FINAL REPORT

Energy Exchange in Plasma Media

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SUMMARY

Energy transfer to solids immersed in rf generated plasma jets has been studied. It was first necessary to generate these plasma jets, and to determine their physical properties. Argon and argon-nitrogen plasmas were generated in a 3 mc induction-coupled plasma torch. Plasma jet properties were measured with a water-cooled calorimetric probe and a 3.4-meter grating spectrograph. Energy transfer rates from the ionized gas to solids were measured with thermocouples injected into these gases for time periods less than 0.1 second A relation was obtained for calculating film heat transfer coefficients in argon and argon-nitrogen plasmas.

The mass and energy transfer between a confined plasma jet and coolant gas stream has been studied experimentally. A dc axially symmetric arc jet was used as the plasma source. The temperature profiles present in the mixing region were determined by optical spectrographic methods. Both the electronic excitation temperature of the argon atoms and the rotational temperatures of the nitrogen molecules were determined. The compositions and axial velocities present in the plasma-coolant mixing region were determined by sampling probe methods. Sampling probe measurements of enthalpy were found to be unreliable. From chemical reaction standpoint, the results of this study indicate that the mixing with the plasma of a reactant injected into a plasma jet reaction chamber would be very rapid but that the internal energy modes of the reactant molecule would not be fully excited during the short residence time in the high velocity flow.

An experimental study of the use of a plasma jet as a photochemical light source has been initiated, as well as a study of velocity profiles in the confined arc jet. A boundary layer analysis of the flow around the enthalpy probe has also begun.

The overall aspects of the investigation are outlined in this final report. The details of the phases of the investigation which have been completed can be obtained from the publication and technical reports listed on page 6.

TECHNIQUES

The following techniques were devised and applied in obtaining experimental data:

A. Total Energy Balances on Plasma Generators

The total energy input to the plasmas was measured calorimetrically by summing the energies absorbed by the water jacket surrounding the plasma-containing tube and by a total gas calorimeter attached to the end of the torch.

B. Enthalpy Probe

The enthalpy probe is a small heat exchanger through which a quantity of hot gas passes, its sensible heat being absorbed by cooling water. The cool exit gas may then be passed through a thermal conductivity cell for composition measurement. An energy balance around the heat exchanger determines the entering gas enthalpy. The temperature is then determined from a Mollier diagram. The enthalpy probe can also be used as a sampling device for measurement of compositions.

C. Spectrographic Measurements

The light emitted from the luminous plasma source was analyzed with a 3.4-meter grating spectrograph equipped with an optical scanning-condensing system. The photographic plates were developed and densitometered to provide raw data on line intensities. This data was then processed to obtain the plasma temperature. Two different methods of calculating plasma temperature were used—the "multi-line" and "absolute intensity" methods.

D. Energy Transfer to Solids

Energy transfer to solids was determined from the dynamic response of thermocouples introduced into the plasma for time periods of about 0.1 second, while the corresponding plasma temperature was measured spectrographically. The heat transfer measuring equipment consisted of a probe for introducing the thermocouples into the hot stream, an electronic timer for setting the immersion time and a high-speed recorder for measuring the emf of the thermocouples.

E. Heat and Mass Transfer in DC Arc Plasmas

An 11 millimeter diameter axially symmetric plasma jet was introduced into a surrounding concentric, cocurrent flow of coolant gas. Argon was used as the plasma gas; nitrogen as the coolant gas. Radial temperature and composition and flow profiles were measured.

F. Photochemical Effects

Work has begun on a kinetic study of the photochemical chlorination of sulfur dioxide utilizing a plasma light source. This light source is capable of producing intensities several orders of magnitude brighter than anything heretofore studied. The reactor in which the chlorination reaction is to be studied will be an annular flow system built up around the plasma light source. The parameters which will be studied are the rate of flow, intensity of radiation, wavelength of radiation, reaction pressure, reaction temperature, and reactor geometry.

G. Boundary Layer Analysis

A boundary layer analysis has been initiated to determine temperature and concentration variations in the cool gas sheath surrounding the enthalpy probe. This analysis will include the effects of ionization and recombination.

RESULTS

A. For the first part of the study, argon and argon-nitrogen plasmas were generated in a 3-mc induction-coupled plasma torch. The torch was operated at atmospheric pressure, with the power input varying from 2 kw to 5 kw at a generator efficiency of 43%. Radiation losses from the plasma accounted for 7% to 14% of the total power input.

