Int. J. Heat Mass Transfer. Vol. 7. pp. 1257–1271. Pergamon Press 1964. Printed in Great Britain

HEAT TRANSFER ON CIRCULAR CYLINDERS EXPOSED TO FREE-JET FLOW

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(*Received* 30 *April* 1964)

Abstract—The mean heat-transfer coefficient was investigated on a circular cylinder placed symmetrically in a two-dimensional jet of limited height. The wall temperature of the cylinder was constant and the Reynolds number based on the cylinder diameter and the speed in the nozzle exit was around 20,000 to 50,000 for most experiments. Surprisingly, the maximum heat-transfer coefficient was obtained for a jet with a height of one eighth of the cylinder diameter and with the cylinder at a distance from the nozzle exit of about 2 to 8 times the jet height; in this case the heat-transfer coefficient was about 20% higher than that for a cylinder in unlimited parallel flow with negligible turbulence in the main stream and with an undisturbed speed equal to that in the nozzle exit. This result is explained by the ability of thin jets to adhere to curved surfaces (Coanda effect) and the high intensity of turbulence in a jet. Heat-transfer coefficients and pressure distributions were measured for variations of the jet height from 2·5 to 0·06 of the cylinder diameter.

NOMENCLATURE

$h = Q/A(T - T_a)$ average heat-transfer coefficient on cylinder with uniform surface temperature;
$h_{\infty, H}$, average heat-transfer coefficient on a cylinder in unlimited parallel flow with undisturbed speed equal to that in the nozzle exit;
$h_{\infty, L}$, average heat-transfer coefficient on a cylinder in unlimited parallel flow with undisturbed speed equal to the local maximum speed in the undisturbed jet at a distance L from the nozzle exit;
p, pressure on cylinder surface;
p_0, pressure at stagnation point;
p_∞, ambient pressure;
u, speed;
u_H, speed in nozzle exit;
u_m, maximum speed in cross section of jet or channel;
Δs, jet height;
t, time;
y, distance from middle plane in jet or from wall in channel;
z, distance from the middle of the jet in direction of the jet width;
A, surface area of cylinder;
B, jet width at nozzle exit;
C, heat capacity of cylinder;
D, cylinder diameter;
G, velocity gradient outside boundary layer at stagnation point;
H, jet height at nozzle exit, also height of channel;
L, distance from stagnation point on cylinder to nozzle exit plane;
Q, heat flow to surface of cylinder at uniform surface temperature;
R, radius of curvature;
$Re_{H,D}$, Reynolds number of cylinder with diameter D and with characteristic speed equal to that in nozzle exit; kinematic viscosity as defined below;
Re_H, Reynolds number for channel with height H and with mean speed in channel;
Re_D, Reynolds number for a cylinder with diameter D in unlimited parallel flow;
T, temperature of cylinder surface;
T_a, ambient air temperature;
T_i, initial temperature;
$\gamma = hA/C$ reciprocal of a time constant;
ϵ, coefficient of emissivity;
ρ, density of air;
φ, angular distance from forward stagnation point;

ν, kinematic viscosity taken at mean temperature between free-stream values and cylindrical wall.

1. INTRODUCTION

HEAT TRANSFER on circular cylinders has been investigated extensively in the past for the case of parallel flow of (theoretically) unlimited extent and with a uniform speed at a large distance from the cylinder (see for instance reference 1). In many cases of practical interest, particularly when cooling cylinders, it may be of advantage to place the cylinder in a jet of limited height. Such cases have apparently not yet been investigated and they are the subject of the present paper.

