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COMPARISON OF OPERATING CHARACTERISTICS FOR AN ARC AIR HEATER USING DIRECT CURRENT AS OPPOSED TO HIGH-FREQUENCY ALTERNATING CURRENT

by William L. Wells

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SUMMARY

Comparison tests at low pressures and enthalpies have been made with an arc air heater where in one case the power supply was a 3,000-cycle-per-second (hertz) single-phase alternator and in another case the power supply was a set of lead-acid cell batteries. The arc air heater used for the tests had water-cooled copper components and an arc gap of 0.25 inch (0.635 cm). The arc was stabilized and rotated around the electrodes by a separately excited magnetic field which was held constant at about 8,000 gauss (0.080 tesla).

Arc chamber pressures were varied from about 46 to 118 psia (317 to 814 kN/m^2) with a resulting variation in air mass flow rates from about 0.007 to 0.029 lb/sec (3.18 to 131.8 g/sec), respectively. The power input to the arc covered the range from 80 to 125 kW for most of the test data. For comparable operating conditions, the operating efficiency (ratio of energy output to the energy input to the arc) of the high-frequency alternating-current system exceeded that of the direct-current system by at least 30 percent of the direct-current value. The highest efficiencies were obtained at the highest air flow rates in either case. When arc current values were nearly equal, the alternating-current and direct-current arc impedance values were about the same except when the direct-current arc shifted to a different mode of operation at low pressures.

The average arc power factor for the high-frequency alternating-current runs was determined to have a value of 0.56.

Although the test range is somewhat limited, the results serve to illustrate the operational concept of the combination high-frequency arc and dc (magnet coil) system and allow a limited comparison (at low pressure and low enthalpy) of the thermal efficiency and operating characteristics for this system and the all dc systems.

INTRODUCTION

In recent years the arc air heater has gained rather wide use as a tool for obtaining high temperature gas flows. This usage is especially prevalent in the case of facilities which are required to produce high-velocity high-enthalpy airstreams for the purpose of simulating the environment encountered by spacecraft reentering the earth's atmosphere. So far, however, an arc air heater has not been developed which can produce a clean, high-pressure, extremely high-enthalpy airstream such as would be required to simulate fully the earth reentry conditions under consideration for advanced space missions.

The direct-current arc air heater which utilizes a magnetic field to stabilize and rotate an electric arc between concentric water-cooled copper electrodes has proven itself to be a valuable tool that can produce relatively clean, high-enthalpy airstreams. (See refs. 1 and 2.) However, in a system of this type whenever efforts have been made to increase the specific enthalpy by reducing the arc chamber pressure and air mass flow rate, the arc heater efficiency has decreased and has severely limited the attainment of the desired high values of enthalpy. This efficiency decrease was believed to be due, in part at least, to the arc-induced rotation of the heated air against the cooled container walls. Therefore, it seemed reasonable to assume that if a high-frequency alternating-current arc could be used instead of a direct-current arc, the direction of rotation of the arc would quickly reverse at each half cycle; thus, the heated air would not be induced to rotate and thereby reduce large convective heat losses and the quality of the test stream would also be improved.

This paper presents a comparison and brief discussion of data obtained during low pressure, low enthalpy tests made with a magnetically stabilized arc air heater (of the type discussed) operated in one case from a direct-current power supply (battery banks) and in another case from a high-frequency alternating-current power supply (3,000 cycles/sec (hertz) single-phase alternator).

Brief descriptions of circuits, equipment, and methods are also presented. Although the test range is somewhat limited, the results serve to illustrate the operational concept of the combination high-frequency arc and direct-current (magnet coil) system and allow a limited comparison of the thermal efficiency and operating characteristics for this system and the all direct-current systems.

EQUIPMENT AND TESTS

Arc Jet System

A sketch of the arc-heater system used in this program is shown in figures 1(a) and 1(b) along with the calorimeter that was used to determine the energy output of the heater.

This heater is normally used for relatively high power, all dc operation (about 750 kW), and is made up of copper components which are water-cooled. (See ref. 1.) The arc was caused to rotate in an annular volume between the electrodes (0.25 inch or 0.635 cm arc gap) by a magnetic field oriented perpendicular to the electric field. The magnetic field (constant at about 8,000 gauss or 0.8 tesla) was established by use of a water-cooled coil which for all the tests utilized a separate dc power supply. The throat diameter of the nozzle was 0.2 inch at the start of the test series and was later increased by about 13 percent as explained in the section "Test Methods."

The cooling water was furnished to the heater, coil, and calorimeter by a high pressure pump. Air was supplied to the heater from a 1,500 psia (10.3 MN/m^2) bottle field and the pressure was reduced to the desired value by a manually controlled regulator.

Direct-Current Circuit

Other than having the coil connected to a separate power supply the dc circuit arrangement was basically the same as that for normal (ref. 1) operation. A diagram of the dc circuit is shown in figure 2. The power source for the dc arc was a bank of batteries which were connected in series to give an open-circuit voltage of 1250 volts. Transfer switches were used in order to either connect the load circuit to the batteries or to recharge them after a run. Circuit breakers were included in order to be able to open or close the circuit remotely. Grid-type resistors were also included to act as ballast for the arc and to afford some regulation of the current.

High-Frequency Alternating-Current Circuit

The ac tests were made with the magnetic coil connected to its dc power supply exactly as it was for the dc arc tests. A diagram of the ac circuit is shown in figure 3. The power source for the 3,000 cycles/sec (hertz) single-phase ac arc was an alternator driven by a 310-hp (231 kW) electric motor. This alternator was designed to be used with an induction heater for commercial applications. The rated output of the alternator was 250 amperes at 800 volts. Power-factor-correcting capacitors were added to the circuit as shown in the diagram. A water-cooled, high-frequency auto-transformer was used between the alternator and the arc with a turn ratio of 50 to 25. Contactors were included for the purpose of opening or closing the circuit.

Test Methods

The data gathered in these tests were taken in three groups. Since the high-frequency ac power supply was very limited, the ac tests were made first at the maximum achievable power input. An attempt was then made to match these conditions with the same facility configuration but using the dc power supply. Although this first attempt resulted in arc currents and arc voltages that were comparable to those achieved with the ac tests, the power input was greater because of the ac arc power factor which is discussed subsequently. Another set of dc data was taken where the dc power input more nearly matched the ac power input. The air mass flow, arc chamber pressure, and output enthalpy relationship suggested that the vortex gas flow induced by the rotating arc resulted in a smaller effective nozzle throat diameter in the dc case. (See ref. 3.) Therefore, the second set of dc tests were conducted with the nozzle throat diameter increased a small amount (which turned out to be about 13 percent) so that the dc pressures and flow rates were in the same range as those obtained in the high-frequency ac tests. The difference in dc power input level from one set of data to the other was accomplished by changing the amount of resistance in the circuit. (See fig. 2.)

The power or energy input to the arc was determined by the product of the arc current and the voltage drop across the arc for the dc case. For the ac case, however, it was necessary to multiply the product of the effective (root-mean-square) arc current and voltage by the arc power factor which was determined as outlined in a subsequent section.

A low value of overall circuit power factor presented one limitation to the amount of power input in the ac case and from this standpoint (arc stability being disregarded), an overall power factor of unity would have been desirable. Since the high-frequency circuit was inherently inductive, seven microfarads of capacitance were added to the ac circuit used in these tests in an effort to get the highest possible circuit power factor.

The energy output of the heater for either the ac or the dc case was determined by making an energy balance on the calorimeter cooling water and the heater exhaust as they flowed through the calorimeter that is described in the section "Instrumentation."

Instrumentation

The total calorimeter which attached to the system as illustrated in figure 1(a) was, in effect, a small multi-pass, cross-flow heat exchanger (fig. 4). The outer shell was a 2-inch (5.08 cm) outside diameter, 18-inches (45.7 cm) long steel tube. Seven copper tubes were inserted in the shell and connected at alternate ends such that the heated air from the arc jet would have to traverse the length of the calorimeter a number of times before being exhausted to the atmosphere. Tube spacers which also acted as baffles were installed to force the cooling water across the tubes in alternating directions as it traveled the length of the tube. Differential thermocouples were installed at the water entrance and exit and in the air line upstream of the heater and at the calorimeter air exit. One calorimeter end plate formed the nozzle throat and had an external thread such that it could be attached to the arc air heater.

The high-frequency ac arc current and voltage were measured by use of the calibrated circuits shown in figures 5 and 6, respectively. A vacuum tube voltmeter and an ammeter (frequency response from dc to 500 kc; accuracy of ±0.5 percent full scale) which were insensitive to waveform became available at the latter part of the test series; thus, further checks on the measurements were made and corrections of the data were made as necessary. These corrections were necessary because of the difference in the actual run wave forms and the sine wave forms used during circuit calibrations.

