Int. J. Heat Mass Transfer. Vol. 17, pp. 1051-1061. Pergamon Press 1974. Printed in Great Britain

EXPERIMENTAL INVESTIGATION OF FREE CONVECTION FLOW FROM WIRES IN THE VICINITY OF PHASE INTERFACES

J. REIMANN*
Institut für Strömungslehre und Strömungsmaschinen, Universität Karlsruhe, Germany

(*Received* 28 *September* 1973)

Abstract—The influence of a horizontal interface on the heat transfer by free convection of horizontal wires at a constant temperature, will be defined by experiment. Such interfaces are (1) the surface of a solid wall (2) a surface of a liquid. The wire is approached to the interface from above or below. The measurements are carried out in air or in water. Moreover, the influence of the wire temperature, the wire diameter, and wire length are investigated. With a decreasing distance from the interface, the free convection heat transfer is strongly reduced, the amount of heat transfer by conduction through the interface depends on the ratio of the thermal conductivity coefficients of the phase concerned. The total heat transfer may therefore, increase or decrease with small distances.

When the wire is situated above an inclined wall, the free convection flow is deflected from the vertical. Under certain circumstances, the flow will be adjacent to the wall.

The temperature field in water will be visualized with the aid of a Mach–Zehnder interferometer.

NOMENCLATURE

b,	wire distance from interface;
c_p,	specific heat of the fluid at constant pressure;
d,	wire diameter;
g,	gravitational acceleration;
Gr,	$g\beta d^3\Delta T/\nu^2$, Grashof number;
Gr,	$g\beta b^3 Q/c_p\rho\nu^3 L$, typical Grashof number of the thermal Coanda-effect;
L,	wire length;
Nu,	$\dot{Q}/\pi\lambda L\Delta T$, Nusselt number;
Pr,	$\nu\rho c_p/\lambda$, Prandtl number;
$\dot{Q}$,	heat generated by the wire;
T,	temperature;
T_∞,	ambient temperature;
ΔT,	wire temperature above ambient temperature;
u,	velocity component in x direction;
x, y,	coordinate system indicated in Fig. 6.

Greek symbols

α,	inclination angle, measured against the horizontal;
β,	coefficient of volumetric thermal expansion;
λ,	thermal conductivity of the fluid;
ν,	kinematic viscosity of the fluid;
ρ,	density of the fluid.

Subscripts

*,	phase in which the wire is not located;
∞,	without influence of the wall ($b \to \infty$);
K,	heat convection;
LP,	heat conduction through the interface.

*Present address: Physik.-Techn. Entwicklungsinstitut Laing, 7141 Aldingen b. Stuttgart, Hofener Weg 35, Germany.

1. INTRODUCTION

THE FREE convection heat transfer from heated horizontal wires is of importance for many applications in technology. Most studies of this subject consider a wire of infinite length which is situated in an infinitely extended fluid. The dependence of the Nusselt number on the Grashof and Prandtl number is investigated. A dimensionless value of the form $\Delta T/T_\infty$ (ΔT = wire temperature–ambient temperature, T_∞ = ambient temperature) does not appear explicitly, its influence is considered by the fact that the fluid properties of the other dimensionless groups are evaluated with an averaged temperature. Representative of this is the study by Gebhart and Pera [1] in which the reader will find further literature on the subject.

In technical applications, the length of the wire is finite. A dependence of the Nu number upon the finite wire length is found when the ratio of wire length L to wire diameter d does not reach a certain value. Investigations in air by Collis and Williams [2] show that the wire may be considered infinite, if L/d exceeds approximately 10^4. As follows from [1], the value decreases with an increasing Pr number.

The influence of an adjacent wall on free convection heat transfer for short wires with regard to the hot-wire anemometry has been investigated by van der Zijnen [3] and Wills [4]. When the wire is approached to the wall and the wire temperature is constant an increasement of heat transfer will result. The influence of the inclination angle and the ratio L/d was not investigated any further.

In [5] the ratio L/d and the inclination angle was varied. Experiments in air, showed that with long wires and an inclined wall, a noticeable thermal Coanda-effect appeared. If a wire of constant temperature is situated above a horizontal wall, the heat transfer passes a minimum when approaching the wall. Using short wires, the minimum disappears, with an inclined wall the Coanda-effect is no longer noticeable.

With regard to measuring methods of multi-phase flows, the influence of a surface of a liquid on heat transfer is of special interest. In this study therefore, both the influence of a horizontal wall and of a surface of a liquid on heat transfer of horizontal wires of constant temperature are to be investigated. In this, the phases involved are to have the same temperatures. As is shown by a dimensional analysis, the Nu number is then depending on the following dimensionless groups

$$Nu = f\left(\frac{b}{d}, \alpha, \frac{\lambda^*}{\lambda}, Gr, Pr, \frac{L}{d}, \frac{\Delta T}{T_\infty}\right)$$

b/d is the ratio of wall distance to wire diameter, α is the inclination angle, at $\alpha = 0°$ the wire is situated above and at $\alpha = 180°$ below the interface. The ratio λ^*/λ is influencing the heat flux flowing through the interface by conduction: The index marks that side of the interface in which the wire is not situated.

2. EXPERIMENTAL SET UP AND TECHNIQUE

The experiments were carried out in air and in water. The solid wall consisted of aluminium. The principal components of the experimental set up are shown in Fig. 1. For the experiments with the interferometer, the PVC container had the inside dimensions (in mm) $W = 500$, $H = 320$, $D = 70$. In this, $D = 70$ was given by the interferometer compensation chamber. The dimensions of the aluminium plate were $W' = 200$, $H' = 3$, $D' = 70$, the height of which being constantly variable by screw bars. A container with $W = 250$, $H = 200$, $D = 200$ and an aluminium plate with $W' = 200$, $H' = 20$, $D' = 70$ was used, especially for the measurements at very small distances. When measuring in air, the containers were enlarged in height by an attachment (as indicated in Fig. 1).

