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Experimental investigation of thermal transport from a heated moving plate

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Abstract—An experimental investigation is carried out to study the thermal transport from a heated aluminum plate being cooled due to its own movement at uniform velocity in a stationary extensive fluid. Time-dependent temperature measurements are carried out for the plate moving vertically downward in water and moving vertically upward or downward in air. The local and average heat transfer rates from the plate are determined. The temperature distribution, within the moving plate and in the induced flow is measured. The thermal field associated with the flow is visualized by means of a shadowgraph. Interesting flow structures, due to separation, are observed when the flow induced by the plate motion and the buoyancy force oppose each other. The experimental results are in fair agreement with the numerical results obtained earlier.

1. INTRODUCTION

IN MANY manufacturing processes such as hot rolling, hot extrusion, wire drawing, continuous casting, fiber drawing and crystal growing [1–3], energy transport occurs between a moving material and the ambient medium. The nature of the flow field and the temperature distribution within the material undergoing the thermal process, as well as that within the cooling or heating medium, are characteristic of each process and depend upon many process variables such as heating or cooling rates, material properties and the geometry. In most cases, the moving material is hotter than the surroundings and the energy transfer to the ambient occurs at the surface of the moving material. In the case of continuous casting, a liquid spray [4] is often used to cool the hot material. Sometimes, cold air is blown across the hot material or the material is passed through a pool of recirculating coolant fluid [3].

When the material is moving in a vast expanse of a stationary medium and in the absence of an externally driven flow, the flow present is largely due to the motion of the material itself. Viscous effects at the surface of the material induce flow in an otherwise quiescent ambient medium. When the temperatures are high enough, buoyancy effects also generate a significant flow which aids or opposes this induced flow, depending upon the orientation. There are many situations in the manufacturing industry, especially in metal forming and heat treatment, in which one encounters energy transfer to the surroundings, from a moving material, as outlined above. In many process industries, the cooling of cylinders, threads or sheets of material is of importance along the production line [5]. The required length of the cooling medium depends upon properties like heat capacity, thermal conductivity of the materials involved and the exit conditions at the die, such as temperature, geometry and the speed of extrusion or withdrawal.

A few other processes that involve thermal transport from a moving surface are hot or cold rolling of metal sheets [3] and continuous casting [4]. In the case of wire drawing and continuous casting processes, the material is cooled by passing it through a colder ambient medium like water or, in some cases, just quiescent ambient air. The properties of the processed material usually depend upon the rate at which the energy is being removed and the resulting temperature gradients. In the case of rolling of steel billets, the molecular structure of steel which is being cooled, strongly depends upon the cooling rate. This, in turn, affects the physical properties of the steel. Similarly, in the drawing of optical fiber, the temperature field in the material affects the diffusion of impurities and, thus, the quality of the final product. This emphasizes the importance of heat transfer in these processes of practical interest.

1.1. *Basic features of the transport process*

The transport process is time dependent at the onset of the process when the material with a leading edge

NOMENCLATURE

C	specific heat
d	half plate thickness
Gr	Grashof number, $g\beta(T_0 - T_\infty)d^3/\nu_f^2$
h	local heat transfer coefficient
k	thermal conductivity
k_f/k_s	thermal conductivity parameter
Nu_d	local Nusselt number, hd/k_f
Pe	Peclet number, $U_s d/\alpha_s$
Pr	Prandtl number, ν_f/α_f
R	physical properties parameter, $(k_f\rho_f C_f/k_s\rho_s C_s)^{1/2}$
Re	Reynolds number, $U_s d/\nu_f$
t	time
T	temperature
U_s	velocity of the plate
x	coordinate along the midplane of the plate
y	coordinate normal to the plane of the plate.

Greek symbols

α	thermal diffusivity, $k/\rho C$
β	coefficient of thermal expansion of the fluid
θ	dimensionless temperature, $(T - T_\infty)/(T_0 - T_\infty)$
ν	kinematic viscosity
ρ	density.

Subscripts

c	centerline of the plate
f	fluid
s	plate
∞	ambient conditions
0	initial conditions.

Superscript

*	dimensionless quantity.

or surface emerges from a die or from a set of rollers. However, at large time, as the tip of the material moves away from the die, the process is expected to approach a steady-state convective transport circumstance. Due to the movement of the material, flow is induced in the fluid near the surface of the material, due to viscosity. This effect penetrates into the quiescent fluid, thus inducing a flow field [6–12].

In most practical situations, the temperature variation within the solid, the nature of boundary conditions at the die or the slot, the orientation of the plate with respect to gravity, and the variation of material and fluid properties, make the problem very complicated. The inclusion of the temperature variation within the material, gives rise to a conjugate boundary condition at the surface. This is particularly important when one is interested in controlling the temperature variation within the solid, which in turn determines the resulting characteristics of the material. Therefore, information on the conjugate transport is often essential in the design of the system.

This paper deals with the experimental investigation of some of the circumstances described earlier. The thermal transport from a long flat plate moving at fixed velocity, through water and air is considered. The conjugate nature of the problem is studied. The effect of buoyancy on the flow is also investigated.

A schematic representation of the situation involving energy transfer from a continuously moving surface is shown in Fig. 1. Assuming the flow generated due to the motion of a solid surface to be a boundary layer, Sakiadis [6–8] studied the characteristics of the flow over a continuous flat plate and a cylinder moving at a uniform velocity. Tsou *et al.* [12] experimentally showed that such a boundary layer flow indeed arises due to the material movement and has the general form sketched in Fig. 1. They found excellent agreement between the measured and predicted velocity and temperature profiles for laminar flow. A fair agreement was also obtained for turbulent flow. A few other investigators such as Jaluria and Singh [4], Horvay [13, 14], Chida and Katto [9, 10], Koldenhof [15] and Karwe and Jaluria [16–18] have employed various other analytical and numerical techniques to study the transport processes involved. Griffin and Thorne [19] experimentally observed the growth of the thermal boundary layer on continuously moving belts coming out of an oven, using optical techniques.

A few other modifications of the flow sketched in Fig. 1 have also been investigated analytically and numerically by Fox *et al.* [20]. Tsou *et al.* [11] carried out a linear stability analysis of the boundary layer flow on continuously moving plates. They found the

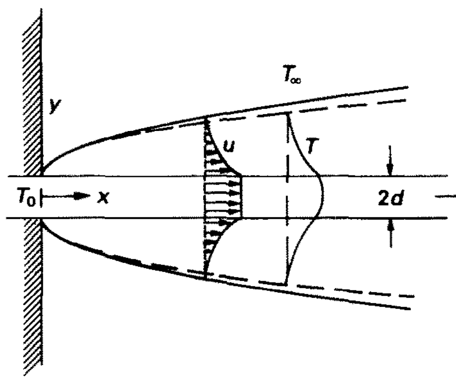


FIG. 1. Schematic of the flow and temperature fields generated by a continuously moving heated plate.

critical Reynolds number to be substantially higher than that for the Blasius flow, i.e. flow over a semi-infinite, stationary, flat plate.

In all the cases mentioned so far, the thickness of the moving material was considered to be negligibly small compared to the distance along the surface. However, in many practical problems, such as extrusion and continuous casting, interest lies mainly in the temperature distribution within the material, which is of finite thickness. In the case of glass fiber drawing, even though the thickness is small, the temperature distribution within the glass determines the resulting material flow and, thus, the properties of the product. The inclusion of conduction within the solid gives the problem its conjugate nature, i.e. coupling of the conductive and convective transport processes in the material and in the fluid, respectively. Recently, many investigators have shown the importance of conjugate of heat transfer in a variety of practical situations [21, 22]. Miyamoto *et al.* [23] have shown that the parameter k_f/k_s (see Nomenclature) plays an important role in the final temperature distribution. It is also shown that the parameter, $k_f\rho_f C_f/k_s\rho_s C_s$, relating the physical properties of the solid to those of the fluid, has a strong influence on the heat transfer. Recently, Dorfman [24] solved the problem of the cooling of a polymer tape issuing from a slot in a die, which is maintained at a fixed temperature. Dorfman also performed experiments with polymer fibers, using water as the coolant; and found good agreement with the theoretical predictions. A few other investigators have focused their attention on the cooling of continuously moving cylindrical fibers [25, 26].

In most of the studies mentioned above, the effects of thermal buoyancy force were neglected. However, buoyancy forces become important when the plate is moving sufficiently slow, for instance, in crystal growing and in continuous casting and when the temperatures are relatively high. This circumstance that involves mixed convection from a continuously moving flat surface has been considered in a few investigations [5, 27, 28].

This paper presents an experimental study of the thermal transport process associated with a continuously moving flat plate of finite length. The plate was heated to a uniform temperature and then moved at a uniform speed into the ambient fluid which was either water or air. The axial temperature variation within the plate and the transverse temperature variation within the fluid were measured. The effect of thermal buoyancy on the flow pattern was also studied qualitatively. No such work has been reported earlier in the literature. This study was undertaken to develop an experimental system and to obtain data which would provide better physical insight into the associated thermal transport.

2. EXPERIMENTAL SET-UP

As mentioned earlier, very few experimental results on the conjugate and mixed convection transport due to a moving plate, have been reported in the literature. The case in which the buoyancy force opposes the fluid flow induced by the plate motion has not been studied numerically or experimentally. As part of this investigation, experiments were conducted for situations involving conduction in the material and mixed convection transport in the fluid. Specifically, the cases studied are:

(a) A flat plate moving vertically upward and downward in air (aiding and opposing buoyancy situations, respectively).

(b) A flat plate moving vertically downward in water (opposing buoyancy situation).

The basic arrangement used for the experimental study is shown schematically in Fig. 2. Only a brief outline of the arrangement is given here. For further details, see ref. [17]. The system consists of a flat plate, the plate traversing mechanism, a tank containing the fluid, a heating unit, a thermocouple rack and a data acquisition system.

