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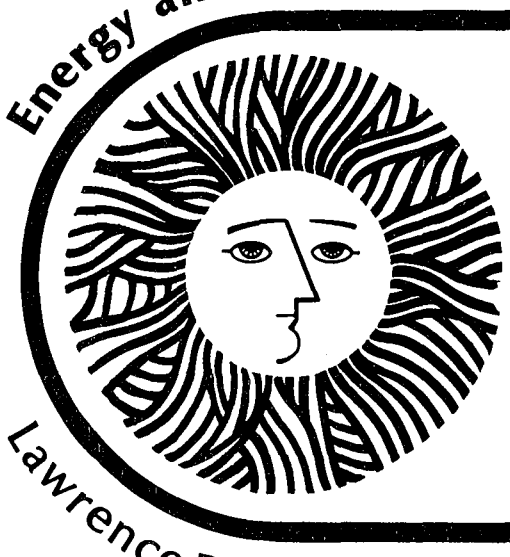
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MOTION OF PARTICLES IN A THERMAL BOUNDARY LAYER[†]

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ABSTRACT

In the course of using LDV to study combustion in a thermal boundary layer, the particle count rate was found to decrease abruptly to zero inside the boundary layer. Experimental and theoretical investigation of this phenomenon was carried out. The motion of the particles may be due to the combined effects of thermophoresis and radiative heating.

INTRODUCTION

In the course of using laser Doppler velocimetry to study combustion in a thermal boundary layer, the particles seeded in the flow were found to move away from the heated surface, and as a result, the particle count rate decreased abruptly to zero inside the boundary layer, making it impossible to obtain measurements near the wall region. Such a disappearance of particles near the plate surface was not noted with the plate unheated. In order to understand this phenomenon and hopefully to find a remedy for this problem, an experimental and theoretical investigation was carried out.

EXPERIMENTAL AND LDV SYSTEM

The experimental configuration for studying a heated boundary layer with combustion consisted of a sharp leading edge quartz plate with vacuum deposited platinum heating strips. The plate was mounted vertically in an upward directed, open atmospheric pressure jet of air or premixed fuel and air. The plate was a 1.5 mm thick, 75 mm square quartz sheet with a sharp leading edge with 2° included angle. The heating strips were oriented perpendicular to the flow and were of varying width in order to improve temperature control near the leading edge. The flow originated from a 5 cm diameter nozzle mounted on a stagnation chamber 20 cm in diameter. The stagnation chamber had internal screens to suppress turbulence, and the open jet produced was of uniform velocity with low turbulence.

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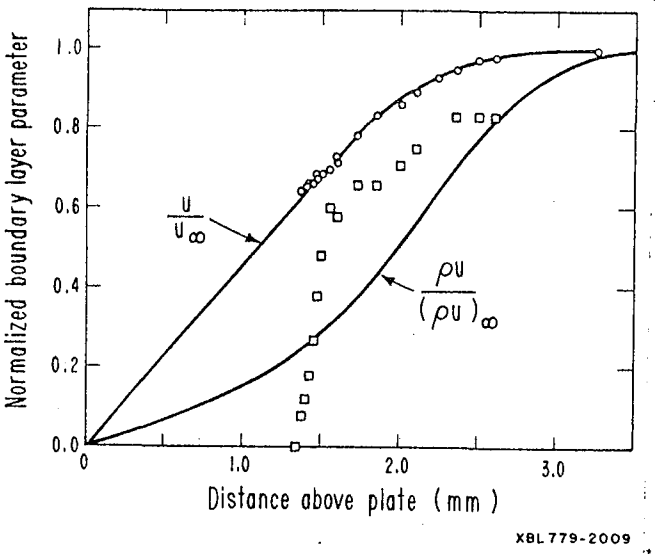


Figure 1.

Comparison of measured velocity, particle count rate and normalized density-velocity product profiles for a heated plate at 1200 K U_∞ = 2.62 m/s.

The laser Doppler velocimeter was of intersecting dual beam type with real fringes. A 4 watt argon ion laser operated at 4880 Å, a cube type beam splitter and a 100 mm focal length lens were used. The beam separation is variable, but was set at 20 mm for all the experiments. The scattering was detected at about a 30° angle from the forward direction with a 55 mm focal length camera lens, which imaged a pinhole on the intersection region, and an RCA type 931 A photomultiplier. The scattering burst was both observed directly on an oscilloscope and the frequency of the burst was determined by a Thermal System Model 1090 frequency tracker.