When investigating the free convection flow above heated wires, the shape of the isolating enclosure is of

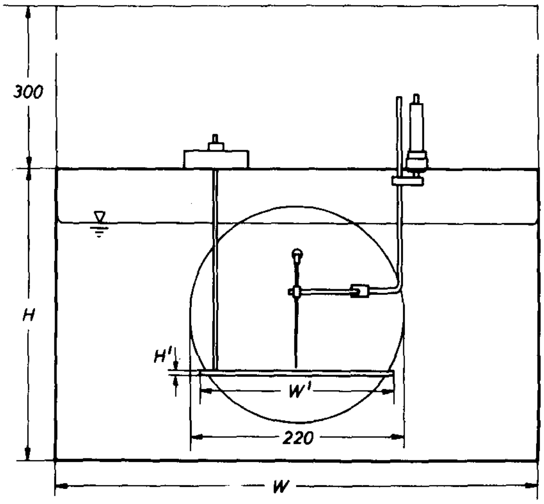

FIG. 1. Schematic diagram of test apparatus.

utmost importance. A comparison with the corresponding results from earlier investigations [5] with very much larger dimensions of the enclosure and the plate ($W = 2700$, $H = 2500$, $D = 500$, $W' = 1100$, $H' = 3$, $D' = 500$ mm) showed good correspondence. Any influence of the dimensions of the enclosure used are therefore non-existent. Tungsten wires with diameters of $d = 5$, 9 and 50 μm were used. At $d = 9$ μm, the ratio L/d was varied in large proportions (Fig. 2).

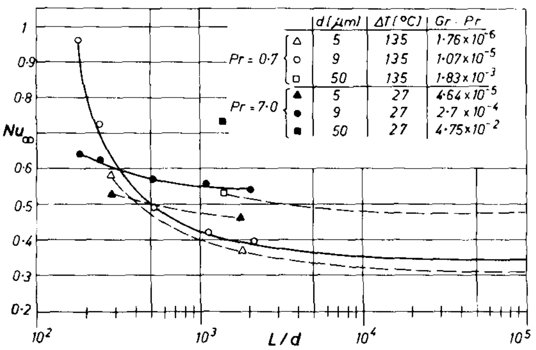

FIG. 2. Nu-number at infinitely great distance vs L/d.

Under the microscope, the wires were welded on the tips of the slender supports (V_2A or Ni resp.). In order to prevent the wire from vaulting when heated, the 50 μm wires were strained by a spring, the 9 μm wires were slightly prestrained during welding. The distance was adjusted by a micrometer head (accuracy 1 μm). The determination of the zero distance was determined, by using a microscope and a 45° mirror when the wall was solid and $\alpha = 0°$. When viewing the wire and its reflexion on the test wall, an accuracy of 3 μm was achieved. The maximum difference of the distances of the wire ends was of the same order of magnitude. When the wire was situated below the solid wall, the zero distance was determined without a microscope. Therefore, the results show more scattering of the measurements when the distances were very small. When approaching the water surface, it was of advantage that the wire was not damaged. The accuracy of the determination of the zero distance was also approximately 3 μm.

For the adjustment of the constant wire temperature, a hot-wire anemometer with current amplifier supplement according to the constant resistance method was used. The potential drop over the wire ends were evaluated by a digital voltmeter. The time dependency was noted either by an oscilloscope or a chart recorder. The temperature of the wire, averaged over its length was computed from its electrical resistance. The coefficient of the electrical resistance of the wires was evaluated in a constant-temperature water bath within the range of 15–80°C, and remained constant for the whole range within the measuring accuracy. In all experiments, both the air and the water temperatures were measured with thermocouples, when using fluids, the surface temperature was also measured. For a part of the experiments, a Mach–Zehnder-interferometer was used for the visualization of the temperature field in water (light wave length: 546 nm). In this, a difference of temperature of 0·086°C caused a displacement by one interference fringe. This measuring method owing to its sensitivity, guarantees a more exact determination of the temperature field, especially near the phase interface, than when using thermocouples.

3. SOME COMMENTS ON THE CONCERNED PHASES

The coefficients of thermal conductivity

$$\lambda_{\text{aluminium}} : \lambda_{\text{water}} : \lambda_{\text{air}}$$

are in the ratio of approximately 1000:25:1. When considering the combination air–solid wall, $\lambda^*/\lambda \approx 1000$. In good approximation, the wall acts as a perfect conductor ($\lambda^*/\lambda \to \infty$), thus, the surface of the wall is at ambient temperature at any time and at any point. The same is true in good approximation for the combination water–solid wall ($\lambda^*/\lambda = 40$). If the wire is situated above the water surface, the ratio $\lambda^*/\lambda = 25$.

In the limit case $\lambda^*/\lambda = 0$, there is no heat flux through the interface, the interface is an adiabatic wall, i.e. there is no normal derivation of temperature. The wire being situated underneath a water surface, $\lambda^*/\lambda = 0{\cdot}04$, thus the water surface at first approach acts like an adiabatic wall in this case.

When the wire was situated near the surface of the liquid, an undesired effect caused by evaporation became noticeable. If the wire is not heated, the different fluids should have the same temperature at any place. Because of the evaporation this claim cannot be fulfilled for the air–water system. By mixing the two phases, the same temperature can be reached at a given point of time. The heat of evaporation is then attained by both, air and water, and causes the temperature of both phases to go down near the surface. This procedure is quasi-steady, and after an infinitely long time, a steady state will be reached, which depends on the conditions of the experimental set up.

In order to fulfil the claim for constant temperature in these experiments as closely as possible, a temperature stratification which might possibly exist, was eliminated by the mixing of the water. It was given consideration to the fact that the temperatures in air and water are approximately the same. The perturbations caused by motion calmed down after a short time. With the help of the interferometer, the setting-up of the temperature profile in water was observed, and the experiment itself was only started when the time change was so minimal that during the time of the experiment (up to approx. 3 min), the temperature profile could be considered constant in time. The max. temperature drop ($T_{b=\infty} - T_{b=0}$) was in the region of 0·01°C.

For the wire temperatures used (in water: $\Delta T =$ 13–41°C, in air: $\Delta T = 27$–135°C) the stratification of temperature has a negligible influence on the heat transfer. The wire being situated above the water surface, attention must be paid to the fact that the properties that are important for the heat transfer are dependent on the partial pressure of the vapor. This influence, however, is smaller than the measuring exactitude at an environment temperature of 20°C.

