AIAA Paper No. 69-348

A HIGH PRESSURE AC ARC HEATER SYSTEM

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AIAA 4th Aerodynamic Testing Conference

CINCINNATI, OHIO/APRIL 28-30, 1969

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Abstract

The results of a research program directed toward establishing design criteria for AC arc heater systems is presented. Particular emphasis is placed on the high pressure (>10 atmospheres) regime. Parameters pertinent to both stable arc heater operation and the scaling of a given unit to higher pressure levels were found. The basic interactions between the AC arc column, the applied magnetic field, the arc chamber gas flow and the arc stabilizing elements are discussed. As a result of analyzing these interactions, a generalization was found that divides all arc heaters into two types or classes. The arc heater developed will withstand pressure levels of 2500 psia with power inputs as high as 3-Mw. The results of tests to establish and evaluate the arc heaters operating characteristics are included. The advantages of the AC arc heater system as well as several instrumentation problems unique to this type arc heater will also be discussed.

I. Introduction

All of the experimental facilities that are capable of true temperature and pressure simulation at the very high Mach numbers (hot shot tunnels, shock tunnels, or shock tubes) are limited by short run times. Pebble bed and resistance heaters are used for longer run times but these devices cannot produce the stagnation temperatures characteristic of hypersonic flight at Mach numbers above 7 or 8. These conditions can, potentially, be effectively produced on a steady state basis by an arc heater. Thus the arc heater has a definite complementary place in the arsenal of high temperature gas dynamic facilities. The task of developing arc heaters for these purposes has been vigorously undertaken by numerous industrial and research organizations. The result of these endeavors has been the development of numerous low pressure DC arc heaters.

This paper summarizes a portion of our research into the heating of a gas flow with an AC arc column. The research was directed toward establishing design criteria for an AC arc heater system. Particular emphasis was placed on operation at high pressure levels while the system design was slanted toward hypersonic tunnel-driver applications.

II. Design Considerations

The main emphasis for this research effort was the development of an AC arc heater with stable, effective operation at elevated pressure levels (> 10 atmospheres). A primary objective was to establish the parameters which would most strongly influence its performance characteristics as arc chamber pressure varied. This task is directly hindered by the absence of research on the AC arc heater system and in particular the paucity of data on the characteristics of an AC arc column in a flowing gaseous environment. Since the majority of data available is on DC arc heaters a comparison study was made. The intent being to see if any analogy could be made between the two systems.

Data was gleaned from existing DC arc heater technology and compared to that obtained from our low pressure AC arc heater system (1). Although a basic difference will exist for the arc column characteristics the trends in performance level with input variables should apply. As a result of this comparison, a generalization was developed which if applied to arc heaters per se would divide them into two classes or groups. Using this generalization a number of analogies between both systems were found. The grouping is based on the arc column-gas flow interaction. The notation adopted for each group is either a "parallel" or "normal" flow arc heater.

The "parallel" flow or tube arc (an outgrowth of the Gerdien arc) takes the form of a water cooled tube in which the arc is contained and the gas to be heated passes through and parallel to the arc column, Fig. 1. The unit usually operates on DC power with the tube or arc chamber serving as one electrode.

The "normal" flow arc heater will have the arc column oriented 90° with respect to the arc chamber gas flow, Fig. 2. A stationary arc column so oriented would fill only a small fraction of the arc chamber cross sectional area and thus lead to inefficient heating of the working fluid.

*This research was supported by Aerospace Research Laboratories, Office of Aerospace Research, U.S. Air Force, Contract AF 33(615)-1326.

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Further, the thermal loads imposed by the concentration of the arc roots on a small area of the electrode would cause frequent burn throughs. To overcome these problems a DC magnetic field, created by a solenoid wrapped around the arc heater is applied to the arc column. The magnetic field vector is so arranged (along the axis of the arc chamber) that the resultant Lorentz force causes the arc column to rotate in the annular region between the electrodes. Thus the applied DC magnetic field becomes an important feature of the "normal" flow arc heater. Since a high arc column rotational rate is desirable, the driving Lorentz forces should be a maximum for a given field strength and electrode configuration. The Lorentz forces is given by:

$$\vec{F} = \vec{B} \times \vec{I} \qquad (1)$$

and the magnitude by:

$$F = BI \sin \theta \qquad (2)$$

Applying Eq. (2) to the geometry of the arc heater, the force will be a maximum when the magnetic field is oriented parallel to and the arc column normal to, the arc chamber axis. This illustrates the advantage of locating two electrodes in the same plane. Further it indicates a disadvantage in using the arc chamber wall as an electrode for then the arc root position on the chamber wall will be a function of arc heater mass flow rate. As the flow rate increased, θ, would decrease thereby reducing, F. Finally, when electrodes fail (as they eventually will) it is far easier to replace a simple electrode than the arc chamber. A disadvantage is that the separate electrode essentially divorces the arc column length from the arc chamber dimensions, thus complicating any scaling process.

It must be pointed out that application of a DC magnetic field is not unique to the "normal" flow arc heater. The "parallel" arc heater must also have some mechanism for spreading the imposed heat of the arc root over the electrode surface area. Here too, the arc root can be rotated; two methods are available, magnetic or aerodynamic. The latter method is accomplished by tangentially injecting the working gas into the arc chamber. The vortex created rotates the arc root. If we consider the region of the arc column in the vicinity of its root, Fig. 1, we find it must turn 90° to the arc chamber wall. The arc current vector is then locally so oriented that a DC magnetic field applied as previously mentioned, will create a Lorentz force which tends to rotate arc root over the surface of the arc chamber wall. We find, however, that for the "parallel" arc heater any magnetic field is applied locally at the arc column roots.

This discussion on the interaction of the arc heater type with the applied DC magnetic is to point out an important input variable for an arc heater system. The consequences of this parameter on arc heater performance is not generally brought out in the descriptions of various existing arc heater systems. In the "normal" flow arc heater the importance of the applied magnetic field cannot be over emphasized. This variable will enter strongly in any initial design considerations or scaling process. Using these arc heater generalizations, analytic models were sought for the arc column-gas interactions.