B. Enthalpies of the rf plasmas as measured with the enthalpy probe correspond to a temperature of about 5800°K ± 1500°K, while spectrographic measurements indicated that the plasmas were nearly isothermal at 10,000°K.

C. The film heat transfer coefficients measured in argon plasmas (100 Btu $hr^{-1}ft^{-2}{}^{\circ}F^{-1}$) were higher than those calculated from a conventional forced convection correlation (40 Btu $hr^{-1}ft^{-2}{}^{\circ}F^{-1}$). The rate of energy transfer increased by as much as 100% with the addition of nitrogen to the argon stream. Energy transfer contributions due to ion-electron and atom-atom recombination occurring near the solid were separated from the overall transfer.

D. In the mixing of a hot argon, direct current, plasma jet, with cool nitrogen, the measured nitrogen temperatures were found to be much lower than the argon temperatures at the same point in the flow.

E. The composition profiles indicated that direct induction of coolant into the high-velocity plasma jet and the formation of a recirculation eddy greatly increased the mixing of plasma and coolant. Mass and energy balances computed at various axial cross-sections in the mixing region indicated that from 1/2 to 3/4 of the nitrogen coolant was present in the high temperature region of the flow but that this coolant fraction contained less that 10% of the total energy present.

PUBLICATION

1. "Heat Transfer Properties of RF Plasmas," G. R. Chludzinski, R. H. Kadlec, and S. W. Churchill, Proceedings of Joint AIChE-IChE Meeting, London, 1965.

TECHNICAL REPORTS

1. "Energy Transfer to Solids in RF Generated Plasmas," G. R. Chludzinski, Ph.D. Thesis, Department of Chemical and Metallurgical Engineering, The University of Michigan, Ann Arbor, August 1964.

2. "Mass and Energy Transfer Between a Confined Plasma Jet and a Gaseous Coolant," D. L. Smith, Ph.D. Thesis, Department of Chemical and Metallurgical Engineering, The University of Michigan, Ann Arbor, February 1965.

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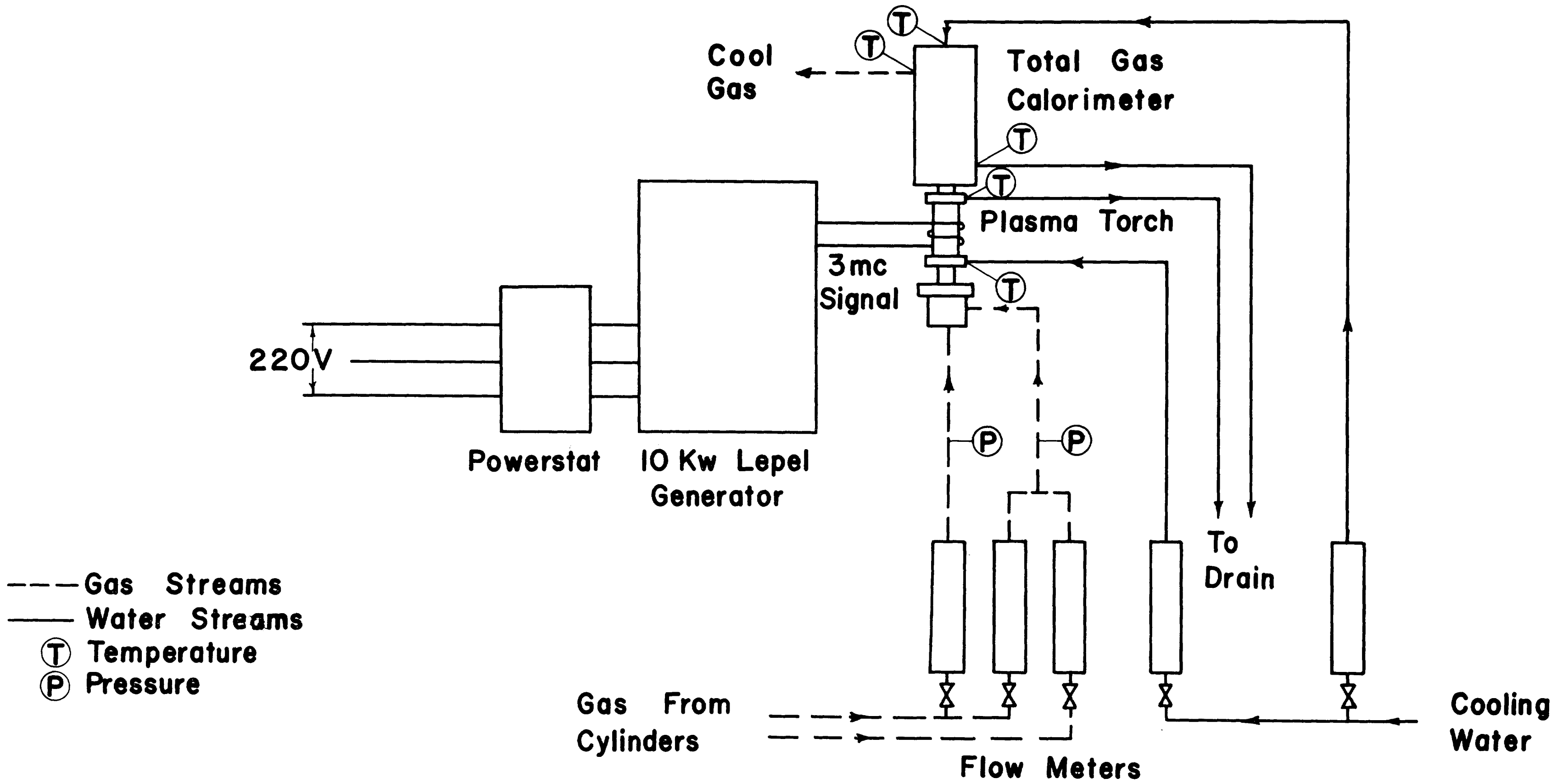