4. RESULTS AND DISCUSSION

4.1 *Steady-state heat transfer*

To clarify the influence of the interface, in each case the ratio of the transferred heat flow per unit time ($\dot{Q}$) to the transferred heat flow per unit time at a very great distance ($\dot{Q}_\infty$), is represented above the distance b. A presentation above a dimensionless group b/d (or b/L) is of no physical signification. Since the difference of temperature ΔT is being kept constant, the ratio $\dot{Q}/\dot{Q}_\infty$ is corresponding to the ratio Nu/Nu_∞. Some results for infinitely great distances are shown in Fig. 2. The Nu number is evaluated with properties at the temperature $(T_D + T_\infty)/2$, the product $Gr \cdot Pr$ with properties at ambient temperature. By decreasing the ratio L/d, the Nu number will increase, this being caused by the increasing part of heat conduction from the wire to the wire supports upon the total heat transfer. The curves for $Pr = 0{\cdot}7$ are approaching in good accordance the values taken from Collis and Williams [2] for $L/d \to \infty$ (right hand side of graph). When $Pr = 7{\cdot}0$, the

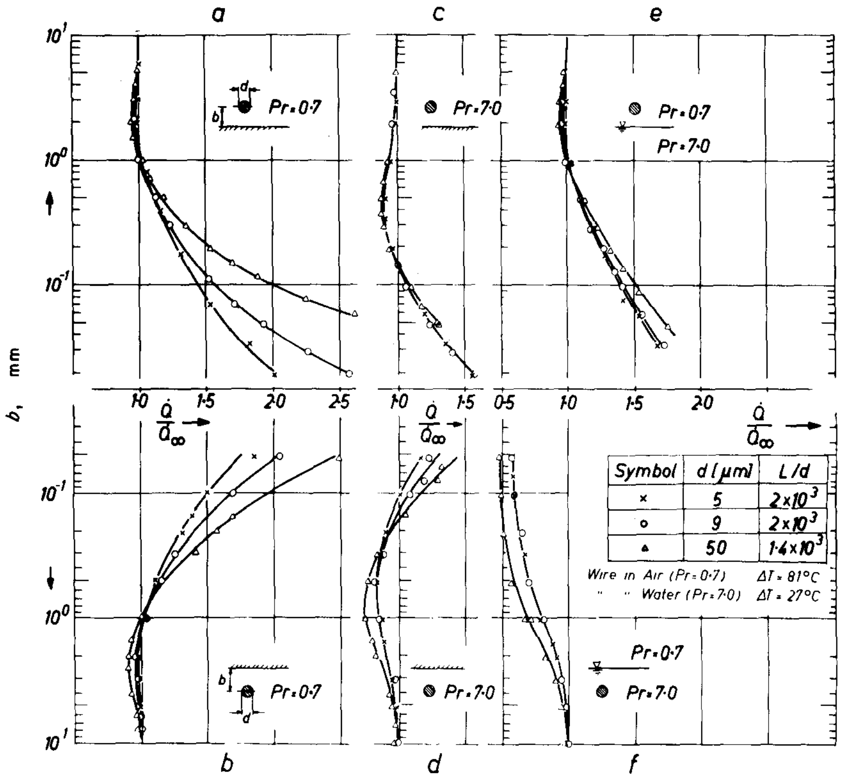

FIG. 3. Heat transfer vs distance; parameter: wire diameter d.

dependency of the Nu number from L/d is essentially smaller, the infinitely long wire is achieved at lower values of L/d. A corresponding result was arrived by Gebhart and Pera [1] for various silicone oils.

Figures 3(a–d) is showing the heat transfer in relation to the distance from a solid wall, the wire diameter being the parameter. The run for all curves is qualitatively equal: when starting from a very great distance, the total heat transfer initially diminishes when approaching the wire to the wall, at very small distances it increases greatly. The wall causes a decreasement of the free convection heat transfer. At $\alpha = 0°$, the heated fluid is flowing off in the vertical, the flow to the wire (ΔT = constant) is being reduced by the wall located below, and thus the free convection heat transfer from the wire. At $\alpha = 180°$, the flow below the wall is being diverted to the horizontal. Because of this, a noticeable free convection flow is prevented at small distances. With decreasing distance, there is an increasing heat conduction into the wall for $\alpha = 0°$ as well as for $\alpha = 180°$, since the gradient of temperature between wire and wall is increasing (the isothermals are being compressed).

The Pr number is characteristic for the ratio of the thickness of the flow field to the thickness of the temperature field. At changing over from $Pr = 0{\cdot}7$ to $Pr = 7{\cdot}0$ the total heat transfer is more strongly reduced since the heat conduction into the wall only becomes noticeable at smaller distances. The minima of the curves at $Pr = 7{\cdot}0$ are located at smaller distances and are, therefore, more obvious than at $Pr = 0{\cdot}7$.

When approaching the wire from above to a water surface ($\alpha = 0°$, $\lambda^*/\lambda = 1$) the curve is similar to when approaching a solid wall, at smaller distances, however, it is located below (Fig. 3e). This is caused by a smaller gradient of temperature at the water surface because of local heating of the water. A comparison of corresponding curves (Fig. 3a–e) shows that, with decreasing diameters of the wire, the influence of local heating diminishes.

If the wire is located underneath the water surface ($\alpha = 180°$, $\lambda^*/\lambda \ll 1$), heat transfer is continuously decreasing when approaching the interface and attains a finite value (Fig. 3f). The dependency upon the diameter of the wire is negligible. In order to define which part of evaporation heat is being brought up by the wire, in some series of tests, the mass transfer was prevented by a thin oil film on the water surface. A comparison of corresponding curves did not show any differences.

With an increasing diameter of the wire, the thickness of the temperature and flow field increases in the ambiance of the wire. According to the stagnant film concept by Langmuir [6], the diameter of the stagnant film is modified by the factor 1·33, when changing from the wire diameter $d = 5\ \mu m$ to $d = 50\ \mu m$ in air. Figure 3 is showing especially at small distances in air, a strong dependence upon the diameter of the wire, respectively the Gr number. This is due to the form of the presentation. The influence of the wire diameter becomes very much smaller if $\dot{Q}/\dot{Q}_\infty$ is represented over the gap between wire and wall $(b-d/2)$.

decreasement of the heat transfer through the wall is, therefore, lower at smaller values of L/b, the minimum of the curve is less distinct. Within the range of very small distances, the ratio of L/b becomes that great, also for short wires that there no longer exists a dependence upon this dimensionless group any further.

