Arc Heater Performance on Hydrogen, Helium, or Air

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Theme

THE objective of this work was to map the performance of a nominal 250 kW Huels-type arc heater using hydrogen at pressures of 10, 15, 25, and 50 atm and helium at pressures of 25, 50, 75, and 100 atm with arc currents of 240,320, and 400 A. A supersonic nozzle with a 0.411 cm diam throat was used to constrict the flow; measurements of the stagnation enthalpy, stagnation pressure, and arc power were made. These performance data were compared with data using air and with computer-coded correlations derived to permit scaling of the arc heater.

Contents

The arc heater used in these tests was a nominal 250 kW Huels-type high-voltage unit (Linde N-250) shown in Fig. 1. Two tandem cylindrical electrodes were separated by a central gas-injection chamber and insulated from each other by a threaded Delrin cylinder insulator. The 14.2 cm long rear electrode (anode) had an inside diameter of 1.59 cm. The front electrode (cathode) had an inside diameter of 0.953 cm. The cathode length was 12.7 cm in most tests and 20.3 cm in the others. Both electrodes and the center chamber were water-cooled. Four tubular gas injectors were used and the gas was injected tangentially to the heater walls in a counterclockwise direction looking downstream. The resultant radial pressure gradient stabilized the arc on the heater centerline. The injection pressure ratio (injector-pressure/arc-chamber-pressure) was varied from 1.1-2.2. A magnetic field coil was used on the rear electrode to rotate the arc termination and prevent arc transfer to the rear plug.

The absolute performance and the relative performance of the N-250 arc heater were determined. The same basic arc heater with only minor changes was operated on all three gases at the same arc currents and overlapping arc pressures. The experimental enthalpy was determined from an energy balance on the arc heater combined with the measured gas flow rate. Table 1 summarizes the energy balance enthalpies measured on the three gases tested over the complete test matrix. Direct comparisons can be made at 25 and 50 atm among the three gases.

The hydrogen enthalpies were a factor of four higher than the helium enthalpies. The helium flow rates were twice those on hydrogen, and the helium arc voltages were less than half the hydrogen arc voltages. Thus, for similar thermal efficiencies, the factor-of-four difference in the enthalpies was accountable. The peak hydrogen enthalpy was 96.8 MJ/kg at 15 atm, and the peak helium enthalpy was 22.6 MJ/kg at 25 atm. An enthalpy of 10.9 MJ/kg was achieved at 100 atm on helium. At the 400 A level, the factor-of-four increase in arc pressure caused only a 25% decrease in the helium energy balance enthalpy.

The air enthalpies were a factor of five to seven lower than those on hydrogen and 38-55% lower than those on helium for the same arc current and pressure. The peak air enthalpy was 16.7 MJ/kg at 10 atm, and the minimum was 7.9 MJ/kg at 100 atm. At a given arc current, a factor-of-ten increase in pressure decreased the enthalpy by as little as 33% and at most 44%.

The energy losses to the anode, cathode-body, and nozzle were measured independently. The anode energy losses varied from 12-32% of the total losses, the cathode-body losses varied from 54-74% of the total, and the nozzle losses varied from 11-25% of the total. The nozzle losses Q_N increased with the gas flow rate $\dot{m}$ to the 0.8 power and linearly with the gas-wall enthalpy difference $h_b - h_w$:

$$Q_N = C\dot{m}^{0.8} \ (h_b - h_w) \tag{1}$$

Equation (1) follows typical turbulent convection correlation equations and thus provides a means for scaling the nozzle losses.

Electrode erosion and test-stream contamination are problems on hydrogen at low pressures where the arc is not properly stabilized at the cathode (front electrode). However, hydrogen, helium and air exhibit less than 0.4% test-stream contamination at pressures above 25 atm. Anode erosion is severe on air at pressures above 75 atm. Electrode erosion on helium was negligible in the anode and minor in the cathode.