2.1. *Flat plate*

The flat plate, which simulates a moving material subjected to thermal transport, was 900 mm long, 300 mm wide and 5 mm thick aluminum. The plate was wide enough to neglect the edge effects and assume the flow and thermal fields to be two-dimensional. Due to the low thermal capacity of aluminum, the time needed to heat the plate to a desired temperature level was small. Due to the high thermal conductivity of aluminum, a good temperature uniformity (within 5%), across the plate, could be achieved without much difficulty. Also, aluminum is one of the common materials subjected to rolling and extrusion processes, and is, thus, suitable for this study.

To measure the temperature inside the plate, type T thermocouples were inserted midway across the plate width and halfway through the plate thickness, as shown in Fig. 3. A few thermocouples were also inserted at locations away from the mid-plane in order to check the temperature uniformity across the plate before each experimental run. The temperature variation in the plate was found to be generally less than 3°C in 100°C. The thermocouples were bonded to the plate with *Omegabond*™ 200 high temperature, high thermal conductivity, epoxy.

2.2. *Plate traversing mechanism*

The plate was mounted on an aluminum frame, as shown in Fig. 2, and could be traversed up and down the two guide shafts of cold rolled and polished carbon steel. The entire plate and frame assembly could be moved upward and downward at a fixed velocity, with the help of a gear-motor, chain and counter-weight arrangement, as shown in Fig. 2. Teflon journal bearings were used to glide the plate assembly up and down smoothly over the two guide shafts. At any fixed r.p.m. of the gear-motor, the time required to establish

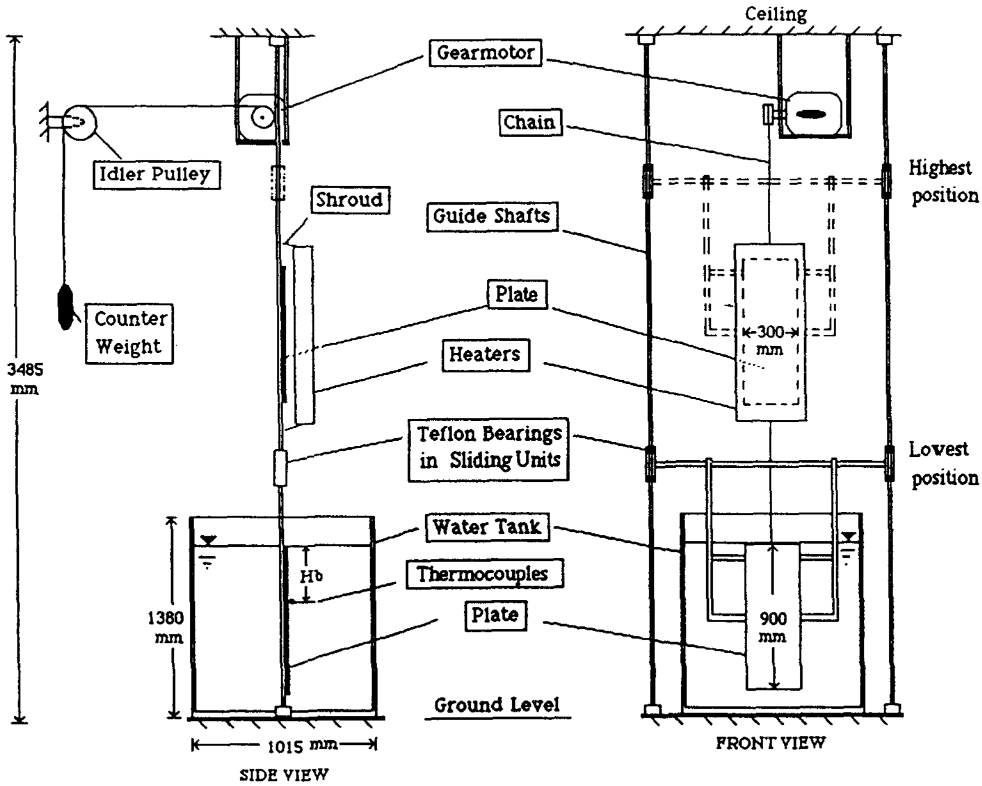


FIG. 2. Schematic of the experimental arrangement.

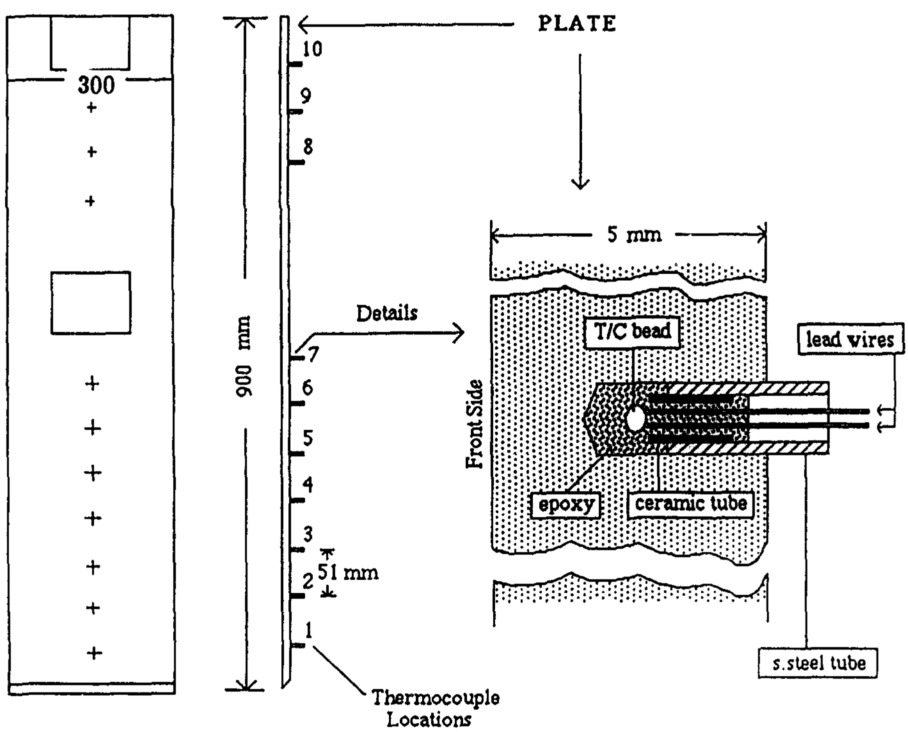


FIG. 3. Plate geometry and the locations of the thermocouples.

a constant speed of the plate was of the order of 1 s, starting from the rest position.

2.3. *Water or air tank*

The tank containing water or air, was made of 9.5 mm thick Plexiglas. The 1 m × 1 m × 1.3 m tank could hold up to 1.365 m^3 (360 gallons) of water. The tank was also suitable for experiments in air, since ambient disturbances had a small effect in the tank. The dimensions of the tank were chosen so as to simulate the conditions of a quiescent, extensive, ambient medium. The width of the tank was large enough to neglect any wall effects on the flow induced by the plate motion.

2.4. *Heating unit*

The heating unit consisted of four flat Nichrome coil heaters embedded in ceramic plates. In order to heat the plate to a desired temperature level, the plate was positioned in front of the heaters. The gap between the aluminum plate and the heaters was about 80 mm. The plate was mainly heated by radiation from the heaters. The output of each heater was controlled through a variable transformer and a temperature controller. During the heating-up, both the plate and the heaters were enclosed in a shroud of aluminum foil. This reduced the radiation losses and formed an enclosure. It also reduced the total time required to heat the plate up to a desired temperature level. Typically, it took about an hour to heat the plate from room temperature (20°C) to about 90°C, which was the maximum temperature of the plate for experiments in which water was the ambient fluid. The final temperature distribution within the plate was almost uniform, with a maximum deviation of about ±2°C. The average temperature was employed in characterizing the transport process.

2.5. *Thermocouple rack*

To measure the temperature distribution within the flow induced in the fluid by the motion of the plate, a thermocouple arrangement was made, as shown in Fig. 4. This arrangement was found to be suitable for measuring the temperature distribution across the flow, normal to the plate surface, assuming temperature uniformity across the width of the plate and two-dimensionality of the induced flow field.

As shown in Fig. 4, five thermocouples and a locator pin were mounted on a Plexiglas arm which could swivel about the vertical axis, thus changing the angle θ_w. The angle θ_w also determined the normal distance of each thermocouple from the plate surface. With the locator pin touching the plate, if the distance, S, between the consecutive thermocouples is known, the normal distance of each thermocouple from the plate surface could be determined using the value of θ_w. The value of S was 2.5 cm and that of θ_w was typically 9°. This would then yield the temperatures at various y locations across the flow, at a given instant of time. To make sure that all the thermocouples remained at a fixed distance from the surface of the plate, the locator pin was kept in contact with the plate surface. This kept all the thermocouples at fixed distances relative to the plate, during the plate motion which was upward or downward.

2.6. *Data acquisition system*

The data acquisition system used to perform the task of rapid temperature measurements was an APPLE IIe based Keithley Series 500 measurement and control system. The block diagram of the data acquisition system and the flow of data are shown in Fig. 5. For further details see ref. [17].

The major task of the data acquisition system was to measure the output from the nine thermocouples inside the plate along its midplane and five in the thermocouple rack. In addition, all the 14 output values had to be read within a very short period of time to get an almost instantaneous variation of temperature within the plate and the flow field. This required small sampling times, which were of the order of 10^{-1} s to record the output of all the thermocouples.