When temperature ratio $\Delta T/T_\infty$ is varied, the increasement of the heat transfer is even larger the smaller $\Delta T/T_\infty$ becomes (Fig. 5). The cause for this is the increasing diameter of the temperature and flow field at decreasing $\Delta T/T_\infty$. At forced convection, this corresponds to an increase of the diameter of the

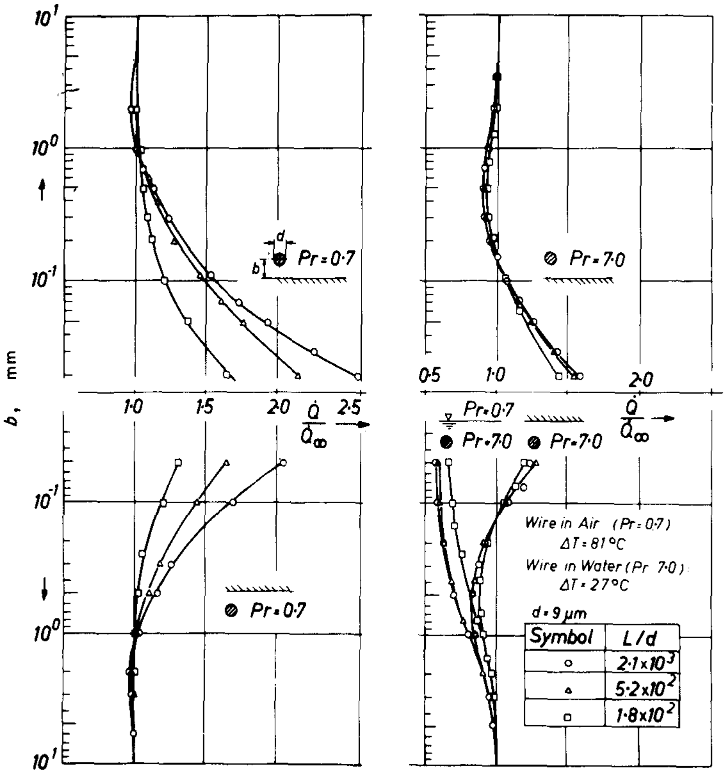

FIG. 4. Heat transfer vs distance; parameter: L/d.

In Fig. 4, the ratio L/d is being varied. Since the part of the heat flow into the wire holding device to the total heat transfer is growing with falling L/d, the influence of the total heat flow through the wall decreases. At an infinitely large distance, the dependence of the Nu number upon L/d at $Pr = 7·0$ is very much smaller than at $Pr = 0·7$ (Fig. 2). This is also why the influence of L/d is less noticeable at $Pr = 7·0$ than at $Pr = 0·7$ when approaching the wall.

Another dimensionless group which can be formed at finite length of the wire, is the ratio L/b. When the wire is infinitely long, the temperature and flow fields are two dimensional. At finite wire length, the flow towards the ends of the wire is three dimensional. The boundary layer with decreasing Re number. A noticeable influence of $\Delta T/T_\infty$ only exists at very small distances and is stronger at $Pr = 7$ than at $Pr = 0·7$.

4.2 *Evaluation of the heat flow through the interface*

In the following, it will be tried to define by experiment the ratio of the heat transfer by conduction through the interface $(\dot{Q}_{LP})$ to the total heat transfer $(\dot{Q})$ for the case that the wire is located near a solid wall. The part of heat transfer by thermal radiation is negligibly small for thin wires. The total heat transfer is then composed of free conduction heat transfer $(\dot{Q}_K)$ and $\dot{Q}_{LP}$ as follows

$$\dot{Q} = \dot{Q}_K + \dot{Q}_{LP}.$$

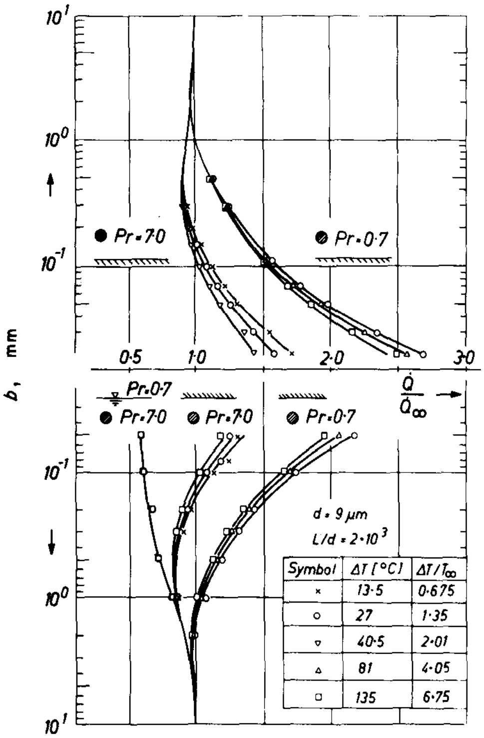

FIG. 5. Heat transfer vs distance; parameter: $\Delta T/T_\infty$.

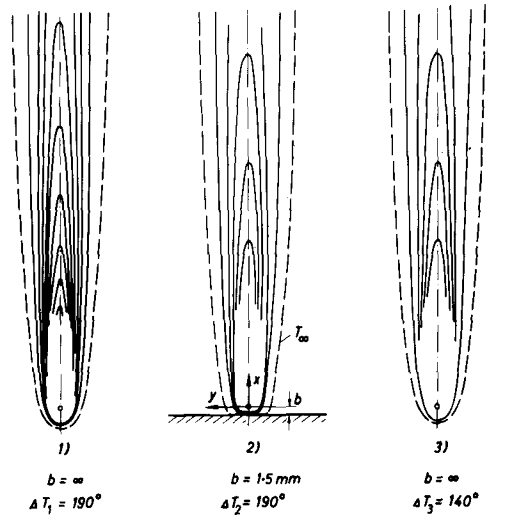

FIG. 6. Model to evaluate the heat transfer by convection.

The measuring of $\dot{Q}$ is simple, since $\dot{Q}$ is equal to the electrical power produced in the wire, the direct measuring of $\dot{Q}_{LP}$ is not possible with a good accuracy, thus $\dot{Q}_K$ has to be defined by experiment.

