High Pressure Arc Heater Electrode Heat Transfer Study

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Theme

THE purpose of this work was to measure the energy losses in the downstream electrode of a high-performance, Huels-type arc heater (the MDC-200) operating over a wide range of pressure and power levels. To define the predominant loss modes, the measurements included axial distributions of both the total electrode heat flux and the radiative heat flux. Development of radiometers capable of sustaining the severe internal environment of the arc heater at pressures of 100 atm and greater became a part of the program after commercial radiometers failed.

Contents

This electrode heat transfer study was conducted using a modified high-voltage, high-pressure, electric-arc air heater designated the MDC-200. The arc heater front electrode was segmented and instrumented for local heat transfer measurements.

The MDC-200 is a Huels-type, high-voltage electric-arc air heater designed for optimum performance at high pressures. A high-voltage arc is maintained between the inside surfaces of two tandem, cylindrical copper electrodes, while high-velocity cold air is injected tangentially between the electrodes through eight ports. The injected air stabilizes the arc on the heater centerline, and it gradually mixes with and is heated by the high-temperature arc column. The heated gas is typically exhausted through a 0.375 in. diam throat nozzle where it is accelerated to Mach 1.7 or greater.

The electrodes of the MDC-200 are thick-wall cylinders made of high-strength, high-conductivity, oxygen-free copper or various copper alloys. The upstream or rear electrode has a 2.0 in. diam and a 0.188 in. wall thickness and is 14.5 in. long. The downstream or front electrode normally has a 1.5 in. diam, a 0.200 in. wall thickness, and a length of 18, 27, 30, 36 or 48 in.

Figure 1 depicts the modified front electrode used in these tests. Four 6 in. long segments were built and linked with an existing 12 in. long segment to form a 36 in. long front electrode assembly with an internal configuration identical to the normal front electrode. Tests were conducted with 24, 30, and 36 in. long assemblies by simply removing the 12 in. segment or a 6 in. segment.

All segments were separately water cooled, and each 6 in. segment was equipped with a radiometer and viewing port. The cooling water was uniformly guided along the outer surface of the electrode segment at velocities varying from 95 to 150 fps by a split-ring aluminum flow guide. The segment and flow guide were housed in a stainless steel outer body. All parts were stressed for 3000 psi operation. All O-ring seals were protected by cooled flanges.

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The matrix of test conditions was selected to yield electrode heat transfer data over the normal range of operation of the MDC-200 arc heater. The arc current was varied from 400 to 800 amp and the arc pressure was varied from 50 to 200 atm.

The segment heating was influenced by the arc pressure as shown in Fig. 2. Increased pressure resulted in increased heating at a fixed arc current level. The functional relationship is similar in all segments with arc location effects exhibited by the flux magnitude. The transition of segment three from a restrike area to an arc residence segment is evident as the pressure increases from 100 to 200 atm. The arc influence can also be noted in segment 4 and to a lesser extent in segment 5 during the same pressure increase. Increased arc pressure was the direct result of increased air flow rate, and thus it was difficult to separate gas momentum effects (increased Reynolds number) and direct pressure effects (such as transport properties, absorption and volumetric radiation). The total heat flux increases approximately as the 0.6 power of the arc pressure (excluding transition effects).

The electrode radiant heat flux in the near constant presence of the arc at lower pressures is shown in Fig. 3. These data were taken 6 in. downstream of the swirl chamber. For arc pressures below 150 atm and arc currents of 400 and 600 amp the radiant flux was proportional to the square root of the arc pressure. The same relation holds for the 800 A data up to 150 atm for the 36 in. electrode.

Up to a pressure of 150 atm and with the exception of the 100 atm, 800 amp data, the electrode radiant flux, q_r, at port 1 can be correlated with the arc current I and arc pressure P_0 with the following equation:

$$q_r = 0.083\, I^{1.15} P_0^{0.50} \text{ (Btu/ft}^2\text{s)} \quad (1)$$

The measured radiative heat flux (Fig. 4) was significant in the arc region and negligible downstream of the arc excursions. The peak radiative flux was 3670 Btu/ft^{2}s. Normal extension and shunting of the arc caused sharp fluctuations in the radiant flux between essentially zero and peak values depending on the proximity of the arc with respect to the radiometer view port. In general, the radiative flux was negligible downstream of the axial midpoint of the electrode.