The arc heater was operated at a peak power level of 1 MW on all three gases. The arc fluctuations were quite strong on hydrogen, requiring additional ballast and inductance in the power circuit. A prolonged test condition could not be achieved on hydrogen without the use of approximately 16 mH additional inductance and 7 Ω ballast resistance in series with the arc. The arc current oscillations without these stabilizing circuit components were significantly stronger, and in some cases the arc was totally unstable. Oscillations in the hydrogen arc voltage were analyzed early in the testing to eliminate data-record noise. Noise frequencies of 150 kHz with a modulation of 2.5 kHz were identified. The signal-to-noise ratio was as low as 0.5. An isolation amplifier was subsequently used to eliminate the noise from the data record. The oscillograph traces of the arc voltage indicate oscillations in excess of ± 12% of the average value at 50 atm and 300 A.

The arc voltage and current on air were very stable over the full range of test conditions. The 10-scan average (0.85 sec elapsed time) voltage at 240 A and 100 atm varied less than

Table 1 Comparative N-250-5-0.162 arc heater performance on H_2, He, and air.

Arc Current (A)	Test Gas	Arc Pressure (atm) 10	15	25	50	75	100
		Average Energy Balance Enthalpy (MJ/kg)					
240	H_2	70.2	77.5	71.9	–	–	–
	He	–	–	–	13.5	11.9	11.1
	Air	13.0	11.4	10.0	8.6	8.1	7.9
320	H_2	76.3	83.0	81.4	72.6	–	–
	He	–	–	19.3	16.7	14.4	14.2
	Air	13.7	13.3	11.9	10.2	9.5	9.1
400	H_2	76.5	90.5	87.9	–	–	–
	He	–	–	21.6	19.3	17.7	17.2
	Air	16.3	14.4	13.3	11.4	10.5	10.2

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Index categories: Radiatively Coupled Flows and Heat Transfer; Research Facilities and Instrumentation; Radiation and Radiative Heat Transfer.

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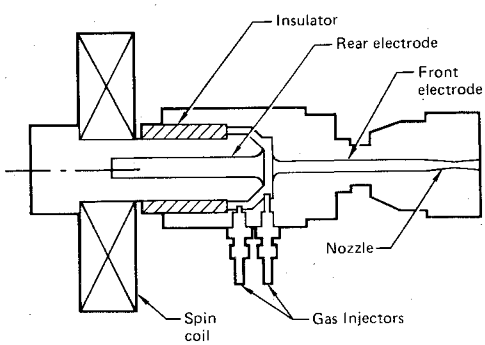

Fig. 1 N-250 arc heater.

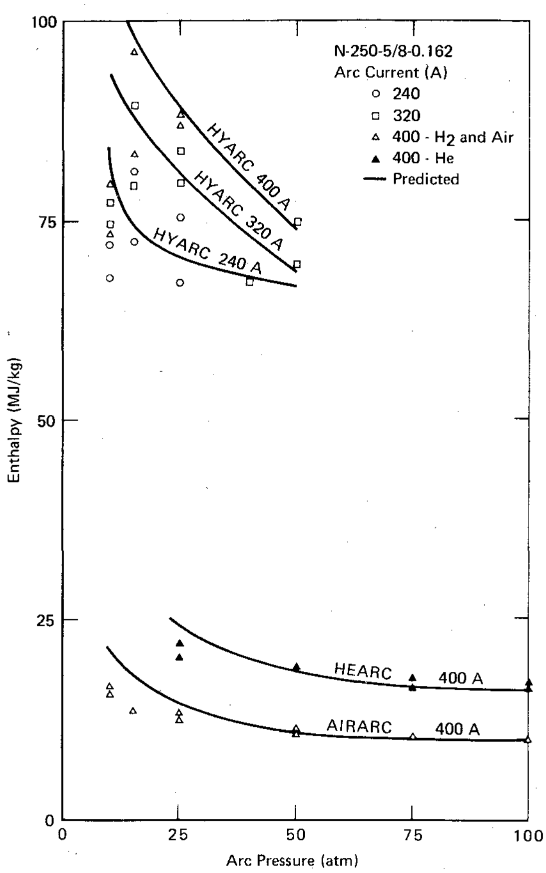

Fig. 2 Comparison of enthalpy-pressure performance on H_2, He, and air.