Currents, voltages, temperatures, pressures, and air and water flow rates were continuously recorded with an oscillograph recorder.

Determination of High-Frequency Alternating-Current Power Input

In order to determine the input power to the high-frequency ac arc, the effective current and voltage product was multiplied by an arc power factor. Photographs of current and voltage waveforms obtained with a dual-beam oscilloscope and camera indicated that the voltage and current were very nearly in phase; however, part of the time the voltage had some high value while the current remained at or near zero. (See fig. 7.) This high voltage and no current condition existed when it was necessary for the arc to restrike at each half cycle.

The power factor used to get the true power input was determined in the following manner. From each photograph of a current and a voltage waveform (one cycle), numerous instantaneous values were taken. The product of these corresponding values of instantaneous current and instantaneous voltage yielded a plot of instantaneous power. The area under this power curve was taken as an indication of the true power for one cycle. This procedure was followed for a number of separate cycles taken during a run and then averaged to give the true power for that run. The power factor for that run was found by dividing the average true power by the product of the measured effective current and effective voltage for the run. This procedure was followed for three runs and the arc power factor of 0.56 that was used for all ac runs was the value of the average arc power factor for these three runs. Table I presents the values determined by the preceding procedures.

RESULTS AND DISCUSSION

In general, the results of these tests indicate that a high-frequency single-phase ac arc can be used as the heat source in an arc air heater and, furthermore, the electrical operating characteristics observed in this investigation were not vastly different from those of an all dc system when the arc environment was the same.

In these tests the ac arc would often extinguish itself after about one minute of operation at the higher arc chamber pressures and air flow rates, probably because the overall circuit power factor was near unity. (See ref. 4.) At the lower investigated pressures and flow rates there was very little change in the ac arcing characteristics, but the dc arc apparently changed to a different mode of operation as indicated by a marked voltage increase at the lower end of the pressure range. The effects of this change are noted in the data that are presented later in this discussion although no further attempt is made to explain the cause. This phenomenon had not heretofore been observed in the normal operation of this arc air heater; however, the normal operating conditions have been very different from those encountered in these tests. (See ref. 1.) Operation was more stable in the ac case where the circuit was more inductive; this result is in agreement with observations reported elsewhere (for example, ref. 4).

Electrical Characteristics

High-frequency ac waveforms.- In figure 7 a sketch of a typical set of arc current and voltage waveforms are shown which were obtained with a dual-beam oscilloscope from the 3,000 cycle per second (hertz) ac system. As can be seen, the voltage waveform approximates a square wave whereas the current waveform appears to be a fundamental sine wave with another higher frequency sine wave imposed upon it (harmonics). Although the current and voltage waves seem to be in phase, the current apparently must wait near its zero value until the voltage reaches a sufficiently high value to reignite the arc. This periodic occurrence of high-voltage—zero-current phenomenon necessitates the use of an arc power factor that is less than unity in order to derive the true power input. In this case a value of 0.56 was obtained. (See section on ac power input.) The required arc reignition voltage will depend partially on the arc environment (ref. 5) so that the arc power factor will probably be affected by variables such as large changes in magnetic field strength, frequency, number of phases, electrode material, etc. Reference 6 reports an arc power factor of about 0.85 for a 2,000-cycle-per-second three-phase arc jet with tungsten electrodes.

Arc current and voltage.- In figure 8 is a plot of the variation of arc current with arc voltage. Recall that two sets of dc data were taken. (See "Test Methods.") The second set was taken when it was found that the dc arc induced-gas vorticity required the use of a slightly larger nozzle throat size in order to match simultaneously pressures, mass flows, and input powers achieved with the ac system. The dc data that are indicated by a circle with a bent flag fall in the range of power inputs from 125 kW to 175 kW and result from the sudden increase in arc voltage when the arc operates in a different mode or position as mentioned earlier. The input power level of the dc data plotted at the far left in the figure more nearly matches the ac power data. Even though the input power and voltages are nearly equal, there is considerable difference in the ac current and the dc current because of the high-frequency arc power factor. In general, the dc curves have a slightly negative slope and the ac curve is very flat over the limited range of data available. A step-type voltage change is evident in either dc curve which reflects the apparent change in the mode of arc operation in the lower operating pressure range.

Arc impedance.- A comparison of the ac and dc impedance as a function of the air mass flow rate is presented in figure 9(a), and as a function of the arc chamber pressure for this flow rate in figure 9(b). The higher pressures correspond to the higher flow rates. (In the discussion immediately following, the transition regions of the dc curves will not be considered.) All the data on these two plots fall within approximately the same range of flow rates and pressures. Although the slopes of the curves indicate that the dc impedance is affected somewhat more than the ac impedance, neither curve indicates a strong influence of pressure and mass flow over the range of the tests. The top dc curve represents the case with a power input comparable to the ac case, but the dc curve that overlaps the ac curve has an arc current that is comparable to the ac case as was noted in figure 8. Apparently, in any case, the arc impedance is more strongly a function of current than of flow rate and pressure. For the same operating conditions (especially current), the ac arc impedance might have been expected to be greater than the dc impedance because of the periodic occurrence of zero current at each half cycle. The physical arc gap was constant at 0.25 inch (0.635 cm) in each case although the actual arc length might in any case be greater. (See refs. 1 and 7.)

Performance Characteristics

Enthalpy.- In these tests the specific air enthalpy as determined by the calorimeter covered a range from about 600 to 1250 Btu per pound (1.40 to 2.94 kilojoules per gram). This range covers all the ac and dc data and in both cases the highest specific enthalpies correspond to the lowest air mass flow rates and arc chamber pressures. Figure 10 presents the enthalpy data as a function of air mass flow rate. The numbers shown on the plot give representative arc chamber pressures in atmospheres. The effect of the air swirl in the dc case can be seen to result in a smaller effective throat size as compared with the ac case. For example, at a flow rate of 0.02 pound per second (9.08×10^{-3} kg/sec) and the same physical nozzle size, the pressure shown on the dc curve is greater than the pressure shown on the ac curve even though the enthalpy on the dc curve is much less.

Efficiency.- The efficiency of either arc air heater system is defined to be the ratio of energy output, as measured by the calorimeter, to the energy input to the arc. Figure 11 gives a comparison of efficiency as a function of air mass flow rate for the ac and the dc systems. As can be seen, the highest efficiencies in either case correspond to the highest air mass flow rates and as the air flow rate decreases, the efficiency drops almost linearly except for the transition regions of the dc data. These step-like changes at the transition regions which result from the different arc operating mode or position clearly are detrimental to the efficiency of operation. The increase in efficiency from the high-power dc curve to the low-power dc curve is probably due to the reduced power level and to some extent because of the increase in throat size. In the region of the curves where comparison can be made, it appears that if the power inputs were equal, the high-frequency ac efficiency would exceed the dc efficiency by at least 30 percent of the dc value.

The plot in figure 12 was made in an effort to show any indication of an increasing energy loss rate for one system relative to the other as the energy input per pound (kilogram) of air is increased. (The dc data obtained in the different operating mode have been omitted.) The ordinate gives the percent of the input energy that is lost to the arc air heater cooling water and the abscissa gives the energy input to the arc per pound (kilogram) of air. In the range where comparative data are available, the slopes of the two curves are essentially the same and indicate a continuing difference in operating efficiency as the specific energy input is increased. The end slopes of the two curves at the highest specific energy input would suggest a continuation of this difference. Although the difference in efficiency previously noted (fig. 11) would seem appreciable, it is very clear from figure 12 that at these high energy loss rates, the effect of the high-frequency change in direction of arc rotation is not sufficient to alter greatly the overall energy loss rate as compared with the unidirectional dc arc rotation. It should be noted that at enthalpies and pressures many times higher than those achieved in these tests, the primary heat loss mechanism may be radiation from the gas which would be independent of the arc motion and hence independent of the power supply.

The arc air heater used for these tests is normally used for high power operation (750 kW). Except for center electrode diameter and nozzle throat size, the heater was used without making modifications and no effort was made to optimize efficiency for any of the tests made. Undoubtedly, all the curves in figure 10 could have been shifted upward somewhat by a proper regulation and redistribution of the cooling water in the heater so that heat losses would have been minimized for these low power tests. The position of one curve relative to another, however, probably would not have been greatly changed.

Electrode observations.- Electrode erosion would not be expected to present a problem at the current levels experienced in these tests; therefore, observation was the only method of comparison used. Very little difference could be seen on the electrode surfaces except there appeared to be slightly less copper oxide build-up for the high-frequency ac case. Furthermore, the appearance of the electrodes would suggest that the high-frequency ac arc tracked in a narrower band than did the dc arc.