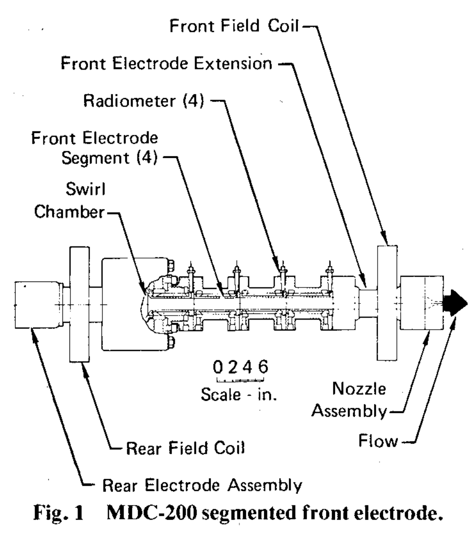

Fig. 1 MDC-200 segmented front electrode.

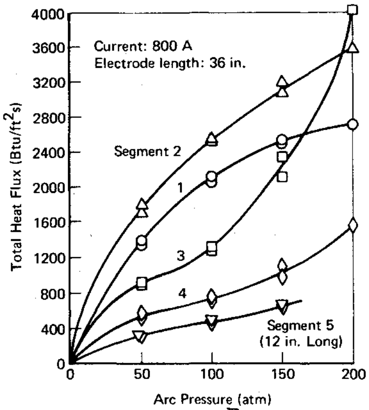

Fig. 2 Effect of arc pressure on total segment heat flux.

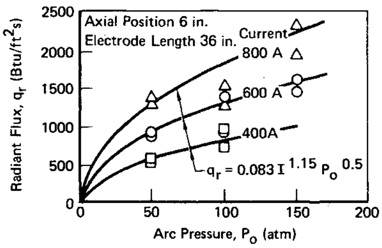

Fig. 3 Arc pressure effects on radiant heat flux.

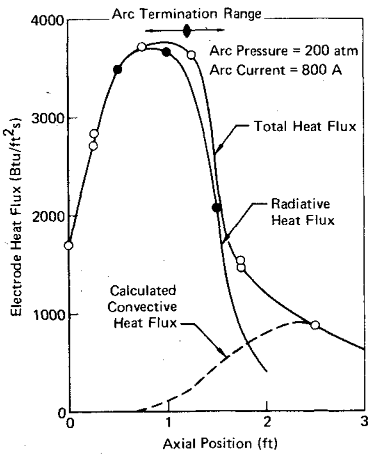

Fig. 4 Electrode heat flux distribution at 200 atm.

The radiant flux in the constant presence of the arc was proportional to the arc current to the 1.15 power and the arc pressure to the 0.5 power.

The total heat flux (Fig. 4) was highest in the arc termination region ranging up to 3950 Btu/ft^{2}s averaged over a 6 in. length. The peak flux location varied downstream of the electrode entrance (gas swirl chamber) depending on the arc current and pressure. The peak total heat flux varied linearly with arc current and to the 0.6 power of the arc pressure.

From these data it is concluded that the MDC-200 downstream electrode heating can be divided into four regions. The entrance region heating is predominantly by radiation with the walls being cooled convectively by the centrifuged cold gas from the primary injection. The arc column is compact and at a very high temperature. In the development region the gas near the wall has been heated sufficiently to cause some convective heating in addition to strong radiation from an ever present growing arc column. The combined heat fluxes increase rapidly in this region. The arc termination region experiences a rapid fluctuation in heating because of the arc extension and shunting. This results in an average heat flux that is intermediate between the continued development and post termination regions. As the arc elongates because of self-magnetic stretching and axial gas momentum, the heat flux rises to a level consistent with the increased convection and leveling radiation. When the arc potential difference at some rearward point is sufficient to cause shunting, the arc length is abruptly reduced and the flux level drops to the post termination level which is predominantly convection. Since the time-averaged presence of the arc is greater near the restrike region, the peak heat flux occurs there, and the level then decreases axially. Estimates of the net energy required to evaporate the electrode material that contaminates the stream were made and found to be negligible. In the post termination region, radiation decays rapidly and the predominant mode of heat transfer is convection. As the gas vortex decays axially, the local velocity decreases. This combined with a decaying gas enthalpy causes a decline in the total heat flux.