The same pressure distribution and heat transfer as in an unlimited flow can be obtained, if the cylinder is placed in the middle of the turbulence-free core of a jet of finite height, provided the size of the jet is sufficiently large, so that the pressure field around the cylinder is fully developed. If one starts with such a jet and gradually diminishes the height of the jet, the pressure field around the cylinder near its maximum cross-section (seen in the flow direction) would be affected first, hence the velocities and consequently also the heat transfer would be decreased in that region and this may even reduce the heat transfer in the wake of the cylinder. With decreasing jet height this tendency might well continue and other adverse effects might occur such as a separation of the jet from the cylinder, if it were not for the effects of jet turbulence. At Reynolds numbers which are of practical interest and which are considered here, the boundary of the jet becomes turbulent within a very short distance from the nozzle and the turbulence spreads quickly to the core of the jet. If a cylinder is placed symmetrically in a jet of sufficiently small height in relation to the cylinder diameter, the jet splits into two halves both of which adhere to the surface of the cylinder forming what is generally called a wall jet. Its turbulence spreads close to the surface of the cylinder and thereby strongly influences the flow field around and the heat transfer on the cylinder. To investigate these phenomena is the main purpose of the present paper. Since the jet gains a considerable amount of surrounding fluid by entrainment, the conditions at the boundary of the jet are important. In the present investigation the speed of the fluid at the boundary of the jet was zero and the temperature there was the same as inside the jet. Only symmetrical flow of the jet around the cylinder was investigated. In this investigation air speeds remained below 50 m/s, thus compressibility effects could be ignored.

2. APPARATUS

The experimental equipment consists of the following main units: (*a*) A jet generator, (*b*) two cylinders for measuring the average heat-transfer coefficient and the pressure distribution respectively, (*c*) a heater, (*d*) a channel

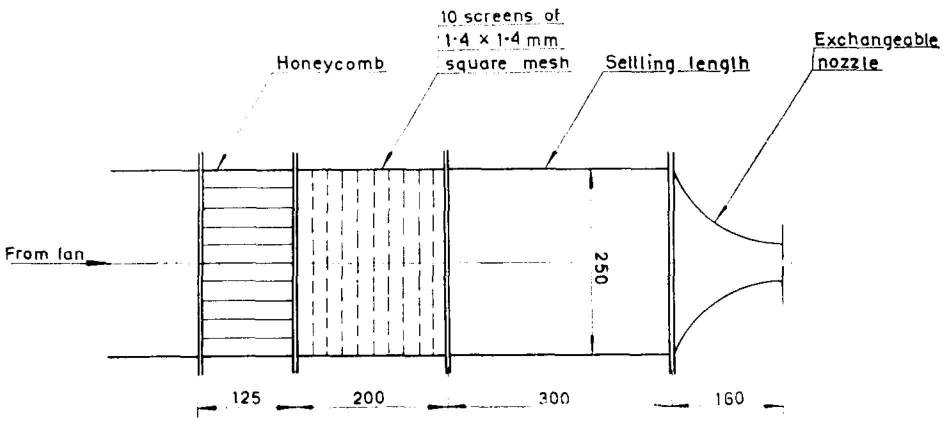

FIG. 1. Jet generator. (Dimensions in mm.)

to be connected to the largest nozzle and (*e*) a recorder for the voltage from the thermocouples.

The jet generator (Fig. 1) is capable of producing two-dimensional jets of 50, 20, 10 and 5 mm height and 250 mm width where all dimensions are taken at the nozzle exit. For this purpose a set of 4 different nozzles is used. Any jet height smaller than 5 mm can be obtained with the help of the 5 mm nozzle which is adjustable (Fig. 2); it is made of two segments of a solid circular bar. With this nozzle the height of small jets can be accurately adjusted and made to be uniform over the entire width.

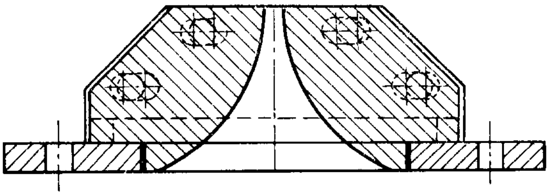

FIG. 2. Adjustable nozzle of 5 mm height.

The heat-transfer cylinder is for measuring the average heat-transfer coefficient over the whole surface (Fig. 3). It is made of copper of 19·5 mm outer diameter, 2 mm wall thickness and is 204 mm long. It is supported at its ends by cone-cylinders made of plastics (not shown in the figure); the cylindrical part of these bodies is of the same diameter as the copper cylinder and their conical part is inserted into the copper cylinder at its ends. The pressure cylinder of 20 mm diameter can be rotated and its angle of rotation can be adjusted to within an accuracy of 0·1 degree. This cylinder has five 0·3 mm pressure holes placed along a generatrix and all holes are vented to the inside of the cylinder which is connected to a Betz manometer. Five holes were used in order to reduce the time-lag of the manometer. In the heater (Fig. 4*a*) the temperature of the copper cylinder is raised to the required initial temperature and at the same time the cylinder is protected by a cover against the external air flow. This is in operation already during the heating period, so that after opening the cover and retracting the heater the desired flow around the cylinder is quickly established. The apparatus (without heater) is shown in Fig. 4*b* together with the 50 mm nozzle and the copper cylinder. The large dial for measuring the angle of rotation is seen in the figure, but it is only used in the pressure measurements. With the help of the support shown in the same figure the cylinder can be accurately brought into the desired position with respect to the jet.