CONCLUSIONS

Observations and a comparison of the data taken from tests at low enthalpies and pressures made with a magnetically stabilized water-cooled copper arc air heater using (1) a 3,000-cycle-per-second single-phase alternator power supply and (2) a direct-current (battery) power supply leads to the following general conclusions:

1. The high-frequency alternating-current arc can be successfully used as the heat source in the type of arc heater investigated and does not exhibit electrical characteristics that are greatly different from those of the direct-current arc.

2. The thermal efficiency of the arc heater is greater when the arc power source is high-frequency alternating current rather than direct current. At about the same power input, the efficiency obtained with the alternating-current supply was about 1.3 times the efficiency obtained with the direct-current supply.

3. The arc heater efficiency increases with an increase in the air mass flow rate and arc chamber pressure for the alternating-current system or the direct-current system.

4. For the same operating conditions (especially arc current), the average high-frequency alternating-current arc impedance only slightly exceeds the direct-current impedance. The direct-current arc impedance can exceed the alternating-current arc impedance when the direct-current arc changes to a different unexplained mode of operation.

5. Observation of electrode surfaces indicated that the alternating-current arc tracked in a narrower band than did the direct-current arc and there was very little difference in the rate of electrode erosion whether operation was with high-frequency alternating current or with direct current.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 13, 1965.

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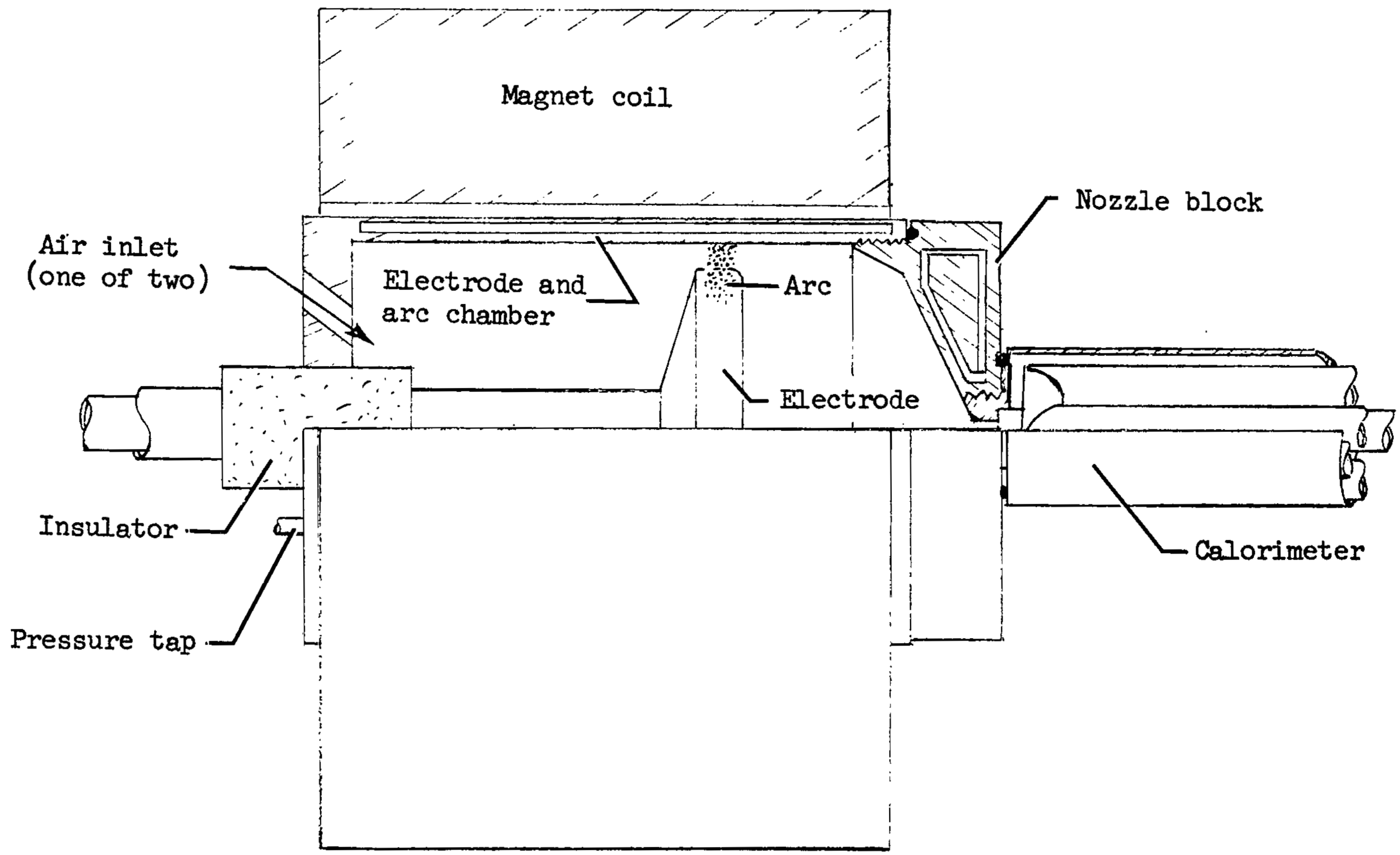
TABLE I.- VALUES USED IN DETERMINING POWER FACTOR

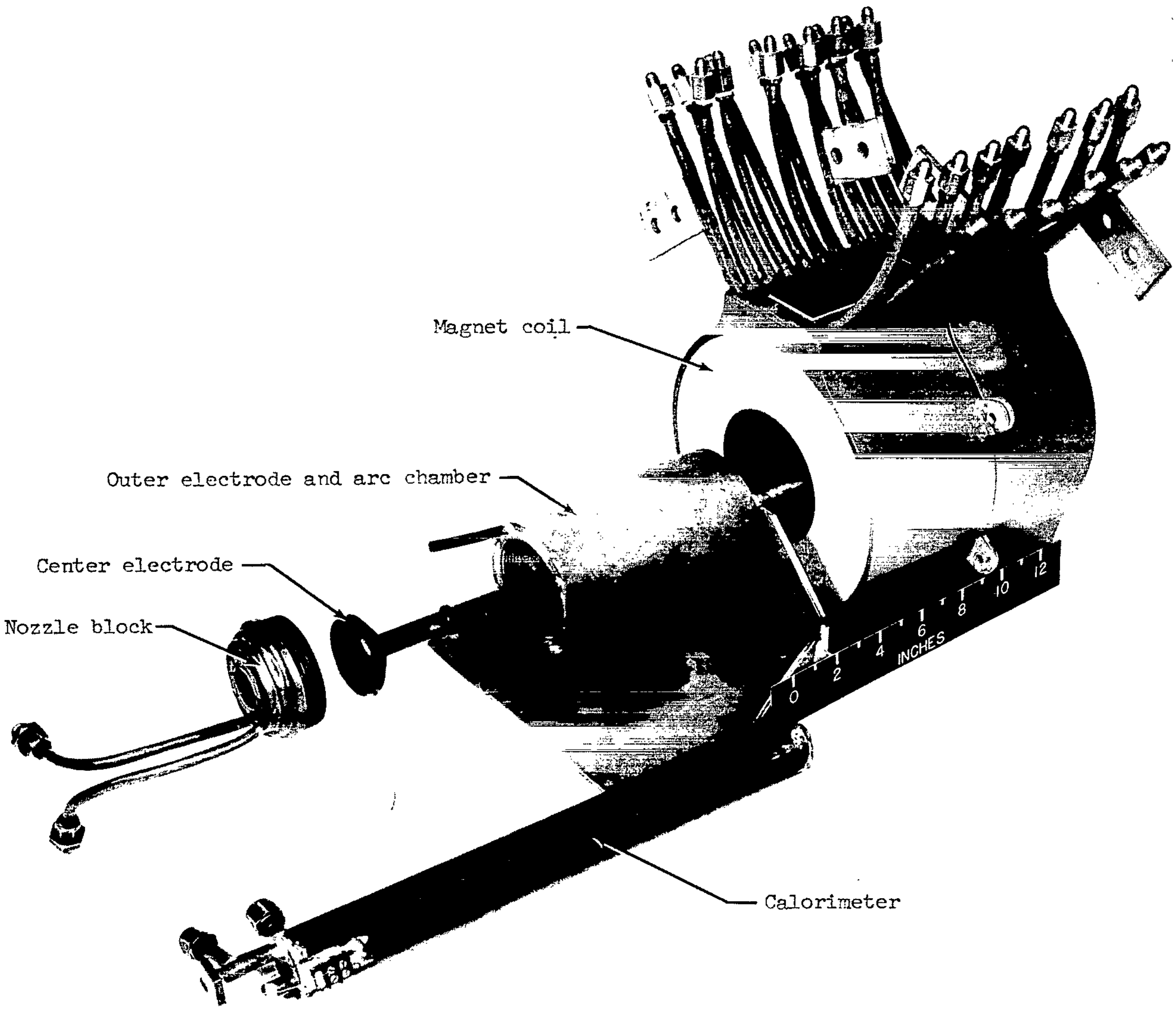
[Average power factor, 0.561]

Plots of instantaneous power	Power, kW, for –		
	Run 1 at arc chamber pressure of 46.2 psia (318 kN/m^2)	Run 2 at arc chamber pressure of 59.5 psia (410 kN/m^2)	Run 3 at arc chamber pressure of 75.3 psia (518 kN/m^2)
1	82.3	78.9	91.0
2	72.4	72.1	78.9
3	92.7	87.7	77.1
4	69.4	76.9	67.2
5			82.8
Average	79.3	78.9	79.4
Current × voltage . . .	139	142	143
Power factor	0.570	0.556	0.555



(a) Sketch of assembly.

