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Rotational Temperature Measurements in an Arc Jet

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Introduction

IN order to simulate the flow conditions around a space vehicle during its hypersonic atmospheric re-entry, a low pressure arc jet is used to create high temperature and high speed flow.[1] It is important to know the physical and chemical conditions of the flow in this jet. The temperatures are important physical parameters to evaluate the degree of simulation of this ground device and to calculate specific chemical rates and transport coefficients. The temperatures are about a few thousands of degrees. We need to design accurate and nonintrusive diagnostics for high temperature measurements in these flow conditions.

In the low pressure arc jet, the plasma is not expected to be in thermal equilibrium. To obtain the jet temperature, gas flow can be excited with a high energy electron beam in order to observe the re-emitted light. This technique can be used for nonionized gas flow.[2] Because plasma jets are luminous, it is not necessary to excite the flow. In these conditions it is possible to determine plasma vibrational distributions and rotational temperatures from optical emission spectroscopy (OES).[3] Using high resolution spectroscopy, Bacri and Lagreca[4] have measured rotational temperatures in an atmospheric nitrogen arc. Using the same technique Blackwell et al.[5] have evaluated temperature in a shock layer. They have used a low resolution monochromator and have recorded mainly vibrational spectra without rotational resolution. This paper presents a new attempt for optical emission spectroscopy measurement of temperature from high resolution spectra in a low pressure arc.

Experiment

The nitrogen arc jet is produced in the Aerothermique Laboratory SR1 wind tunnel (Fig. 1). The plasma is produced, with a vortex stabilized dc arc, between a thoriated 2% tungsten cathode and a copper anode used as a nozzle. Typical flow conditions are: arc discharge current from 50–150 A; gas flow rate from 5–15 liters/min (0.1–0.3 g/s); static pressure from 0.1–10 Torr; velocity from 2000–5000 m/s. In order to investigate axial and longitudinal profiles, the plasma generator can be moved on a Cartesian axis. The plasma jet is stationary (several tens of hours) and large (length $\approx$ 1 m and diameter $\approx$ 0.5 m at a pressure of 13.3 Pa). The light emitted from the plasma, observed through a fused silica window, is focused by the fused silica lens on the entrance slit of a 150-cm focal length monochromator (Sopra). A 1200 lines/mm grating was used in this monochromator. In order to increase the signal over noise ratio, an optical chopper (300 Hz) modulated the light beam. The photomultiplier (Hamamatsu R928) output signal was detected by a lock-in amplifier (NF Electronics Instruments 5610B), tuned on the chopper modulation frequency, and connected to a microcomputer.

In this paper measurements are presented on the first negative system of nitrogen: $N_2^+(B^2\Sigma_u, v' = 0) \rightarrow N_2^+(X^2\Sigma_g, v'' = 0)$. This band, observed in the plasma jet, is also emitted

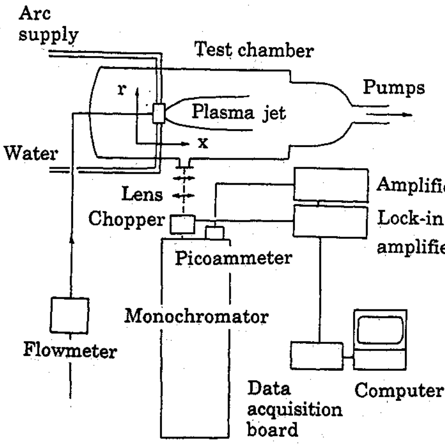

Fig. 1 Schematic of apparatus used for rotational temperature measurements.

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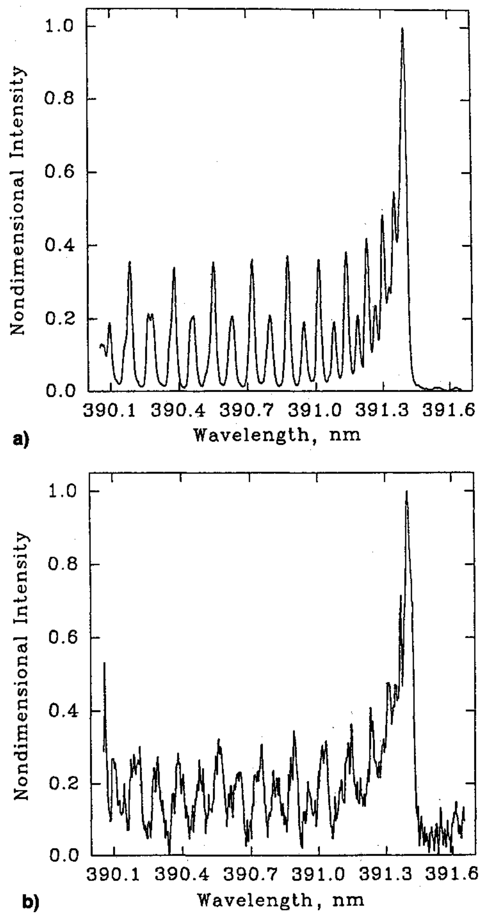