Additional quantities that were then measured were the velocity U_s of the plate, by timing the motion over a fixed distance, the vertical locations of thermocouple rack with respect to the water level, and the time measured from the instant at which the plate started moving. The time at which the tip of the plate entered

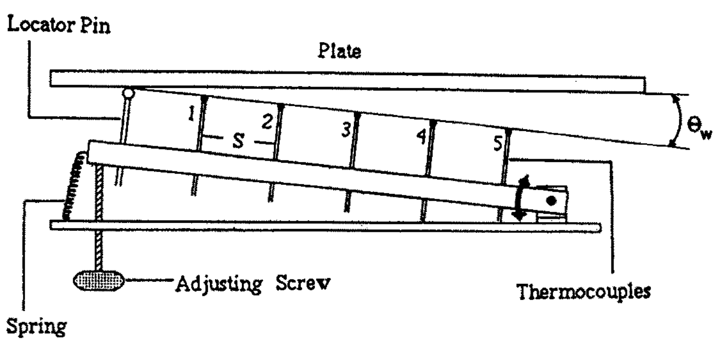


FIG. 4. Thermocouple arrangement to measure the temperature distribution in the flow (top view).

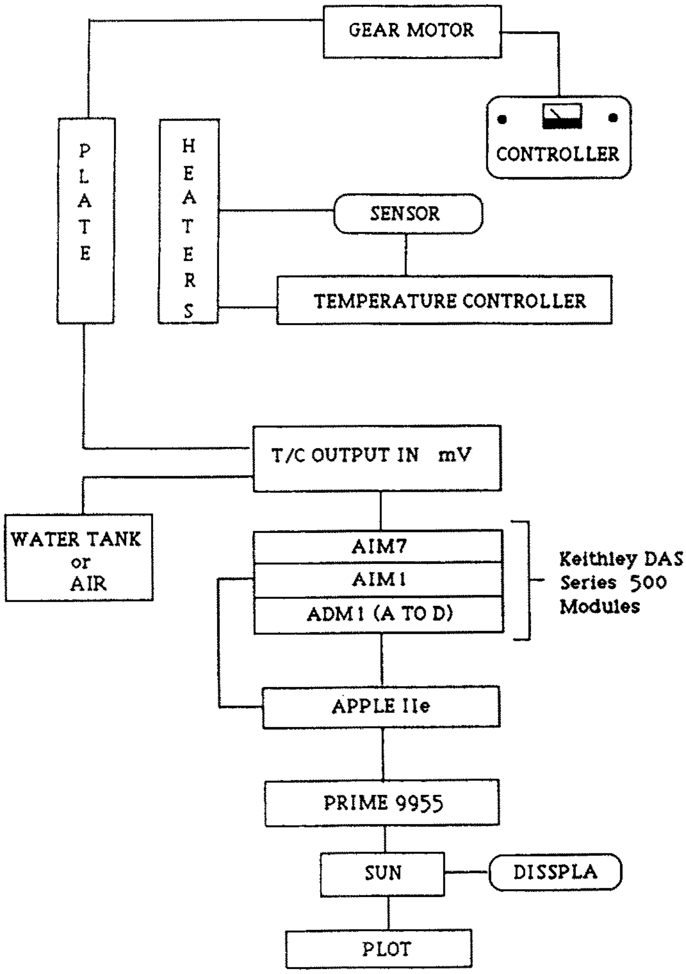


FIG. 5. Data acquisition system and the flow of data.

the water surface was also recorded for experiments with water.

For the aluminum plate and air, or water, as the working fluid, the ranges of the various parameters and quantities covered during the experiments, are given below:

plate velocity, U_s	3–100 mm s^{-1}
plate temperature	25–100°C (limited due to water)
Reynolds number, Re	0–250 in water; 0–20 in air
Peclet number, Pe	0–3.0
Grashof number, Gr	0–25 000 in water; 0–1000 in air
Gr/Re^2	0–2500
physical properties parameter, R	7.24×10^{-2} for aluminum and water; 2.57×10^{-4} for aluminum and air
thermal conductivity parameter, k_f/k_s	2.94×10^{-3} for aluminum and water; 1.35×10^{-4} for aluminum and air.

All the material and fluid properties are taken from *Marks' Handbook for Mechanical Engineers* [29] and from Gebhart [30].

3. RESULTS AND DISCUSSION

The results reported in this paper are for the experiments conducted with the aluminum plate, and employing water or air as the ambient fluid. With water, only the case of the plate moving vertically downward into the quiescent tank of water could be studied with the present experimental system. In this case, the buoyancy force is directed upward, whereas the flow induced by the plate motion is downward. With air as the fluid, experiments were carried out with the plate moving vertically upward, as well as vertically downward. The case of a hot plate moving upward is, thus, the aiding mixed convection flow situation, since the buoyancy force is in the direction of the forced flow. Similarly, the opposing mixed convection circumstance is obtained for the downward motion of the plate.

Test runs were carried out to calibrate and check the repeatability of the temperature measurement system. These tests were carried out on the same aluminum plate. The plate was heated and the temperature of the plate was brought to a uniform level. Then it was allowed to cool by natural convection at ambient conditions. The temperature variation across the natural convection thermal boundary layer set up on the plate surface, was measured at the midpoint of the plate using the thermocouple rack described earlier. The temperature variation was compared with the similarity solution [31] and the agreement was found to be good. To check the repeatability, test runs were performed under the same experimental conditions on two different days. The temperature variation along the centerline of the plate, for the two test runs, was compared. The deviation was within 5%.

The data obtained in each run consisted of 20 samples, each sample containing temperature values indicated by each of the 14 thermocouples (nine in the plate and five in the fluid) at a given instant of time. The velocity of the plate, U_s, was obtained from the time required to travel a measured distance. The value of x, the axial coordinate, was always measured from the point where the plate entered the ambient fluid. The location of the water level on the plate surface, at any instant of time, can be calculated knowing the plate velocity U_s and the time at which the leading edge of the plate enters water.

The experimental results were plotted in terms of the following dimensionless quantities:

$$X^* = x/d, Y^* = y/d, t^* = tU_s/d, \theta = \frac{(T-T_\infty)}{(T_0-T_\infty)} \quad (1)$$

where X^*, Y^*, t^* and θ are dimensionless. The physical quantities employed in the definitions above are the characteristic of the thermal transport process considered here, namely, d is the half plate width, U_s the plate velocity, T_0 the plate inlet temperature and T_∞ the coolant or ambient temperature.

3.1. *Results for water*

As mentioned earlier, all the experiments with water involved the opposing buoyancy situation. In addition, the temperature of the plate had to be maintained below 100°C so as to prevent any boiling when the plate was immersed in water. Figure 6 shows the results for the aluminum plate moving vertically downward at $U_s = 7$ mm s^{-1} into water in the tank. Figure 6(a) shows the variation of the plate temperature with time, as measured by the various thermocouples within the plate. Each curve represents the time–temperature record of a given thermocouple. The arrow indicates the time at which a particular thermocouple entered the water and the corresponding temperature. It is seen that the local temperature of the plate has already dropped by a significant amount even before it enters the water. This suggests a strong upstream penetration of conduction effects, i.e. the effect of energy loss to the water propagates along the plate in the direction opposite to the plate motion. The drop in the plate temperature, in air, before it enters the water, was found to be small, as expected. The portion of the plate which is in water is much cooler than the rest of the plate. This temperature variation along the plate length results in strong longitudinal conduction transport, thus lowering the plate temperature before it enters water.

Figure 6(b) shows the corresponding spatial temperature distribution within the plate at various instants of time. The temperature variation within the plate, before it enters the water (first sample) is fairly uniform, to within 5%. From the successive plots shown in Fig. 6(b), one can ascertain whether the temperature variation within the plate is approaching the steady-state variation with increasing time t^*. However, due to the finite length of the plate, the steady-state situation could only be achieved approximately in the present set-up. At large times, particularly for small velocities, the steady-state situation was closely attained.

The flow induced in the water by the plate motion and the buoyancy effects was visualized using a shadowgraph. A parallel beam of light was used to obtain the shadowgraph. Figures 7–9 show a sequence of photographs indicating the thermal field evolving with time. For these figures, the velocity of the plate was 13, 20 and 37 mm s^{-1}, respectively. As seen from the photographs of Fig. 7, there are no oscillations in the flow and no flow separation is seen to occur. At higher values of the velocity, U_s, waves or disturbances appear in the flow. This is seen in Fig. 8 for a plate velocity of 20 mm s^{-1}. However, no flow separation seems to have occurred. At still higher values of velocity, as shown in Fig. 9, the onset of unsteady flow structures and flow separation near the top is clearly visible. Lumps of fluid mass are seen to travel upward and then separate from the plate. A few of the last frames in Fig. 9 show a strong recirculation, indicating hot and cold regions. The circulating flow was seen to be clockwise. This phenomenon occurred only at higher velocities of the plate.

The flow separation was not found to have a significant effect on the spatial variation of temperature within the moving plate. This is mainly due to the fact that the flow separation occurred in the regions where the plate had already cooled substantially to temperatures close to that of the ambient fluid. It is known [18] that the distance from the inlet at which the plate temperature approaches the temperature of the ambient fluid is mainly governed by the conductivity parameter k_f/k_s. For the case of water and aluminum, the value of this parameter was high enough to cool the plate to the ambient level before the entire plate was immersed.