At first, $\alpha = 0°$ is considered, i.e. the wire is situated above the wall. For a fully developed two dimensional free convection flow (infinitely long wire) follows (Fig. 6)

$$\dot{Q}_K = Lc_p\rho\left(\int_{-\infty}^{+\infty} u(T-T_\infty)\,dy\right)_{x=\text{const.}}$$

The temperature field is being measured with an interferometer, the determination of the velocity field with small particles (compare Brodwidz [7]) is not suitable here, since some particles could set down on the plate and could thus change the conditions on the surface. The procedure is carried out in accordance with the method fully described in [5]. A condition for this is that the wall in the first approximation, causes only a decrease of the heat flow transferred by free convection, however the wall will not have any further impact in a great distance $x(x/b \gg 1)$ on the velocity and temperature profiles. Thus, when the temperature fields in some distances from the wire are equal for the cases $b \to \infty$ and $b \to 0$, in the first approximation there will be the same heat transfer by free convection.

For Fig. 6 (from [5], $d = 0{\cdot}1$ mm) interferometer fringes were analysed. The temperature fields in Fig. 6 (2) and (3) are equal within the measuring accuracy in the represented range, which is a confirmation of the condition made at the beginning.

Figure 6, (1) is showing the temperature field at $b \to \infty$ and a given temperature difference ΔT_1. The total heat flux $\dot{Q}_1$ is only transferred by free convection. At a small distance b [Fig. 6, (2)] and at the same temperature difference $\Delta T_2 = \Delta T_1$, the total heat flux transferred by the wire is only a little different from $\dot{Q}_1$. The power is transferred by free convection and conduction to the wall. In Fig. 6, (3), the heat flux $\dot{Q}_3$ is adjusted at $b \to \infty$ in a way that, after great distance x, there is the same temperature field as in Fig. 6, (2) ($\dot{Q}_3 < \dot{Q}_2, \Delta T_3 < \Delta T_2$). Since a heat conduction to the wall does not exist, $\dot{Q}_3 = \dot{Q}_{2_K}$. Thus it follows

$$\frac{\dot{Q}_{2_K}}{\dot{Q}_1} = \left[\frac{\dot{Q}_K}{\dot{Q}_\infty}\right]_{\Delta T=\text{const.}}$$

Figure 7 (top) shows that at small distances, the heat transfer by free convection is very strongly reduced, the heat conduction into the wall increases strongly. The measuring points scatter, a noticeable dependence upon the temperature difference ΔT is not existent. The results for $Pr = 0{\cdot}7$ were taken from [5].

At $\alpha = 180°$ and $Pr = 7{\cdot}0$, $\dot{Q}_{LP}$, in the first approximation, is the result of the difference of the total heat transfer at approaching the solid wall, and of the total heat transfer at approaching the water surface (Fig. 7, bottom):

$$\dot{Q}_{LP} = \dot{Q}_{(\lambda^*/\lambda)\to\infty} - \dot{Q}_{(\lambda^*/\lambda)\to 0}\,.$$

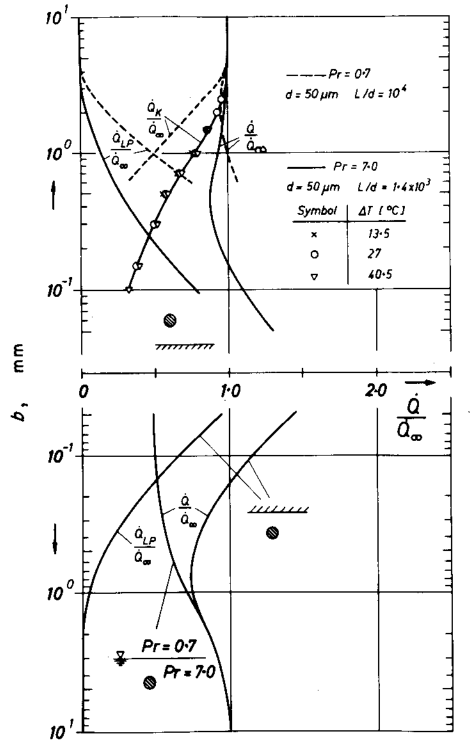

FIG. 7. Heat transfer by conduction into the wall.

4.3 *Unsteady heat transfer*

The time dependence after switching on the electric current at the moment $t = 0$ is considered. Vest and Lawson [8], Ostroumov [9] and Siencnik [10] among others have investigated this phenomenon without the influence of an adjacent wall.

Figure 8 is showing (for the case $\alpha = 180°$, $(\lambda^*/\lambda) \to 0$) the heat transfer as a function of time. The

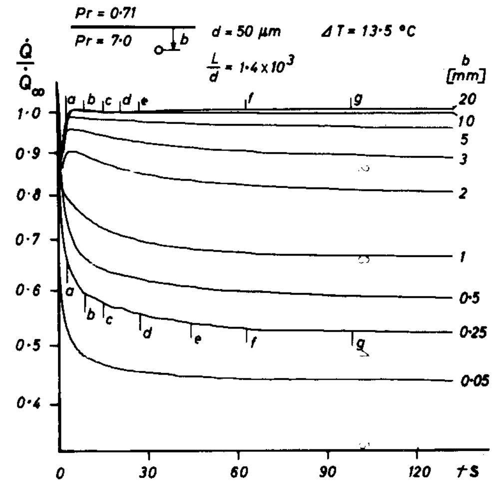

FIG. 8. Heat transfer vs time.

distance b is the parameter. Figures 9 and 10 are showing the isothermals of the temperature field. For $b = 20$ mm, there is almost no influence by the wall.

After the current has been switched on, heat is at first only transferred by conduction, the isothermals are concentric circles. Since the isothermals go into the medium, the temperature gradient at the wire surface is decreased, the heat flow diminishes. The onset of free convection causes a strong increase of heat transfer. Because of the stored energy, an increased flow around the wire appears, which goes down to the steady-state value during the further stages of the experiments. For the values chosen in Fig. 9, the mimimum of the curve appears at $\approx 1{\cdot}5$ s, the steady-state value of the heat transfer is already reached at the moment of Fig. 9(b), although the temperature field will still change strongly at greater distances away from the wire.