A number of analytic developments were found which applied directly to the "parallel" flow arc heater. This type of gas flow-arc interaction can be solved by using an asymptotic column solution (2). In general, the theory of the cylindrically symmetric arc is firmly established and compares well with experiments; one of the more accurate investigations being made by Stine and Watson (3). The effects of pressure and enthalpy levels on this arc-gas interaction can be estimated by following an analysis first proposed by Suits (4); the arc column being treated as if it were a hot cylindrical body. This analysis, however, neglected the effect of radiation losses and forced convection. These effects are important when operating at high pressure levels and mass flows and have been included in a similar analysis (5). Using these analyses, the effect of the various input parameters on arc heater performance characteristics was evaluated. If one now considers the coupling that exists between the arc chamber and the arc column, a fairly general set of scaling parameters can be established for this type of arc heater. This scaling process is discussed in Ref. 6. It is felt that the above mentioned analyses along with the experimental data available on both the gas-arc interaction and from existing "parallel" flow type arc heaters present an established basis for designing and/or extending its performance range. These remarks are predicated on the assumption that DC power is used in this type of arc heater. The application of AC power to this unit has not proved successful. As a result of our research it is, in general, concluded that the "normal" flow type arc heater is best suited to AC power applications. This statement will be enlarged upon in the following paragraphs. Since this paper is concerned with an AC arc heater system, the normal flow arc heater will be discussed in more detail.

As previously mentioned there are a number of problems which directly hindered any investigations into the characteristics of the "normal" flow arc heater. The lack of a suitable analytic model for the gas flow-arc column interaction is one of the primary difficulties. This model is further complicated if one is to analyze the arc column in the presence of DC magnetic field and gas flow. A basic requirement for stable arc heater operation is that the arc column have sufficient freedom to physically change its shape. This is especially true if operation over a large range in pressure levels, mass flows, enthalpy levels, etc., is required. Since most arc heater applications need stable operation over a given range this is considered a primary requirement for both the "parallel" and "normal" flow arc heaters. In the former arc heater we find that this is allowed since the arc column is free to assume the arc chamber dimensions. Hence the arc heater must be designed with sufficient volume to allow changes in arc column diameter (variation in current levels) and/or arc column length (variation in arc heater mass flow). A change in any one of a number of input variables can result in a change in arc column dimensions.

Referring again to the "normal" flow arc heater shown in Fig. 2, the mechanism which allows for changes in arc column dimensions are not as evident. While the arc column has no definite limits on changes in its diameter, it would appear that the arc column length is governed by the electrode spacing. The type of arc heater, however, has two mechanisms which will allow a change in arc column length without physically changing the electrode spacing; a necessity if stable operation is required over a range of arc heater power, mass flow, and pressure levels. The "effective" electrode spacing can be changed by either blowing (magnitude of gas velocity vector through the electrode region) on the arc column or by applying a DC magnetic field to the arc column. Each mechanism will cause the column to lengthen in one of two different planes, the resultant arc column becoming a rather complicated three-dimensional shape. Figures 3 and 4 illustrates these effects. These features were used in designing the 2500 psia arc heater described herein.

As shown in Fig. 3, the effect of increasing the velocity vector into the arc column causes the column to bow thereby lengthening it in the axial plane and moving the arc root forward, axially, around the electrode. The effect of the DC magnetic field, Fig. 4 is to rotate the arc column at constant angular velocity. Therefore, that part of the arc column farthest from the axis of rotation will tend to have the highest velocity.

Defining for the moment, the head of the arc column as that part moving at the highest velocity and the base the slowest velocity, our investigations with the low pressure arc heater showed that the head of the arc column would lead its base by as much as 90°, this lead being a function of DC field strength and arc chamber pressure. The angular lead was limited by the maximum field strength available (3000 gauss). It has been shown theoretically and verified experimentally (7) that the shape of the arc column in the radial plane would be that of a cycloid of a circle. Therefore, the length of an arc, so driven, can be significantly greater than the physical electrode spacing, approaching what may be considered a mean circumference between the electrodes.

An interesting limit is evident for by creating a large enough Lorentz force, the head of the arc column can lead its base by 360°. The resultant discharge would no longer take the form of a column, but rather that of a current sheet completely filling the annular electrode gap. This phenomenon, referred to as a diffuse arc, would spread the concentrated heat load of the arc column roots over the entire electrode surfaces, significantly reducing their rate of erosion. This type of arc discharge would be very desirable from the standpoint of arc heater operation, particularly the normal flow type which requires a strong applied DC magnetic field. Although frequently mentioned in the literature, no arc heater system has been developed that can produce a diffuse arc at moderate pressure levels. The primary difficulty is the large field strengths required ($>$ 20,000 gauss) to overcome the aerodynamic drag forces experienced at high pressure levels. We find, then, the length of the arc column can be significantly larger than the physical spacing of the electrodes and that its shape will be more than a simple cylinder normal to the electrode surface. Both now become a strong function of arc chamber mass flux and the applied DC magnetic field strength. These features not only serve to complicate any scaling between the arc column and some characteristic length (e.g. electrode spacing) but also require that any meaningful theoretical model of the arc column must assume it to be three dimensional. It is felt that this lack of a theoretical model is the major difficulty found in either initially designing the normal flow arc heater for a given operational regime or scaling a given design to new performance levels.

To establish the variation in arc heater performance as a function of its input parameters the results of the analytic models used for the "parallel" flow arc heater were qualitatively modified for the arc column-gas flow interaction found in the "normal" flow arc heater. Since a strong applied DC magnetic field is an important variable now, its effect on arc heater performance must be included. Lacking experimental as well as theoretical information on these arc interactions most of the trends and conclusions were obtained from the research done on our low pressure arc heater system.

It is felt that, in general, the following describes the coupling between the arc heater gas flow and the arc column. These parameters were chosen since they most strongly effect the design of the "normal" arc heater system. An increase in arc chamber pressure level increases the arc column voltage gradient, power loss due to radiation, and gross power input, and decreases the arc column diameter and arc column rotational rate (the latter decreasing arc column length). An increase in chamber mass flow increases the arc column voltage gradient, arc column length, and the gross power input and decreases the gas enthalpy and arc column diameter, power loss due to radiation, and arc column rotational rate. An increase in arc current increases the arc column diameter, power loss due to radiation, arc column rotational rate, and decreases the arc column voltage gradient and the gas enthalpy level. It can either increase or decrease the arc column length.

Assuming one has a "normal" flow arc heater operating at a given pressure, enthalpy, and mass flow level and a new unit is to be developed to operate with an increase in one of these variables, the direction of change and/or scaling parameters can be obtained from the above trends. Table I summarizes this for three particular cases; I) increased pressure while holding mass flow and enthalpy constant; II) increased mass flow while holding pressure and enthalpy constant; III) increased enthalpy while holding pressure and mass flow constant.

Changes in arc heater parameters, length and diameter, were also included in Table I. Changes in these variables were based on the assumption that if one were scaling to a new performance regime, the resulting unit would be slanted toward improving and/or at best maintaining thermal and structural efficiency. However, due to the weak coupling between the arc chamber and the arc column, the scaling of the arc heater dimensions can become quite arbitrary. This is particularly true with respect to the arc heater length (so designated by bracketing the suggested changes). In fact, quite often these dimensions can be completely dictated by other arc heater components, e.g., optimum size of the solenoid needed to produce the required DC magnetic field strength. This type of interaction turned out to have a significant effect on the eventual design of the 2500 psia arc chamber.

