-dimensional jet at various distances from the source. The cylinder Reynolds number range was $2 \times 10^4$ to $5 \times 10^4$, and the jet velocity profile was assumed to be fully-developed and turbulent. Maximum heat transfer to the cylinder
was found to occur with a jet width 1/8 that of the cylinder diameter, and with the cylinder at a distance from the nozzle of 2 to 8 times the jet width, where there exists a high intensity of turbulence. Gardon and Akfirat (45, 46) have shown that the heat transfer characteristics of impinging jets cannot be explained in terms of velocity and position-dependent boundary layer thicknesses alone. These characteristics must also take into account the influence of turbulence which may manifest itself by a transition from a laminar to a turbulent boundary layer.
APPARATUS

THE PLASMA JET AND ITS CONFINING SYSTEM

The apparatus used in this study has already been described in detail in Part 1, and only an outline will be presented here.

The plasma generator was of the direct-current type, a Thermal Dynamics Model F-40 torch. The central, water-cooled thoriated tungsten cathode was located at the entrance of the water-cooled copper anode nozzle. The gas was fed axially through the annulus between the two electrodes, and thus through the arc whose path was between the cathode tip and a circular region down the nozzle. Ignition was accomplished by means of a temporary high-frequency, high-voltage arc. Two sizes of nozzle were used: the No. 1, with a diameter of 0.219 in., and the No. 3, with a diameter of 0.312 in.

The gas employed was nitrogen, at flow rates from 50 to 250 s.c.f.h., at total power inputs of up to 36 kw., and with an efficiency of about 65 percent.

The plasma jet was fed vertically downward through an 8.00-in. i.d. and 10.0-in. o.d. closed graphite tube, 71.75-in. long at essentially atmospheric pressure. Six sealed graphite ports were mounted in three diametrically-opposed pairs with their centres at distances of 12.0, 36.0, and 60.0 in. from the top of the chamber. They allowed for the visual observation of the processes occurring in the chamber, and for the insertion
of probes and stationary test specimens into the confined plasma jet. The reactor was insulated with a 12-in. thickness of "Fiberfrax", a material of high porosity and low thermal conductivity. The system was enclosed in a steel shell, and purge lines were provided to flush it clear of air. The gas leaving the graphite chamber passed through double-pipe coolers before entering the atmosphere.

MEASUREMENT TECHNIQUES

The graphite reactor wall temperature was measured at various distances down its length by chromel-alumel thermocouples, which were connected to a Minneapolis-Honeywell 12-point strip chart recorder. The nitrogen temperature at the top port (port 1) was obtained with bare-wire 0.005-in. diameter tungsten-5 percent rhenium/tungsten-26 percent rhenium thermocouples, enclosed inside a water-cooled tube with a conical end, out of which the bare tip was made to protrude. Radiation and conduction corrections were calculated according to the method of Scadron and Warshawsky (22).

The gas velocity profiles at port 1 were determined by means of a water-cooled total-head probe. The static pressure was obtained from the reading of the probe pointing in the direction opposite to the low-velocity flow near the wall. The exact location of the level at which the temperature and velocity profiles were obtained was 10.5 in. below the entry of the plasma jet into the chamber. The above measurement techniques were described in detail in Part 1 of this thesis.
The configurations of the calorimetric spheres and cylinder which were exposed to the hot nitrogen on the axis of the reactor at port 1, with their equators at the level of the measured temperature and velocity profiles, are shown in Fig. 1 and 2 respectively. The heat transfer rate $Q$ was simply quantified in each case by a cooling water stream, from the flow rate and the change in temperature through the sphere or cylinder:

$$Q = wc_p \Delta T_w$$ (26)

Two sizes of sphere were employed: 5/8-in. and 1.00-in. o.d. with wall thicknesses of 0.010 and 0.014 in. respectively, and made of type 302 stainless steel. They were manufactured by Industrial Tectonics, Inc. of Ann Arbor, Michigan. Water was fed in and out via long copper supporting tubes which were soldered to the sphere. The water temperatures were measured by teflon-insulated chromel-alumel thermocouples which were held in place by thin plastic supports. A third thermocouple was soldered to the surface of the sphere. This set-up was, of necessity, very delicate, and great care had to be taken during assembly to prevent contact between the bare thermocouple tips and the supporting tubes. An ohmmeter was frequently used to check for grounding. The supporting tubes extended through the ports and through the quartz discs to the outside where water connections were made and where the thermocouple wire was separated from the water flow. It was thus possible to view the spheres during their exposure to the plasma jet. Provision was made to tighten the supporting tubes during operation, since they expanded, and caused the sphere to vibrate. The surface thermo-
couple was connected to the twelve-point recorder, while the outputs of the water-in and water-out thermocouples were measured on a Minneapolis-Honeywell variable-zero and variable-span strip chart recorder, whose range was adjusted to 0-5 millivolts. The water flow rate was varied by means of a micrometer control valve from 0 to 250 ml./min., and was measured with a graduated cylinder.

The calorimetric cylinder (Fig. 2) was placed transverse to the nitrogen plasma jet axis. It was of similar construction as the sphere, except that it acted as its own supporting tube since it extended right through the reactor. It consisted of a 0.250-in. o.d. brass tube with a 0.035-in. wall thickness. A test section, 0.500-in. long, was located at the centre of the reactor, enclosed by a brass sleeve with plastic orifice plates at each end. At the centre of each 0.050-in. diameter orifice was located a thermocouple to measure the inlet and outlet water temperatures.

Fluctuations in the water thermocouple outputs were damped out by means of a sensitivity knob so that average values could more easily be taken. The temperature rise varied from about 20 to 60 °F., which corresponded to output differences of about 0.5 to 1.5 millivolts. The highest values were obtained with the spheres since they had a large heat transfer surface area in comparison to the cylinder test section. For a given set of plasma jet conditions, heat transfer rates could be obtained at several water flow rates, and hence several water temperature differences. Runs were carried out with the reactor
cold ($\leq 400^\circ$F.), so that there was no radiation contribution from the walls.