To see the effect of the plate velocity on the final temperature distribution within the plate, the plate was initially heated to a uniform temperature of T_0 and was moved at different velocities. Figure 10 shows the temperature variation with time, for increasing values of the plate velocity, as measured by the first thermocouple which was located at 3.8 cm from the leading edge of the plate. At lower velocities, the temperature starts droppng earlier, even before the thermocouple has entered water. At higher plate velocities,

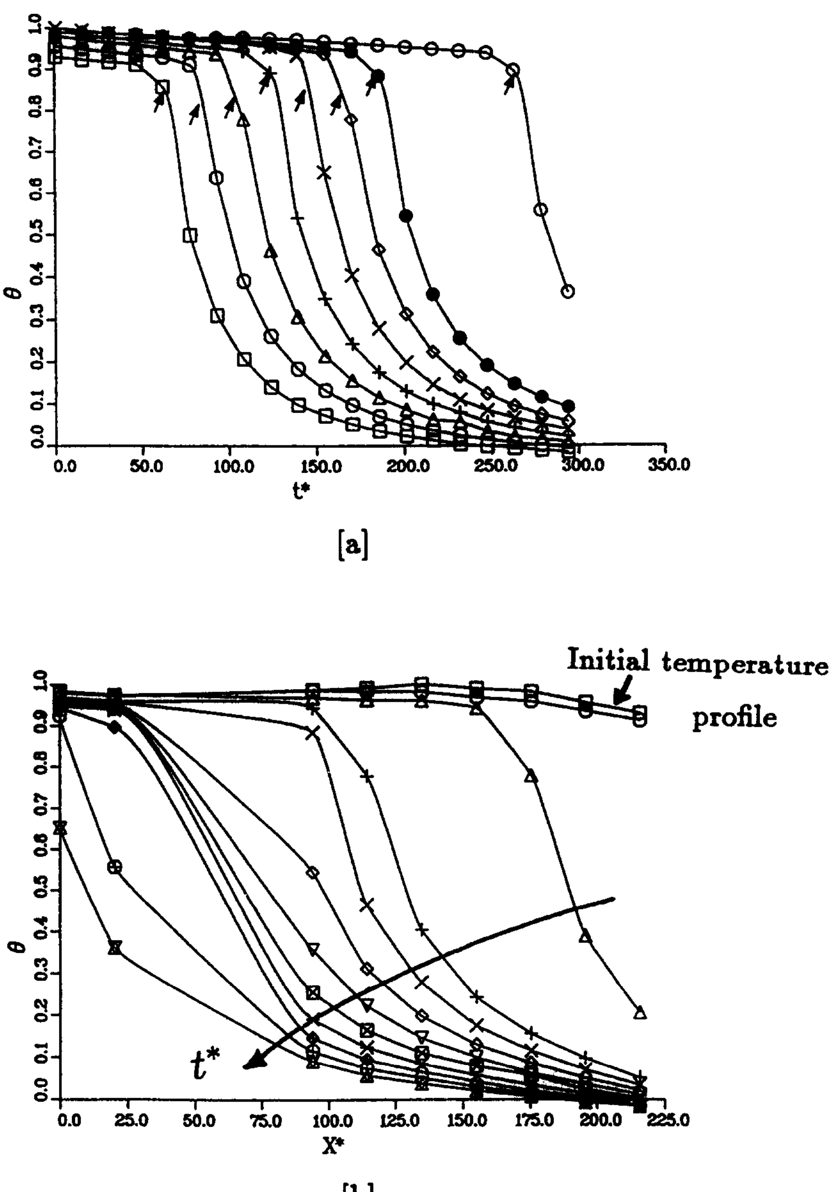


FIG. 6. Measured spatial and temporal distributions of temperature within the plate along the vertical midplane for the aluminum plate moving vertically downward at 7.0 mm s^{-1} in water: $Re = 26.6$, $Pr = 4.31$, $Pe = 0.20$, $Gr/Re^2 = 11.06$, $k_f/k_s = 2.936 \times 10^{-3}$. (a) Temporal variation of temperature within the plate. (b) Spatial variation of temperature within the plate.

the temperature drops more gradually. At larger plate velocity, the material has less time to cool, over a given distance. The induced flow velocities are also higher. However, the increased cooling due to higher flow velocities is not large enough to overcome the decrease in the exposure time for cooling over a given distance. Therefore, at higher velocity, i.e. higher Peclet number *Pe*, the temperature variation with time becomes more gradual, especially near the point of entry. This indicates that at lower Peclet number *Pe*, the downstream cooling effects penetrate over a larger upstream distance. Similar trends were also found in the numerical investigation carried out earlier [18].

3.2. *Results for air*

In the case of air, experiments were carried out for both aiding as well as opposing mixed convection flow situations. Unlike the experiments with water, there is no definite boundary or interface where the plate enters the ambient medium. Therefore, the edge of the heating unit, from where the plate starts emerging, is taken as the entrance point into the ambient air, since the heated plate leaves the heated zone at this location and enters the ambient fluid.

3.2.1. *Plate moving vertically downward.* Figures 11 and 12 show some typical results for a heated aluminum plate moving vertically downward in air.

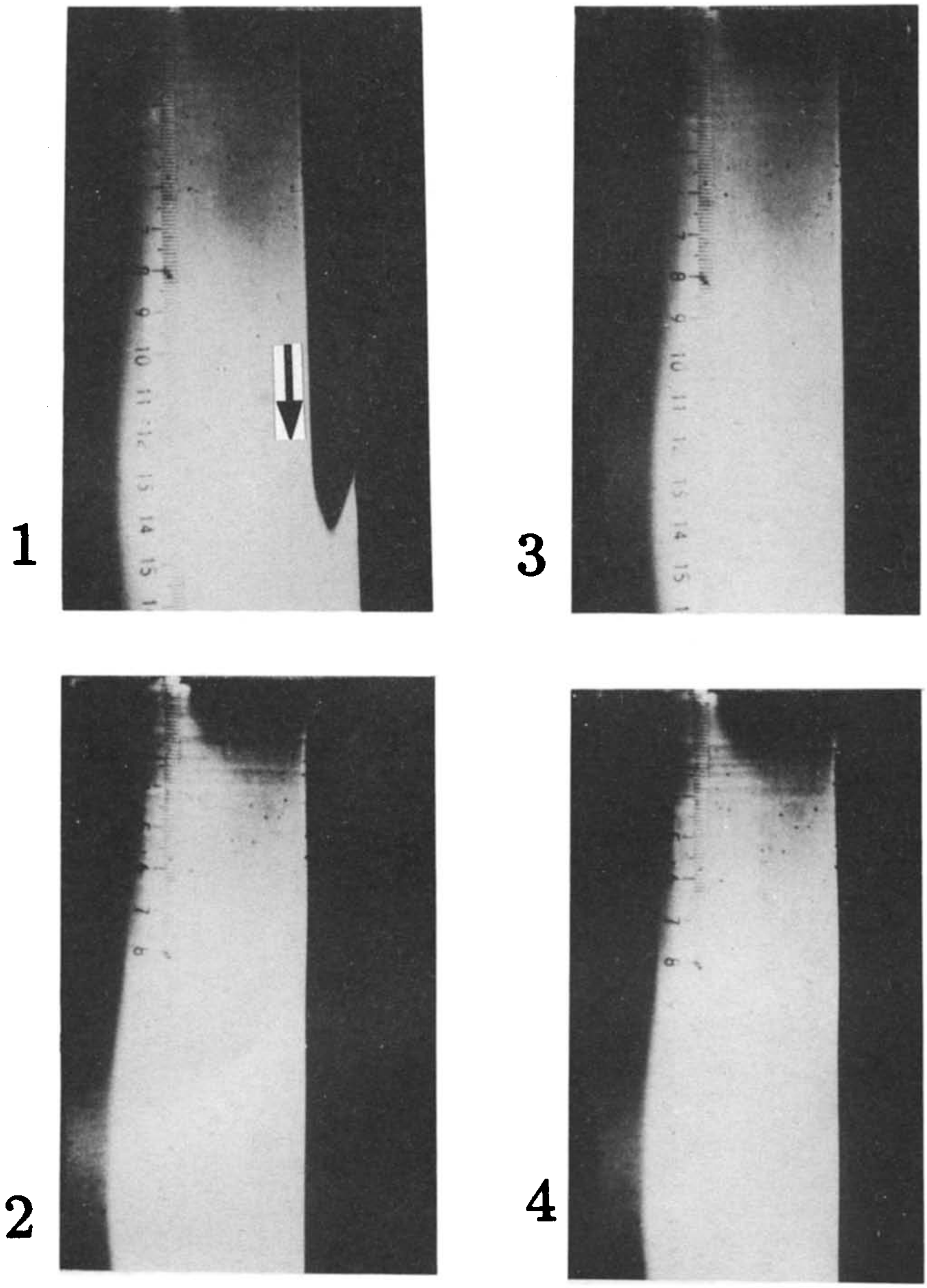


FIG. 7. Sequence of photographs showing the flow near the surface of the aluminum plate moving vertically downward at $U_s = 13$ mm s^{-1} in water: $Re = 49.32$, $Pe = 0.37$, $Pr = 4.31$ and $Gr/Re^2 = 3.65$ (opposed flow).