The channel is of 50 mm height and 3000 mm length and at its exit, the turbulent velocity profile can be assumed fully developed. A chart-

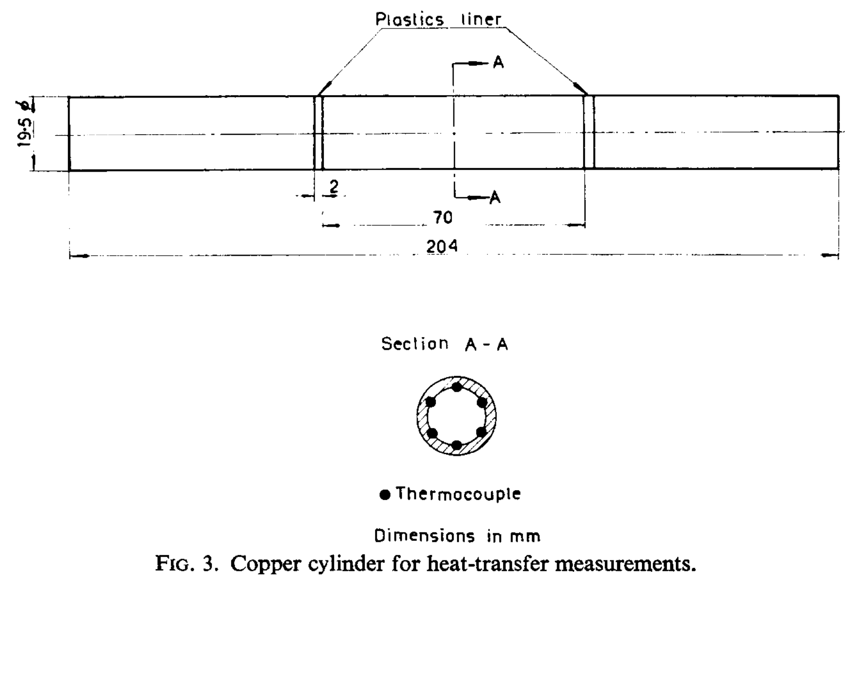

FIG. 3. Copper cylinder for heat-transfer measurements.

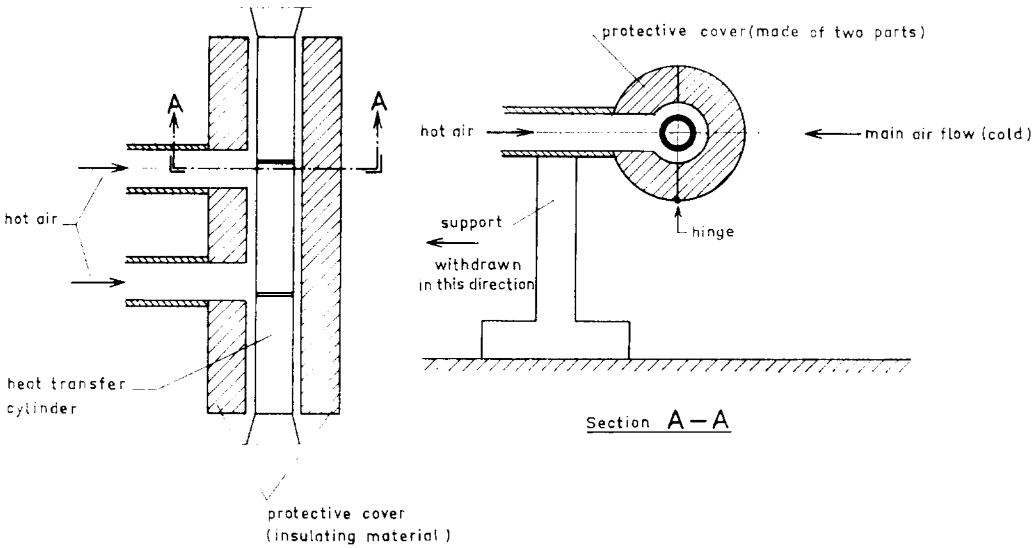

FIG. 4(*a*). Heater; shown as closed (schematic).

recording voltmeter of the type "Speedomax" with an accuracy of 0·2 per cent of the maximum reading was used for measuring the temperature–time history of the copper cylinder.