In order to determine the effect of the presence of the spheres on the flow patterns of the jet, spheres of both sizes were inserted into the reactor, with the coolant tubes enclosed in a 3/16-in. o.d. brass tube which was soldered to one side only. It was thus possible to approach the sphere closely with the total-head probe and thermocouples. In addition, the spheres were provided with a single surface thermocouple. Rotation of the sphere support thus provided the means for the measurement of angular variation in surface temperature.
FIGURE 1

CONFIGURATION OF CALORIMETRIC SPHERE
WATER IN PLASTIC THERMOCOUPLE SUPPORT
THERMOCOUPLE WIRES CHROMEL & ALUMEL 0.007 - in. o.d.
WATER OUT SUPPORTING TUBES COPPER 0.070 - in. o.d.
0.060 - in. i.d.
SURFACE THERMOCOUPLE
SPHERE STAINLESS STEEL 0.625 - in. o.d.
0.010 - in. WALL
PLASTIC THERMOCOUPLE SUPPORT
PLASTIC THERMOCOUPLE SUPPORT
FIGURE 2

CONFIGURATION OF CALORIMETRIC CYLINDER
RESULTS

OPERATING CONDITIONS

The twenty sets of plasma jet operating conditions, based on nozzle size, net power input to the gas, gas flow rate, and time of measurement are shown in Table III of Part I. The power range was from 3.5 to 23.4 kw., and the nitrogen flow rate from 50 to 250 s.c.f.h. For ease of identification, each run was designated by a set of figures. For example, Run 3-11.0-150 employed a No. 3 nozzle with a net power input to the gas of 11.0 kw., and at a nitrogen flow rate of 150 s.c.f.h. The temperature and velocity ranges on the axis of the reactor at port 1 were from 1100 to 5100 °F., and from 39 to 147 ft./sec. respectively, as listed in Tables V and VI of Part I. Near the wall, there was an upward recirculatory flow whose mass flow rate was 9 to 28 times that of the nitrogen input.

DATA FOR SPHERES

The effect of the presence of the 5/8-in. and 1-in. o.d. spheres on the velocity profiles for a typical run, in this case Run 1-7.0-100, is shown in Fig. 3 and Table 1. The graphite tube blockages for the two spheres were 0.6 and 1.6 percent of the total cross-sectional area respectively. The velocity at the equator of each sphere was found to be generally within 5 percent of the value at the axis of the reactor for the twenty sets of operating conditions. The temperature profiles were unaffected by the presence of the spheres.
FIGURE 3

THE EFFECT OF THE PRESENCE OF 5/8-IN. AND 1-IN. O.D. SPHERES ON THE VELOCITY PROFILES AT PORT 1 FOR RUN 1-7.0-100
TABLE I

THE EFFECT OF THE PRESENCE OF 5/8-IN. AND 1-IN. O.D. SPHERES ON THE VELOCITY PROFILES AT PORT 1 FOR RUN 1-7.0-100

<table>
<thead>
<tr>
<th>Distance from Centreline (in.)</th>
<th>Gas Velocity (ft./sec.)</th>
<th>5/8-in. Sphere</th>
<th>1-in. Sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>68</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.25</td>
<td>61</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.35</td>
<td>-</td>
<td>68*</td>
<td>-</td>
</tr>
<tr>
<td>0.50</td>
<td>50</td>
<td>56</td>
<td>68*</td>
</tr>
<tr>
<td>0.54</td>
<td>-</td>
<td>-</td>
<td>68*</td>
</tr>
<tr>
<td>0.63</td>
<td>-</td>
<td>-</td>
<td>59</td>
</tr>
<tr>
<td>0.75</td>
<td>43</td>
<td>46</td>
<td>48</td>
</tr>
<tr>
<td>1.00</td>
<td>35</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>1.25</td>
<td>25</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>1.50</td>
<td>17</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>1.75</td>
<td>13</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>2.00</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

*within 0.04 in. of sphere surface

The angular variation in the surface thermocouple was also measured with the 1-in. o.d. sphere, and the results are shown in Table II. It was felt that the temperature readings obtained were lower in value than the actual surface temperature due to the contact with water at 50 to 90 °F.; thus, they should be considered as of qualitative value only.
TABLE II

ANGULAR VARIATION OF SURFACE THERMOCOUPLE READING ON 1-IN. O.D. SPHERE FOR RUN 1-7.0-100

<table>
<thead>
<tr>
<th>Angular Position</th>
<th>Thermocouple Reading (°F.)</th>
<th>Cooling Water Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° (front)</td>
<td>163</td>
<td>Flow Rate = 32 lb./hr.</td>
</tr>
<tr>
<td>30°</td>
<td>162</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>145</td>
<td>Water Temperature</td>
</tr>
<tr>
<td>90°</td>
<td>135</td>
<td>= 50 to 90 °F.</td>
</tr>
<tr>
<td>120°</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td>150°</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>180° (rear)</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

The sphere heat transfer data were put into the form of the Nusselt number

\[ \text{Nu} = \frac{hD}{k} \quad \text{(27)} \]

using the relationship

\[ Q = \text{hS}_0 (T_b - T_s) \quad \text{(28)} \]

where \( S_0 \) is the outside surface area

Hence,

\[ \text{Nu} = \frac{Q}{\pi kD} (T_b - T_s) \quad \text{(29)} \]

The bulk temperature \( T_b \) was that averaged from the temperature profile data over the projected area of the sphere. Because of the relative uniformity of the temperature profile near the reactor axis, the \( T_b \) value used was 90 °F. or less lower in value.
than the central nitrogen temperature. The surface temperature $T_s$ was taken as 210 °F, which was generally higher than the surface thermocouple readings. This was assumed to be close to the actual value of $T_s$ since the water in contact with the surface was in a state of boiling, or close to it. Any deviation from 210 °F. would thus be negligible in comparison with $(T_b - T_s)$. The Reynolds number was calculated using for velocity the central value obtained with the undisturbed jet. This was shown earlier to be equivalent to the velocity at the equator of the sphere. The Nusselt and Reynolds numbers were evaluated with the gas properties taken at both the bulk gas temperature $T_b$, and the mean film temperature $T_f$. The results are listed in Tables III, IV, V and VI, and plotted properties used are shown in Fig. 1, 2, 3 and 4 of Part I. The calculated Prandtl numbers were virtually constant at 0.693 between 1,000 and 5,000 °F.
### TABLE III