This represents a mixed convection flow with the buoyancy force opposing the flow induced due to plate motion. The temporal and spatial variations within the plate, along its midplane, are shown in Figs. 11(a) and (b), respectively, for a plate velocity $U_s = 4.4$ mm s^{-1}. During each experimental run, the temporal variation of temperature, measured by the thermocouples located along the vertical midplane of the plate, was recorded. Knowing the velocity of the plate, U_s, the location of the thermocouples on the plate and the instant of time, at which the tip of the plate entered the ambient fluid, the spatial variation of temperature along the vertical midplane of the plate, at any instant of time can be calculated. The temperature drop is found to be much smaller than that obtained in water, see Fig. 6. This is obviously expected physically, since

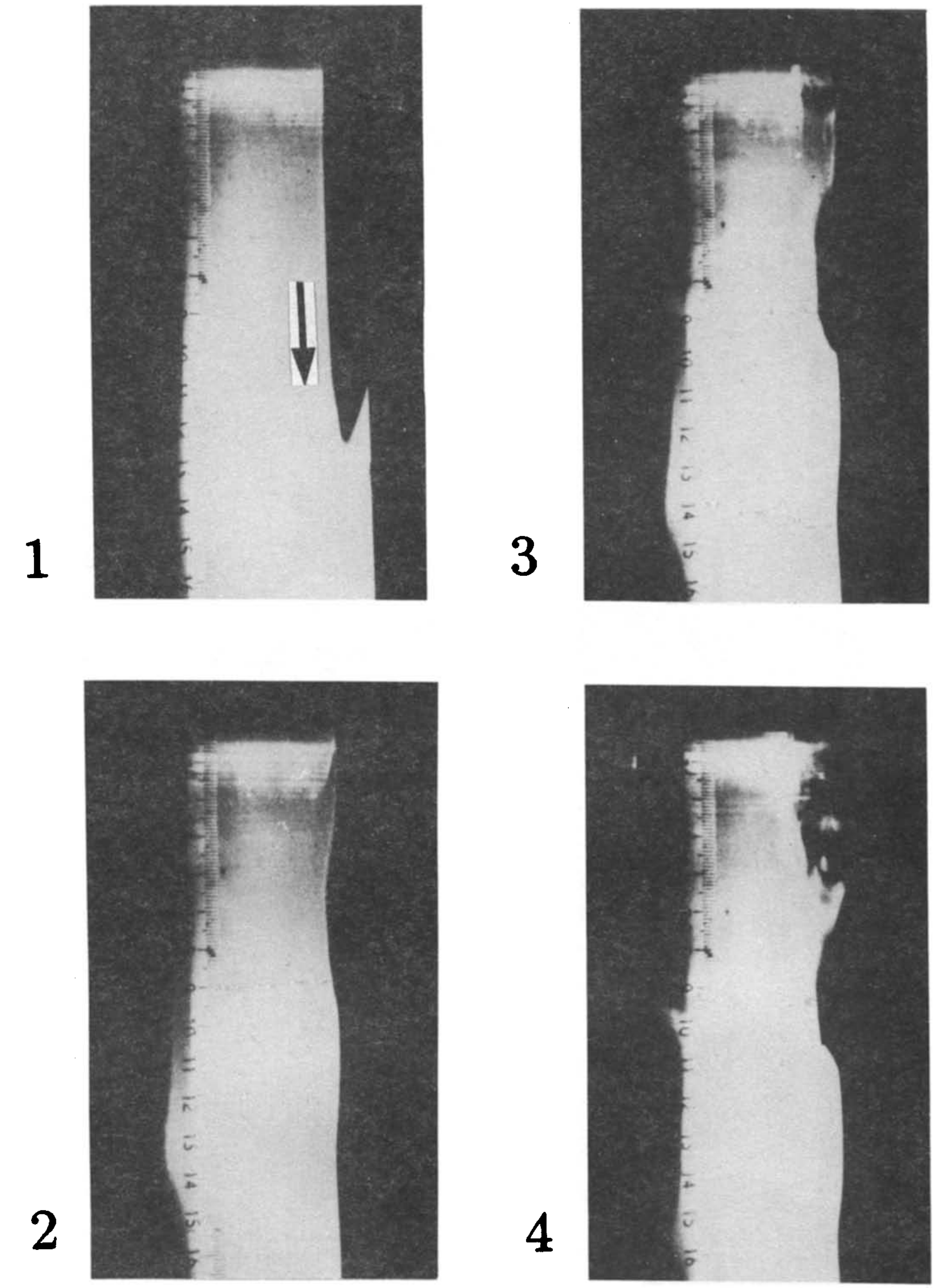


FIG. 8. Sequence of photographs showing the flow near the surface of the aluminum plate moving vertically downward at $U_s = 20$ mm s^{-1} in water: $Re = 75.87$, $Pe = 0.57$, $Pr = 4.31$ and $Gr/Re^2 = 1.54$ (opposed flow).

the value of the physical properties parameter R for air and aluminum is 2.57×10^{-4}, whereas, for water and aluminum it was 7.24×10^{-2}. Therefore, higher temperature levels are observed at a given x location and plate velocity U_s, at lower values of R [16, 17]. Similar trends have been reported earlier on the basis of numerical computations, see refs. [16, 18].

Figure 12 shows the corresponding temperature distributions in air. The temporal variations shown in Fig. 12(a) indicate that the transport processes have

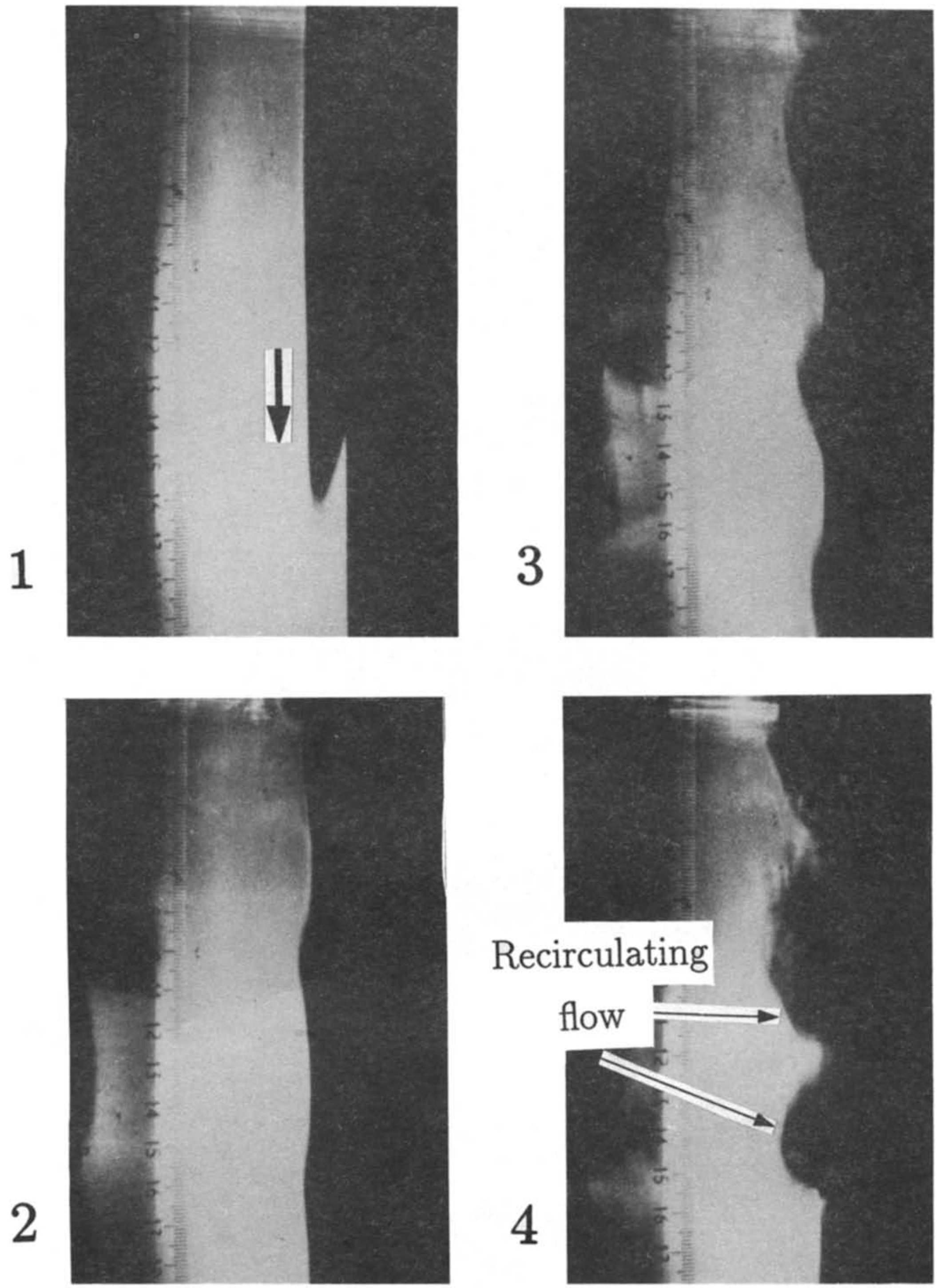


FIG. 9. Sequence of photographs showing the flow near the surface of the aluminum plate moving vertically downward at $U_s = 37$ mm s^{-1} in water: $Re = 140.36$, $Pe = 1.05$, $Pr = 4.31$ and $Gr/Re^2 = 0.45$ (opposed flow).

essentially reached steady-state conditions. Figure 12(b) shows the temperature distribution, in the fluid, normal to the plate surface. The thermal boundary layer is seen to be thicker for air than for water at a given x location and for a given value of the plate velocity U_s, as expected from the higher Prandtl number Pr for water.