III. Arc Heater Power Considerations

Considering now the question of using AC applied directly to the arc heater electrodes instead of DC, it is felt that the "normal" flow arc heater is best suited to AC operation. This statement is based on the assumption that if one uses AC it would take the form of multiphase AC. The minimum number of electrodes needed would then be three which, looking at possible electrode configurations, will lend itself best to the normal flow arc heater. These statements are not meant to exclude single phase AC for it can readily be used in either type of arc heater. However, it is concluded, as a result of our research and others, that there are few, if any, advantages of using single phase AC instead of DC power. Some reservations must be made, however, as this conclusion is usually based on single phase AC operation of an arc heater designed for DC power.

IV. High Pressure AC Arc Heater

The objective for this system was stable operation at pressure levels up to 2500 psia. As previously indicated a low pressure unit was designed and tested in our laboratory facilities. The test data from this arc heater indicated that increases in operational pressure levels would require substantial changes in both the arc heater design and its support systems. The study just described was initiated for two reasons: 1) to establish which arc heater configurations were best suited to high pressure operation and 2) to establish whether or not a modeling of the arc heater was possible. The latter was aimed at developing the design guide lines or scaling trends that would allow an orderly extrapolation of the AC arc heater system. It is felt that the generalization based on the arc column-gas flow interaction satisfied both needs. Hence the indicated changes in arc heater parameters shown in Table I established the basis for the high pressure arc heater design.

Case I of Table I best represents our particular design requirements. Table I shows that the high pressure arc heater must be capable of handling higher arc voltages, power levels, and thermal heat loads; the applied DC magnetic field strength would have to be increased and the arc chamber volume decreased. These trends were also supported by the experimental data from our low pressure unit. These data showed that for a given open circuit voltage, power input, and DC magnetic field strength, an increase in arc chamber pressure produced a decrease in arc heater stability (arc column extinction), increased electrode erosion (decrease in arc column rotational rate), and an increase in thermal losses to the arc chamber walls (increased radiative heat losses).

The arc chamber and nozzle were considered to be the major arc heater components most affected by the increase in pressure level. The final design of these two components were particularly influenced by the above trends. As previously mentioned, the applied DC magnetic field can interact strongly with the design of the "normal" flow arc heater. This was particularly true with regard to this arc heater system. Experimental data from the low pressure arc heater indicated that a DC magnetic field increase on the order of six (18,000 gauss) would be optimum for high pressure operation. Since the existing DC power supply for the magnetic field is limited to 120 KW, it was impossible to achieve the desired six fold increase and still have an arc chamber capable of withstanding the new performance levels. Accordingly, a compromise was made, resulting in a solenoid design producing 11,500 gauss.

Arc Heater System

The major components of the arc heater system are the primary power source, stabilizing elements, arc heater, DC magnetic field coils, and arc heater electrode system. Support equipment include the necessary instrumentation to monitor arc heater operation, magnetic field power system, high pressure water-cooling system and the arc heater high pressure air system. The arc heater system is shown schematically in Fig. 5.

Power Supply

Considering this particular aspect of any arc heater system, the simplicity and versatility of the power supply for an AC arc heater becomes one of its primary attributes. The power supply takes the form of an uncomplicated, low cost, commercially available transformer. The unit can be either a step-up or step-down type dependent on the available AC power in the area and the arc heater voltage requirements. Another advantage is the availability of high voltage AC power at high power levels. If high pressure arc heater operation is required, the generation of high voltage power becomes a major problem.

The power available for our arc heater facility comes from a three phase source. The source voltage is approximately 17,000 VAC. This is stepped-down to 4800 VAC before it is applied to the primary of any arc heater power supply. The power supply is a step-down transformer with a multi-tapped secondary. The adjustment in arc heater open circuit voltage being made by manually changing the tap position. Five voltage levels from 1000 to 4800 VAC are available.

Stabilizing Element

A necessity in any arc heater system is the stabilizing element. This element affects both the arc column stability and the level of power dissipated in the arc heater. The need for such an electrical element arises from the voltage-current relationship of the arc column (i.e., a falling voltage characteristic with increasing current, $dV/dI < 0$). In the AC arc heater system it must provide two functions; limit the current level in the arc column and provide sufficient voltage for arc re-ignition. The latter function is necessary since the arc current is in the form of a 60 cycle sine wave. If we consider an arc column burning with a positive voltage, (positive half of the current wave-form) the arc will extinguish when the current falls to zero. There must be some mechanism which restores (re-ignites) the arc column so that it can burn during the negative portion of the current wave form. Figure 6 shows the arc pattern for a 3-phase electrode system. The extinction and re-ignition process is evident here.

This particular process (re-ignition process) is required to maintain stable arc heater operation. The term stable, effective operation used a number of times in this paper infers that this re-ignition process is continuous with only small periods of arc column extinction.

The AC system has available two electrical elements to produce this stabilization, either a resistor or inductor in series with each electrode. A study was made to establish the general character of an AC arc column using each element (8). The results of this study established that only the inductive element gives the large stability range needed for arc heater operation. The type of inductors used for this arc heater system are commercially available sub-station reactors. A multi-tap reactor is placed in each phase of the transformer primary. The combination of multi-tapped inductors and transformer provides a wide variation in both arc heater voltage and current levels.

Arc Heater

The arc heater consists of a cylinder chamber with suitable end closures. The air heater effluent enters through the rear closure while the nozzle is held in the front closure. The latter closure is designed with a removable section allowing a number of different nozzles to be installed. The closures are secured to the arc chamber by large threads. The system allows the end closures to be removed in a few minutes.

The heat transfer analysis made on the arc chamber indicated that structural material would be subjected to high heat fluxes. A study was made to establish which materials had the necessary structural characteristics. The analysis made assumed the arc chamber to be analogous to a thin walled tube subjected to thermal and pressure stresses. The following equation involving the material characteristics was obtained.

$$\frac{\sigma^2 K}{E\alpha} = \frac{q\,d\,\Delta P}{(1-\mu)} \qquad (3)$$

This gives a relationship between the physical properties of a material and the parameters pertinent to the design of the arc heater. Therefore, to withstand high pressure and thermal loads, the allowable stress and thermal conductivity of the material should be high while the modulus of elasticity and thermal expansion coefficient should be small.

Using this relationship, thirteen materials were surveyed, of which only two copper alloys — copper-zirconium and copper beryllium — had the necessary properties. Of the two copper alloys, copper-zirconium was the final choice for the arc heater structural material. Copper-beryllium was found to be brittle and notch sensitive, hence it was considered unsuitable for an arc chamber which uses threads as a structural element.