Figure 1. Schematic diagram of radio frequency plasma generator with total gas calorimeter.

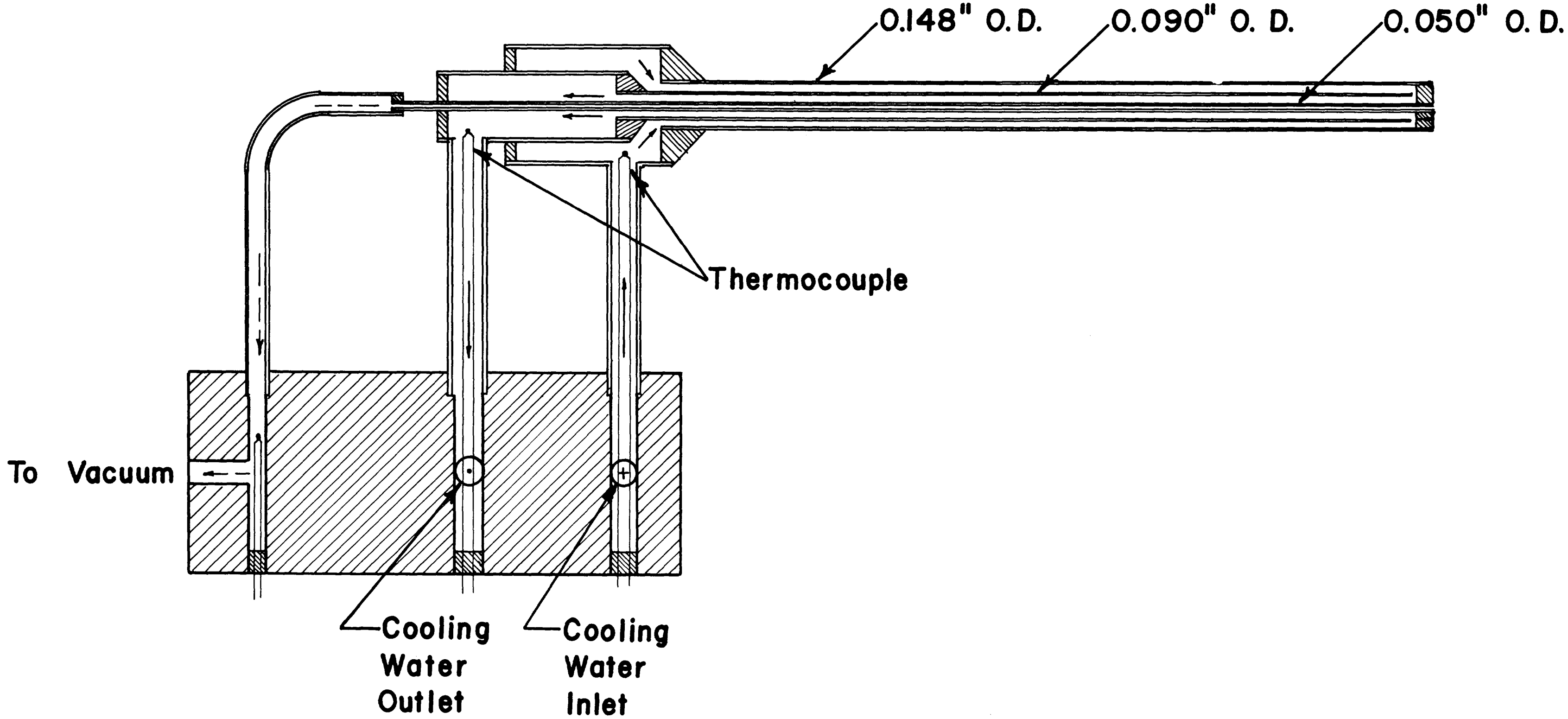