In Fig. 13, the temperature variation measured by the thermocouple closest to the tip of the plate, 3.5 cm from the leading edge of the plate, is plotted at

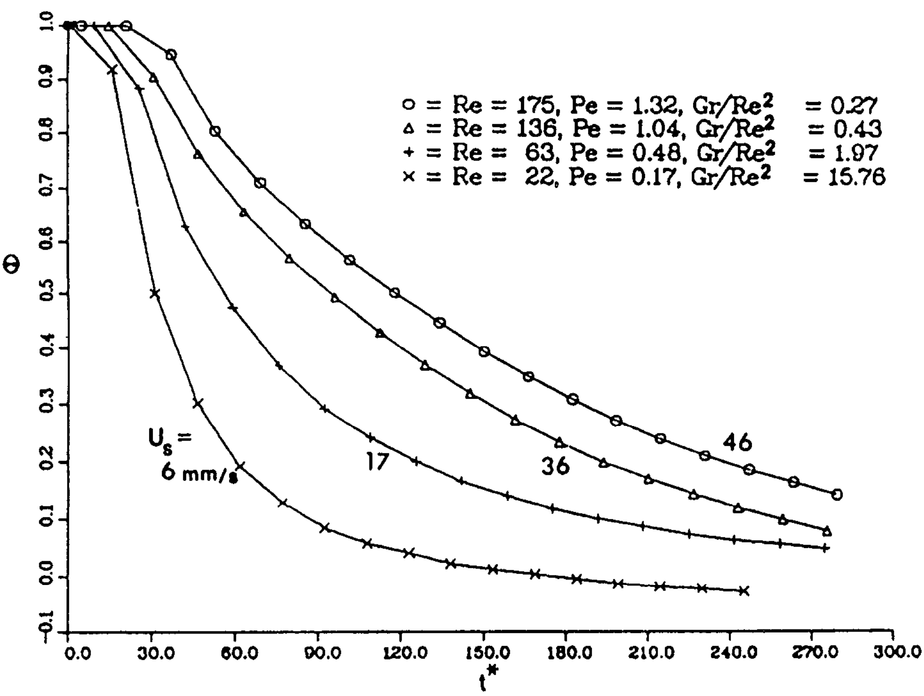


FIG. 10. Measured temperature profiles for the aluminum plate moving vertically downward in water at different velocities, showing the effect of the plate velocity on the temperature as measured by the thermocouple located at 3.8 cm from the leading edge of the plate.

different values of U_s. It shows a significant effect of velocity, indicating lower temperature levels at lower velocity. This is due to the small amount of energy entering the plate at the lower velocity, as discussed earlier. Also, at lower velocity, more time is available to cool, up to a given axial location x. This results in lower temperature levels. The results for air, shown in Fig. 13, can be compared with those for water, shown in Fig. 10. It is seen that in the case of water, the plate cools much more rapidly as compared to air. The effect of the Peclet number, Pe, on the temperature variation near the entrance point is seen to be more significant in the case of water.

3.2.2. *Plate moving vertically upward.* Experiments

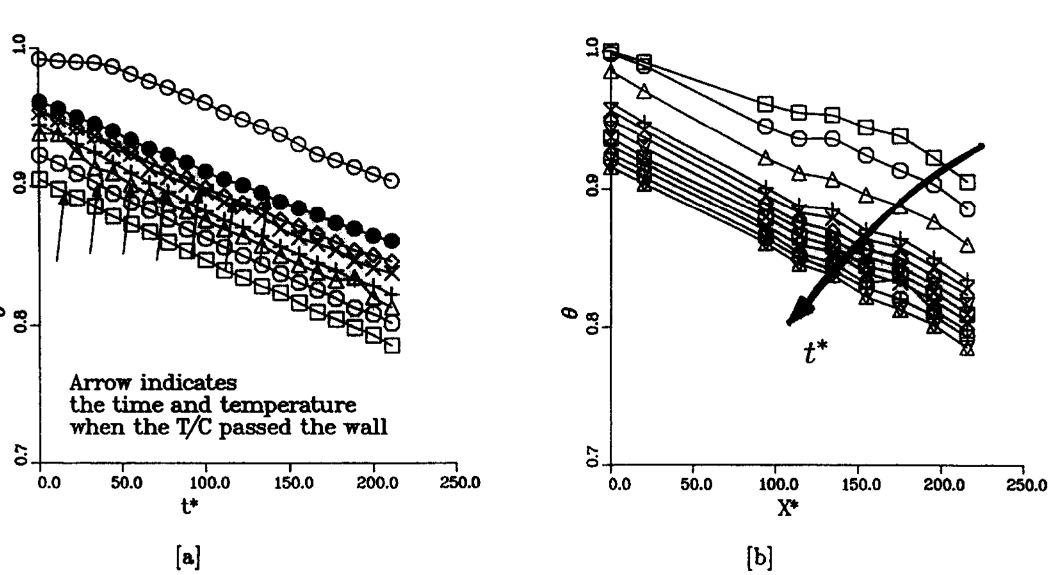


FIG. 11. Measured temporal and spatial temperature variations along the vertical midplane for the aluminum plate moving vertically downward at $U_s = 4.4$ mm s^{-1} in air: $Re = 0.65$, $Pe = 0.13$, $Gr/Re^2 = 222$, $Pr = 0.7$, $k_f/k_s = 1.35 \times 10^{-4}$. (a) Temporal variation. (b) Spatial variation.

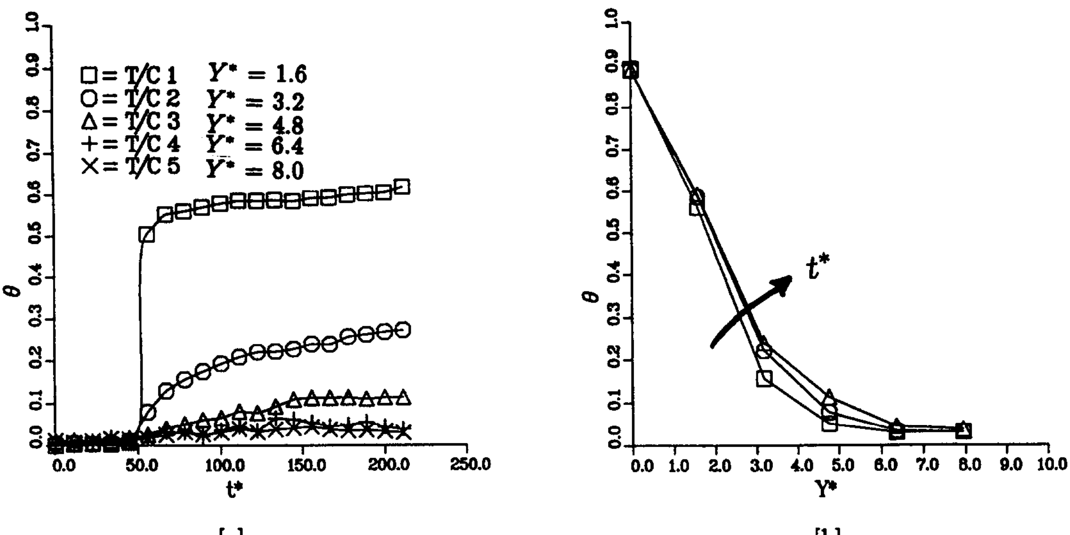


FIG. 12. Measured temporal and spatial temperature variations in air for the aluminum plate moving vertically downward at $U_s = 4.4$ mm s^{-1}, $Re = 0.65$, $Pe = 0.13$, $Gr/Re^2 = 222$, $Pr = 0.7$, $k_f/k_s = 1.35 \times 10^{-4}$. (a) Temporal variation. (b) Spatial variation.

were also carried out with the aluminum plate moving vertically upward at different velocities. In this case, the heating units were located at the bottom, near the tank floor, and the plate was moved vertically upward. When the plate was moved vertically downward, the heating units were positioned at the top. Therefore, in the latter case, the plume of hot air rising upward from the heaters did not affect the flow near the plate surface. However, when the plate was moved vertically upward, the plume of hot air rising upward from the heating units could affect the flow near the plate. To reduce this effect, a horizontal blocker plate was placed just above the heaters to divert the plume of hot air away from the moving plate.

Figures 14 and 15 show the results for the plate moving vertically upward at $U_s = 4.34$ mm s^{-1}. As shown in Fig. 14(a), the temperature levels have dropped by about 17% from the inlet temperature. This is more than the corresponding value for the plate moving vertically downward, in which case it was about 12%. This is because, when the plate is moving upward, the buoyancy force is in the same direction as the flow induced by the plate, which gives rise to an aiding mixed convection flow situation. This

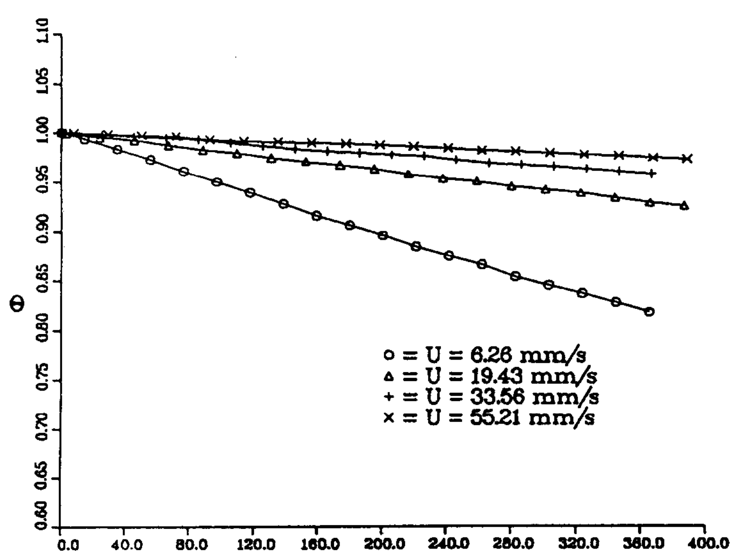
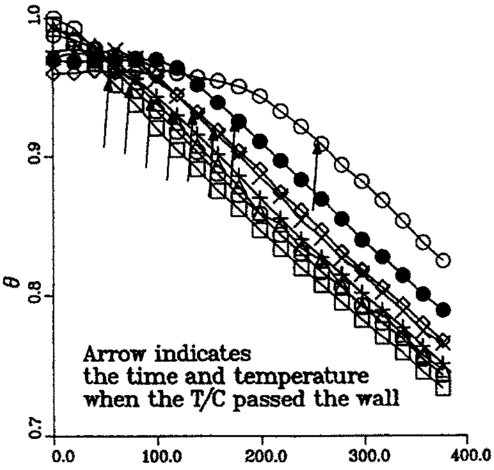
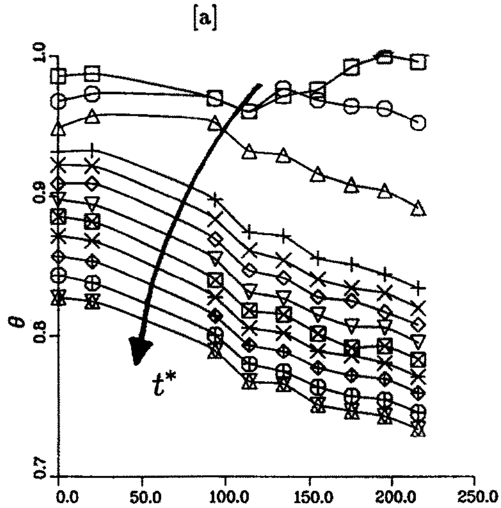


FIG. 13. Effect of the plate velocity U_s on the temporal variation of temperature at a distance 3.8 cm from the leading edge of the plate for the plate moving vertically downward in air.