The arc chamber consists of a tube 20 in. long with a 6 in. diameter. A finned surface was machined on this outside of the chamber. Soft copper tubing was imbedded between and soldered to the finned surface thereby forming the arc chamber cooling system. This arrangement allows the cooling water temperature gradient along the arc chamber to be monitored and to locally apply more coolant if hot spots are found. The electrodes pass through three outlets in the chamber wall and are oriented 120° around its circumference.

Electrode System

In general, the electrode system takes the form of three water cooled copper rings each connected to one phase of the power supply. Their main function is to electrically support and orient the arc columns with respect to the arc chamber gas flow and the applied DC magnetic field. This is shown in Fig. 7. For the high pressure arc heater a coaxial electrode leg was developed. This allows the cooling water inlet and outlet to be brought through two copper tubes one inside the other. Although this arrangement increased the size of the electrode leg it reduced their number to three. A similar reduction in electrode glands and opening in the arc chamber was then possible. It was also necessary to develop an electrode gland to withstand the high pressure and voltage levels. The general electrode arrangement as it would appear in the arc heater is shown in Fig. 8.

Magnetic Field System

As previously mentioned the particular aspect of the arc heater system was limited by the available DC power supply. The resulting field coil design produces a maximum field strength of 11,500 gauss. A saturable reaction control system on the DC power supply allows the magnetic field strength to be varied during arc heater operation.

Instrumentation

Only one particular feature of the instrumentation will be discussed in any detail since it is believed to be unique to an AC arc heater system. In general, the instrumentation consists of the necessary items to monitor arc voltage, current, power, etc., and made an enthalpy balance on the arc heater system.

Two measurements, however, required more accuracy than afforded by conventional electrical instrumentation. The power measurements on the arc heater system included the total system power and the input power to the arc columns; both were initially measured with the conventional wattmeters. Due to the V-I characteristics of an AC arc column, the arc voltage waveform approaches a 60 cycle square wave instead of the usual sine wave. In addition, the arcing sequence between electrodes is such that a continuous load is not applied across the respective phases. Problems were anticipated in these measurements, however, the magnitude of this error was not realized until a complete calibration of the wattmeters and voltmeters was made. A circuit was designed, for calibration purposes, that would supply the wattmeter with a 60 cycle sine wave of current and a 60 cycle square of voltage. The result of these calibrations showed that a conventional wattmeter would read from 15 to 30% low. The magnitude of the error was also a function of the voltage level.

The complexity of the arc voltage and hence arc power measurement is readily seen in Fig. 9. This shows an oscillogram of the arc voltage and current. The waveform of the arc voltage is much more complicated than a 60 cycle square wave. The effect of this waveform on any voltage measurement is also evident; trace 1 which is produced by a galvanometer of a lower frequency response than traces 2 and 3 show a lower arc voltage. The high frequency spikes superimposed on the 60 cycle wave are caused by the movement of the arcs over the electrode surfaces. Fastax movies taken of the rotating arc columns shows that the arc column length is continually changing.

Adequate power readings are presently being obtained by using a wattmeter with Hall effect elements. Arc voltage readings are taken on a VTVM. It is felt, however, that another possible error in these measurements may come from the potential and current transformer needed to isolate these instruments from the high arc current and voltage levels. Basic voltage and current sensors incorporating vacuum thermo elements directly connected to the power supply secondary are presently being considered.

V. System Operational Characteristics

Three series of tests were conducted. These tests were made to 1) prove or disprove the design guide lines and procedures used in arriving at the arc heater design; 2) evaluate the arc heater performance characteristics as a function of pressure level. The primary data obtained in these tests were effluent enthalpy, arc heater total pressure, efficiency, and arc voltage. The effluent enthalpy was found by taking an energy balance on the arc heater and by the sonic flow method (9). In general, good agreement was found between both techniques. Deviations were noticed, however, if the arc heater exhibited poor arc column stability. For these tests only one nozzle was used; the throat diameter was 0.11 in. allowing a mass flow on the order of 0.25 lbm/sec at 2500 psia. The working gas used in these tests is air.

The first series was aimed at testing the new arc heater system components as well as establishing the initial arc heater performance characteristics. The complete arc heater is shown in Fig. 10. The gross power input for these initial runs was set at 800 KW with a maximum open circuit voltage capability of 1000 VAC. The electrode gap was 1/2 in. The results of these tests are shown in Fig. 11 through 13. As shown in Fig. 11, the enthalpy levels varied from about 3000 BTU/lb to 5000 BTU/lb. The effect of pressure level on voltage requirements is shown in Fig. 12. As the pressure increased to the 400 psia range, the stability of the arc heater was markedly poorer. The efficiency at these levels was also very low, 5 to 18% as seen in Fig. 13. This is attributed to the low mass flow rates. The magnetic field also had to be limited to 5000 gauss. Field strengths above this level would extinguish the arc columns. The net result of these tests was to substantiate the need for higher voltages at higher pressures.

The second series of tests was aimed at producing high operational pressure levels. The gross power input for these runs was one megawatt with a maximum open circuit voltage of 2000 VAC. The electrode gap was again 1/2 in. The results of these tests are shown in Fig. 14 through 16. The enthalpy range for these runs, Fig. 14, was lower than the previously measured, falling to about 1500 BTU/lb at 1300 psia. The calculated efficiency was no higher than 20%. The stability of the arc heater at pressures above 1000 psia was also erratic. This is reflected in both the low efficiencies and the low values of arc voltages, Fig. 15. This was attributed primarily to the small electrode gaps used for these tests. An electrode failure was encountered after 35 minutes of operation.

Considering the electrode configuration initially used in the arc heater, Fig. 8, there is a large area in the center of the smallest electrode through which gas can flow without directly contacting the arc columns. By eliminating this area it was felt that the enthalpy level and efficiency of the arc heater might be increased. A cylindrical electrode was designed to replace the smallest ring electrode. The final series of tests used this electrode in conjunction with two ring electrodes, Fig. 17. The gross power input for this test series was 1 Megawatt with a maximum open circuit voltage of 2000 VAC. The electrode gaps were increased to one inch. The magnetic field strength was 9000 gauss. The results of these tests are shown in Fig. 18 through 20. As shown, the enthalpy levels were increased to 3800 BTU/lb at 1300 psia. Increasing the electrode gap resulted in an increase in arc voltage, Fig. 19, and a corresponding increase in arc heater stability. The resulting efficiency of the unit is 40% for pressures above 1000 psia. The electrode erosion for this particular configuration was negligible over a period of one half hour. The improvement in overall arc heater performance by this electrode change is felt to be one of the most important results of the test program.