Fig. 2 Experimental spectra for arc discharge current of 100 A: a) at $x = 0$; b) at $x = 40$ cm.

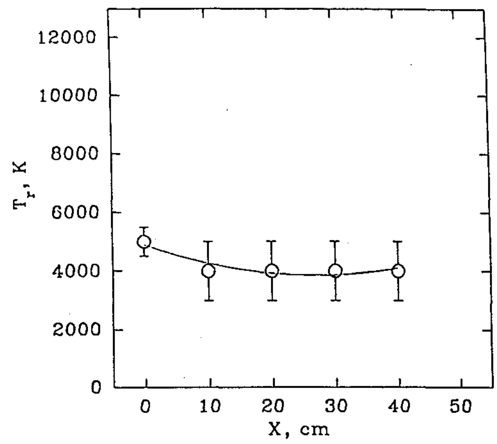

Fig. 3 Rotational temperature along the plasma axis, 15 l/min flow rate, static pressure of 13.3 Pa.

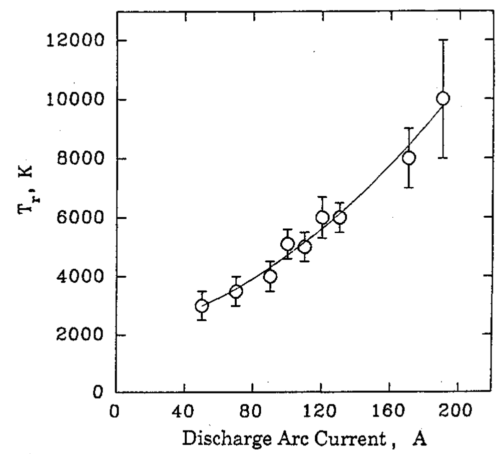

Fig. 4 Rotational temperature at the nozzle exit as a function of the arc generator discharge current; 15 l/min flow rate, static pressure of 13.3 Pa.

in flowing afterglows, and gives what is called the "pink afterglow."[6] Figure 2 presents spectra recorded at the nozzle exit $x = 0$, and 40 cm downstream, respectively.

Calculated Spectra

The experimental spectrum is very sensitive to the monochromator resolution. In order to fit the rotational temperature, we compute spectra for several monochromator resolutions and rotational temperatures.

The intensity of an emitted rotational line is given by

$$S(J', J'') = D(J') \exp\left(-\frac{B_{v'} J'(J' + 1)hc}{kT_R}\right)$$

where $B_{v'}$ is the calculated rotational constant of the v' upper level and $D(J')$ is a spectroscopical function taking into account the transition probabilities and the partition function.[7]

The rotational spectrum involves high rotational levels. Then the wavelength of each rotational line is calculated from the vibrational fitted constants of the upper and lower levels.[8] The whole spectrum is the sum of the rotational lines of the ro-vibrational band $v' - v''$. Each line presents a Doppler profile due to the translational temperature supposed to be in equilibrium with the rotational temperature. The calculated spectrum is then convoluted with the monochromator apparatus function. At low temperature, the rotational lines are well resolved, but at high temperature, some overlapping of R and P lines is observed. The low rotational lines do not present such overlapping, but to resolve these lines, we need a good resolution monochromator. A Gaussian apparatus function of 0.018 nm midwidth is deduced from the comparison between calculated and experimental spectra. The spectrum near the bandhead is very sensitive to the apparatus function. In our case, this function has been determined from the resolution of the lines $J' = 19$ and 20 of the P line.[8]

Temperature Measurement and Discussion

The measurements are performed for a gas flow rate of 15 liters/min, and a static pressure of 13.3 Pa. The rotational temperature is deduced from comparison between experimental and calculated spectra.

