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EXPERIMENTAL OBSERVATIONS OF WAKE FORMATION OVER CYLINDRICAL SURFACES IN NATURAL CONVECTION FLOWS

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INTRODUCTION

Natural convection flows generated adjacent to horizontal cylinders, spheres and other submerged shapes has received considerable attention in the past. However, most studies concern the nature of the portions of such flows attached to the surface. These may be described by simplified mathematical models, such as boundary layer theory. The subsequent regions, where the flow may separate from the surface and rise perhaps as a buoyant plume, has not been considered in detail. The mathematical difficulties are extreme. apparently nothing is known concerning the possible occurrence in natural convection flows of the analogue of separation in forced flows. There have been no studies of these regions or demonstration of the flow reversal commonly observed in forced flows, although such terminology has often been used in describing natural convection flows. However, in such flow the mechanism must be very much more complicated. There is no external mechanism driving separation as does the pressure gradient in forced flows. This separates the flow. In natural convection the principal driving mechanism is the body force which operates only near the surface.

The experiment described here was an attempt to observe the nature of thermally induced convection flow on the upper side of a cylindrical surface, to determine some of its characteristics, and to study any flow separation and reversal near the surface. We are concerned with sufficiently vigorous flows so that the boundary-layer regime is found upstream. It is well known that similar boundary layers form on the opposite sides of a heated cylinder placed horizontally in an extensive fluid. The fluid in each of these layers generated by buoyancy forces will rise and move around the cylindrical surface toward the top. Near and at the top they merge to form a two-dimensional plume which rises above the cylinder. The present experiment was designed to attempt to observe the mechanism of this interaction and to detect any separation and secondary flows which may be generated.

Most previous studies of natural convection flow around spherical and cylindrical objects were concerned with either attached flows or only with overall transport characteristics. Merk and Prins [1] (1954) presented analytical results of the heat transfer around horizontal cylinders and spheres. They estimated the location of the region where the boundary layer was said to separate from the variation of the heat transfer around the heated surface. Bromhan and Mayhew [2] (1961) presented an experimental correlation of the heat transfer around spheres in air and also observed from smoke tests flow separation near the upper section of the sphere. The observed separation point depended on the location of smoke injection. Thus, there is some question of the meaning of these observations.

Kranse and Schenk [3] (1965) studied the natural convection from spheres by melting solid benzene spheres in liquid benzene. The local Nusselt number around the sphere was measured by recording the rate of decrease of the sphere's diameter. Schenk and Schenkels [4] (1968) carried out a similar experiment with melting spheres of ice in water. It was observed that when a positive thermal expansion coefficient prevails (above 4°C) the downward boundary layer separates ahead of the lower stagnation point.

The only analytical study of wakes in natural convection flows was presented by Yang [5] (1964). The region above a heated finite thin vertical plate was considered by boundary-layer analysis. These results do not apply to wakes formed above thick bodies. Thus, separation in natural convection flows has been observed on several occasions but apparently no understanding has been achieved concerning the flow behavior in a separated region or in the region of wake formation. The present communication concerns some visual observations of that region over a heated cylindrical surface submerged in water. The experiment is described below.

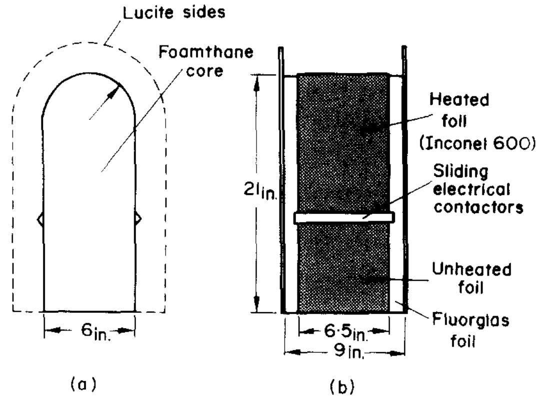

FIG 1. Diagram of the cylindrical surface used for the study of the wake in natural convection flows (a) side view (b) front view.

THE EXPERIMENT

A glass tank of dimensions 30 by 30 by 36 in. high, initially filled with distilled water, was used for the experiment. Since the formation of air bubbles on the heated surface would disrupt the flow during the experiment, the system was provided with a water heater, a water cooler and a circulating pump. A small flow of water was continually boiled, vented and cooled to remove the dissolved air. This system was operated until no bubbles were observed on the heated surface. The tank was enclosed in Foamthane insulation sheets to prevent exchanges of heat with the environment, which would generate circulations in the tank. An opening in the insulation permitted the entrance of the light beam. Observations and photographs of the wake region were made through a second opening.