Aluminum oxide particles of nominally 2.0 μ diameter were used. The particles were suspended in water and dispersed into droplets by a collision type atomizer. This technique was satisfactory; particle count rates varying from 300 to 1000 s^{-1} were attained.

EXPERIMENTAL RESULTS

With an unheated plate, the particle count rate in the boundary layer was proportional to the velocity, as would be expected for a uniform particle density in the original flow. With the plate heated to temperatures in the range of 1000°K, visual observation of the light scattered from the laser beam indicated a dark region near the plate surface.

The observed particle count rate and flow velocity as a function of distance above the plate surface is shown in Figure 1. Also shown are the normalized velocity distribution (U/U_∞) and the expected decrease in particle count rate due to variation in velocity and density across the boundary layer, $\rho u/\rho u_\infty$. It can be seen that the particle count becomes larger than expected at the outer region of the boundary layer but decreases to zero abruptly at a point approximately half way through the boundary layer, creating a well defined particle-free region which can be called the dark boundary layer. Such behavior is consistent with the presence of a force acting on particles near the plate which moves the particles away from the hot surface.

A comparison of the hydrodynamic and dark boundary layer thickness is shown in Figure 2. The dark boundary layer thickness appears to scale with the hydrodynamic boundary layer thickness. Similar results were obtained over a range of temperatures from 670 K to 1280 K and at velocities of 1.2 and

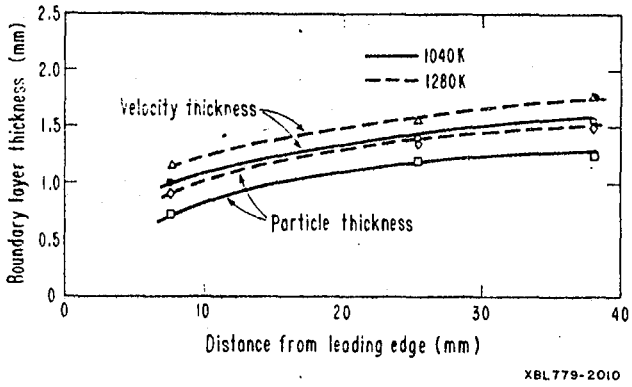


Figure 2. Comparisons of hydrodynamic boundary layer thickness ($U/U_\infty = 0.7$) and dark boundary layer thickness.

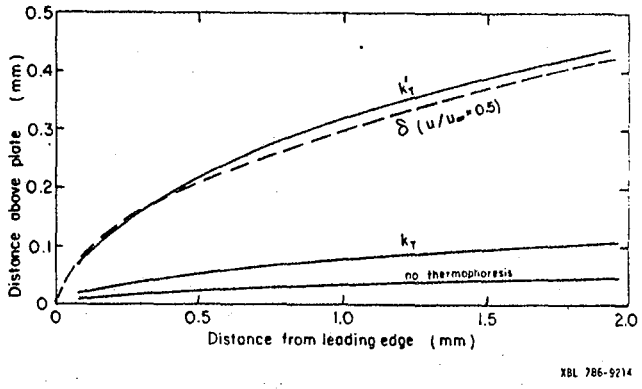


Figure 3.

Calculated dark boundary layer thickness.

2.6 m/sec. The ratio of the boundary layer thicknesses was also found to be approximately independent of the plate temperature, free stream velocity and the distance downstream from the leading edge, over the range of conditions investigated.

Additional experiments were performed to determine whether the particle disappearance was due to evaporation or burning up of the particles. The particles were passed through a CH_4/Air conical flame ($\phi = 1.1$, $U_\infty = 0.6$ m/s). It was found that the decrease in particle count rate agreed with the decrease in density across the flame front. Since the boundary layer temperatures are considerably lower than the flame temperature, the loss of particles near the plate surface is not due to their destruction by the elevated temperature.

PROPOSED EXPLANATION AND COMPUTATIONAL RESULTS

One possible explanation for the observed particle disappearance that may be consistent with the above observations is a phenomenon known as thermophoresis. It is a relatively well understood phenomenon with extensive description in the aerosol and particle research literature. Thermophoresis is the result of radiometric forces exerted by a gas on a nonuniformly heated object which it surrounds [1,2]. Under such conditions a flow is induced along the surface of the particle in the direction of increasing temperature, due to a temperature gradient along its surface. This gas flow, known as thermal creep, exerts an equal but opposite force on the surface in the direction of decreasing temperatures. For the case of a sphere in which the diameter is much greater than the mean free path, the thermophoresis force is given by [3]:

$$F_t = - \frac{6\pi M g D_p \lambda_g \sigma}{P(2\lambda_g + \lambda_p)} \frac{\partial T}{\partial x} \qquad (1)$$