The axial variation of the rotational temperature is measured for an arc discharge current of 100 A. At the nozzle exit, $x = 0$, (Fig. 2a), the line intensities are intense, and then the recorded spectrum is easily analyzed. The deduced rotational temperature is 5000 ± 500 K. For an observation far from the nozzle exit, $x = 40$ cm, (Fig. 2b), the line intensities are weak, and then the signal noise ratio limits the measurement accuracy. Between 10 and 40 cm along the plasma axis, no significant differences on the spectra are noted and the rotational temperature is about 4000 K (Fig. 3). The effect of arc discharge current on rotational temperature is studied at the nozzle exit. The rotational temperature accuracy decreases at high temperature (above 8000 K). This is due to a weak evolution of the calculated spectra in the studied wavelength range for these temperatures. The spectra can be modified by rotational-vibrational interactions and also by perturbation of the $N_2^+(X^2\Sigma_g)$ and $N_2^+(A^2\Pi_u)$ states.[9,10] We observe the increase of rotational temperature with arc currents (Fig. 4). This effect can be explained by the increase of the power deposed from the arc to the plasma jet.

Conclusion

The optical emission spectroscopy (OES) technique gives an accurate, nonperturbating, real-time temperature measurement, using a well-chosen instrument with a narrow apparatus function. The arc plasma jet is a versatile ground device to simulate re-entry plasma over large temperature ranges with high velocities. The rotational temperature has been measured in the plasma jet wind tunnel and by changing the electric power in the arc, the possibility to tune the temperatures is demonstrated.

Acknowledgments

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Analytical Investigation of the Rewetting of Grooved Surfaces

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Nomenclature

c = specific heat of the plate
G = mass flux
h_f = liquid latent heat
k = conductivity of the plate
Q = total heat input
q'' = heat flux
R = groove radius
T = temperature
U = average velocity of the liquid
α = thermal diffusivity
δ = thickness of the plate
ρ = density

Subscripts
l = liquid
max = maximum
w = wetting

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Introduction

RECENT developments in high-density electronic components and two-phase heat rejection systems for spacecraft thermal control have focused attention on the problems associated with heat transfer in the thin film region. Of particular interest are the rewetting characteristics of heated plates, determination of the maximum heat flux a plate with a given film thickness can sustain, and the rate at which a liquid will rewet a surface once all of the liquid has evaporated. Several investigations have been conducted to determine the rewetting characteristics of liquid films on heated surfaces. Shires et al.[1] experimentally investigated the rewetting characteristics of liquid on the outer surfaces of heated rods. Elliot and Rose[2] confirmed the experimental results of Shires et al., but found that the wetting front velocity U_w to be independent of the liquid flow rate. Several other researchers[3,4] investigated the effects of mass flux, flow quality, thermal properties of both the cooling liquid and the heated surface, and surface characteristics of heated surface on the rewetting rates for both the inside and outside of circular tubes. In two separate investigations, Ueda et al.[5,6] studied the rewetting characteristics of a falling liquid film on the surface of a hot stainless steel tube, both theoretically and experimentally.

In addition to the investigations into the rewetting characteristics of heated rods and tubes, several investigations have been conducted to evaluate the rewetting of liquid flowing over a flat plate. Bankoff[7] and Orell and Bankoff[8] conducted analytical investigations of dryout and rewetting of thin liquid films flowing on flat heated plates and Stroes et al.[9] experimentally investigated the heat-flux-induced dryout and rewetting in thin films, focusing on the effects of film thickness, flow rate, and inclination angle.

Although these investigations have provided substantial experimental data and considerable insight into the behavior of thin films on both circular tubes and flat plates, no general physical model exists that is capable of describing the governing phenomena or the behavior of the liquid in this region. In order to understand better the rewetting characteristics of liquid flowing over a heated plate with parallel grooves, a physical model was developed and an analytical expression for the rewetting velocity as a function of the fluid properties, the physical geometry, and the applied heat flux was derived.

Development of the Physical Model

Although liquid flow and heat transfer on rough surfaces is considerably more complex than flow on smooth surfaces, one of the principal areas of interest to the designers of high-capacity heat pipes for spacecraft applications is the rewetting behavior of thin liquid films on heated grooved surfaces. For this type of flow, the rewetting may be assisted or hindered by gravity, depending upon the gravitational vector. It has been previously shown[10] that the liquid film thickness has a significant effect on the rewetting and heat transfer characteristics, however in the application of interest here—the evaporator section of high-capacity heat pipes—the liquid film only fills the grooves; that is, for a wetting fluid, the level of liquid is never higher than the surface of the grooved plate,