Figure 1.- Arc heater with calorimeter.



(b) Photograph, exploded view.

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Figure 1.- Concluded.

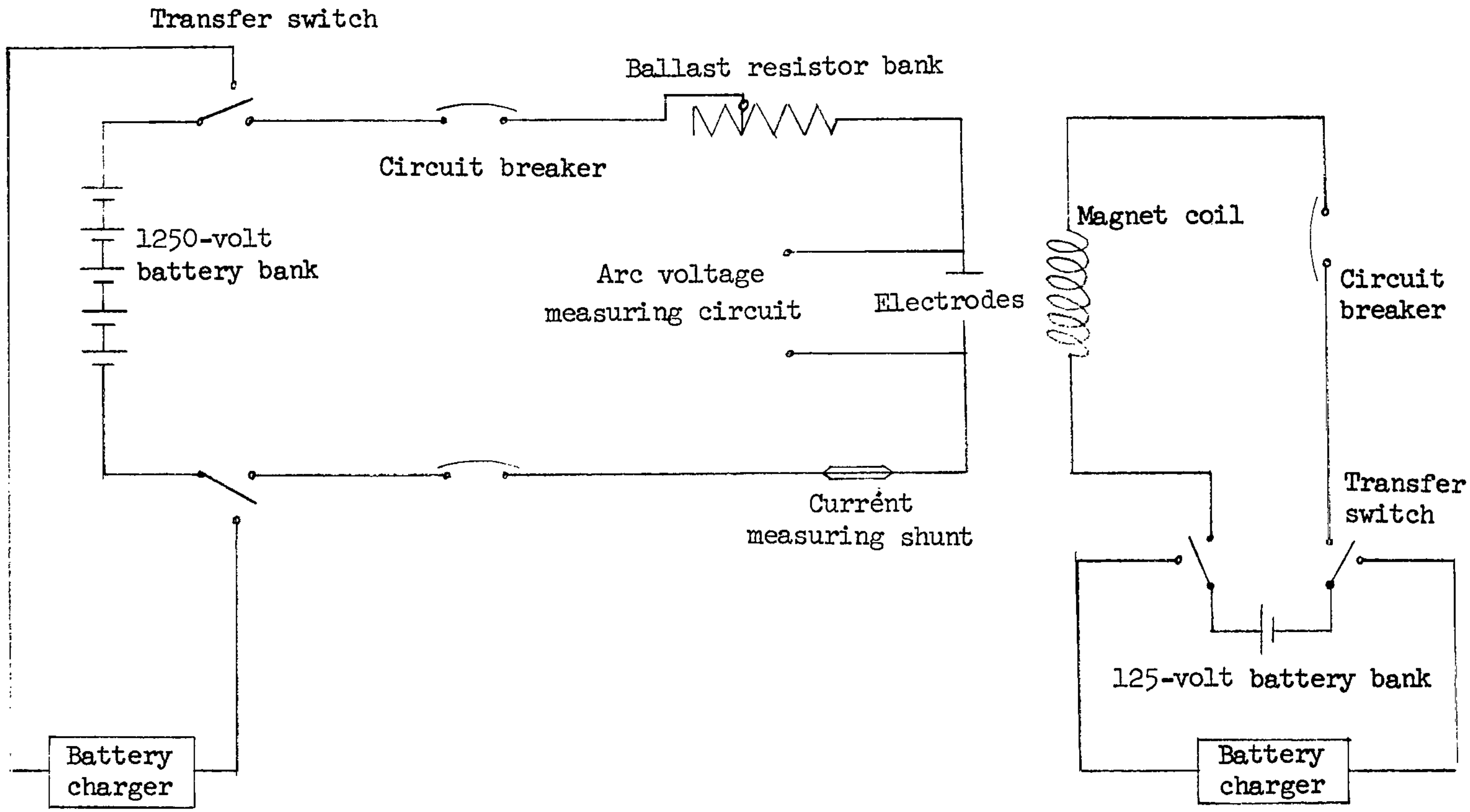


Figure 2.- Schematic diagram of direct-current circuit.

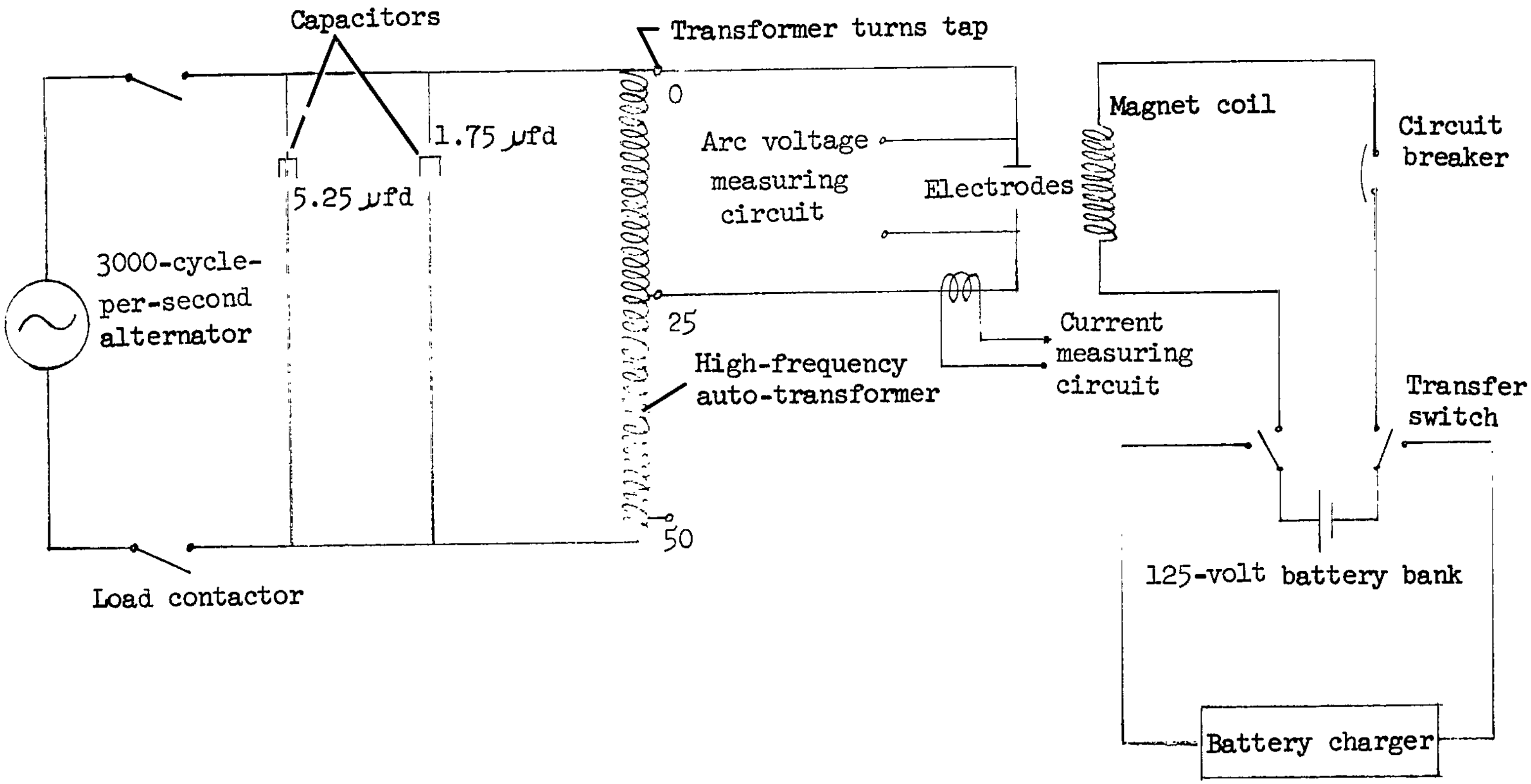


Figure 3.- Schematic diagram of high-frequency alternating-current circuit.