Electrode erosion levels for these tests were calculated and found to be below 0.5% on a mass basis. The relative energy losses to the various arc heater components are given in Fig. 21. As shown the electrodes account for the highest energy loss. It is felt that the main parameter effecting the arc heater performance, for this test program, was the mass flow. The data generally shows an increase in performance with increasing mass flow. Since the nozzle was designed for a pressure of 2500 psia, the flow rate in this pressure range is not considered to be optimum. The gas residence time in the arc chamber at these flow rates is excessive, hence low efficiencies were encountered. A more realistic procedure would be to have at least three nozzles, each designed to operate over one third of the maximum design pressure level. It is believed that a mass flow up to 0.2 lb/sec within a given pressure level would be optimum for these power levels.

VI. Summary and Concluding Remarks

An AC arc heater has been designed and built for steady state operation at 2500 psia. The heater has been tested at pressures up to 1400 psia. This represents an extension of our earlier investigations into the heating of gas streams by an AC arc column.

The experimental data from the new arc heater system indicates that the arc heater is capable of producing gas enthalpy levels from 5000 to 3000 BTU/lb with flow rates as high as 0.135 lb/sec and stagnation pressure levels up to 1400 psia. Power dissipated in the unit for these conditions was 1 Megawatt with arc voltages on the order of 1000 VAC. An electrode configuration was devised that significantly increased the arc heater efficiency and reduced the electrode erosion rate.

It is believed that the data shown herein does not represent the optimum performance attainable from the arc heater at a given pressure level. However, from these tests it is concluded that the unit will operate stably at 2500 psia with the existing arc heater system. The anticipated operating conditions would be; an open circuit voltage of 3000 VAC, an input power of 1.5 Megawatts, and a DC magnetic field strength of 11,500 gauss. The resulting effluent would have an enthalpy level of 3000 BTU/lb at a flow rate of 0.25 lb/sec. It is also concluded that further investigations into the affect of electrode configurations on the arc heater operation would lead to improvements in the existing performance levels. Finally, the AC arc heater represents a stable, effective, low cost system for producing high enthalpy, high pressure, low contaminate gas flows.

List of Symbols

B	magnetic field strength
d	diameter
E	modulus of elasticity
F	force
I	current
K	thermal conductivity
P	pressure
q	heat flux
α	linear coefficient of thermal expansion
μ	Poisson's ratio
σ	allowable stress

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Scaling Parameter	Case I	Case II	Case III
Arc voltage	increase	increase	decrease
Power	increase	increase	increase
Applied D.C. magnetic field	increase	increase	increase
Thermal losses	increase	increase	increase
Arc heater length	(decrease)	(decrease)	(decrease)
Arc heater diameter	decrease	increase	increase

*Thermal losses are shown here in lieu of a scaling parameter that would reflect the arc heater thermal "efficiency."