The visualization of the flow was done by introducing small solid particles into the fluid. Granules of Pliolite plastic of density 1·026 were pulverized and then mixed with water in a secondary container. The particles that remained in suspension with the water for several hours were introduced in the main tank, and we assume that the particles perfectly follow the fluid motion. The observation station was illuminated with a narrow beam, $\frac{1}{8}$ in. thick and 5 in. wide, of laser light. The laser beam was first expanded, collimated and then concentrated to a narrow beam by a combination of spherical and cylindrical lenses. Pictures of the particles paths were taken on a high speed photographic film (3000°ASA). The particles trajectories appear as visible bright lines. This visualization method has been extensively used for both forced and natural convection flows with success.

The essential features and dimensions of the first heated body used in this experiment are shown in Fig. 1. It consists essentially of a solid core of Foamthane insulation material covered by a thin (0·003 in. thick) impermeable Fluorglass adhesive foil. The exterior surface of the waterproof body was covered with a thin inconel foil 0·0005 in. thick and 6·5 in. wide that served as an electrical heater. The length of the electrically heated surface could be varied by moving the mercury-filled electrical contactors up and down. A generation of a two-dimensional flow was essential for this experiment. Incoming flow from the sides was prevented by two sheets of transparent plastic as seen in Fig. 1. The electrical power delivered to the foil was externally adjusted to the desired level.

A second cylindrical body used in this experiment was a $\frac{1}{4}$ in. thick aluminum tube of $12\frac{3}{4}$ in. diameter and 12 in. length. Both ends were closed by a solid insulating material. The surface was heated by admitting steam inside. The condensate was drained as formed. This cylinder was used only for the study of steady state flow since the thick wall required a considerable time to reach steady state temperature.

EXPERIMENTAL OBSERVATIONS AND CONCLUSIONS

The flow adjacent to the cylindrical region shown in Fig. 1 was observed for a range of surface heating rates and with the electrical contactors positioned at several vertical locations along the foil. Thus, the flow Grashof number at the beginning of the cylindrical region could be varied over a wide range. The maximum value of the flux Grashof number obtained at that location, for the maximum heating rate and foil length was $1{\cdot}3 \times 10^{12}$. This corresponds approximately to an average surface temperature difference of 23°F and a temperature difference Grashof number of $0{\cdot}5 \times 10^{10}$. The flow under those conditions is essentially laminar. Typical photographs of the resulting wake formed at the top of the cylindrical section are shown in Figs. 2 and 3. The results of Fig. 2 are for steady flows for two flow conditions. The boundary layers coming along the two sides are seen to join and rise in a plume flow. These photographs show that no separation of the boundary layer, with asso-

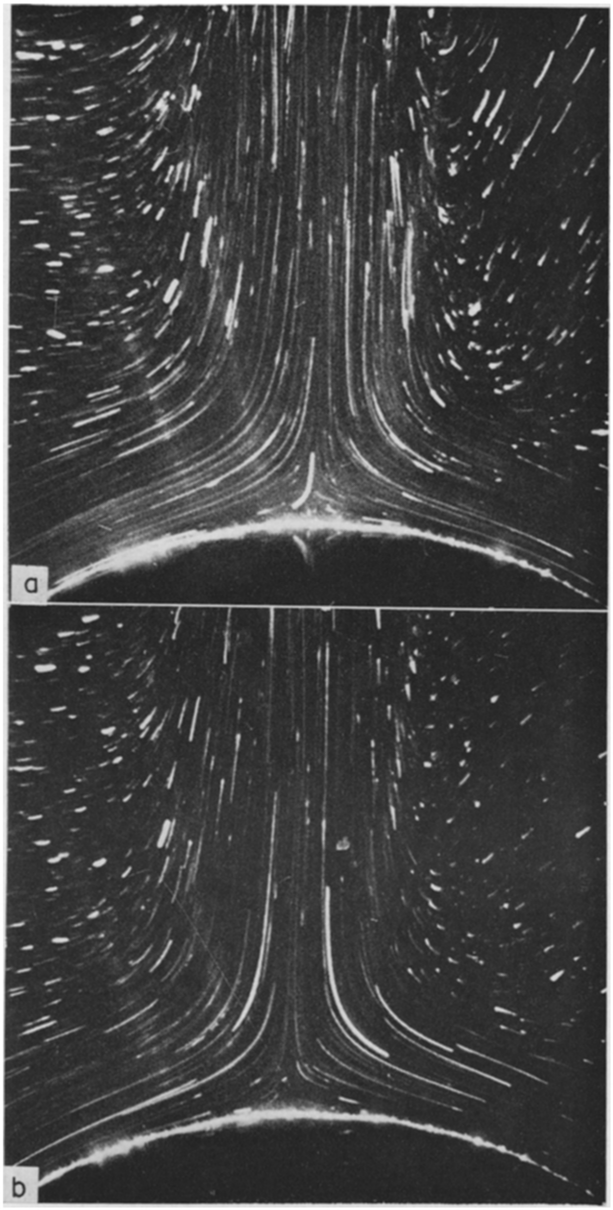

FIG. 2. Steady natural convection flows in the wake of the horizontal heated cylindrical surface (Fig. 1) in water. At the beginning of the cylindrical region: (a) $Gr = 0{\cdot}5 \times 10^{10}$, (b) $Gr = 0{\cdot}25 \times 10^{10}$.