At very small distances (e.g. $b = 0{\cdot}25$ mm), heat is mainly transferred into the water by heat conduction and the influence of the free convection is very small (Fig. 10). The steady state is reached later than at large distances.

When interpreting the interferometer fringes, the effect of evaporation must be taken into account. When the wire is unheated, a temperature drop is observed near the water surface because of evaporation. The photographs of the heated wire show a distinct gradient of temperature at the water surface. The influence of evaporation is eliminated if the temperature field at the unheated wire is subtracted from the temperature field according to Figs. 9(a)–(g) and (10(a)–(g), respectively. Figures 9(h), or 10(h) respectively, are showing Fig. 9(g), or 10(g), respectively, without the influence of evaporation. The gradient of temperature at the water surface is in good approximation zero in the represented range, and thus also the heat flux into the air by conduction.

4.4 *Thermal Coanda-effect*

When the wire is located above an inclined wall ($0° < \alpha \leqslant 90°$), the free convection flow bends to the wall. Under certain circumstances, the flow may become attached to the wall. This effect is described in more detail in [5] and [11].

Figures 11 and 12 are showing the development of free convection flow in water. After the electric current has been switched on, the flow develops approximately in the vertical [Fig. 11(a) to 11(c)], bends to the wall, and reaches the steady-state position in Fig. 11(e). In Fig. 12, the distance was decreased and the wire temperature was the same as in Fig. 11. The flow bends stronger from the vertical and becomes finally attached to the wall [Fig. 12(e)].

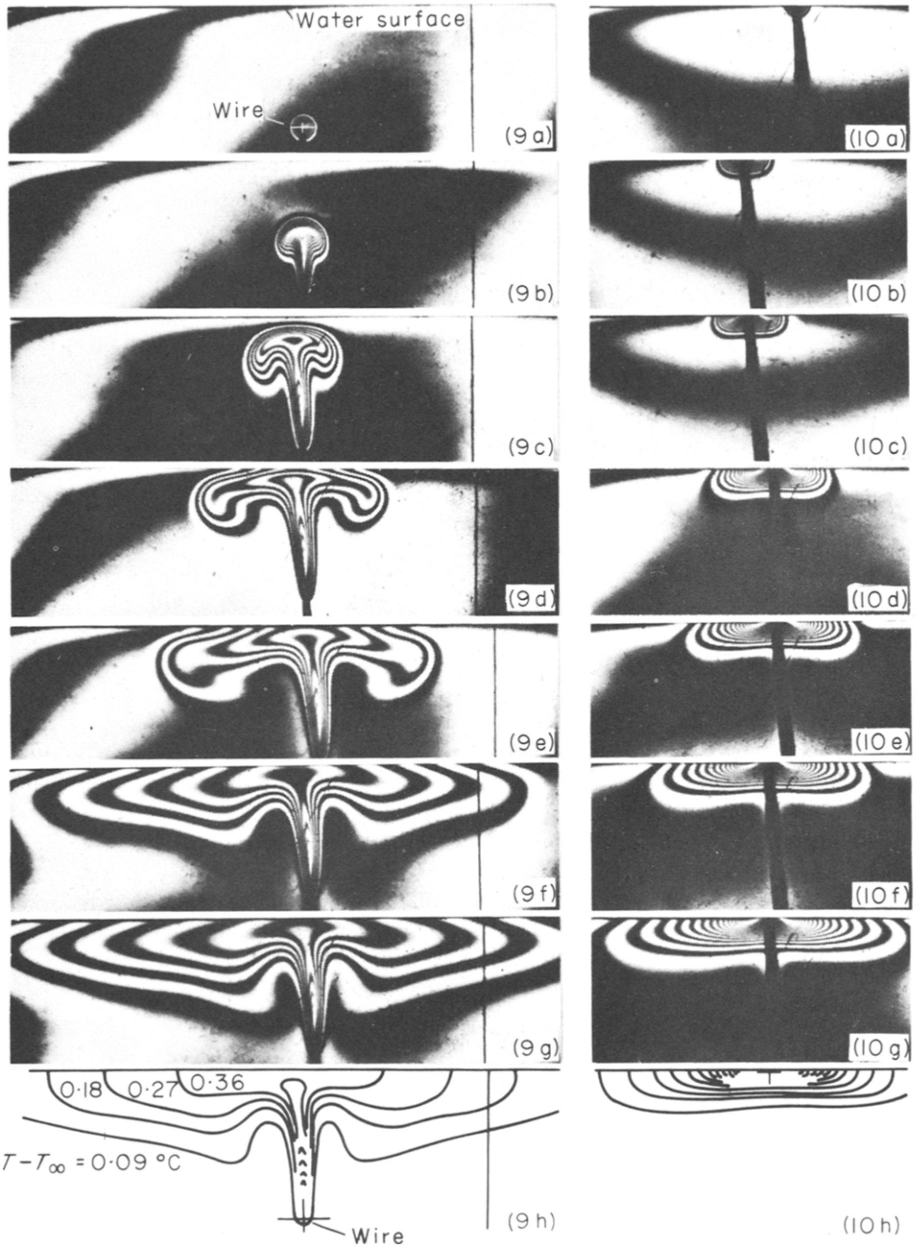

FIG. 9. Interferogram of the temperature field above the wire; $d = 50\ \mu m$; $\Delta T = 13{\cdot}5°C$; $b = 20\ mm$; $(\dot{Q}/L)_{t\to\infty} = 18{\cdot}5\ W/m$.
FIG. 10. Interferogram of the temperature field above the wire ; $d = 50\ \mu m$; $\Delta T = 13{\cdot}5°C$; $b = 0{\cdot}25\ mm$; $(\dot{Q}/L)_{t\to\infty} = 9{\cdot}8\ W/m$.