3. MEASURING TECHNIQUE

In order to avoid disturbances from the ends, the copper cylinder of Fig. 3 was divided into three sections of which the middle one was used for the heat-transfer measurements and was insulated from the two outer sections by plastics liners of 2 mm thickness. The corresponding middle part of the inside of the cylinder is insulated by cotton plugs in order to avoid undesired air drafts inside the cylinder; these plugs also serve to press the thermocouple leads against the walls for close thermal contact in order to reduce undesirable heat conduction in the thermocouple leads.

A transient technique for measuring heat-transfer coefficients was used. Initially all three sections of the cylinder are heated to the same temperature, while the cover of the heater is shut. At the start of the measurements the cover is suddenly opened and the heater is quickly withdrawn (see Fig. 4*a*), so that the measurements can begin almost at once. Six thermocouples are equally distributed around the circumference of the inside of the cylinder; although there were only very small temperature differences among them during cooling, their leads were made of equal length and connected in parallel, so that the temperatures measured were mean values over the surface of the cylinder. Since all other losses are practically negligible, the copper cylinder loses heat only by heat transfer at its surface; since the temperatures are uniform across the thickness of the cylinder wall, the balance of heat flow is

$$C\frac{dT}{dt} = h\,A\,(T_a - T) \qquad (1)$$

where C and A are, respectively, the heat capacity and surface area of the middle part of the cylinder, h the average heat-transfer coefficient, T_a the ambient air temperature, T the cylinder temperature and t the time. If C, h and T_a are constant, equation (1) can easily be solved and yields

$$\frac{T - T_a}{T_i - T_a} = \exp\,[-\gamma t] \qquad (2)$$

where T_i is the initial temperature and $\gamma = h\,A/C$. The specific heat of copper depends only to a small degree on the temperature (± 2 per cent) within the temperature range investigated here; hence the fact that the measured temperatures could be closely approximated by equation (2)

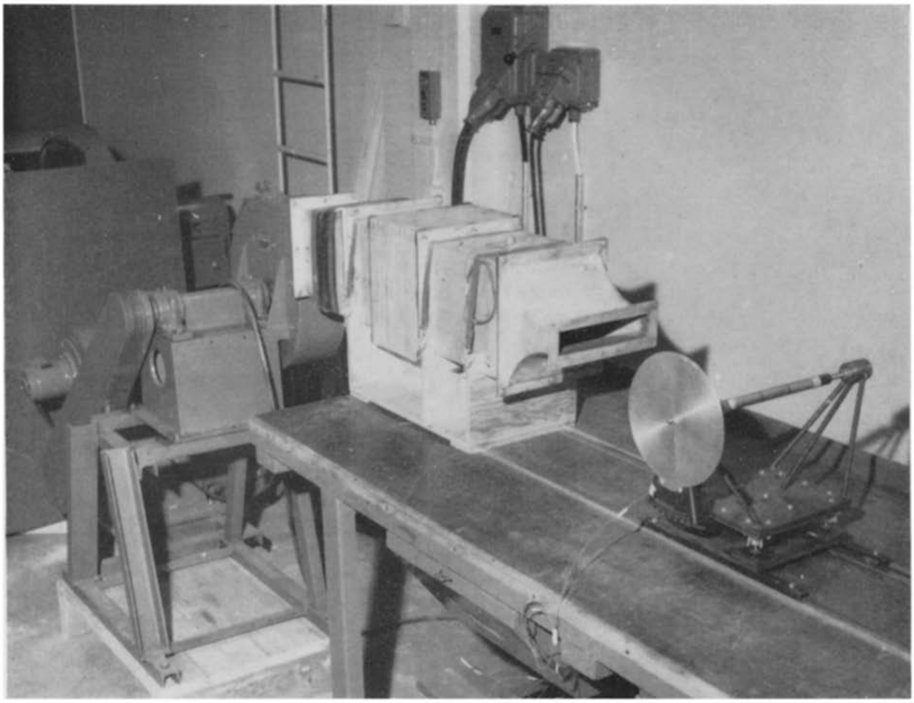

FIG. 4(*b*). View of apparatus.

indicates that the heat-transfer coefficient depends only in a negligible degree on the temperature within the temperature range of the measurements (120° to 20°C).

