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THERMAL PROPERTIES OF KRYPTON AND XENON LAMINAR ARC PLASMAS

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INTRODUCTION

In support of industrial and research applications of the cascade arc plasma, considerable effort has been devoted to the theoretical determination of arc thermal properties. Although emphasis has been placed on the argon arc, some consideration has been given to hydrogen, helium and nitrogen arcs as well. For this purpose numerous equilibrium models have been developed, the most rigorous of which is that due to Bower and Incropera [1]. Although more recent work has revealed the existence of thermochemical non-equilibrium effects [2, 3], the equilibrium model has been found suitable for many engineering purposes. In particular, results obtained from this model suggest important trends and provide excellent reference conditions for comparison with data and more refined non-equilibrium calculations.

In this study the equilibrium model of Bower and Incropera [1] has been extended to krypton and xenon arc plasmas operating in a laminar mode. Interest in these gases has been stimulated by their intense radiation characteristics. Since krypton and xenon are more readily ionized than most other arc gases, they provide potentially excellent sources of both visible and ultraviolet radiation for photochemical processing.

FLOW MODEL AND RESULTS

The flow model used in this study is identical to that developed by Bower and Incropera [1] and is based upon the assumption of local thermochemical equilibrium. Although calculations have been performed for both the entrance and asymptotic arc regions, results presented in this article are restricted to the asymptotic region. In this region, flow properties depend only upon radial location in the arc (for prescribed arc operating parameters), and the dissipation of electrical energy is identically balanced by convective and radiative losses. The transport coefficients required for the calculations were obtained from Devoto [4], and the thermodynamic properties were computed from statistical mechanics [5]. The radiation source term required for the model was determined from microscopic considerations which accounted for both continuum and line contributions. Details are provided by Greene [5].

Parametric calculations were performed in which the arc operating parameters (pressure, current and radius) were varied over wide ranges. Dependent variables of particular interest include the temperature profiles, the total wall heat flux, and the relative contribution of radiation to this heat flux.

Temperature profiles computed for a range of currents are shown in Figs. 1 and 2. The profiles are extremely flat in the arc core, with sharp gradients existing near the wall. This behavior is due to the comparatively high thermal conductivities which characterize both gases at elevated temperatures and to the fact that radiation emission from the gases is intense and a strong function of temperature. Note that, for a prescribed set of arc operating conditions, the tempera-

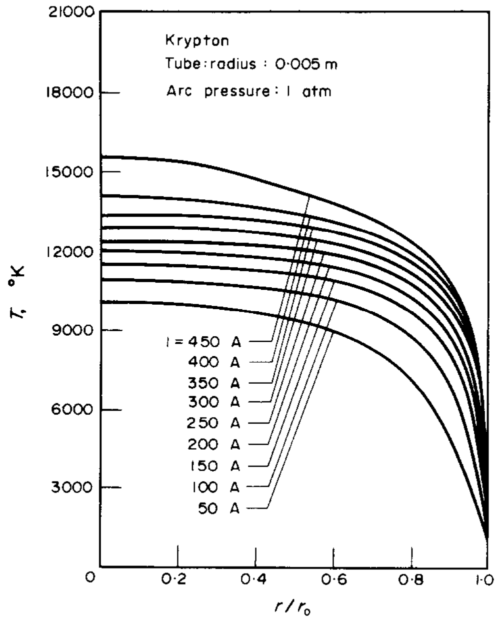

FIG. 1. Temperature profiles for the asymptotic region of a krypton arc.

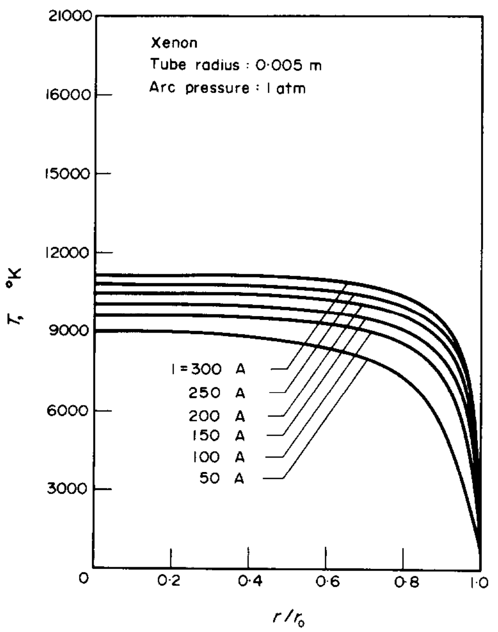

FIG. 2. Temperature profiles for the asymptotic region of a xenon arc.

ture, as well as the electron concentration, levels are a strong function of the ionization potential of the operating gas. For example, in considering the noble gases He (I = 24·58 eV), Ar (I = 15·75 eV), Kr (I = 14·00 eV) and Xe (I = 12·13 eV), there occurs a general reduction in temperature but an increase in electron concentration with decreasing species ionization potential. This is due to the consumption of a greater portion of the electrical energy in species ionization, leaving less for elevating the thermal state of the gas.

In addition to the temperature level increasing with current, it will increase with decreasing tube radius and, with one exception, decreasing arc pressure [5]. The exception pertains to He, for which case temperature increases with pressure. This reverse trend is due primarily to the fact that, in the range considered ($0{\cdot}65 \leqslant p \leqslant 10$ atm), radiation from the He arc is negligible.