**HEAT TRANSFER DATA FOR 5/8-IN. O.D. SPHERE**

*With gas properties taken at bulk temperature*

<table>
<thead>
<tr>
<th>Run</th>
<th>U_b (ft./sec.)</th>
<th>T_b (°F)</th>
<th>T_b/T_s</th>
<th>Reynolds Number</th>
<th>Nusselt Number*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-7.0-100</td>
<td>68</td>
<td>1980</td>
<td>3.64</td>
<td>1700</td>
<td>31.2, 31.5</td>
</tr>
<tr>
<td>3-7.0-100</td>
<td>49</td>
<td>2430</td>
<td>4.32</td>
<td>925</td>
<td>20.1, 20.2</td>
</tr>
<tr>
<td>1-7.0-150</td>
<td>74</td>
<td>1480</td>
<td>2.90</td>
<td>2680</td>
<td>41.5</td>
</tr>
<tr>
<td>3-7.0-150</td>
<td>61</td>
<td>2290</td>
<td>4.10</td>
<td>1251</td>
<td>23.8, 24.0, 24.7</td>
</tr>
<tr>
<td>3-7.0-200</td>
<td>64</td>
<td>1940</td>
<td>3.59</td>
<td>1643</td>
<td>25.4, 25.6, 25.8</td>
</tr>
<tr>
<td>3-7.0-250</td>
<td>71</td>
<td>1690</td>
<td>3.21</td>
<td>2180</td>
<td>32.2, 32.5, 35.2, 35.6</td>
</tr>
<tr>
<td>1-11.0-150</td>
<td>110</td>
<td>2170</td>
<td>3.93</td>
<td>2430</td>
<td>34.0</td>
</tr>
<tr>
<td>3-11.0-150</td>
<td>77</td>
<td>3180</td>
<td>5.43</td>
<td>981</td>
<td>17.3, 17.6, 18.4</td>
</tr>
<tr>
<td>3-11.0-200</td>
<td>84</td>
<td>2390</td>
<td>4.25</td>
<td>1625</td>
<td>26.2, 28.0, 28.1, 30.1</td>
</tr>
<tr>
<td>3-14.0-100</td>
<td>72</td>
<td>4070</td>
<td>6.76</td>
<td>629</td>
<td>12.6, 13.4, 14.0</td>
</tr>
<tr>
<td>3-14.0-150</td>
<td>81</td>
<td>3200</td>
<td>5.47</td>
<td>1020</td>
<td>19.0, 19.7, 20.5</td>
</tr>
<tr>
<td>3-14.0-200</td>
<td>96</td>
<td>2760</td>
<td>4.81</td>
<td>1520</td>
<td>26.8, 27.3</td>
</tr>
<tr>
<td>3-19.5-150</td>
<td>102</td>
<td>4330</td>
<td>7.14</td>
<td>803</td>
<td>17.9, 18.2</td>
</tr>
<tr>
<td>3-19.5-200</td>
<td>124</td>
<td>3870</td>
<td>6.74</td>
<td>1265</td>
<td>21.1, 22.4</td>
</tr>
<tr>
<td>3-23.4-150</td>
<td>128</td>
<td>5040</td>
<td>8.21</td>
<td>804</td>
<td>15.1, 15.4</td>
</tr>
<tr>
<td>3-23.4-200</td>
<td>147</td>
<td>4520</td>
<td>7.43</td>
<td>1078</td>
<td>19.5, 20.0</td>
</tr>
</tbody>
</table>

*Includes results of replicate runs*
## TABLE IV

### HEAT TRANSFER DATA FOR 1-IN. O.D. SPHERE, WITH GAS PROPERTIES TAKEN AT BULK TEMPERATURE

<table>
<thead>
<tr>
<th>Run</th>
<th>$U_b$ ft./sec.</th>
<th>$T_b$ °F.</th>
<th>$T_b/T_s$</th>
<th>Reynolds Number</th>
<th>Nusselt Number*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3.5-50</td>
<td>39</td>
<td>1640</td>
<td>3.13</td>
<td>1980</td>
<td>33.2, 34.4</td>
</tr>
<tr>
<td>1-3.5-100</td>
<td>47</td>
<td>1360</td>
<td>2.61</td>
<td>3025</td>
<td>42.1, 43.1</td>
</tr>
<tr>
<td>1-3.5-150</td>
<td>50</td>
<td>1090</td>
<td>2.31</td>
<td>4180</td>
<td>54.4, 57.3</td>
</tr>
<tr>
<td>1-7.0-100</td>
<td>68</td>
<td>1970</td>
<td>3.63</td>
<td>2740</td>
<td>41.7</td>
</tr>
<tr>
<td>3-7.0-100</td>
<td>49</td>
<td>2410</td>
<td>4.28</td>
<td>1493</td>
<td>27.8, 28.5</td>
</tr>
<tr>
<td>1-7.0-150</td>
<td>74</td>
<td>1470</td>
<td>2.88</td>
<td>4330</td>
<td>59.8, 61.1</td>
</tr>
<tr>
<td>3-7.0-150</td>
<td>61</td>
<td>2260</td>
<td>4.06</td>
<td>2030</td>
<td>33.9, 34.9</td>
</tr>
<tr>
<td>3-7.0-200</td>
<td>64</td>
<td>1930</td>
<td>3.57</td>
<td>2645</td>
<td>39.2</td>
</tr>
<tr>
<td>3-7.0-250</td>
<td>71</td>
<td>1670</td>
<td>3.18</td>
<td>3560</td>
<td>49.4, 53.1</td>
</tr>
<tr>
<td>3-11.0-150</td>
<td>77</td>
<td>3130</td>
<td>5.36</td>
<td>1600</td>
<td>29.3, 29.8</td>
</tr>
<tr>
<td>3-11.0-200</td>
<td>84</td>
<td>2370</td>
<td>4.22</td>
<td>2640</td>
<td>41.7, 41.9</td>
</tr>
</tbody>
</table>

*includes results of replicate runs
FIGURE 4

HEAT TRANSFER RESULTS FOR SPHERES, WITH GAS PROPERTIES TAKEN AT BULK TEMPERATURE
$\text{Nu} = 0.104(\text{Re})^{0.757}$

5/8-in. o.d. SPHERE

1-in. o.d. SPHERE

$\text{Nu}_{\text{b}}$ vs $\text{Re}_{\text{b}}$ graph
### TABLE V

**HEAT TRANSFER DATA FOR 5/8-IN. O.D. SPHERE, WITH GAS PROPERTIES TAKEN AT MEAN FILM TEMPERATURE**

<table>
<thead>
<tr>
<th>Run</th>
<th>Reynolds Number</th>
<th>Nusselt Number*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-7.0-100</td>
<td>3570</td>
<td>45.6, 45.9</td>
</tr>
<tr>
<td>3-7.0-100</td>
<td>2110</td>
<td>30.2, 30.3</td>
</tr>
<tr>
<td>1-7.0-150</td>
<td>5230</td>
<td>57.8</td>
</tr>
<tr>
<td>3-7.0-150</td>
<td>2790</td>
<td>35.7, 35.9, 37.1</td>
</tr>
<tr>
<td>3-7.0-200</td>
<td>3505</td>
<td>36.3, 36.6, 37.0</td>
</tr>
<tr>
<td>3-7.0-250</td>
<td>4580</td>
<td>46.4, 46.6, 50.4, 52.6</td>
</tr>
<tr>
<td>1-11.0-150</td>
<td>5300</td>
<td>50.3</td>
</tr>
<tr>
<td>3-11.0-150</td>
<td>2390</td>
<td>26.5, 27.0, 28.4</td>
</tr>
<tr>
<td>3-11.0-200</td>
<td>3650</td>
<td>39.3, 41.9, 42.2, 45.1</td>
</tr>
<tr>
<td>3-14.0-100</td>
<td>1630</td>
<td>19.8, 21.0, 22.0</td>
</tr>
<tr>
<td>3-14.0-150</td>
<td>2490</td>
<td>29.1, 30.4, 31.5</td>
</tr>
<tr>
<td>3-14.0-200</td>
<td>3510</td>
<td>40.4, 41.1</td>
</tr>
<tr>
<td>3-19.5-150</td>
<td>2125</td>
<td>28.2, 28.7</td>
</tr>
<tr>
<td>3-19.5-200</td>
<td>2990</td>
<td>32.8, 34.7</td>
</tr>
<tr>
<td>3-23.4-150</td>
<td>2170</td>
<td>24.3, 24.8</td>
</tr>
<tr>
<td>3-23.4-200</td>
<td>2885</td>
<td>30.7, 31.6</td>
</tr>
</tbody>
</table>