where D_p is the particle diameter, λ is the thermal conductivity, μ is the viscosity, P is the gas pressure, σ is the thermal slip factor and subscripts g and p denote gas and particle properties. The resulting motion of a particle in a fluid flow with a temperature gradient then represents a balance between thermophoresis forces (Eq. (1)) and Stokes drag. This is given by the following expression:

$$\frac{dv_p}{dt} = -\frac{k_T}{2\alpha}\frac{\partial T}{\partial y} + \frac{1}{2\alpha}(v_p - v_g) \tag{2}$$

where

$$k_T = \frac{2\sigma\,\lambda_g^2}{p\,\lambda_p} \tag{3}$$

$$\alpha = \frac{\rho_p\,D^2}{9\mu_g} \tag{4}$$

Equation (2) was introduced into a finite difference computer code previously developed to solve the governing differential equations for gas flow over a heated flat plate [4]. Particle trajectories were calculated for several different cases. Particles were introduced at 40 different locations across the boundary layer to determine the sensitivity of particle movement to distance from plate. The particles were also introduced at two different locations slightly downstream from the leading edge. Figure 3 shows the predicted dark boundary layer thickness as a function of distance along the plate. This is comparable to the approximate point at which the particle count decreased to zero in the experimental measurements. Also shown is the calculated hydrodynamic boundary layer thickness based on $u/u_\infty = 0.5$. The results presented are for a wall temperature of 1300 K and a free stream velocity of 3 m/s. The curves labeled "no thermophoresis" and k_T represent results for the case of particle motion under the influence of Stokes drag alone and for motion with the thermophoresis force. It can be seen that the calculated particle movement is significantly less than that found experimentally even when the thermophoresis effect is included. Variations of the x location of particle injection from x = 0.016 mm to x = 0.0016 mm had negligible effect on these results.

The coefficients k_T and α in Eq. (2) are based on properties of the bulk material, and there is some uncertainty in the values of these properties in medium sized particles. A set of calculations was made to determine the effect of variation in these constants. As can be seen in Figure 3, k_T must be increased by a factor of 25 ($k_T' = 25\ k_T$) before approximate agreement is obtained with experimental observations. On the other hand, the dark boundary layer thickness was found to be relatively insensitive to variations in α.

The particle trajectories were studied assuming that $k_T' = 25 k_T$. The thermophoresis force results in initial acceleration of the particles away from the surface until the Stokes drag force balances the thermophoresis force. Further downstream there is a small deceleration of the transverse particle motion due to both the decreased rate of thickening of the boundary layer and the reduction in the temperature gradient. Calculations were carried out with surface temperatures from 800 K to 1600 K, and the results were in reasonable agreement with the experimental observations of increased particle density at approximately half the hydrodynamic boundary layer, independent of surface temperature and distance from the leading edge.

As was mentioned above, it was necessary to increase the thermophoresis force by a factor of approximately 25 to obtain agreement between calculated and experimental results. In the calculations it was assumed that the particle temperature gradient was equal to that existing in the gas at the same location. It is possible, however, that due to radiative heating the temperature gradient in the particle is greater than that of the gas. As a limiting case,

the calculation was repeated with the additional assumption that the hot side of the particle was at the same temperature as the surface. The particle motion is significantly different than was found previously. In this case a rapid increase in dark boundary layer thickness occurs near the plate leading edge to a value somewhat greater than the hydrodynamic boundary layer thickness. Farther downstream, the rate of increase diminishes but the thickness ratio continues to increase with distance along the plate. Thus the predicted thickness ratio is significantly greater than that found experimentally.

CONCLUSIONS

The results of this investigation indicated that it may be possible to explain the particle motion normal to the streamlines in a heated boundary layer by the concept of thermophoresis. A much better understanding of the process would be obtained if the properties of the particles were known and the proper magnitude of the radiative heating were taken into consideration. Towards this aim, further experimental investigation is planned.

REFERENCES

1. Fuchs, N. A. 1964. The Mechanics of Aerosols, p. 66, Pergamon Press, New York.

2. Loeb, L. B. 1961. The Kinetic Theory of Gases, p. 353, Dover Publications, New York.

3. Waldman, L. 1961. Proc. Second International Symposium on Rarefied Gas Dynamics (L. Talbot, editor).

4. Schefer, R. and F. A. Robben, 1977. Catalyzed Combustion in a Flat Plate Boundary Layer II. Numerical Calculations. Paper presented at the Western States Section of the Combustion Institute, Stanford, October 17-18.

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