Since the dissipation of electrical energy is balanced entirely by heat losses from the arc in the asymptotic region, the results of Fig. 3 reflect entirely the arc electrical characteristics. Results obtained previously for Ar and He are

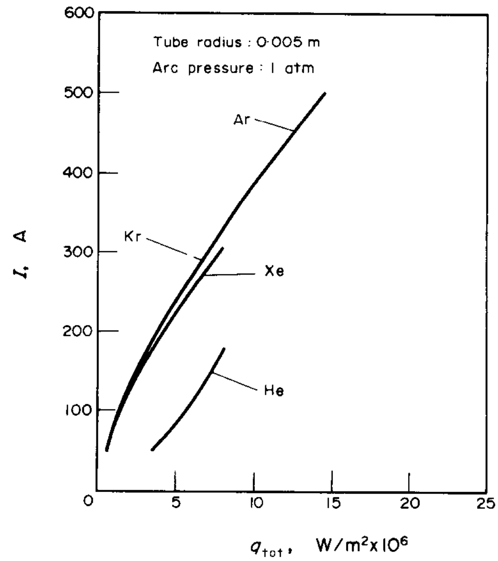

FIG. 3. Total wall heat flux as a function of current for the asymptotic arc.

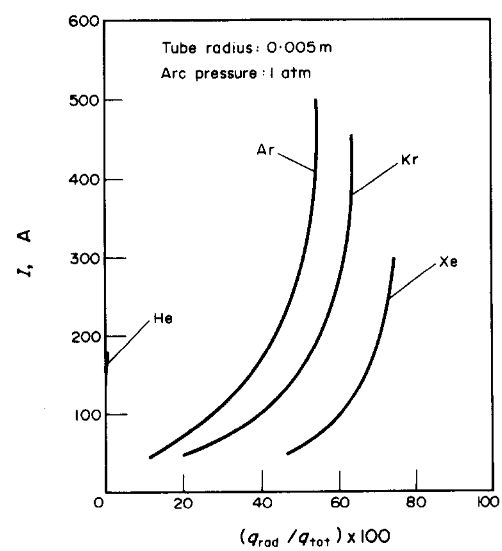

FIG. 4. Per cent contribution of radiation to the total wall heat flux for the asymptotic arc.

presented for comparison [1]. Since the characteristics are very similar for Ar, Kr and Xe, the total wall heat flux from these arcs are virtually identical. Since the electrical resistance, and hence the field intensity, for the He arc is much in excess of that for Ar, Kr and Xe, the total wall heat flux for He will exceed the values for the other gases. For each of these gases, the total wall heat flux, as well as the total wall heat transfer per unit length of tube (W/m), decreases significantly with increasing radius [5]. Although the total wall heat flux increases with pressure for Ar, Kr and Xe, it decreases with increasing pressure for He [5].

For use of the arc as a radiation source, a quantity of particular interest is the fraction of the total heat loss due to radiation. This is shown as a function of arc current in Fig. 4. The merit of the Xe arc is readily apparent. In contrast to negligible radiation from He and peak radiation efficiencies of 53 and 62 per cent for Ar and Kr, respectively, the radiation efficiency of Xe is approximately 75 per cent for the indicated operating conditions. Although there is little effect of changing tube radius, the radiation efficiency is increased significantly with increasing arc pressure. For a 1 cm dia Xe arc operating at 100 A and 10 atm, the calculations suggest a conversion efficiency of 99 per cent [5].

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EFFECT OF RADIAL VELOCITY COMPONENT ON LAMINAR FORCED CONVECTION IN ENTRANCE REGION OF A CIRCULAR TUBE

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NOMENCLATURE

a,	tube radius;
D,	tube diameter;
I_0, I_1, I_2,	modified Bessel functions;
Nu,	Nusselt number;
Pr,	Prandtl number, ν/α;
R, X,	cylindrical coordinates;
r, x,	dimensionless cylindrical coordinates;
Re,	Reynolds number, $U_m D/\nu$;
T,	temperature;
U, V,	velocity components in X and R directions;
β,	parameter, a function of X alone;
θ,	dimensionless temperature, $(T - T_w)/(T_0 - T_w)$.

Subscripts

m,	mixed mean value or mean value;
0,	condition at tube inlet;
w,	condition at tube wall;
x,	local value.

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INTRODUCTION

Due to mathematical difficulties, steady laminar flow in hydrodynamic entrance region of tubes and ducts does not have any exact solution. So far, several approximations have been devised to solve the problem. One of the earliest investigations was done by Langhaar [1] in 1942. By means of a linearizing approximation, the Navier–Stokes equations were solved for the case of steady flow in the transition length of a straight tube. Han [2] and Sparrow *et al.* [3] applied this approximation to the cases of rectangular ducts and parallel-plate channels, respectively. But no detailed information was given about velocity components in the directions normal to the axial flow in the above papers [1–3].

Considering the laminar convection in combined hydrodynamic and thermal entrance region of tubes, kays [4] utilized the Langhaar's axial velocity profile [1] in the energy equation without considering the convective term in radial direction and obtained heat transfer results for three boundary conditions. He claimed that at $4\,(X/D)/(Pr\,Re) = 0{\cdot}004$ the convective term in radial direction is only 10 per cent of that in axial direction in energy equation at one point in the flow cross section, and that if the convective term in the radial direction is neglected, the local Nusselt number