γ was determined by fitting the exponential curve to the measured temperatures by the method of least squares with the help of a digital computer.* The observed heat-transfer coefficients could be reproduced within a margin of ± 1 per cent, but the total error is higher and roughly estimated at ± 3 per cent. Among these errors are the losses due to heat radiation. The copper surface was kept glossy by regular cleaning with a suitable chemical to remove oxygen layers. With an estimated value of the coefficient of emissivity of $\epsilon \approx 0{\cdot}2$, the error due to the neglect of heat radiation would be about 1 to 3 per cent. The temperature differences between the outer sections and the middle section of the copper cylinder were kept to a few degrees centigrade, so that the errors due to heat conduction across the plastic liners of Fig. 3 were negligible.

4. RESULTS

(a) *Velocity distribution*

The velocity distributions at the nozzle exit are reproduced in Fig. 5. For the smallest nozzle height of 1·2 mm, the contraction is too gradual, so that the thickness of the boundary layer at the walls of the nozzle is not small as compared with the nozzle height; otherwise the velocity distributions were almost rectangular except for the corners. Measurements have also been made of the velocity distributions across the jets at different distances from the nozzles in order to check the development of the jet (Fig. 6). For comparison the diameter of the cylinder D (about 20 mm) is also given in the figures. For fully developed jet flow and at sufficiently large distances from the nozzle (i.e. $L \gg H$) a comparison of the velocity profiles has been made with Reichardt's measurements [1a] and agreement is good except for the largest nozzle; in that case differences apparently occur because the jet deviates at large distances already from two-dimensional flow, since for the largest nozzle ($H = 50$ mm) the ratio of the nozzle height to width is only 1:5. For moderate values of L/H corresponding to the region where transition to fully developed turbulent jet flow occurs, no measurements have apparently been made before for two-dimensional jets. The development of the centre-line velocity of the jet with distance from the nozzle exit is given later in Fig. 12 for better correlation to the heat-transfer measurements.

(b) *Pressure distributions*

An insight into the nature of the flow around the cylinder can be gained in a simple way by measuring the pressure distribution on the cylinder. If the cylinder is smaller than the jet

* This procedure rather than plotting a straight line of log $(T - T_a)$ against time was used, because the error in the instrument recording is a certain fraction of the maximum value recorded by the instrument; hence the recordings for small values of $T - T_a$ would give a larger scatter in the logarithmic plot than those for large values of $T - T_a$. Thus in the logarithmic plot the experimental errors would have unequal weight and hence this method of finding γ would be less accurate than the one used in the present paper.

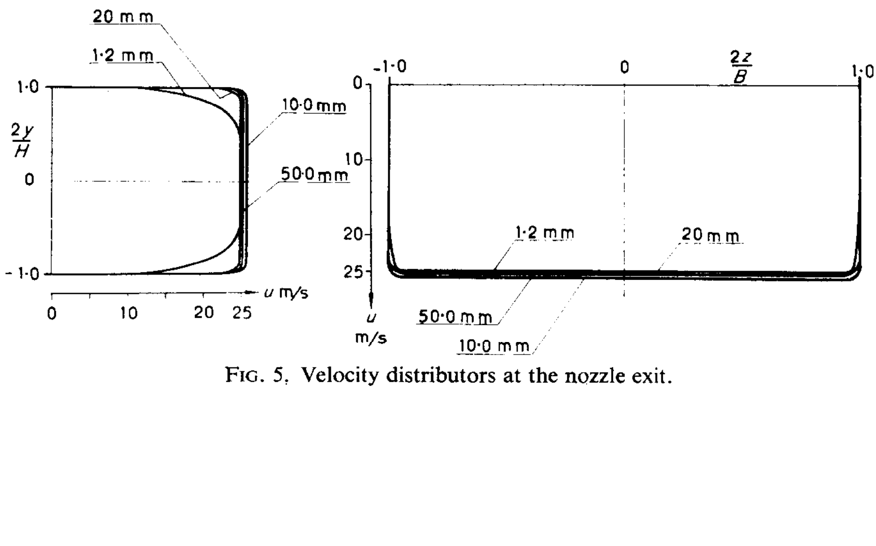

FIG. 5. Velocity distributors at the nozzle exit.