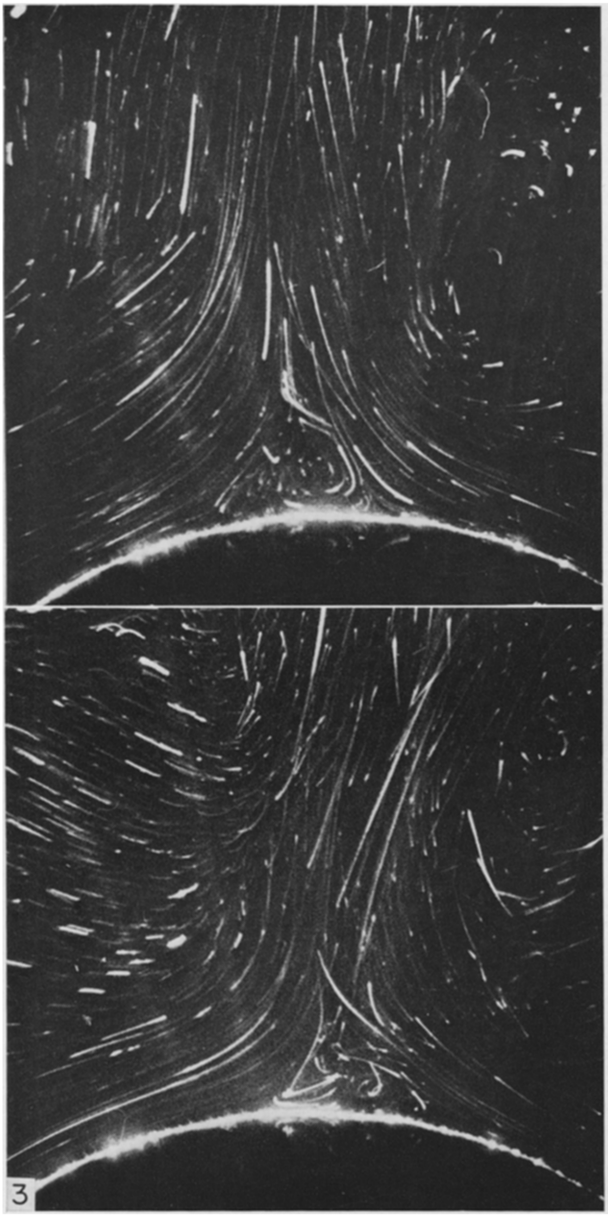

FIG. 3. Starting transient on natural convection flows in the wake of the horizontal heated cylindrical surface (Fig. 1) in water.

ciated flow reversal, takes place. The same results were found for the other steady flow situations investigated.

Wake formation was also observed above the upper part of the steam heated cylinder. The surface of the cylinder was approximately isothermal, due to the condensation of steam on the interior wall. The Grashof number based on the cylinder diameter was 1×10^{10}. The steady state flow patterns were identical to those discussed above for the other geometry.

During transient flow periods for the geometry shown in Fig. 1, very irregular flow separation and reversal were seen near the center of the upper part of the surface for short periods. Figure 3 shows such a regime. Stagnation points are seen near the centerline of the surface and are similar to the kind of flow reversal which appears in a forced flow separated by unfavorable pressure gradients. However, this separation during the transient period is thought to be generated by the incoming leading edge effects. No such reversals were observed after the starting transient. Since there was no noticeable fluid circulation or stratification in the tank during the short experiment, it is not thought that the observed separation was caused by peculiar conditions in the tank.

The above observations suggest that the usual expression "flow separation" is not an appropriate term for natural convection flows. The suggested mechanism is apparently not in operation as a flow turns away from the surface under increasing action of a component of the buoyancy force normal to it. Of course the flow must separate as two opposed buoyancy generated layers from opposite sides of a surface meet at the top. But the impetus for this, the pressure field which changes their direction, is generated in the flow layers and immediately adjacent to the surface, not in an external region.

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A NOTE ON THE TURBULENT SCHMIDT AND LEWIS NUMBERS IN A BOUNDARY LAYER

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NOMENCLATURE

D_1, molecular mass diffusion coefficient of component 1 into component 2, $\dot{m}_1'' = -D_1\rho\frac{\partial Z_1}{\partial y}$ [m²/s];

$\frac{k}{U_\infty}$, $\frac{m_{1w}''}{\rho_\infty U_\infty(Z_w - Z_\infty)}$, mass diffusion coefficient, [dimensionless];

Le_t, $\frac{Pr_t}{Sc_t}$, turbulent Lewis number [dimensionless];

$\dot{m}_1''$, mass flux of component 1 into component 2 [kg/m²s];

Pr_t, $\frac{\varepsilon_M}{\varepsilon_H}$, turbulent Prandtl number [dimensionless];

Sc, $\frac{\nu}{D_1}$, molecular Schmidt number, [dimensionless];