Figure 2. Enthalpy probe.

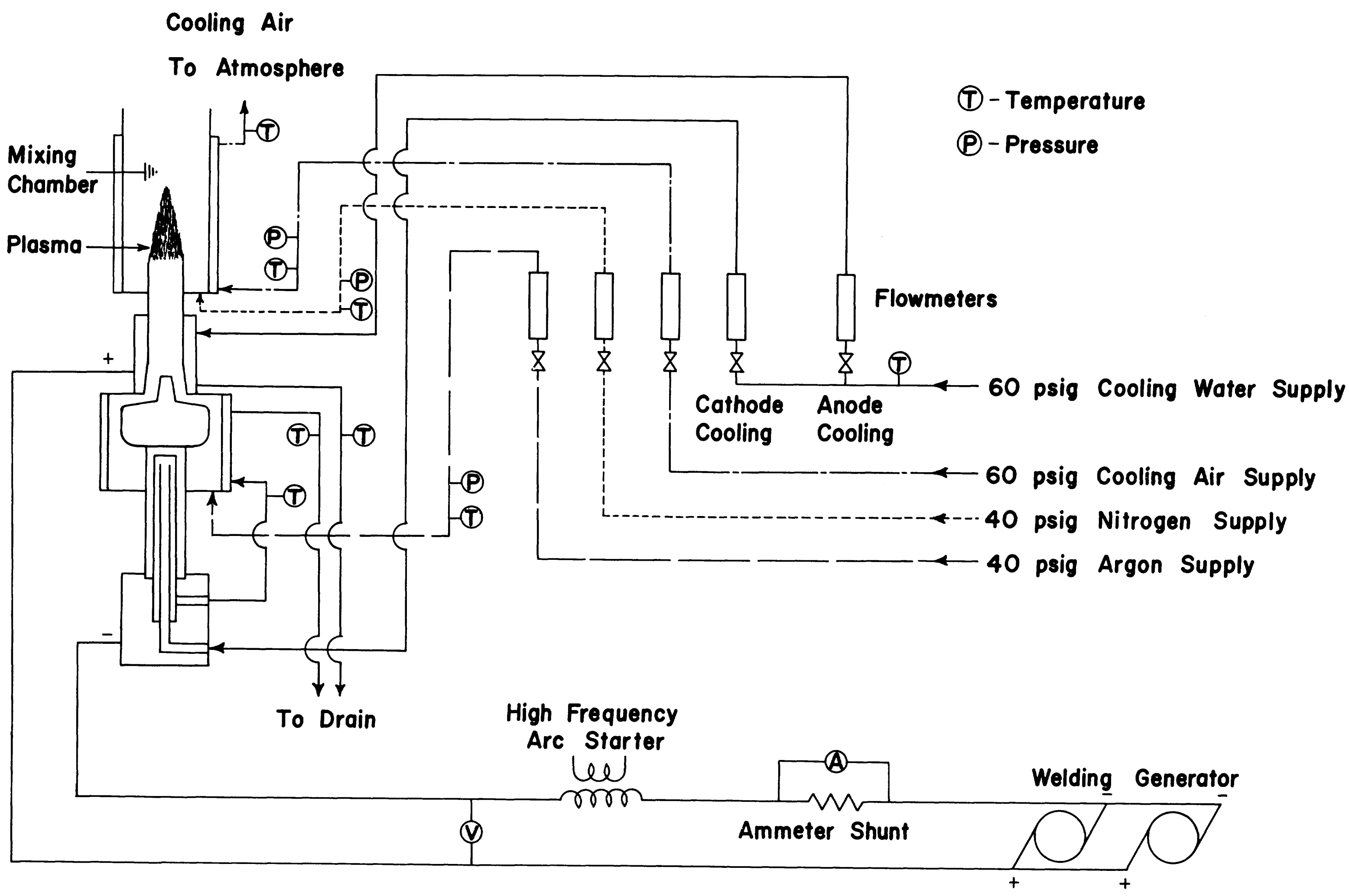

Figure 3. Schematic diagram of direct current plasma generator.