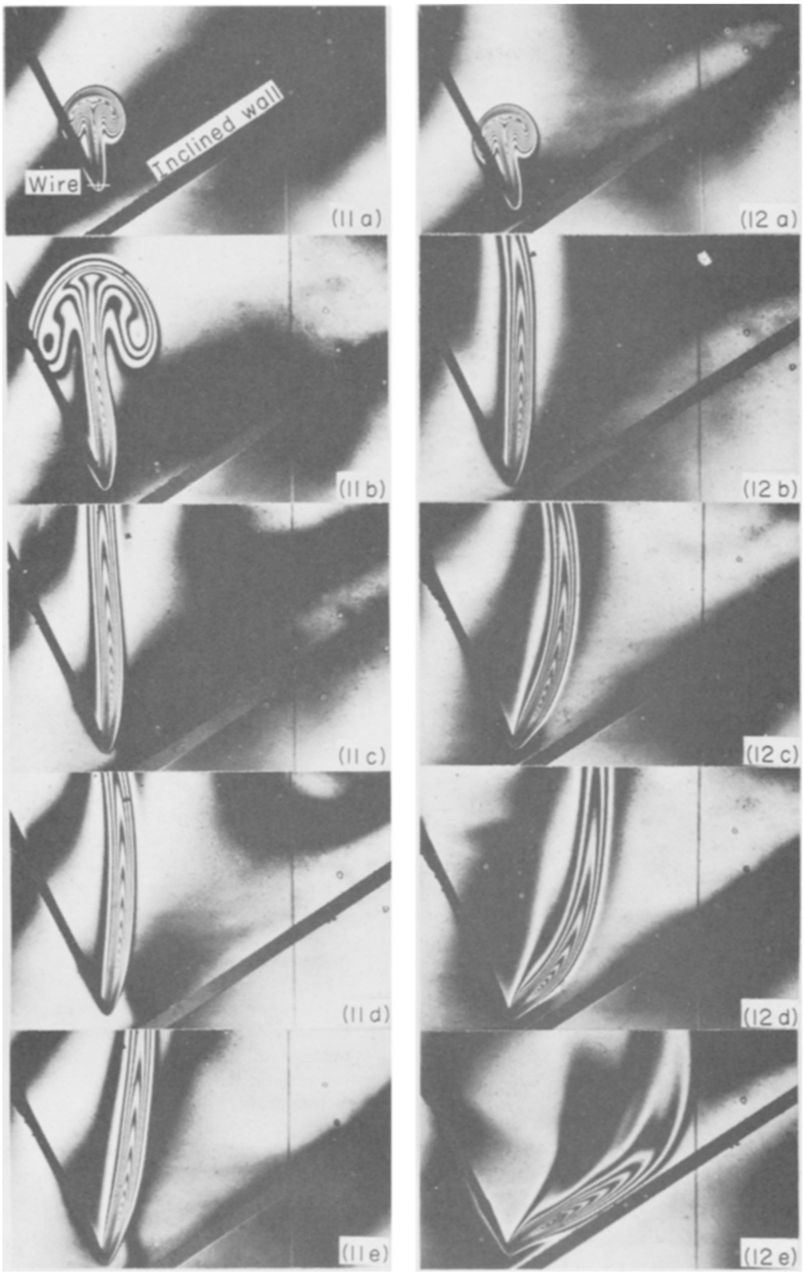

FIG. 11. Thermal Coanda-effect; $d = 50\,\mu m$; $\Delta T = 27°C$; $\alpha = 33°$; $\dot{Q}/L \approx 50\,W/m$;

$$Gr = \frac{g\beta b^3}{\nu^3 \rho c_p} \cdot \frac{\dot{Q}}{L} = 8{\cdot}1 \,.\, 10^4 > Gr_{crit}.$$

FIG. 12. Thermal Coanda-effect; $d = 50\,\mu m$; $\Delta T = 27°C$; $\alpha = 33°$; $\dot{Q}/L \approx 50\,W/m$;

$$Gr = \frac{g\beta b^3}{\nu^3 \rho c_p} \cdot \frac{\dot{Q}}{L} = 1{\cdot}5 \,.\, 10^4 < Gr_{crit}.$$

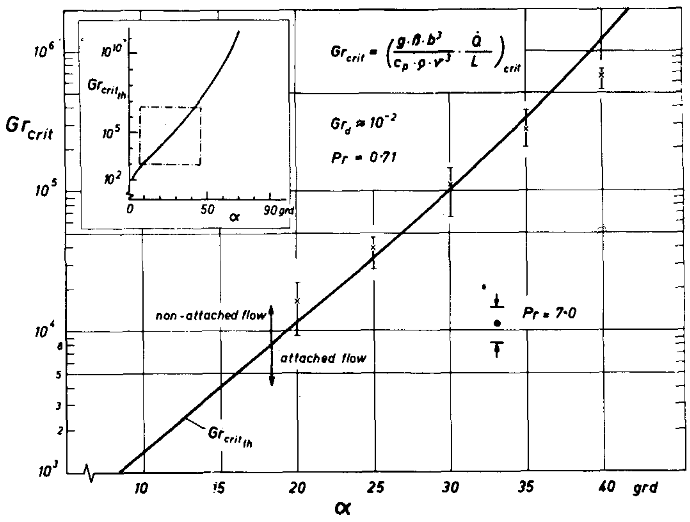

FIG. 13. Dependance of the critical Gr-number on the inclination angle of the wall.

The values at which an attachment can occur are called "critical values".

Theoretical considerations for long wires ($L/d \to \infty$) showed the dependence of the critical Gr number upon the Pr number and the inclination angle.

$$Gr_{\text{crit}} = \left(\frac{g\beta b^3}{\nu^3 \rho c_p} \cdot \frac{\dot{Q}}{L}\right)_{\text{crit}} = f(\alpha, Pr).$$

The critical Grashof number grows with an increasing inclination angle of the wall, respectively with falling Pr number. Measurements in air, show good accordance to the theory. In Fig. 13, the arithmetic average values of all measurements are noted, 90 per cent of all measuring points lie within the limits. The power transferred by the wire is only very weak depending on the bending of the flow from the vertical. In order to evaluate whether the flow becomes attached to the wall the heat flux $\dot{Q}_\infty$ which is transferred from the wire at an infinitely larger distance, that is without the influence of a wall (e.g. see Collis and Williams [2]) can therefore be taken in the first approximation. For $Pr = 7{\cdot}0$ and $\alpha = 33°$ (Figs. 11 and 12) is $8{\cdot}1 . 10^4 > Gr_{\text{crit}} > 1{\cdot}5 . 10^4$, is thus definitely below the corresponding value at $Pr = 0{\cdot}7$ ($Gr_{\text{crit}} = 2{\cdot}5 . 10^5$).