Table I

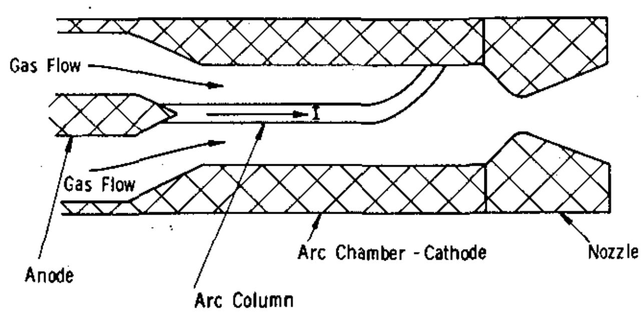

Fig. 1. Parallel Flow Arc Heater

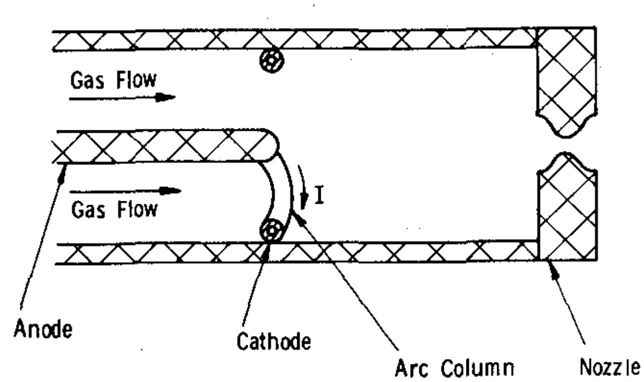

Fig. 2. Normal Flow Arc Heater

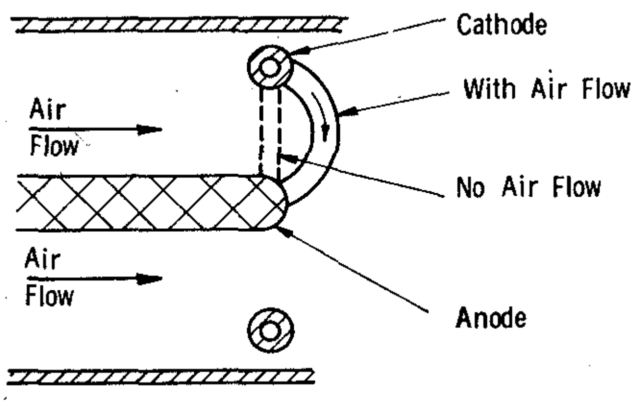

Fig. 3. Effect of Blowing on Arc Column

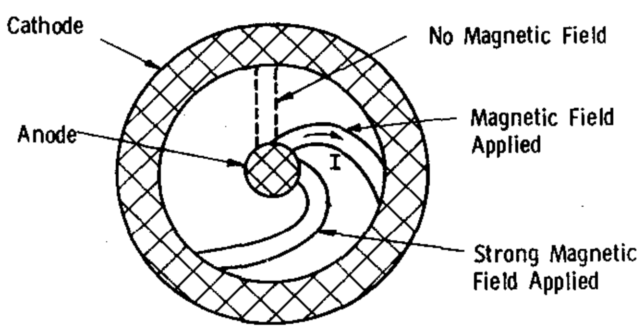

Fig. 4. Effect of Magnetic Field on Arc Column

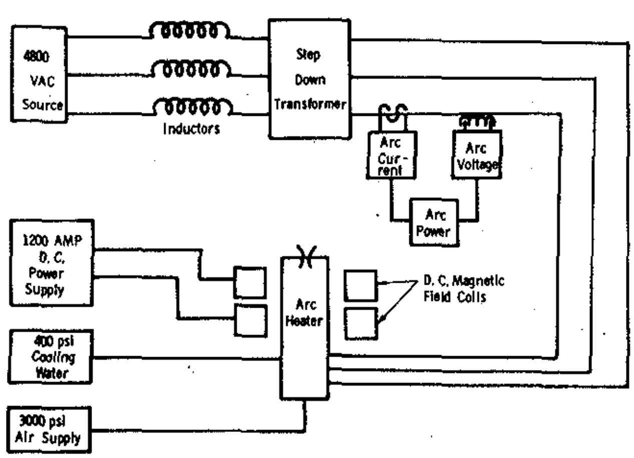

Fig. 5. Arc Heater System-Schematic

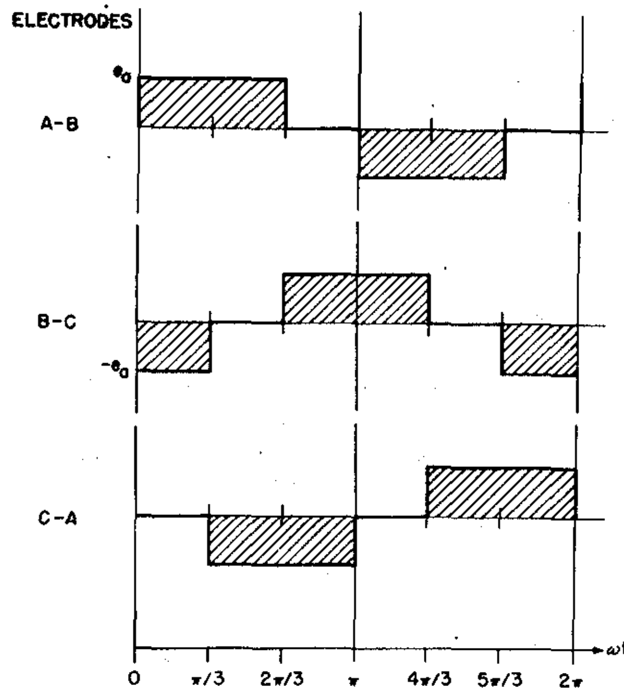

Fig. 6. 3-Phase Arc Pattern

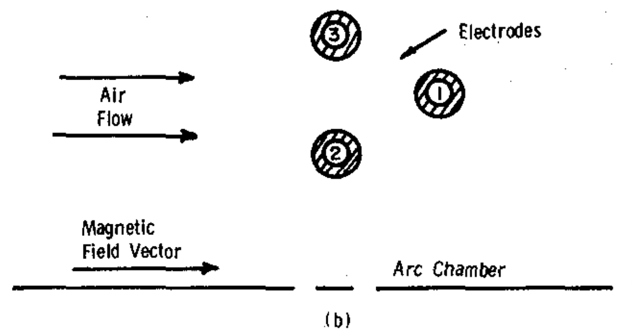

Fig. 7. Electrode Configuration

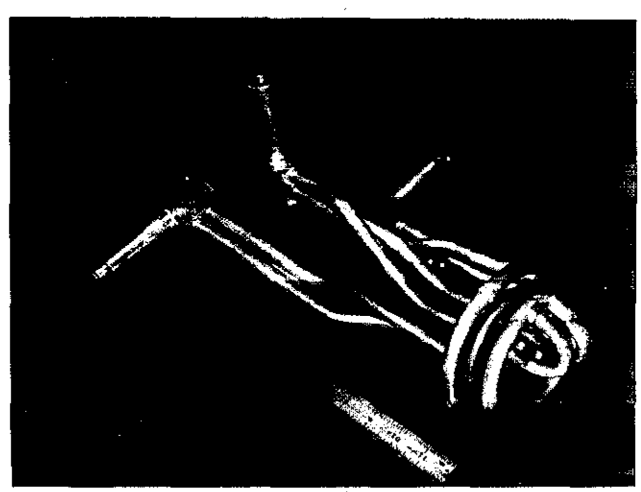

Fig. 8. Arc Heater Electrode Assembly

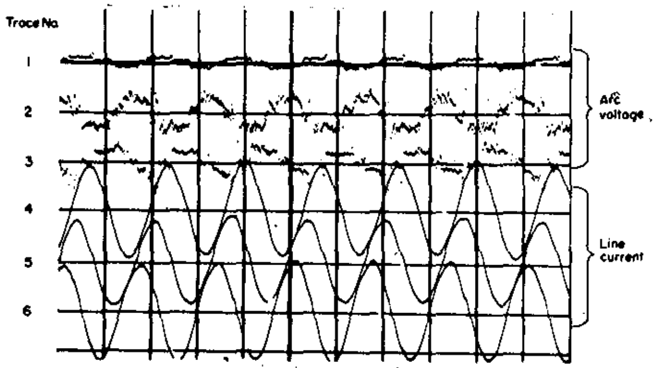