*includes results of replicate runs*
<table>
<thead>
<tr>
<th>Run</th>
<th>Reynolds Number</th>
<th>Nusselt Number*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3.5-50</td>
<td>4120</td>
<td>48.2, 49.9</td>
</tr>
<tr>
<td>1-3.5-100</td>
<td>5880</td>
<td>58.8, 60.0</td>
</tr>
<tr>
<td>1-3.5-150</td>
<td>7570</td>
<td>73.4, 77.8</td>
</tr>
<tr>
<td>1-7.0-100</td>
<td>5770</td>
<td>60.4</td>
</tr>
<tr>
<td>3-7.0-100</td>
<td>3410</td>
<td>41.9, 42.9</td>
</tr>
<tr>
<td>1-7.0-150</td>
<td>8480</td>
<td>84.1, 85.7</td>
</tr>
<tr>
<td>3-7.0-150</td>
<td>4580</td>
<td>50.9, 52.4</td>
</tr>
<tr>
<td>3-7.0-200</td>
<td>5720</td>
<td>57.6</td>
</tr>
<tr>
<td>3-7.0-250</td>
<td>7320</td>
<td>71.0, 76.7</td>
</tr>
<tr>
<td>3-11.0-150</td>
<td>3930</td>
<td>45.0, 45.7</td>
</tr>
<tr>
<td>3-11.0-200</td>
<td>5930</td>
<td>62.5, 62.9</td>
</tr>
</tbody>
</table>

*includes results of replicate runs
FIGURE 5

HEAT TRANSFER RESULTS FOR SPHERES, WITH GAS PROPERTIES TAKEN AT MEAN FILM TEMPERATURE
Nu = 0.0488 (Re)^{0.823}

5/8 - in. o.d. SPHERE

1 - in. o.d. SPHERE

Nu$_f$ vs. Re$_f$ graph for SPHERE film temperature.
DATA FOR CYLINDERS

The heat transfer data for the cylinder were similarly put into the form of the Nusselt number by means of the following relationship:

$$\text{Nu} = \frac{Q}{\pi k L (T_b - T_s)}$$  \hspace{1cm} (30)

where $L$ is the length of the cylindrical test section. The results are listed in Tables VII and VIII, and plotted in Figs. 6 and 7.

In Fig. 7, comparison is made with the correlation proposed by Douglas and Churchill (8), with gas properties based on the film temperature $T_f$, while Fig. 8 is a comparison of the present data, with gas properties taken at bulk gas temperature, and the data points of Churchill and Brier (7). In the latter, the temperature ratio factor $(T_b/T_s)^{0.12}$, which ranged in value from 1.085 to 1.184, was replaced by an average value of 1.134 in order to simplify the comparison.
TABLE VII

HEAT TRANSFER DATA FOR 1/4-IN. O.D. CYLINDER,
WITH GAS PROPERTIES TAKEN AT BULK TEMPERATURE

<table>
<thead>
<tr>
<th>Run</th>
<th>( U_b ) ft./sec.</th>
<th>( T_b ) oF.</th>
<th>( T_b/T_s )</th>
<th>Reynolds Number</th>
<th>Nusselt Number*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3.5-50</td>
<td>39</td>
<td>1660</td>
<td>3.19</td>
<td>485</td>
<td>12.8, 12.9, 13.7</td>
</tr>
<tr>
<td>1-3.5-100</td>
<td>47</td>
<td>1370</td>
<td>2.73</td>
<td>750</td>
<td>17.2</td>
</tr>
<tr>
<td>1-3.5-150</td>
<td>50</td>
<td>1100</td>
<td>2.32</td>
<td>1030</td>
<td>27.2, 27.9</td>
</tr>
<tr>
<td>1-7.0-100</td>
<td>68</td>
<td>1980</td>
<td>3.64</td>
<td>686</td>
<td>17.6, 18.0</td>
</tr>
<tr>
<td>3-7.0-100</td>
<td>49</td>
<td>2430</td>
<td>4.30</td>
<td>370</td>
<td>10.6, 10.8</td>
</tr>
<tr>
<td>1-7.0-150</td>
<td>74</td>
<td>1480</td>
<td>2.74</td>
<td>1070</td>
<td>24.3, 24.5, 24.7</td>
</tr>
<tr>
<td>3-7.0-150</td>
<td>61</td>
<td>2290</td>
<td>4.10</td>
<td>500</td>
<td>13.8, 14.1, 14.8</td>
</tr>
<tr>
<td>3-7.0-200</td>
<td>64</td>
<td>1940</td>
<td>3.58</td>
<td>656</td>
<td>17.2, 18.3, 18.9</td>
</tr>
<tr>
<td>3-7.0-250</td>
<td>71</td>
<td>1690</td>
<td>3.20</td>
<td>873</td>
<td>20.9, 21.5, 21.7</td>
</tr>
<tr>
<td>1-11.0-100</td>
<td>104</td>
<td>2840</td>
<td>4.92</td>
<td>628</td>
<td>16.1, 16.5, 17.0</td>
</tr>
<tr>
<td>1-11.0-150</td>
<td>110</td>
<td>2170</td>
<td>3.92</td>
<td>972</td>
<td>22.8, 24.3</td>
</tr>
<tr>
<td>3-11.0-200</td>
<td>84</td>
<td>2390</td>
<td>4.25</td>
<td>650</td>
<td>15.3, 16.2, 16.4</td>
</tr>
<tr>
<td>3-14.0-150</td>
<td>81</td>
<td>3200</td>
<td>5.45</td>
<td>407</td>
<td>11.5, 11.9, 12.4, 12.6</td>
</tr>
<tr>
<td>3-14.0-200</td>
<td>96</td>
<td>2760</td>
<td>4.81</td>
<td>581</td>
<td>15.8, 15.8, 17.2</td>
</tr>
<tr>
<td>3-19.5-150</td>
<td>102</td>
<td>4330</td>
<td>7.16</td>
<td>321</td>
<td>10.3, 10.4</td>
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<tr>
<td>3-19.5-200</td>
<td>124</td>
<td>3870</td>
<td>6.45</td>
<td>506</td>
<td>12.6, 12.6</td>
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<td>3-23.4-150</td>
<td>128</td>
<td>5040</td>
<td>8.20</td>
<td>322</td>
<td>9.7, 10.0, 10.1</td>
</tr>
<tr>
<td>3-23.4-200</td>
<td>147</td>
<td>4520</td>
<td>7.42</td>
<td>432</td>
<td>11.6, 11.7, 11.8</td>
</tr>
</tbody>
</table>