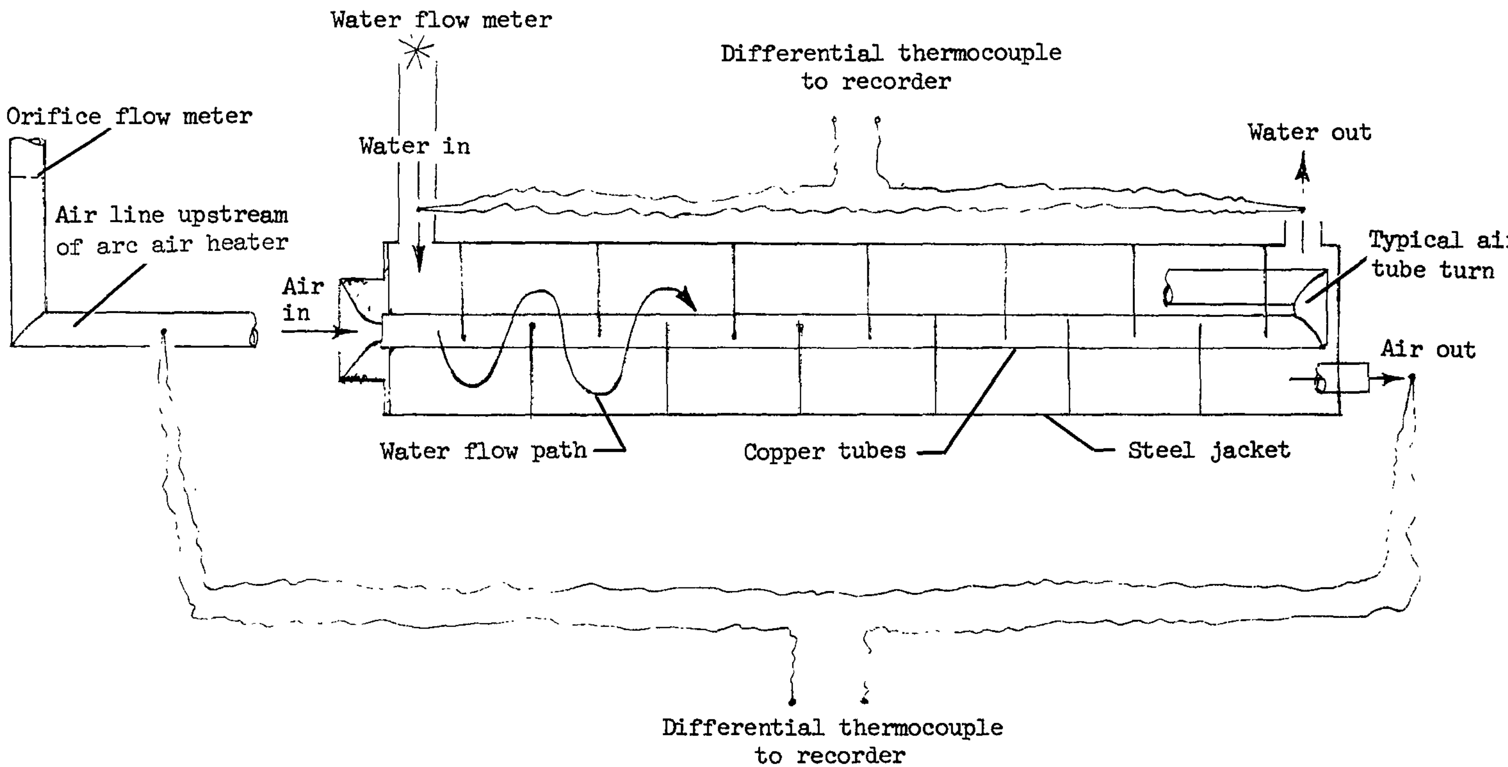


Figure 4.- Sketch of calorimeter.

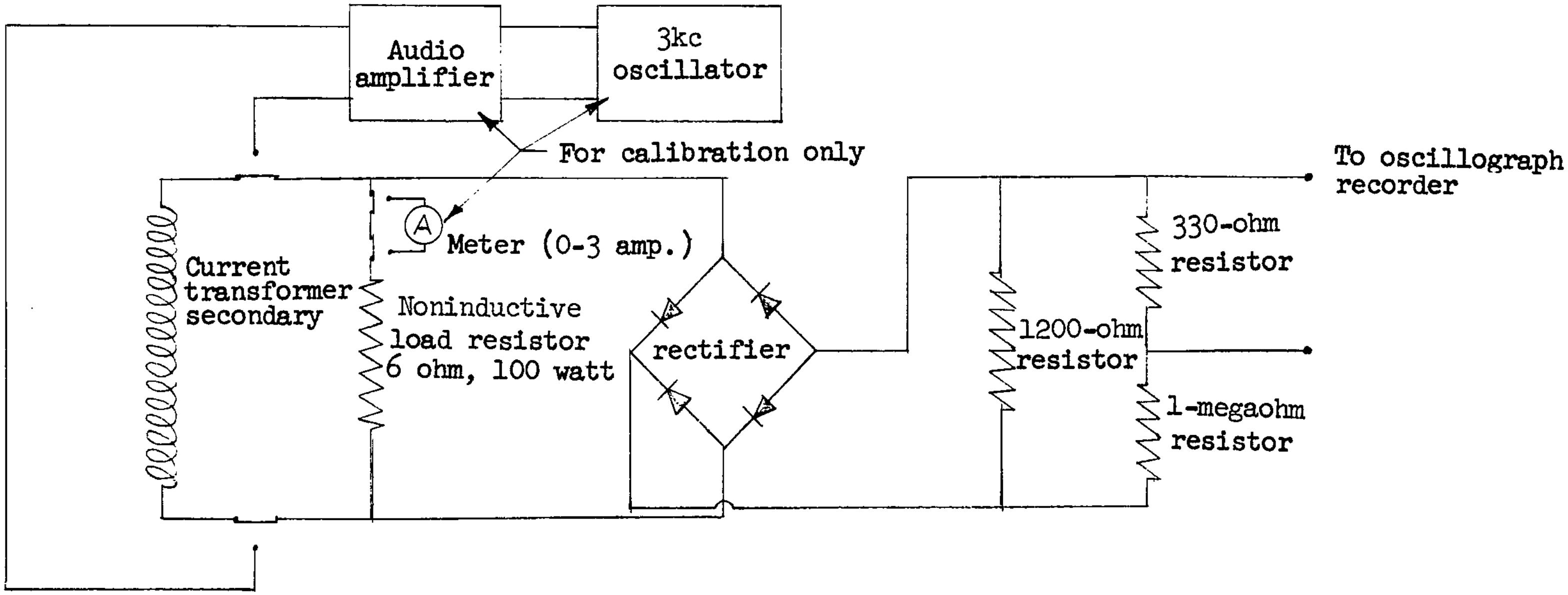


Figure 5.- High-frequency alternating-current measuring circuit.

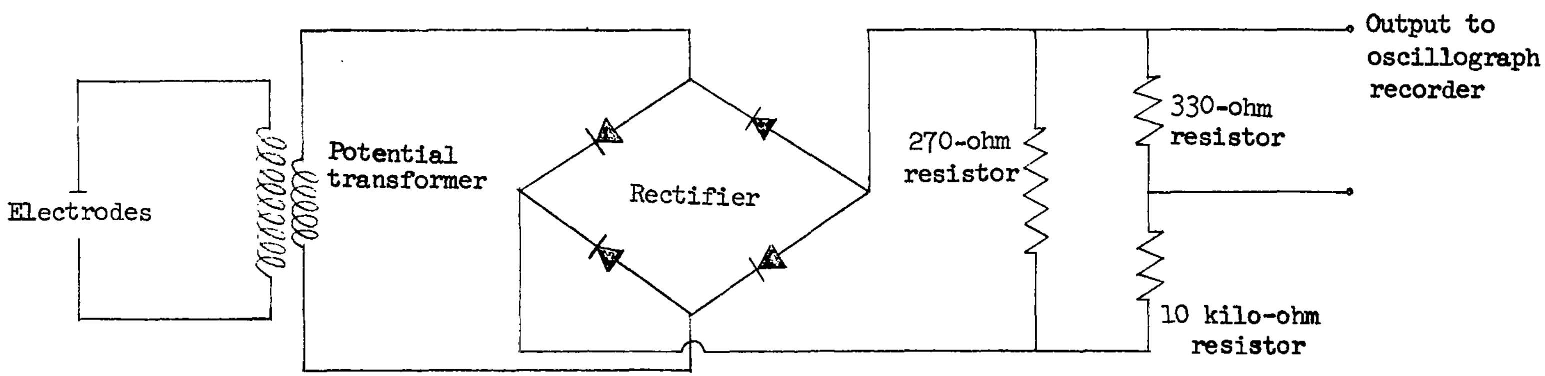


Figure 6.- High-frequency alternating-current arc voltage measuring circuit.