Fig. 9. Arc Voltage and Current Waveforms

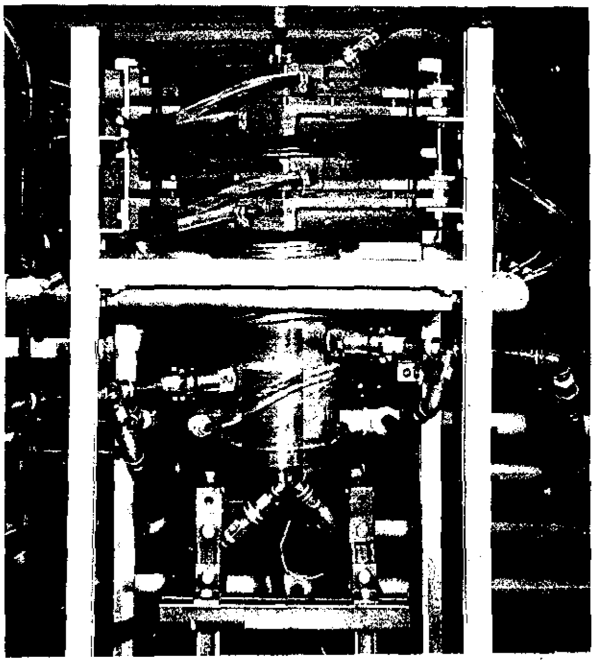

Fig. 10. Arc Heater Installed in Arc Heater Facility

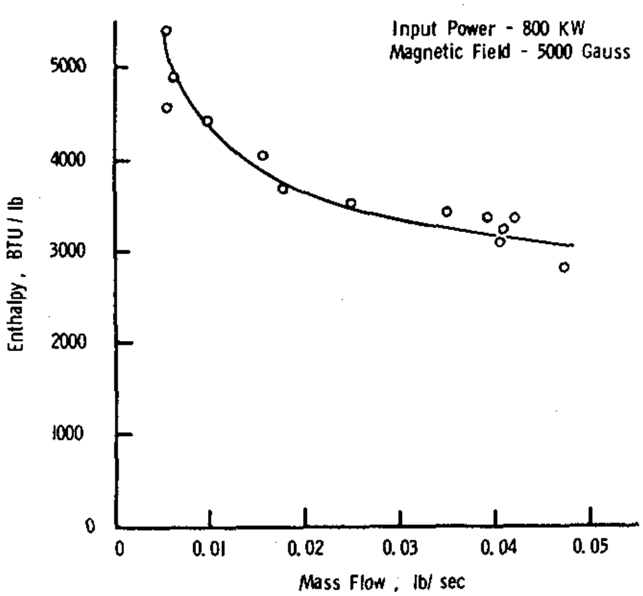

Fig. 11. Effluent Stagnation Enthalpy

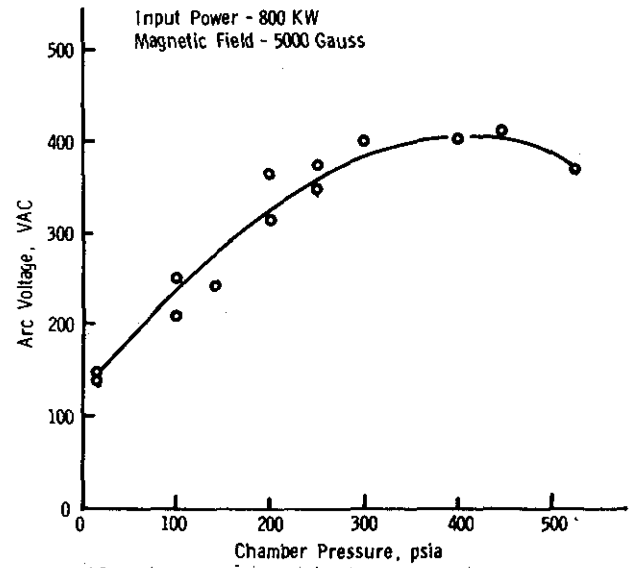

Fig. 12. Arc Voltage vs Stagnation Pressure

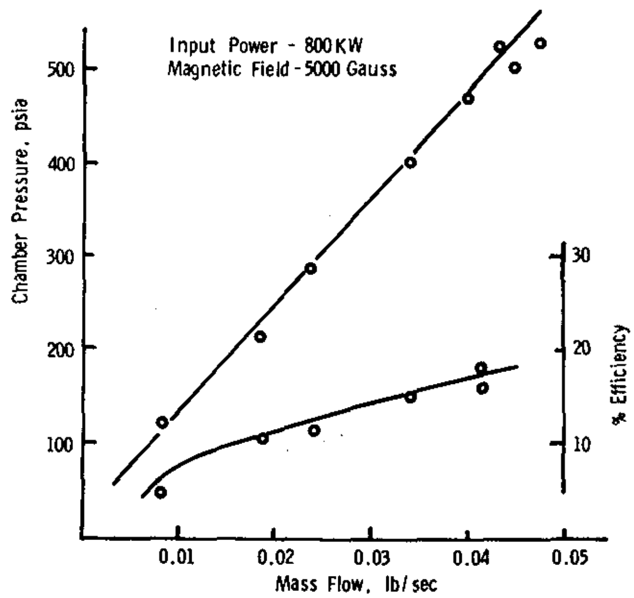

Fig. 13. Stagnation Pressure and Efficiency

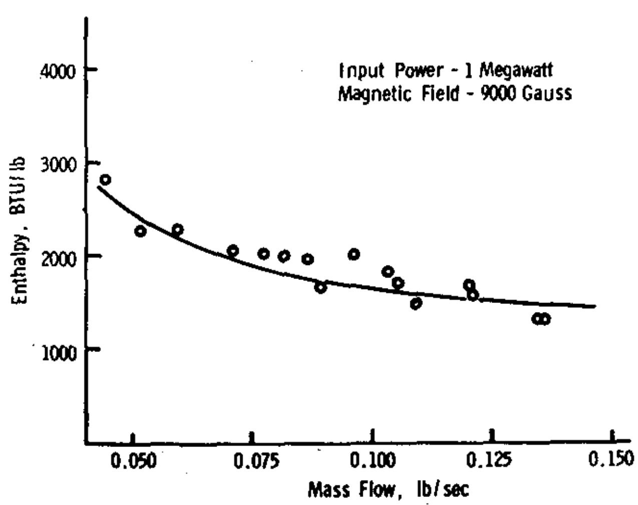

Fig. 14. Effluent Stagnation Enthalpy

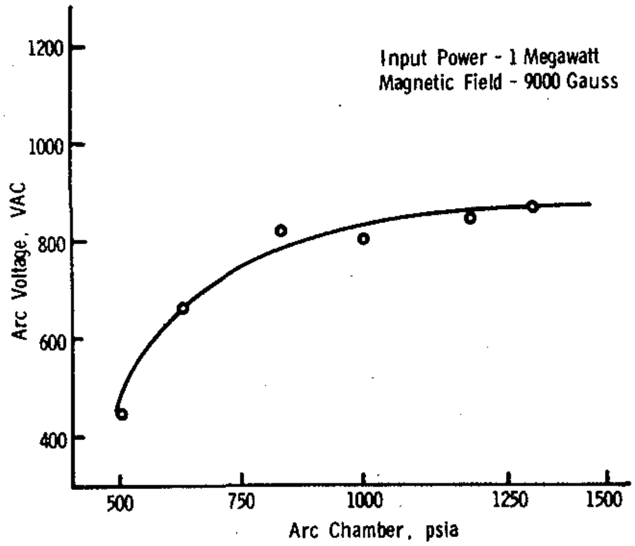

Fig. 15. Arc Voltage vs Stagnation Pressure

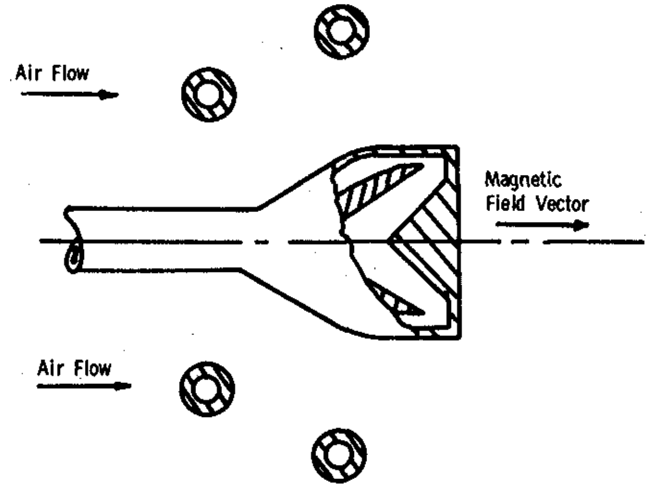

Fig. 17. Revised Electrode Configuration.