*includes results of replicate runs
FIGURE 6

HEAT TRANSFER RESULTS FOR 1/4-IN.
O.D. CYLINDER, WITH GAS PROPERTIES
TAKEN AT BULK TEMPERATURE
CYLINDER

bulk temperature

Nu = 0.100 (Re)^0.792
### TABLE VIII

**HEAT TRANSFER DATA FOR 1/4-IN. O.D. CYLINDER, WITH GAS PROPERTIES TAKEN AT MEAN FILM TEMPERATURE**

<table>
<thead>
<tr>
<th>Run</th>
<th>Reynolds Number</th>
<th>Nusselt Number*</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3.5-50</td>
<td>974</td>
<td>17.8, 18.0, 19.1</td>
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<td>1-3.5-100</td>
<td>1390</td>
<td>23.4</td>
<td></td>
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<td>1-3.5-150</td>
<td>1770</td>
<td>35.3, 36.3</td>
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</tr>
<tr>
<td>1-7.0-100</td>
<td>1425</td>
<td>25.7, 26.2</td>
<td></td>
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<tr>
<td>3-7.0-100</td>
<td>820</td>
<td>15.6, 15.9</td>
<td></td>
</tr>
<tr>
<td>1-7.0-150</td>
<td>2050</td>
<td>33.4, 33.6, 34.0</td>
<td></td>
</tr>
<tr>
<td>3-7.0-150</td>
<td>1090</td>
<td>20.4, 20.7, 21.9</td>
<td></td>
</tr>
<tr>
<td>3-7.0-200</td>
<td>1350</td>
<td>24.9, 26.5, 27.4</td>
<td></td>
</tr>
<tr>
<td>3-7.0-250</td>
<td>1725</td>
<td>29.6, 30.5, 30.8</td>
<td></td>
</tr>
<tr>
<td>1-11.0-100</td>
<td>1460</td>
<td>24.2, 24.7, 25.5</td>
<td></td>
</tr>
<tr>
<td>1-11.0-150</td>
<td>2070</td>
<td>33.3, 35.4</td>
<td></td>
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<tr>
<td>3-11.0-200</td>
<td>1425</td>
<td>22.6, 23.9, 24.1</td>
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<td>3-14.0-150</td>
<td>1000</td>
<td>17.6, 18.2, 18.9, 19.2</td>
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<td>3-14.0-200</td>
<td>1390</td>
<td>23.6, 23.6, 25.7</td>
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<td>3-19.5-150</td>
<td>850</td>
<td>16.3, 16.4</td>
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<td>3-19.5-200</td>
<td>1200</td>
<td>19.1, 19.1</td>
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<td>3-23.4-150</td>
<td>870</td>
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<td>3-23.4-200</td>
<td>1160</td>
<td>18.4, 18.5, 18.7</td>
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</table>

*includes results of replicate runs*
FIGURE 7

HEAT TRANSFER RESULTS FOR 1/4-IN. O.D. CYLINDER, WITH GAS PROPERTIES TAKEN AT MEAN FILM TEMPERATURE
CYLINDER
film temperature

\[ Nu = 0.0388(Re)^{0.891} \]

LINE OF DOUGLAS & CHURCHILL
FIGURE 8

COMPARISON OF PRESENT CYLINDER RESULTS WITH DATA OF CHURCHILL AND BRIER (7), WITH GAS PROPERTIES TAKEN AT BULK TEMPERATURE
The graph shows the relationship between the Nusselt number \( \frac{Nu_b}{Pr_b} \) and the Reynolds number \( Reb \) for a cylinder. The bulk temperature is indicated along the y-axis, ranging from 10 to 35.

- **Data of Churchill & Brier**:
  - Equation: \( Nu = 0.681 (Re)^{0.5} (Pr)^{0.33} \)

- **Present Investigation**:
  - Equation: \( Nu = 0.114 (Re)^{0.792} (Pr)^{0.33} \)

The graph compares these data points with the lines calculated from the equations provided.
CORRELATION OF SPHERE AND CYLINDER DATA

The four sets of sphere and cylinder data, which were based on properties taken at both the bulk and mean film temperatures, were processed in an IBM 1620 computer. An equation of the form of

\[ \text{Nu} = b (\text{Re})^p \]  

was fitted to the data, and the correlation coefficient, and the 95 percent confidence limits of the exponent \( p \) were also calculated. Table IX lists the values obtained.

### Table IX

**HEAT TRANSFER DATA PROCESSED BY COMPUTER**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Temperature Basis</th>
<th>Correlation</th>
<th>Correlation Coefficient</th>
<th>95% Confidence Limits of ( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPHERE</td>
<td>( T_b )</td>
<td>( \text{Nu} = 0.104(\text{Re})^{0.757} )</td>
<td>0.975</td>
<td>0.725 0.788</td>
</tr>
<tr>
<td></td>
<td>( T_f )</td>
<td>( \text{Nu} = 0.0488(\text{Re})^{0.823} )</td>
<td>0.964</td>
<td>0.781 0.865</td>
</tr>
<tr>
<td>CYLINDER</td>
<td>( T_b )</td>
<td>( \text{Nu} = 0.100(\text{Re})^{0.792} )</td>
<td>0.964</td>
<td>0.746 0.837</td>
</tr>
<tr>
<td></td>
<td>( T_f )</td>
<td>( \text{Nu} = 0.0388(\text{Re})^{0.891} )</td>
<td>0.923</td>
<td>0.816 0.966</td>
</tr>
</tbody>
</table>

After the inclusion of a \( (\text{Pr})^{0.33} \) term which generalized the correlations for use with other gases, the following equations were obtained:

**SPHERE**

at \( T_b \)

\( \text{Nu}_b = 0.118 (\text{Re}_b)^{0.757} (\text{Pr}_b)^{0.33} \) \hspace{1cm} (32)

at \( T_f \)

\( \text{Nu}_f = 0.0552 (\text{Re}_f)^{0.823} (\text{Pr}_f)^{0.33} \) \hspace{1cm} (33)
Each of the above correlations was checked for its dependence on the gas temperature, by plotting the ratio of \( \frac{Nu}{(Re)^D} \) against \( \frac{T_b}{T_s} \) as shown in Figs. 9, 10, 11 and 12. The equations and correlation coefficients for this dependence are listed in Table X.