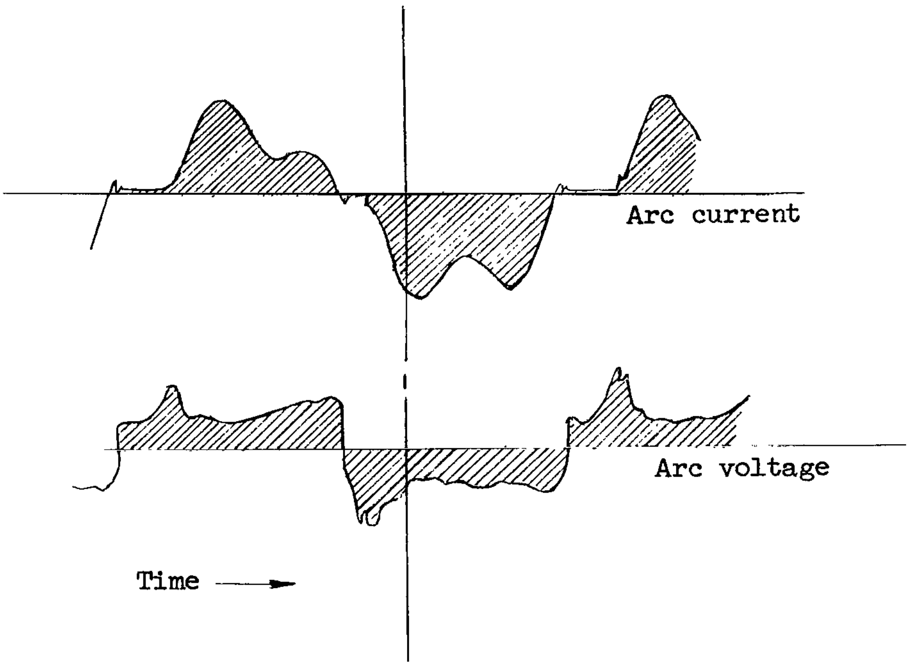


Figure 7.- Typical current and voltage waveforms for the 3000-cycle-per-second (hertz) single-phase alternating-current arc.

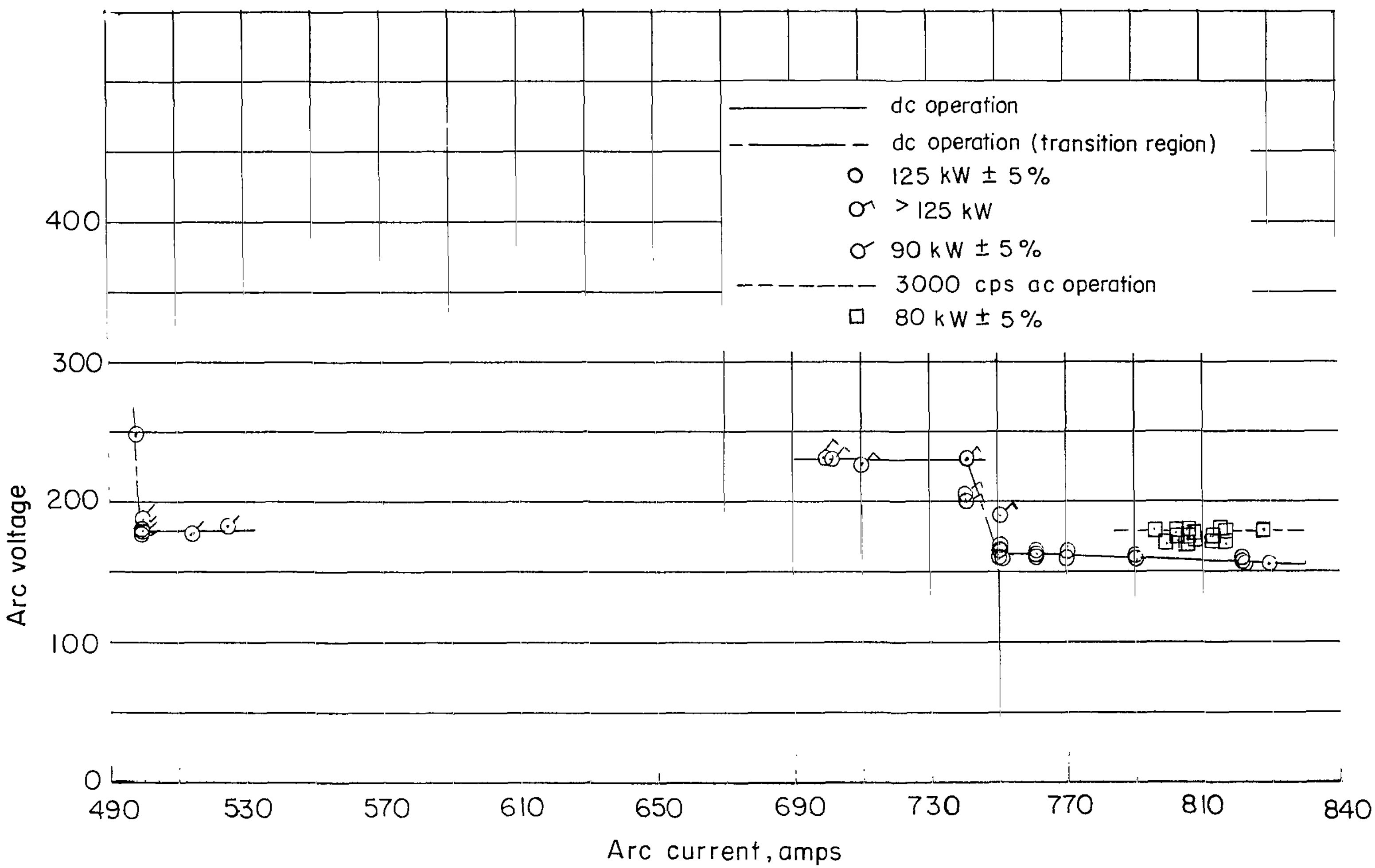
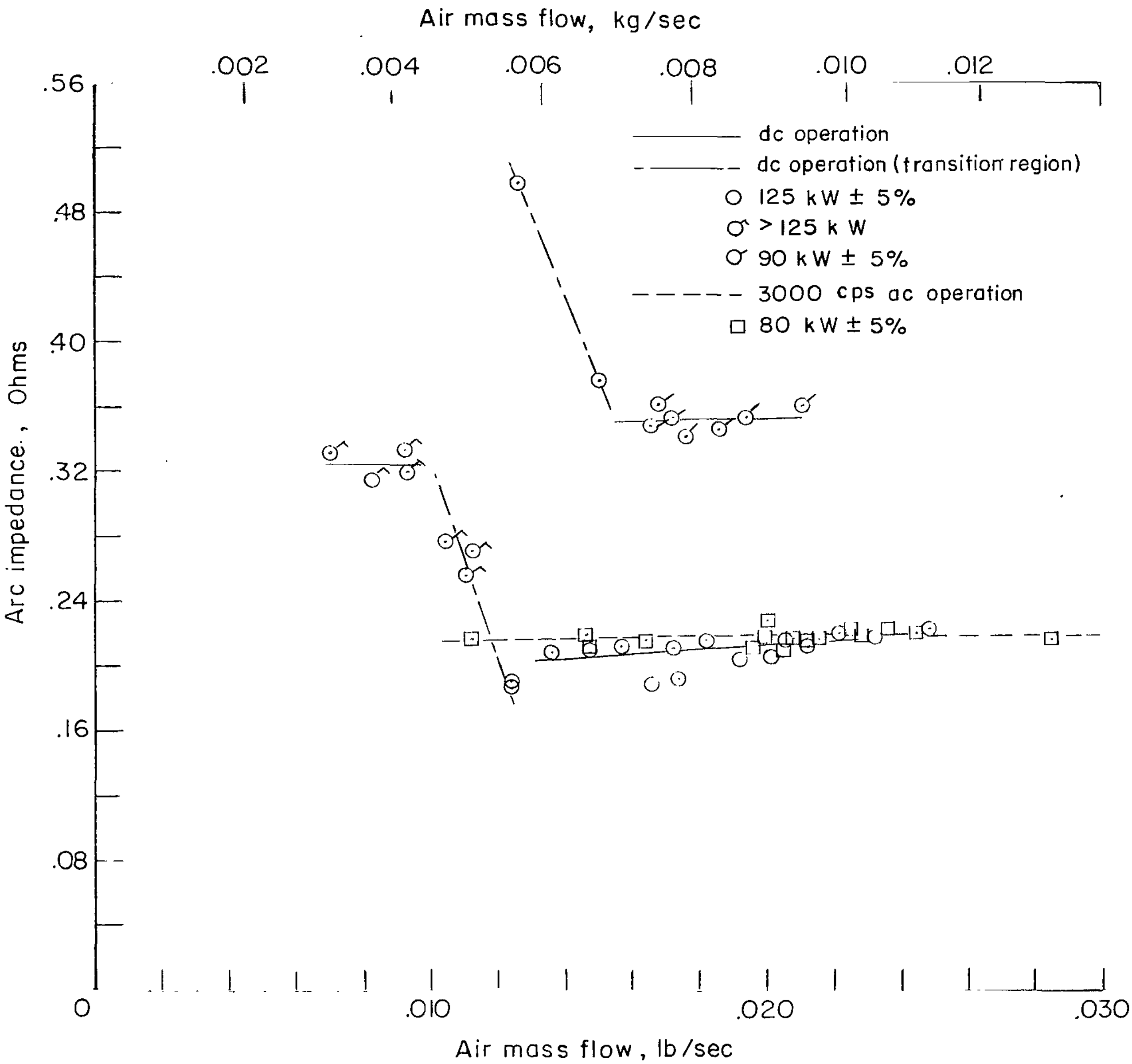
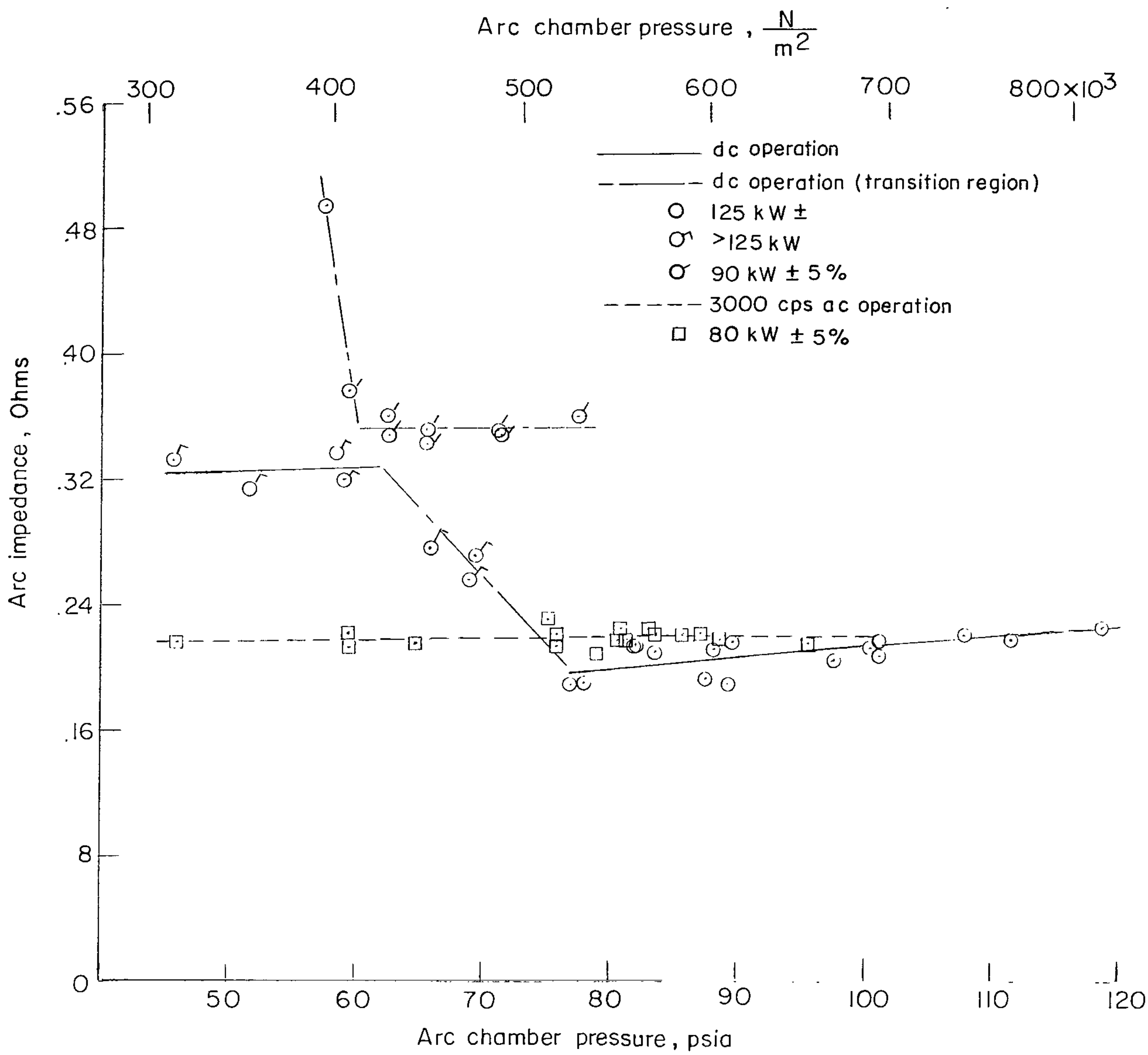