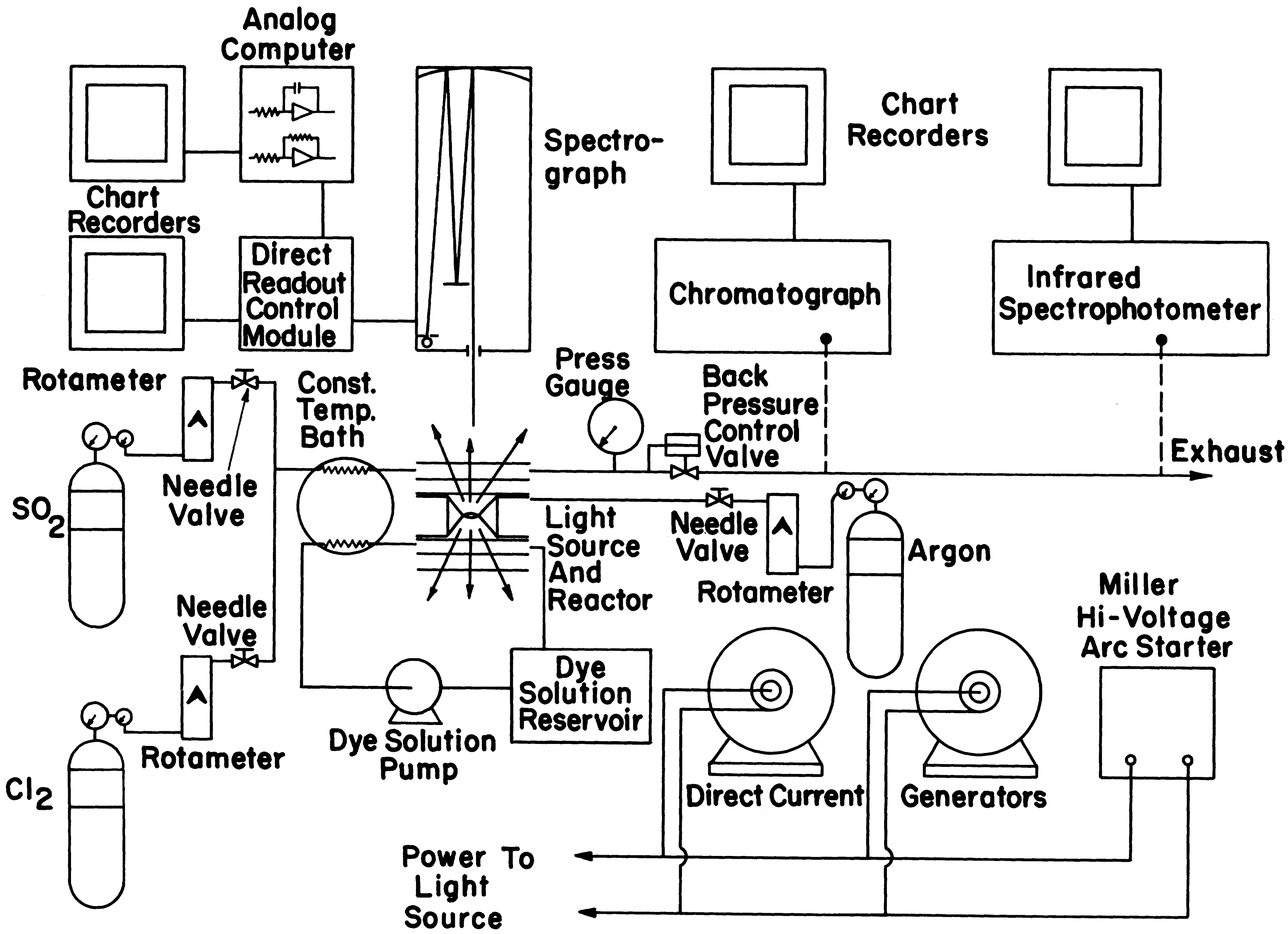

Figure 4. Schematic diagram of photochemical reactor system.