**TABLE X**

**EFFECT OF TEMPERATURE ON HEAT TRANSFER CORRELATIONS**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Temperature Basis</th>
<th>Correlation</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPHERE</td>
<td>( T_b )</td>
<td>( \frac{Nu}{(Re)^{0.757}} = 0.105 \frac{T_b}{T_s}^{-0.008} )</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>( T_f )</td>
<td>( \frac{Nu}{(Re)^{0.823}} = 0.101 \frac{T_b}{T_s}^{-0.057} )</td>
<td>0.056</td>
</tr>
<tr>
<td>CYLINDER</td>
<td>( T_b )</td>
<td>( \frac{Nu}{(Re)^{0.792}} = 0.107 \frac{T_b}{T_s}^{-0.051} )</td>
<td>0.082</td>
</tr>
<tr>
<td></td>
<td>( T_f )</td>
<td>( \frac{Nu}{(Re)^{0.891}} = 0.048 \frac{T_b}{T_s}^{-0.151} )</td>
<td>0.512</td>
</tr>
</tbody>
</table>
FIGURE 9

EFFECT OF TEMPERATURE ON SPHERE HEAT TRANSFER RESULTS, WITH GAS PROPERTIES TAKEN AT BULK TEMPERATURE
FIGURE 10

EFFECT OF TEMPERATURE ON SPHERE HEAT TRANSFER RESULTS, WITH GAS PROPERTIES TAKEN AT MEAN FILM TEMPERATURE
FIGURE 11

EFFECT OF TEMPERATURE ON CYLINDER HEAT TRANSFER RESULTS, WITH GAS PROPERTIES TAKEN AT BULK TEMPERATURE
FIGURE 12

EFFECT OF TEMPERATURE ON CYLINDER HEAT TRANSFER RESULTS, WITH GAS PROPERTIES TAKEN AT MEAN FILM TEMPERATURE
DISCUSSION

Turbulence Characteristics of the Plasma Jet

The intermittent nature of the arc process inside the nozzle is an important feature of the operation of plasma jets generated by means of direct current. It has been reported (47) that this cyclic process has a frequency of about 10,000 c.p.s. for the type of torch and gas employed in this investigation. At this frequency, and in the velocity range of 1,000 to 2,500 ft./sec. corresponding to that of the plasma jet at the nozzle exit, pockets of plasma about one inch long with a 0.2 to 0.3-in. diameter would have been superimposed on the flow entering the reactor. The time required to reach the level of port 1, where the axial velocities ranged in value from 40 to 150 ft./sec., was thus of the order of milliseconds. In this short time span, the temperature had dropped by several thousand degrees, which in itself would have caused an increase in the density. The latter, in turn, would have decreased the size of the pockets of plasma by a factor of about three.

Another important consideration was the interaction between the plasma jet and the recirculatory flow of much lower temperature and velocity. Because of the fact that the kinematic viscosity and thermal conductivity are high in the plasma jet, viscous and conduction effects are important in its core. In the vicinity of the outer edge of the core, and in the mixing region of the jet, however, the molecular effects are unimportant in comparison with turbulence effects. Typical values of the
intensity of turbulence on the axes of free (48, 49, 50) and confined (51, 52) jets at distances of about 40 diameters from the nozzle are between 20 and 25 percent. Due to the presence of the high turbulence intensities and the large axial and radial velocity gradients, the pockets of plasma issuing from the nozzle would lose energy to the main turbulent flow, and decrease in size. The scale of the fluctuations caused by the arc intermittency process must have therefore decreased until it became small in comparison with the diameter of the spheres and cylinder employed.

Heat Flux Rates

The heat flux range for the spheres and cylinder was from $2 \times 10^4$ to $20 \times 10^4$ Btu/hr.ft$^2$, while the gas film transfer coefficients varied from about 20 to 50 Btu/hr.ft$^2$ °F. Results were found to be reproducible within about 10 percent.

According to the correlation for heat transfer in argon-nitrogen plasma jets, equation (19), proposed by Chludzinski et al. (29), there would be no contribution to heat transfer due to recombination of nitrogen atoms and ions at the low concentrations of these species present in this investigation, of the order of $10^{14}$ particles ft$^{-3}$.

It was also ascertained that the radiation heat flux from the wall to the particles was negligible at the graphite wall temperatures of less than 400 °F. Similarly, the radiation heat flux from the plasma jet was insignificant due to the small solid angles subtended by the spheres and cylinder at the plasma
radiating region near the nozzle.

In order to confirm that natural convection was not acting in combination with the forced convection, the parameter $\left(\frac{Gr}{Re^2}\right)$, which is used for predicting the predominant form of heat transfer, was calculated and found to have a value of about $10^{-4}$. Comparison with the figure of 0.05, below which natural convection is negligible (53) showed that the mechanism of heat transfer was indeed one of forced convection.

A calculation was also carried out of the heat conduction along the wall of the sphere-supporting tube, and the 0.035-in. thick wall of the cylinder, caused by the temperature rise of the water along their respective lengths. In each case, the conduction contribution was found to be insignificant. In addition, it was determined that the gas film heat transfer coefficient was the controlling one in the overall thermal transport, since the wall-equivalent heat transfer coefficients were about 8,500 and 19,000 Btu/hr.ft.$^2$ OF. for the sphere and cylinder walls, respectively, while the water film coefficients varied from about 400 to 1,500 Btu/hr.ft.$^2$ OF. The higher figure in the latter case corresponds to typical values in the nucleate boiling range of heat transfer. Boiling was indeed observed in runs utilizing high power inputs and low cooling water flow rates to the particles, but it was ascertained that the heat transfer rate was independent of the water flow rate.

**Boundary Layer Behaviour**

The Reynolds number range, based on sphere diameter,
was 600 to 4,300. In isothermal turbulence-free streams, the above range is one in which the lower critical Reynolds number has been exceeded (54), since the vortex system associated with the sphere is feeding into the wake. The sharp drop in surface thermocouple reading, shown in Table II, in the region between 90° and 120° from the front stagnation point indicates the approximate latitude of the point of separation. Because of the large intensities of turbulence present in the vicinity of port 1, the boundary layer was probably itself turbulent. When values of 20 and 25 percent were substituted for the intensity in equation (23), obtained by Torobin and Gauvin (35), a laminar-turbulent boundary layer transition was predicted at Re = 1,100 and 700 respectively, which is at the lower limit of the present data. Such a transition may also have been triggered by high temperature gradients and the fluctuations caused by the intermittency of the arc process. Thus it appears that the present data lie above the higher critical Reynolds number. This view is supported by the fact that no apparent change in slope is shown in Fig. 4 and 5. This indicates that no change in mechanism occurred throughout the Reynolds number range investigated. It also indicates that the correlations were independent of sphere diameter. The Reynolds number exponents for the sphere and cylinder data were close to 0.8, which value is characteristic of turbulent systems. The slope of the two Nu-Re graphs for cylinders, shown in Fig. 6 and 7, was also constant although the Reynolds number range extended down to 300.
Comparison with Other Investigations