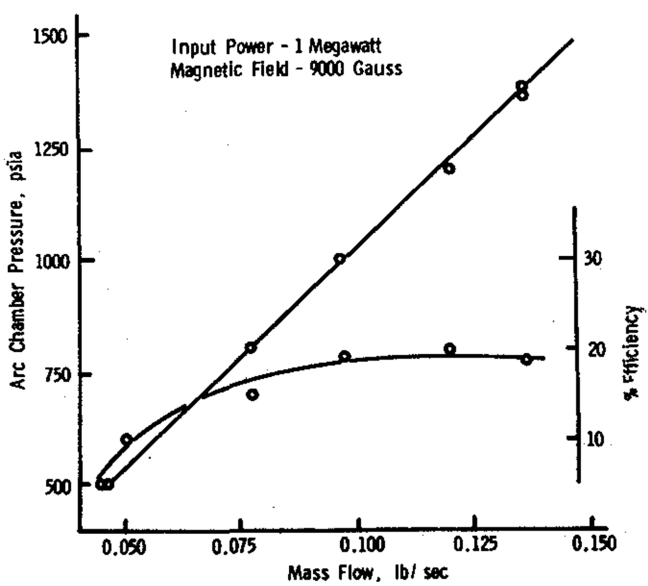

Fig. 16. Stagnation Pressure and Efficiency

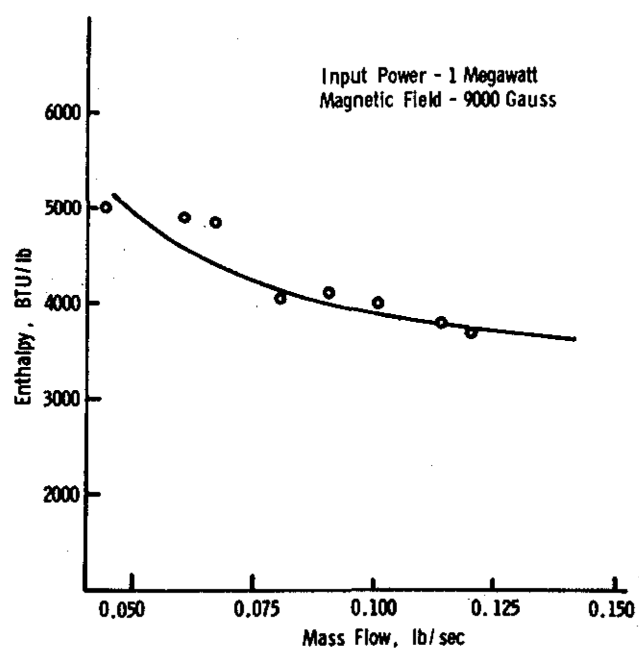

Fig. 18. Effluent Stagnation Enthalpy

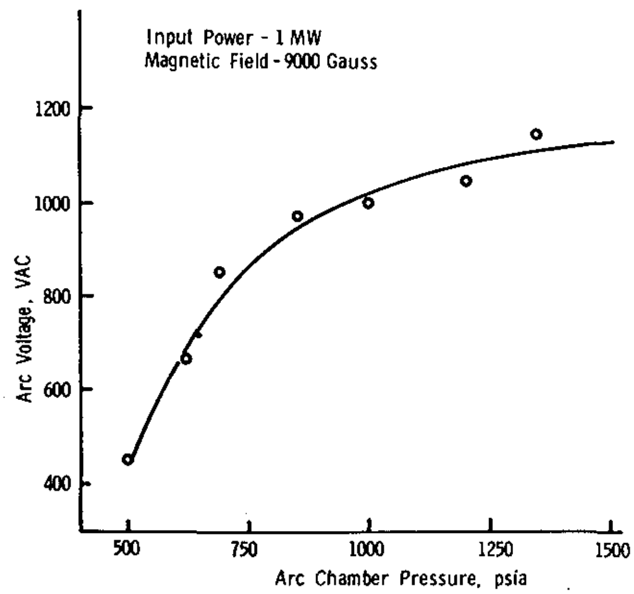

Fig. 19. Arc Voltage vs Stagnation Pressure

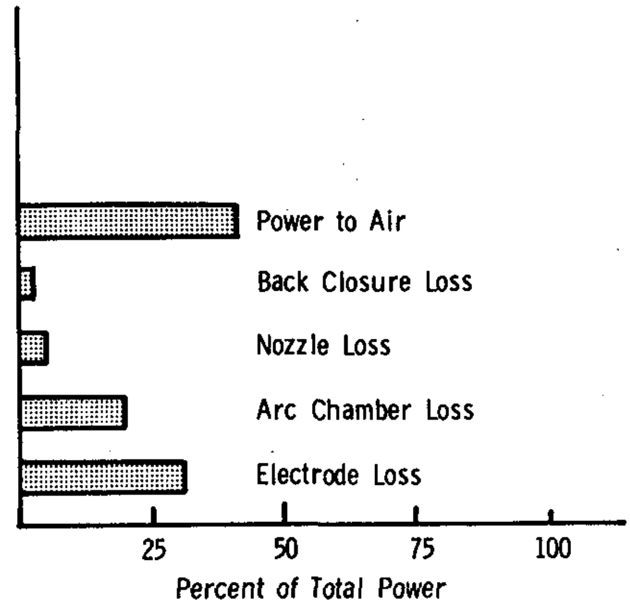

Fig. 21. Power Loses to Arc Heater Components

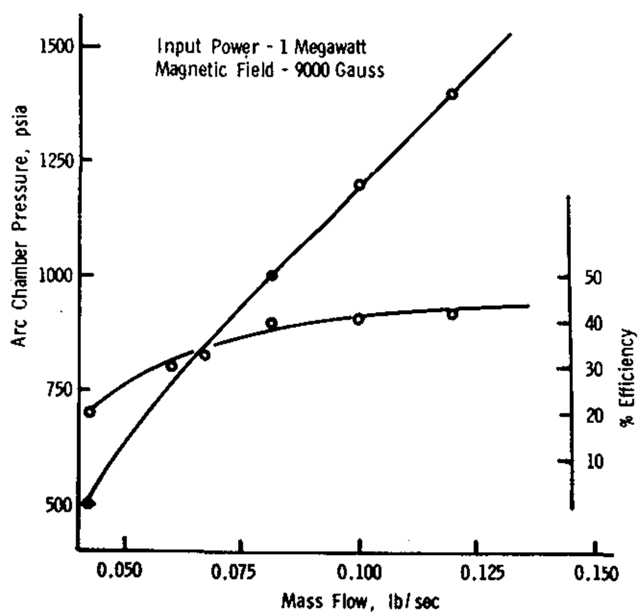

Fig. 20. Stagnation Pressure and Efficiency