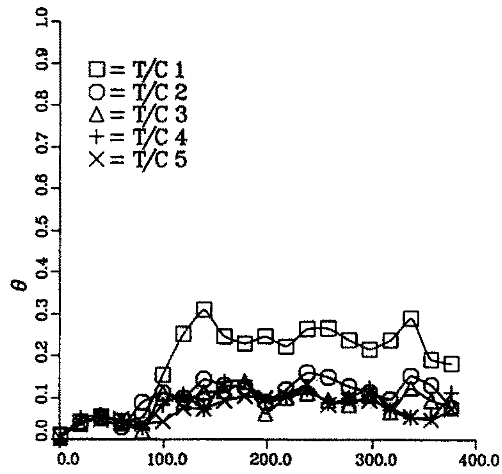


[a]

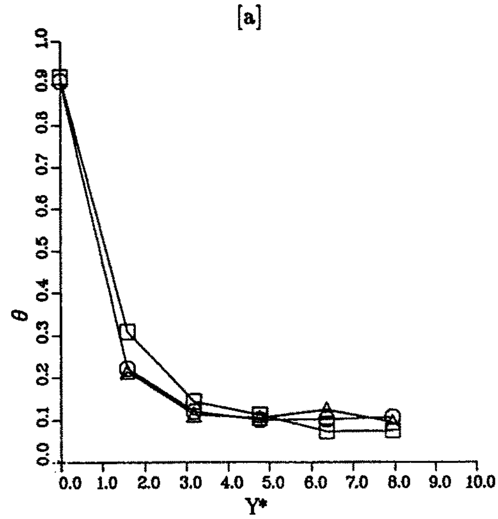


[b]

FIG. 14. Measured temporal and spatial temperature variations along the vertical midplane for the aluminum plate moving vertically upward in air at $U_s = 4.34$ mm s^{-1}: $Re = 0.65$, $Pe = 0.124$, $Gr/Re^2 = 230.0$, $Pr = 0.7$, $k_f/k_s = 1.35 \times 10^{-4}$. (a) Temporal variation. (b) Spatial variation.



[a]



[b]

FIG. 15. Measured, temporal and spatial temperature variations in air for the case of the aluminum plate moving vertically upward in air at $U_s = 4.34$ mm s^{-1}: $Re = 0.65$, $Pe = 0.124$, $Gr/Re^2 = 230.0$, $Pr = 0.7$, $k_f/k_s = 1.35 \times 10^{-4}$. (a) Temporal variation. (b) Spatial variation.

results in a higher rate of heat transfer, for a given velocity, and hence a lower temperature level. For a plate moving downward, the buoyancy force opposes the flow induced by the plate motion, thus reducing the heat transfer rate.

The effect of a variation in the plate velocity U_s on the temperature measured by the first thermocouple, which is 3.8 cm away from the leading edge of the plate, is shown in Fig. 16. Again, higher temperature levels are seen at higher velocities. These trends are similar to those seen earlier in Fig. 13 for a plate moving vertically upward, leading to an opposed mixed convection flow. The plate is found to attain lower temperature levels for the aiding mixed convection situation.

3.3. *Comparison between the results for aiding and opposing buoyancy circumstances*

It is expected that the results for the opposing and the aiding buoyancy situations, described in the previous sections, would differ from each other for given values of the governing parameters, particularly at large temperatures and small velocity levels. In the two extreme cases: (1) flow predominantly due to natural convection and (2) flow predominantly due to the induced flow arising from the plate motion, the results are expected to be independent of whether the motion of the plate is upward or downward. Of course, in the first case, the inclination with the vertical will be very important [31]. For the cases lying between these extremes, the flow is characterized by

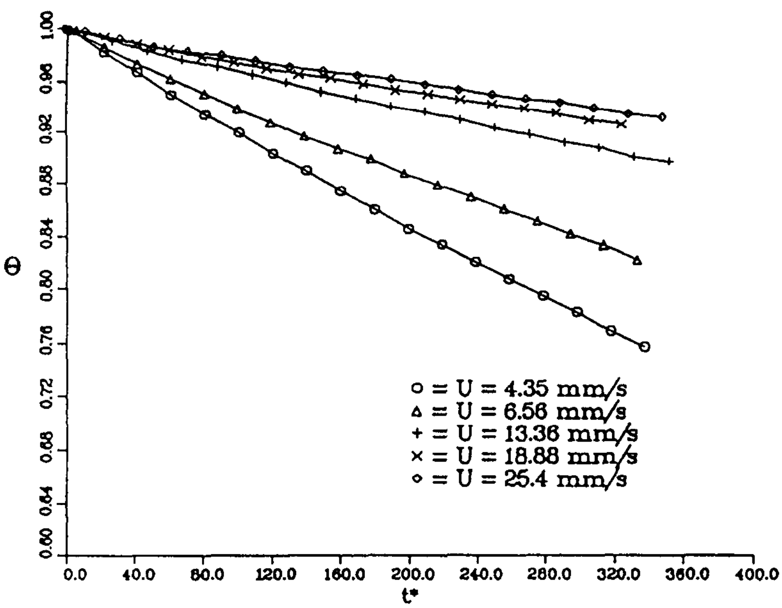


FIG. 16. Effect of the plate velocity U_s on the temporal variation of temperature at a distance 3.5 cm from the leading edge of the plate moving vertically upward in air.

the mixed convection heat transfer mechanisms and the direction of motion is expected to have a strong effect on the resulting temperature and flow fields. The results from the experiments carried out to verify these trends, are presented here.

Figure 17(a) shows the temporal variation of the temperature measured by the fifth thermocouple, which is located at a distance of 24.0 cm from the leading edge of the plate. The magnitudes of the velocity U_s and the mixed convection parameter Gr/Re^2 were 6.5 mm s^{-1} and 101, respectively, in the aiding as well as in the opposing buoyancy situations. In both cases, the flow was mainly due to natural convection and, therefore, the direction of motion had almost no effect on the temperature, as long as the orientation of the plate is vertical. The temperature variations at higher velocity, $U_s = 19.5$ mm s^{-1}, $Gr/Re^2 = 12.0$, are shown in Fig. 17(b). This figure shows lower temperature levels in the aiding buoyancy situation, as compared to the opposing situation, as expected. This indicates that the generated flow is in the mixed convection domain. However, at still higher velocity, $U_s = 33.5$ mm s^{-1} ($Gr/Re^2 = 3.97$), as shown in Fig. 17(c), the deviation between the two temperature variations is much less. This suggests that the generated flow is mainly due to the plate motion and, thus, in the forced convection domain. In fact, at even higher velocity, for a given Grashof number Gr, the temperature variation within the plate was found to be essentially independent of the direction of motion.

3.4. *Heat transfer rates*

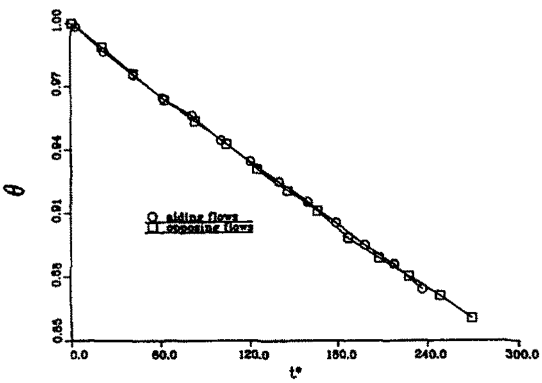
As described earlier, the transverse temperature variation, normal to the plate surface, was measured using the thermocouple rack. From this one can estimate the values of local heat transfer coefficient h and the Nusselt number Nu_d, as follows:

$$h = \frac{k_f(\partial T/\partial y)_w}{T_w - T_\infty} \tag{2}$$

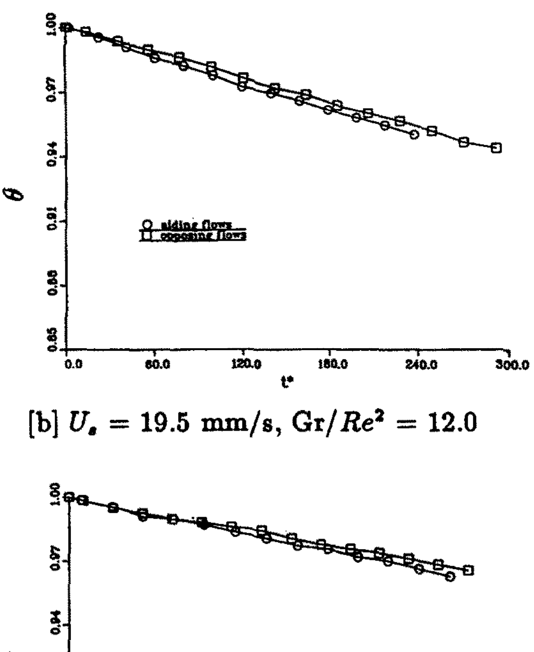
$$Nu_d = \frac{hd}{k_f} \tag{3}$$

where T_w is the local temperature at the surface of the plate. For the range of parameters considered here, the values of Nu_d ranged from 1.8 to 2.2 for the case of water, from 0.4 to 0.65 for the case of the plate moving vertically downward in air and from 0.45 to 0.55 for the case of the plate moving vertically upward in air.