In Fig. 8, a comparison is made between the correlation obtained for cylinders in the present investigation and the data obtained by Churchill and Brier (7):

\[ \text{Nu}_b = 0.60(Re_b)^{0.5}(Pr_b)^{0.33}(T_b/T_s)^{0.12} \]  

To test this correlation, and more particularly the validity of the temperature ratio factor, the latter was replaced by an average value to simplify the comparison. This procedure was justified by the fact that their plot of \( \text{Nu}_b/(Re_b)^{0.5}(Pr_b)^{0.33} \) against \( (T_b/T_s) \) showed considerable scatter. After processing of their data with a computer, it was found that the correlation coefficient was less than 0.2. It thus appears that the inclusion of the ratio \( (T_b/T_s) \) in their correlation is not warranted. On the other hand, application of the Torobin and Gauvin (35) relationship for laminar-turbulent transition gave a rough approximation of \( 10^5 \) for the higher critical Reynolds number at the two percent intensity of turbulence prevailing in Brier and Churchill's study. It may, however, be clearly observed in Fig. 8 that there exists an unsystematic change in slope at \( Re_b = 1,000 \). Their data above and below \( Re_b = 1,000 \) were fitted successfully to two separate lines:

\[
\begin{align*}
\text{Re} \leq 1000 & \quad \text{Nu}_b = 1.01(Re_b)^{0.440}(Pr)^{0.33} \quad (37) \\
\text{Re} \geq 1000 & \quad \text{Nu}_b = 0.319(Re_b)^{0.640}(Pr)^{0.33} \quad (38)
\end{align*}
\]

with correlation coefficients of 0.933 and 0.964 respectively. The break at \( Re_b = 1,000 \) in their data may thus possibly be due to laminar-turbulent transition in the boundary layer. The lower
Reynolds number range corresponds to the higher temperature data points (up to 1800 °F.) in which viscous effects would be expected to overcome the small turbulence effects. In the present investigation, it appears that the high intensity of turbulence was dominant even in the lower Reynolds number range, and at the high temperatures encountered. It is also the high intensity which was responsible for the fact that the present data gave higher results for heat transfer than did those of Churchill and Brier (Fig. 8), and the correlation of Douglas and Churchill (Fig. 7). It is interesting to note that the data points of the former lie consistently above the correlation of Douglas and Churchill (8), probably for the same reason.

Comparison of the sphere data with the correlation proposed by Richardson (30) to represent the data of Yuge (19), equation (20), also demonstrated marked increases in heat transfer rates in the present study. These increases were most marked at the higher Reynolds numbers at which the temperature was lower, and the viscous forces were unimportant.

**Present Correlations**

Fig. 9 to 12 and Table X show the effect of temperature on the four heat transfer correlations. It may be seen that only the cylinder data plotted on the film temperature basis might be amenable to a temperature correction, but that even it was rather indefinite. The other three correlations were clearly independent of temperature.

It is clear in Table IX and Fig. 4 to 7 that correlation
of the present data was best accomplished when the gas properties were taken at the bulk temperature. Not only was the correlation coefficient higher, but the scatter in the data was less marked, the 95 percent confidence limits were closer, and the temperature effect was smaller. The following generalized correlations are thus proposed:

**SPHERE**

\[ \text{Nu} = 0.118 \times (Re)^{0.757} \times (Pr)^{0.33} \]  

(39)

**CYLINDER**

\[ \text{Nu} = 0.114 \times (Re)^{0.792} \times (Pr)^{0.33} \]  

(40)

where the gas properties are to be evaluated at the bulk gas temperature.
CONCLUSIONS

The plasma jet reactor system was successfully employed for the measurement of heat transfer rates to stationary water-cooled spheres and cylinders. It was shown that the results were reproducible to within 10 percent, and that the radiation, conduction, recombination and natural convection contributions were negligible.

Consideration of the intermittent nature of the arc process inside the plasma torch nozzle led to the hypothesis that the pockets of plasma entering the reactor continuously decreased in Eulerian scale, due to the high turbulence intensity present, and were small in comparison with the diameter of the particles employed at the test section.

It was demonstrated that laminar-turbulent boundary layer transition was expected in the Reynolds number and turbulence intensity ranges investigated, and that transition might even have been triggered by the high temperature gradients and intermittency fluctuations at a still lower Reynolds number. The presence of a turbulent attached boundary layer was also indicated by the high values of the Reynolds number exponent in the correlations presented for the Nusselt number. Comparison of the results with those of other investigators attested to the fact that high turbulence levels increase the heat transfer rate appreciably, particularly at higher particle Reynolds numbers.

Correlation of the data was best accomplished by taking the gas properties at bulk temperature. The following
correlations were proposed:

**SPHERE**

\[ \text{Nu} = 0.118 \text{ (Re)}^{0.757} \text{ (Pr)}^{0.33} \]  \hspace{1cm} (41)

**CYLINDER**

\[ \text{Nu} = 0.114 \text{ (Re)}^{0.792} \text{ (Pr)}^{0.33} \]  \hspace{1cm} (42)
### NOMENCLATURE

#### ROMAN SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>constant</td>
</tr>
<tr>
<td>b</td>
<td>constant</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat at constant pressure, Btu/lb. °F.</td>
</tr>
<tr>
<td>$C_{A^+}$, $C_{N^+}$, $C_N$</td>
<td>concentration of $A^+$ ions, $N^+$ ions, $N$ atoms respectively, ft.$^{-3}$</td>
</tr>
<tr>
<td>D</td>
<td>diameter, ft.</td>
</tr>
<tr>
<td>$D_M$</td>
<td>molal diffusivity, lb. mole./hr.ft.</td>
</tr>
<tr>
<td>$D_V$</td>
<td>mass diffusivity, ft.$^2$/hr.</td>
</tr>
<tr>
<td>$g_c$</td>
<td>gravitational constant, 32.17 ft.lb./lb.force sec.$^{-2}$</td>
</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient, Btu/hr.ft.$^2$ °F.</td>
</tr>
<tr>
<td>i</td>
<td>enthalpy, Btu/lb.</td>
</tr>
<tr>
<td>$l_r$</td>
<td>relative intensity of turbulence, dimensionless</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity, Btu/hr.ft. °F.</td>
</tr>
<tr>
<td>$k_G$</td>
<td>mass transfer coefficient, lb.mole./hr.ft.$^2$</td>
</tr>
<tr>
<td>L</td>
<td>length, ft.</td>
</tr>
<tr>
<td>$L_X$</td>
<td>Eulerian macroscale of turbulence, ft.</td>
</tr>
<tr>
<td>p</td>
<td>constant</td>
</tr>
<tr>
<td>q</td>
<td>constant</td>
</tr>
<tr>
<td>Q</td>
<td>heat transfer rate, Btu/hr.</td>
</tr>
<tr>
<td>$S_o$</td>
<td>outside surface area, ft.$^2$</td>
</tr>
<tr>
<td>T</td>
<td>temperature, °F. or °R.</td>
</tr>
<tr>
<td>$u'$</td>
<td>fluctuation of velocity, ft./hr.</td>
</tr>
<tr>
<td>U</td>
<td>velocity, ft./hr.</td>
</tr>
<tr>
<td>$U_r$</td>
<td>relative velocity, ft./hr.</td>
</tr>
<tr>
<td>w</td>
<td>mass flow rate, lb./hr.</td>
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</tbody>
</table>
GREEK SYMBOLS