Figure 8.- Current-voltage curves for a high-frequency single-phase arc and a direct-current arc. Pressure and air mass flow increases with current on each curve.



(a) Arc impedance as a function of air flow rate.

Figure 9.- Comparison of arc impedance in a high-frequency single-phase alternating-current arc circuit and a direct-current arc circuit.



(b) Arc impedance as a function of arc chamber pressure.

Figure 9.- Concluded.

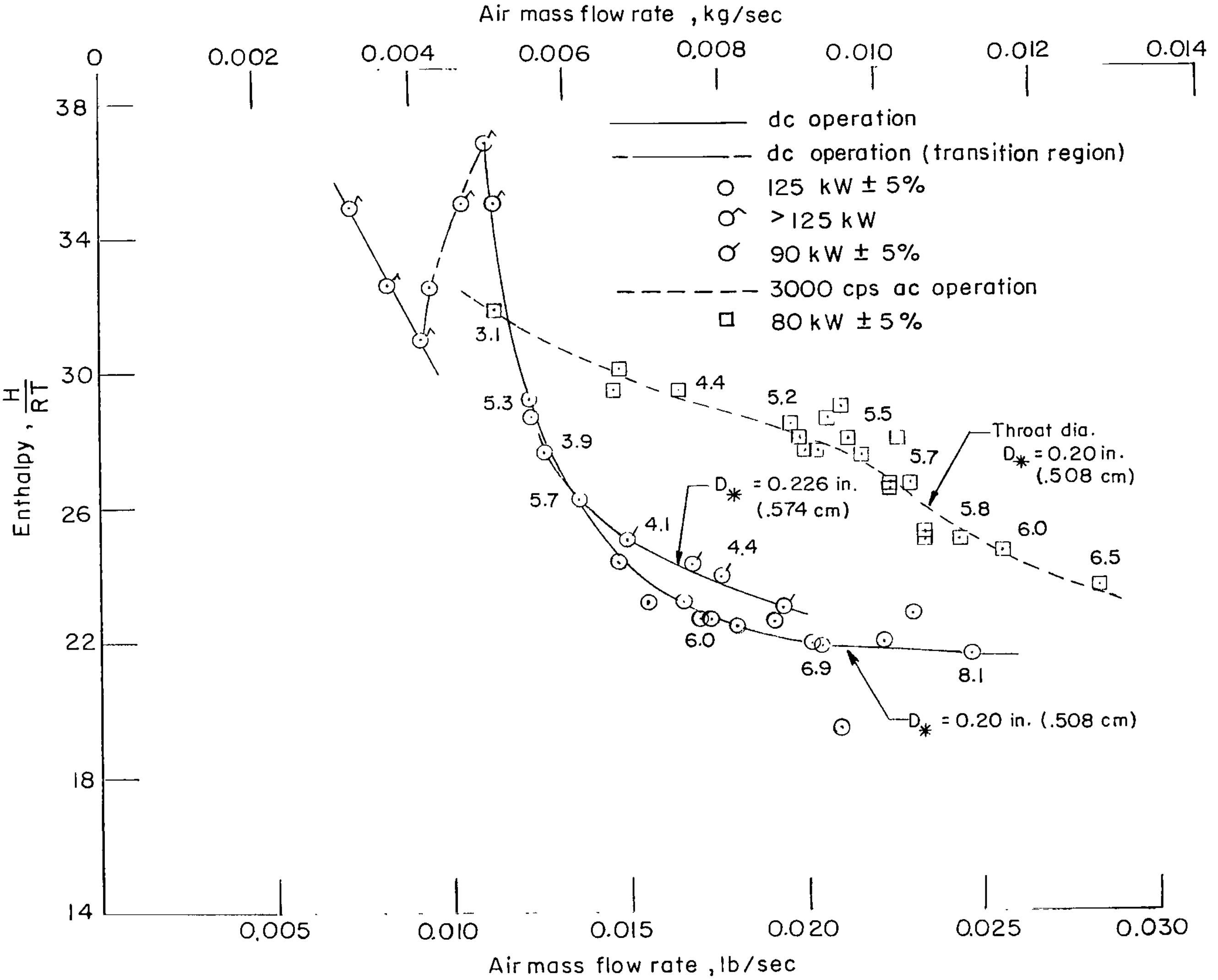


Figure 10.- Comparison of airstream enthalpy for the arc air heater using the high-frequency alternating-current supply as opposed to the direct-current supply. H denotes enthalpy; R, gas constant; T, absolute temperature. Numbers give representative arc chamber pressure in atmospheres. RT = 33.86 Btu/lb = 7.868 × 10^4 joules/kg.