± 1%. Above 15 atm, the arc voltage repeatability was remarkable compared with other Huels-type heaters. At 50, 75, and 100 atm, the test voltages were repeatable within the accuracy of the measurements.

The helium operating characteristics were similar to those on air but with better stability, significantly less electrode erosion, and higher gas enthalpies. Nozzle throat-area reduction problems were not encountered. A scaling code was adapted for hydrogen and helium, and correlated to the performance of the N-250 heater. In the physical model for the high-pressure arc heater, the arc column is considered a central conductive body (wire-like) at a uniform high temperature, and is the only source of ohmic heat. The bulk gas in the annulus surrounding the arc is heated by convective turbulent transfer from the arc. The arc column, in addition to heating the gas, loses energy directly to the constrictor wall by volumetric radiation. The arc and bulk gases are considered to be optically thin; the bulk gas loses energy to the constrictor wall by convection. The solution is based on the principles of energy conservation, minimum energy addition, total gas energy balance, and nozzle throat sonic flow. The code is the same for each operating gas, with appropriate changes of thermodynamic and transport properties.

The code has been adapted to characterize Huels-type configurations by incorporating the appropriate energy losses in the energy balance equations. This model recognizes that in Huels-type configurations, convective losses to the wall of the front electrode occur from the hot gas downstream of the arc termination; the rear electrode has no convective losses because of the reverse flow of the cool inlet gas, and there are losses to the nozzle.

The power balance per unit length of the arc column is obtained by setting the electrical power input equal to the radiation loss to the wall plus the power turbulently convected to the bulk gas. The turbulent heat transfer coefficient is based on the conventional formulation of the Nusselt number which includes the Reynolds number and hence mass flow rate and constrictor diameter.

The arc diameter is a solution of the power balance relation for a given arc temperature, bulk gas temperature, mass flow rate, arc current, chamber pressure, and constrictor diameter. The arc temperature is that value for which the power input is minimum. Stagnation enthalpy and temperature, voltage gradient, arc voltage, and efficiency are computed once the arc temperature, arc diameter, bulk gas temperature, mass flow rate, and gas power are determined. Thermodynamic and transport property ranges are given in Ref. 1. Helium radiation was modeled as free-bound and assumed proportional to $N_e^2/\sqrt{T}$.

The scaling code was correlated with the N-250 experimental parameters (observables) of arc voltage, power input, efficiency, front and rear electrode losses, enthalpy, and front and rear electrode arc tracks. The correlation goal was to obtain the best possible agreement between the code predictions and the observables over the entire pressure-current test matrix. Code parameters adjusted were: the relative radiation level; the front and rear arc lengths; and the temperature used to evaluate the thermal conductivity in the expression for energy transfer between the bulk gas and constrictor wall. Fitting the code model to experiment provided scaling confidence for predicting performance of other heaters. This approach also removed possible discrepancies of the theoretically calculated thermodynamic and transport properties.

The predicted enthalpy characteristics are compared with experimental data in Fig. 2. In general, the agreement is good except at the lowest pressure and the highest arc current on hydrogen. For these conditions, erosion of the front-electrode entrance was severe, disrupting the gas vortex and resulting in a shorter arc length and lower arc voltage than predicted. The gradual decay of enthalpy as the pressure was increased at a fixed arc current is normal for a Huels-type arc heater. The increase in arc voltage as pressure increases does not compensate for the higher gas flow rate and energy losses; thus, the enthalpy decreases gradually.

The projected results for a current of $I/N = 800$ A (N= constrictor diam/1.9 cm) were enthalpies of 53 and 46 MJ/kg for heater scales of $N = 1$ and $N = 1.73$, respectively, relatively independent of pressure from 25-100 atm.

References

[1] Painter, J. H. and Shaeffer, J. F., "Performance Characteristics of a Huels-Type Arc Heater Operating on Hydrogen, Helium or Air," Arnold Engineering Development Center, Tullahoma, Tenn. AEDC TR-76-25, March 1976.