\[ \beta \] - coefficient of volume expansion, \( (^{\circ} \text{R.})^{-1} \)

\[ \theta \] - angle, radians

\[ \lambda \] - mean-free path of gas, ft.

\[ \mu \] - viscosity, lb./ft.hr.

\[ \nu \] - kinematic viscosity, ft\(^2\)/hr.

\[ \pi \] - 3.14159

\[ \rho \] - density, lb./ft\(^3\)

DIMENSIONLESS GROUPS

\[ \text{Gr} \] - Grashof number, \( \frac{D^3 g \beta (\Delta T)}{\nu^2} \)

\[ \text{Kn} \] - Knudsen number, \( \frac{\lambda}{D} \)

\[ M \] - Mach number

\[ \text{Nu} \] - Nusselt number, \( \frac{hD}{k} \)

\[ \text{Pr} \] - Prandtl number, \( \frac{c_p \mu}{k} \)

\[ \text{Re} \] - Reynolds number, \( \frac{DU \rho}{\mu} \)

\[ \text{Re}_c \] - higher critical Reynolds number

\[ \text{Sc} \] - Schmidt number, \( \frac{\mu}{\rho D_v} \)

\[ \text{Sh} \] - Sherwood number, \( \frac{k_G D_v}{D_M} \)

SUBSCRIPTS

\[ b \] - bulk or free stream

\[ f \] - film

\[ l \] - local

\[ o \] - outside

\[ r \] - relative

\[ s \] - surface

\[ t \] - total

\[ w \] - water


41. Iskachenko, V. P. and Vzorov, V. V., Teploenergetika 3 : 57 (1961).
APPENDIX

TABLES OF EXPERIMENTAL DATA
<table>
<thead>
<tr>
<th>Run</th>
<th>Radial Distance from Centre (in.)</th>
<th>0</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>3.75</th>
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<td>1340</td>
<td>1065</td>
<td>955</td>
<td>860</td>
</tr>
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<td>1160</td>
<td>880</td>
<td>835</td>
<td>745</td>
</tr>
<tr>
<td>1-3.5-150</td>
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<td>1045</td>
<td>945</td>
<td>750</td>
<td>670</td>
<td>585</td>
</tr>
<tr>
<td>1-7.0-100</td>
<td></td>
<td>1780</td>
<td>1685</td>
<td>1390</td>
<td>1260</td>
<td>1100</td>
</tr>
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<td>1475</td>
<td>1325</td>
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<td>1455</td>
<td>1270</td>
<td>1120</td>
</tr>
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<td>3-7.0-200</td>
<td></td>
<td>1655</td>
<td>1505</td>
<td>1270</td>
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<td>1035</td>
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SUMMARY AND CONTRIBUTION TO KNOWLEDGE

1. A plasma jet research facility was designed and constructed for high temperature investigations such as pure heat transfer, simultaneous heat and mass transfer, chemical kinetics with fixed bodies of various shapes, and multi-particle solids-gas reactions in conveyed systems.

2. The operating characteristics of the system were obtained for twenty nitrogen plasma jet power levels and flow rates of up to 36 kw. and 250 s.c.f.h. respectively. In particular, gas velocities and temperature profiles were determined at a selected test section, together with the measurement of wall temperatures at various locations.

3. Consideration of the species present in the nitrogen plasma jet led to the conclusion that both thermal and composition equilibrium conditions were closely approached.

4. Calculations of the recirculation rates and estimates of both the radial and axial positions of the eye of the recirculation eddy agreed well with published analyses of isothermal confined jets, in spite of the fact that high velocity and temperature gradients were present.

5. The plasma jet reactor system was successfully employed for the measurement of heat transfer rates to 0.625-in. and 1.000-in. o.d. water-cooled spheres and 0.25-in. o.d. cylinders at levels of turbulence, temperature differences of up to 5,000 °F. and velocities not previously reported.
in the literature. The sphere Reynolds number range was from 600 to 4300 while that of the cylinder was from 300 to 1100, with gas properties taken at the bulk temperature.

6. The high intensity of turbulence increased the heat transfer rates to above those previously reported, and Reynolds number exponents were obtained typical of those in other turbulent systems.

7. Correlation of the data was best accomplished by taking the gas properties at the bulk temperature. The following correlations were proposed:

**SPHERE**

\[ \text{Nu} = 0.118 \text{(Re)}^{0.757} \text{(Pr)}^{0.33} \]

**CYLINDER**

\[ \text{Nu} = 0.114 \text{(Re)}^{0.792} \text{(Pr)}^{0.33} \]
SUGGESTIONS FOR FURTHER WORK

It is suggested that the following areas of investigation will prove to be of interest, both from a fundamental and practical point of view:

1. The investigation of heat transfer at lower Reynolds numbers by the use of smaller particles with a view to determining if there is a change in the mechanism of heat transfer, which would probably manifest itself by a decrease in slope of the Nu-Re plot and a closer approach of the data to correlations obtained at low intensities of turbulence.

2. Assessment of the quenching of the plasma jet by a secondary coolant gas stream in the graphite chamber. This would also involve a systematic analysis of the recirculation phenomenon.

3. The study of simultaneous heat and mass transfer from porous particles under conditions of high turbulence intensities, and large temperature and concentration gradients.

4. A fundamental investigation of the turbulence characteristics of both free and confined plasma jets using a constant-temperature, water-cooled hot film anemometer.

5. A kinetic study of the formation of metal nitrides in a nitrogen plasma, and of the reduction of metal oxides in hydrogen, using both fixed and pneumatically-conveyed multi-particle solids-gas systems. Other reactions of interest would include the hydrogenation of coal and wood.
in a plasma jet.

6. Various gas-phase reactions, such as the pyrolysis of hydrocarbons and the fixation of nitrogen, could also be carried out in the present apparatus, after minor modifications. An important factor in gaseous reactions is the rate of quenching, and this technique would require much development.
HEAT TRANSFER TO SPHERES AND CYLINDERS IN A CONFINED PLASMA JET