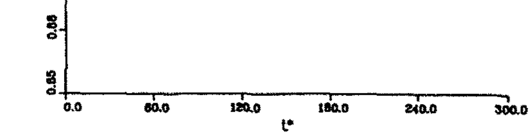
The thermocouple rack was located at some distance, typically 200 mm, downstream of the point where the plate enters the ambient medium. Therefore, the measured temperature levels were lower than the initial plate temperature. Also, the local Nusselt number was based upon the half plate thickness 'd', which was 2.5 mm, and not the downstream distance x. For the sake of comparison, the corresponding values of the local Nusselt number for a similar isothermal plate in a natural convection circumstance are 0.28 for air and 1.58 for water. In the case of an isothermal plate, the entire plate is maintained at a fixed temperature, whereas, in the experiments reported here, the part of the plate near the leading edge is exposed to the colder ambient fluid for a longer time and hence it is at a lower temperature than the remaining part of the moving plate. In spite of this the local Nusselt numbers are higher for a moving plate. Thus it can be concluded that, as expected, the



[a] U_s = 6.5 mm/s, Gr/Re^2 = 101.0



[b] U_s = 19.5 mm/s, Gr/Re^2 = 12.0



[c] U_s = 33 mm/s, Gr/Re^2 = 3.97

FIG. 17. Comparison between the aiding and the opposed flow situations in terms of the temporal temperature variation measured by the thermocouple located at 24 cm from the leading edge of the aluminum plate moving at different values of U_s.

moving plate has higher heat transfer rates than a stationary plate.

3.5. *Comparison with the numerical results*

The experimental results obtained are compared with the numerical results, in terms of variation of the centerline temperature of the plate with downstream distance x. For details of the numerical scheme, see refs. [16–18]. Figure 18 shows the comparison between the experimental and the numerical results, with water as the ambient fluid, for two different values of the mixed convection parameter Gr/Re^2. The numerical solution is obtained for an aluminum plate moving vertically upward and the experimental result is for the plate moving vertically downward in water. It is seen from Fig. 18 that a good agreement is obtained over most of the plate except near the leading edge. This is expected, because in the analysis it is assumed that the tip of the plate is far away from the point of entry. Nevertheless, the comparison shows similar trends in theory and in practice.

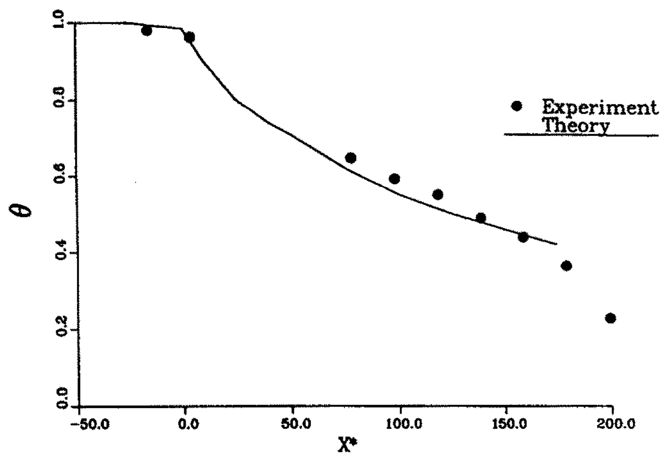
4. CONCLUSIONS

An experimental study has been carried out on the thermal transport from a heated plate moving in a stationary fluid. The plate material is taken as aluminum and air and water are the ambient fluids considered. The experiments investigated vertical upward and downward motion in air, and vertical downward motion in water. Thus, the experiments with water gave rise to a buoyancy force opposing the flow due to the plate motion. Experiments in air simulate opposed, as well as aided, mixed convection flow situations.

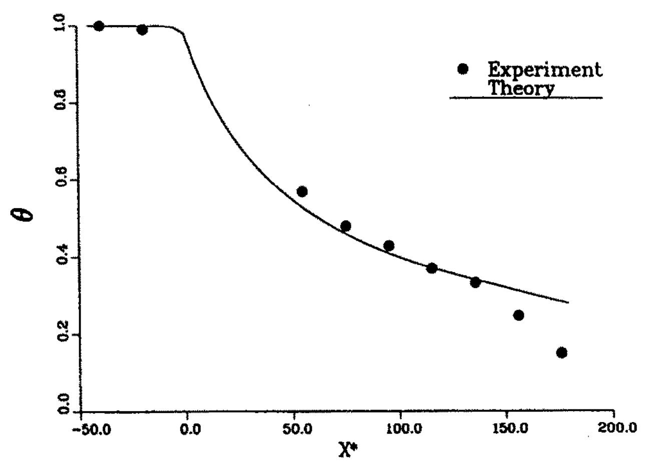
In the experiments with water, the results indicated a fairly close attainment of steady-state conditions. However, with air, a quasi-steady-state circumstance was achieved, which approaches steady state at large times. In water, the plate temperature dropped to the ambient temperature level very rapidly because of the much higher value of the physical property parameter R, as compared to that for air with aluminum as the moving material. With air, much larger distances are required to obtain a comparable drop in temperature and to obtain steady-state conditions.

The temperature profiles obtained with water, as well as with air, showed similar trends found in the earlier numerical study. At low plate velocity, implying small Peclet number Pe, the upstream penetration of the downstream cooling effects, was substantial. This effect decreased with an increase in the plate velocity.

The variation of the temperature along the vertical centerline of the plate was measured for various values of the mixed convection parameter Gr/Re^2 and also for the opposing and aiding buoyancy situations. The results indicated that the temperature level along the centerline strongly depends upon the mixed convection parameter as well as on the flow configuration. In the case of the buoyancy force opposing the flow induced by the plate motion, higher plate temperatures were obtained as compared to the aiding case, due to smaller heat transfer rates in the former circumstance. This difference, however, decreased with an increase in the plate velocity.



[a]



[b]

FIG. 18. Comparison between the experimental and numerical results: variation of the plate centerline temperature along the downstream distance for aluminum plate moving in water: $Re = 103$, $Pe = 0.727$, $k_f/k_s = 2.936 \times 10^{-3}$. (a) $Gr/Re^2 = 0.2$. (b) $Gr/Re^2 = 0.8$.

The experimental results obtained were in fair agreement with the numerically predicted results. The deviation between the two was larger near the tip of the plate.

A flow visualization of the opposing buoyancy flow situation with water, indicated the presence of recirculating flows which moved upward, followed by flow separation, for $Gr/Re^2 \leqslant 3.9$. At higher values of Gr/Re^2, the flow was found to be stable. The complex nature of the flow observed in the opposed mixed convection flow situation is difficult to simulate numerically and the experimental results indicate the basic trends which may be employed in the development of a suitable mathematical model.

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ETUDE EXPERIMENTALE DU TRANSPORT THERMIQUE DEPUIS UNE PLAQUE CHAUDE MOBILE

Résumé—Une étude expérimentale est conduite sur le transport thermique depuis une plaque chauffée en aluminium qui se refroidit par son propre mouvement à vitesse constante dans un fluide étendu et au repos. Les mesures de température variable dans le temps sont faites pour la plaque en mouvement vertical ascendant ou descendant dans l'air. On détermine les flux thermiques locaux et moyens sur la plaque. On mesure la distribution dans la plaque et dans l'écoulement induit. Le champ thermique associé à l'écoulement est visualisé. On observe des structures d'écoulement intéressantes dues à la séparation lorsque l'écoulement induit par le mouvement de la plaque s'oppose à la force de flottement. Les résultats expérimentaux s'accordent bien aux résultats numériques antérieurement obtenus.

EXPERIMENTELLE UNTERSUCHUNG DES WÄRMETRANSPORTS AN EINER BEWEGTEN BEHEIZTEN PLATTE

Zusammenfassung—Es wird der Wärmetransport an einer beheizten Aluminiumplatte experimentell untersucht. Die Platte wird aufgrund ihrer Eigenbewegung mit gleichförmiger Geschwindigkeit in einem unbewegten, ausgedehnten Fluid gekühlt. Der zeitliche Temperaturverlauf der Platte wird gemessen, wenn diese sich vertikal abwärts in Wasser und vertikal aufwärts oder abwärts in Luft bewegt. Die örtlichen und mittleren Wärmeübergangskoeffizienten an der Platte werden bestimmt. Die Temperaturverteilung im Inneren der bewegten Platte und in der induzierten Strömung wird gemessen. Das Temperaturfeld in der Strömung wird mit Hilfe des Schlierenverfahrens sichtbar gemacht. Bei der Strömungsablösung werden interessante Strukturen beobachtet, wenn die durch die Plattenbewegung induzierte Strömung und die Auftriebskraft entgegengerichtet sind. Die Versuchsergebnisse stimmen mit früheren numerischen Ergebnissen befriedigend überein.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПЕРЕНОСА ТЕПЛА ОТ НАГРЕТОЙ ДВИЖУЩЕЙСЯ ПЛАСТИНЫ

Аннотация—Экспериментально исследуется теплоперенос от нагретой алюминиевой пластины, охлаждаемой за счет ее перемещения с постоянной скоростью в большом объеме неподвижной жидкости. Выполнены измерения нестационарной температуры для случаев движения пластины вертикально вниз в воде, а также вертикально вверх или вниз в воздухе. Определены локальная и средняя скорости теплопереноса от пластины. Измерены распределения температур в движущейся пластине и в индуцированном потоке жидкости. Тепловое поле, создаваемое перемещением жидкости, визуализировалось методом теневой фотографии. В случае противоположного направления движения пластины и подъемной силы наблюдались интересные структуры течения, обусловленные его отрывом. Экспериментальные данные удовлетворительно согласуются с ранее полученными численными результатами.