Acknowledgements—Grateful acknowledgement is made to the Sonderforschungsbereich Technische und Chemische Verfahrenswissenschaften (SFB 62) of the University Karlsruhe. The author thanks Miss B. Masurath for translating the paper.

REFERENCES

1. B. Gebhart and L. Pera, Mixed convection from long horizontal cylinders, *J. Fluid Mech.* **45**, 49–64 (1970).
2. D. C. Collis and M. J. Williams, Free convection of heat from fine wires, A.R.L. Aeron. note 140 (1954).
3. B. G. Hegge van der Zijnen, Preliminary measurements of the distribution of the velocity of a fluid in the immediate neighbourhood of a plane, smooth surface, Verhandelingen der Koninklijke Akademie van Wetenschappen te Amsterdam Eerste Sectie Deel XIII, Nr. 3 (1924).
4. J. A. B. Wills, The correction of hot-wire readings for proximity to a solid boundary, *J. Fluid Mech.* **12**, 388 (1962).
5. J. Reimann, Freie Konvektionsströmung kleiner Grashof-Zahl verursact durch waagerechte Zylinder unter dem Einfluß einer ebenen Wand, Dissertation, Universität Karlsruhe (1972).
6. I. Langmuir, Convection and conduction of heat in gases, *Phys. Rev.* **34**, 401–422 (1912).
7. K. Brodowicz, Experimental investigation of laminar free convection flow in air above horizontal wire with constant heat flux, *Int. J. Heat Mass Transfer* **9**, 81–84 (1966).
8. C. M. Vest and L. Lawson, Onset of convection near a suddenly heated horizontal wire, *Int. J. Heat Mass Transfer* **15**, 1281–1283 (1972).
9. G. A. Ostroumov, Unsteady heat convection near a horizontal cylinder, *J. Tech. Phys. U.S.S.R.* **1**, 2627–2641 (1956).
10. L. Siencnik, Der Wärmeübergang eines beheizten Zylinders beim Übergang von freier zu erzwungener Konvektion, Abhandlungen aus dem Aerodynamischen Institut Aachen, Heft 18 (1965).
11. J. Reimann, Ebene freie Konvektionsströmung über waagerechten Zylindern kleiner Grashof-Zahl unter dem Einfluß einer ebenen Wand, *Z. Angew. Math. Mech.* **53**, 115–116 (1973).

ETUDE EXPERIMENTALE DE LA CONVECTION LIBRE PAR LES FILS AU VOISINAGE DES INTERFACES

Résumé—On définit expérimentalement l'influence d'un interface horizontal sur le transfert de chaleur par convection thermique naturelle, à partir d'un fil horizontal chauffé à température constante. Ces interfaces sont (1) la surface d'une paroi solide, (2) la surface d'un liquide. Le fil est approché de l'interface soit par dessus, soit par dessous. Les mesures sont effectuées dans l'air ou dans l'eau. On étudie l'influence de la température, du diamètre et de la longueur du fil. Pour une distance décroissante à l'interface, la convection naturelle de chaleur est fortement réduite, le flux de chaleur transféré par conduction à travers l'interface dépend du rapport des conductivités thermiques des phases concernées. Le transfert thermique total peut néanmoins croître ou diminuer à des petites distances.

Lorsque le fil est situé au dessus d'une paroi inclinée, la convection naturelle est défléchie par rapport à la verticale. Dans certaines conditions, l'écoulement sera adjacent à la paroi.

Le champ de température dans l'eau peut être visualisé à l'aide d'un interféromètre Mach-Zehnder.

EXPERIMENTELLE UNTERSUCHUNG DER FREIEN KONVEKTIONSSTRÖMUNG VON DRÄHTEN IN DER NÄHE VON PHASENTRENNFLÄCHEN

Zusammenfassung—Es wird experimentell der Einfluß einer waagerechten Trennfläche auf die Wärmeabfuhr durch freie Konvektion von waagerechten Drähten konstanter Temperatur bestimmt. Solche Trennflächen sind 1. die Oberfläche einer festen Wand, 2. eine Flüssigkeitsoberfläche. Der Draht wird von oben und von unten der Trennfläche genähert. Die Messungen werden in Luft und Wasser durchgeführt; außerdem wird der Einfluß der Drahttemperatur, des Drahtdurchmessers und der Drahtlänge untersucht. Mit kleiner werdendem Abstand von der Trennfläche wird die Wärmeabfuhr durch Konvektion stark reduziert, die Größe der Wärmeabfuhr durch Wärmeleitung durch die Trennfläche hängt vom Verhältnis der Wärmeleitzahlen der beteiligten Phasen ab. Der insgesamt abgeführte Wärmestrom kann daher bei kleinen Abständen zu- oder abnehmen.

Befindet sich der Draht oberhalb einer geneigten Wand, so wird die freie Konvektionsströmung aus der Vertikalen ausgelenkt. Unter Umständen legt sich die Strömung an die Wand an.

Das Temperaturfeld in Wasser wird mit Hilfe eines Mach-Zehnder-Interferometers sichtbar gemacht.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ СВОБОДНОЙ КОНВЕКЦИИ ОТ ПРОВОЛОК ВБЛИЗИ ГРАНИЦЫ РАЗДЕЛА ФАЗ

Аннотация — Экспериментально исследуется влияние горизонтальной поверхности раздела на теплообмен при свободной конвекции от горизонтальных проволок постоянной температуры. Такими поверхностями раздела являются: (1) поверхность твердой стенки и (2) поверхность жидкости. Проволочка располагалась над или под поверхностью раздела. Эксперименты проводились в воздухе или в воде. Кроме того, исследовалось влияние температуры, диаметра и длины проволоки. При уменьшении расстояния от поверхности раздела значительно уменьшается теплообмен свободной конвекцией; количество переносимого путем теплопроводности тепла через поверхность раздела зависит от отношения коэффициентов теплопроводности рассматриваемых фаз. Следовательно, суммарный теплообмен увеличивается с уменьшением расстояний от границы раздела.

В случае расположения проволоки над наклонной стенкой поток при свободной конвекции отклоняется от вертикали. При определенных условиях поток прилипает к стенке.

Температурное поле в воде визуализировалось с помощью интерферометра Маха–Цендера.