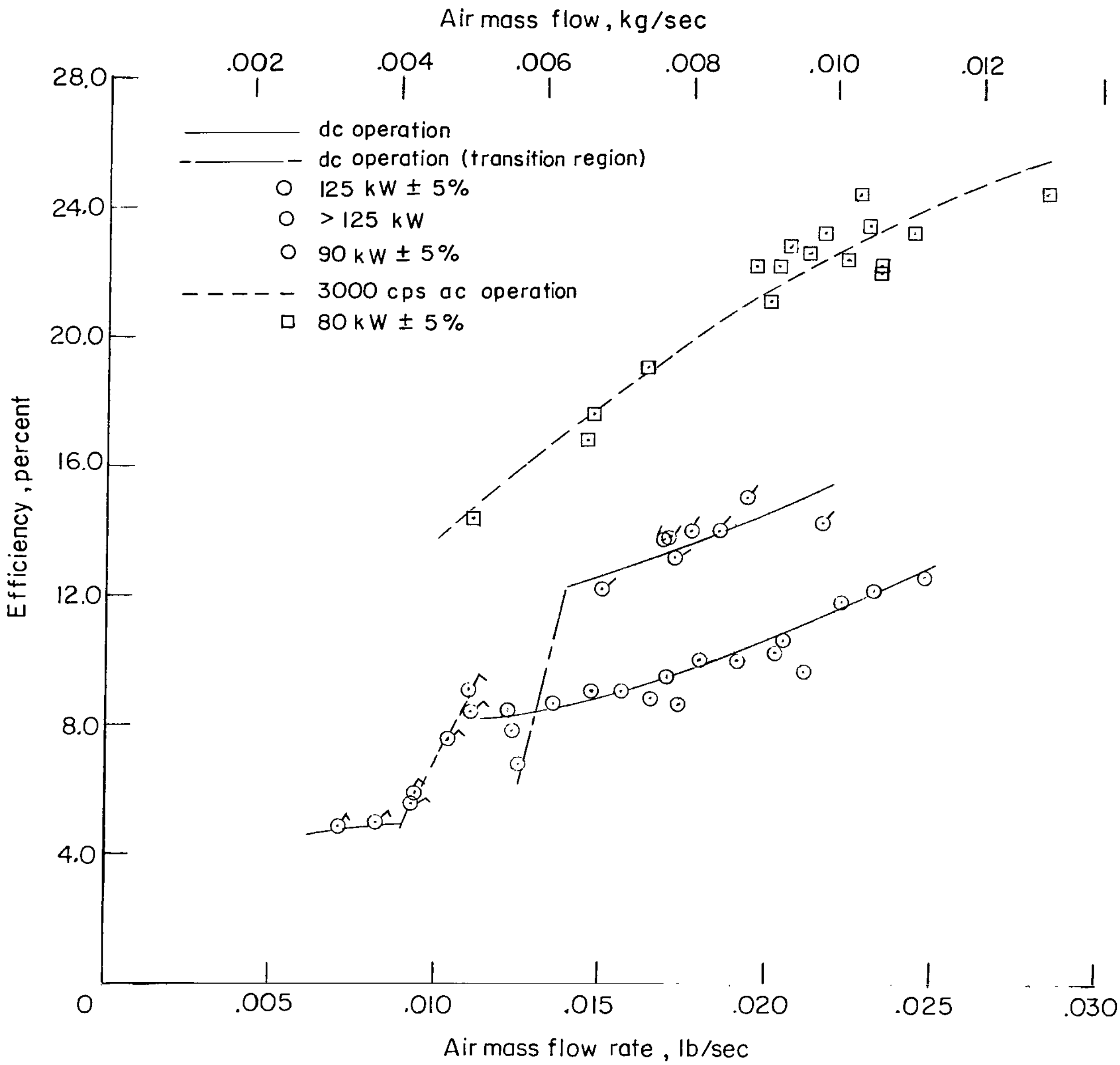


Figure 11.- Comparison of arc air heater efficiency as a function of air flow rate for the high-frequency single-phase arc and the direct-current arc.

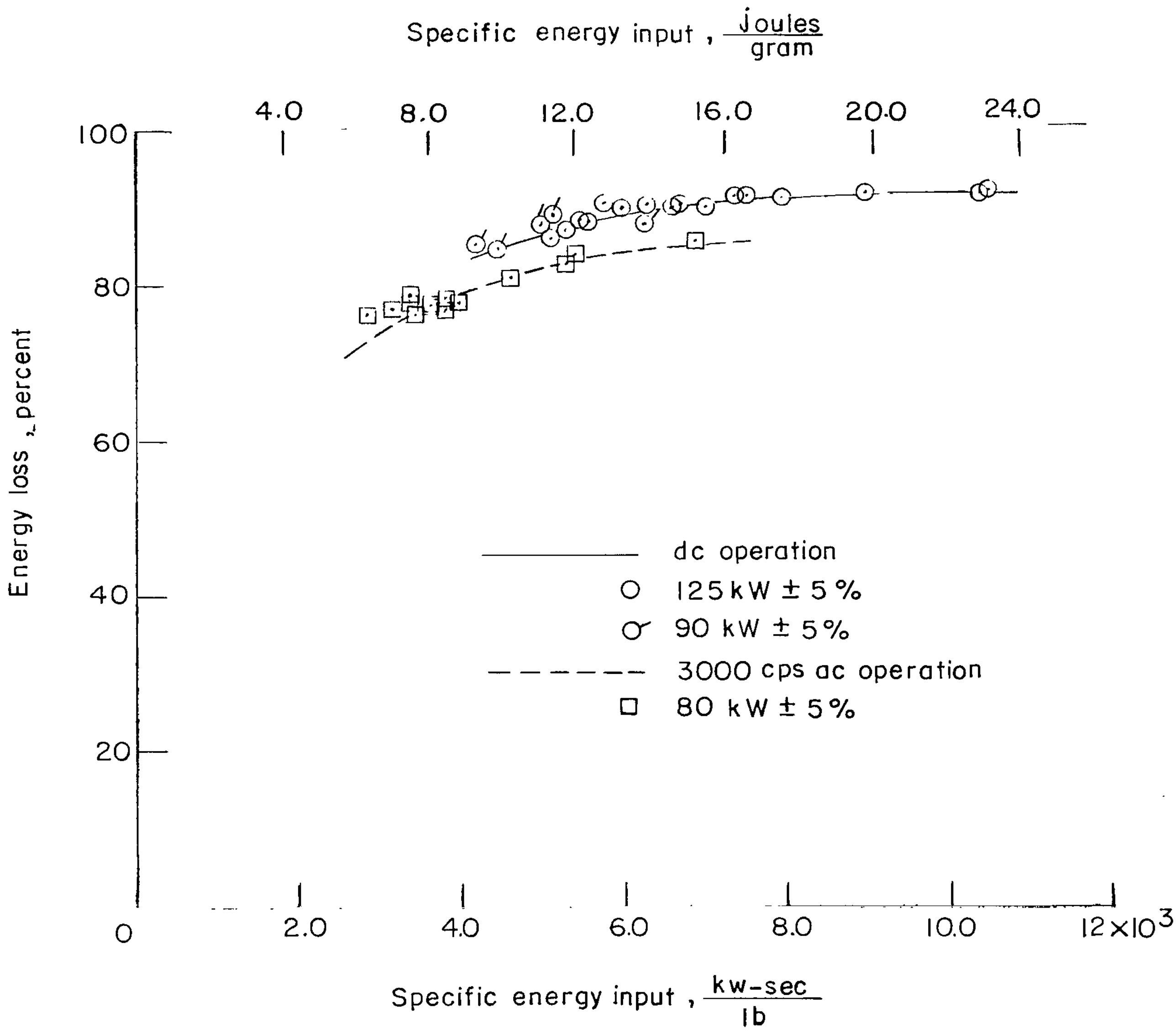


Figure 12.- Comparison of energy loss from the arc air heater for the two power supplies as a function of the energy input per pound of air flowing.

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