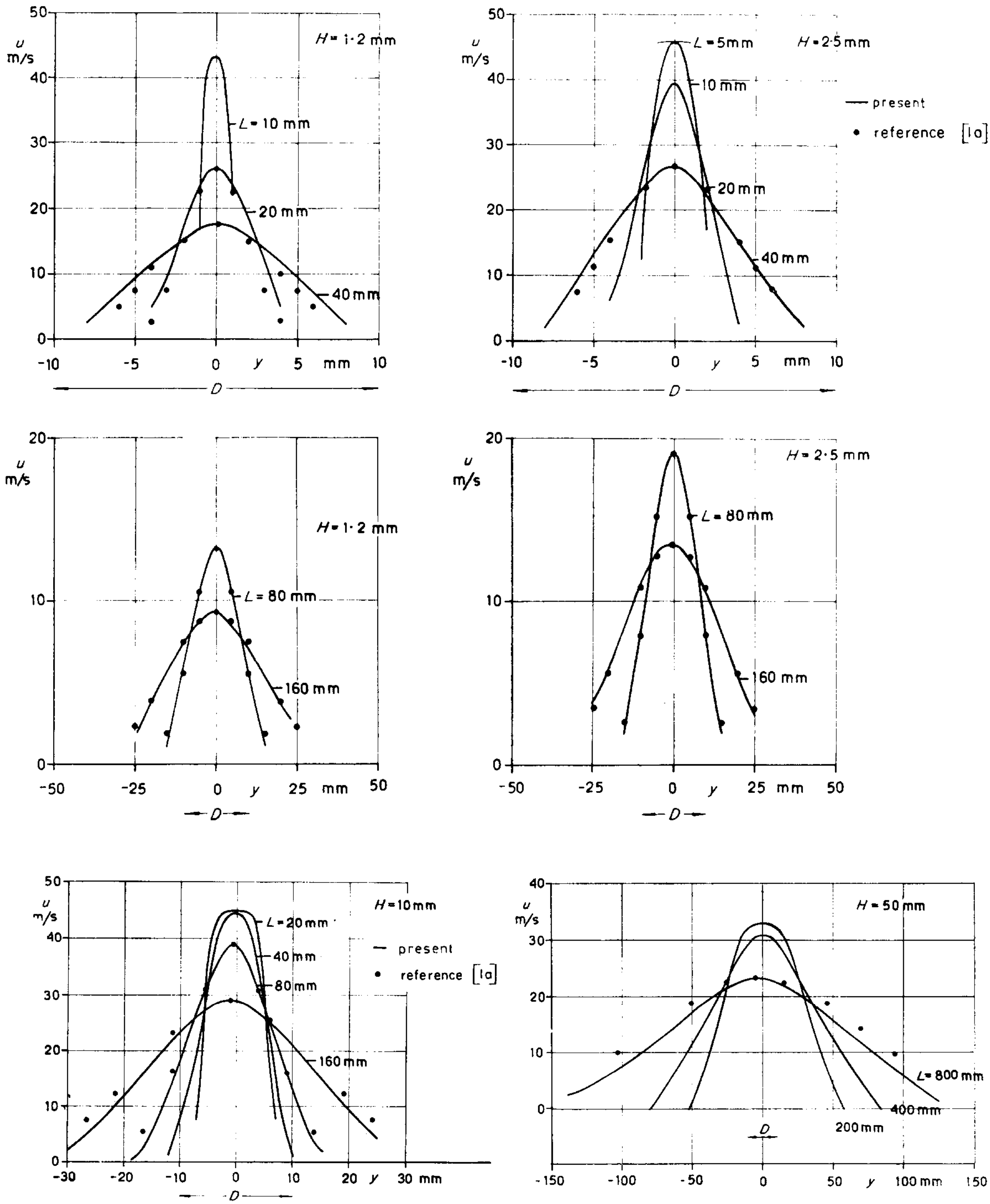

FIG. 6. Velocity profiles across jets.

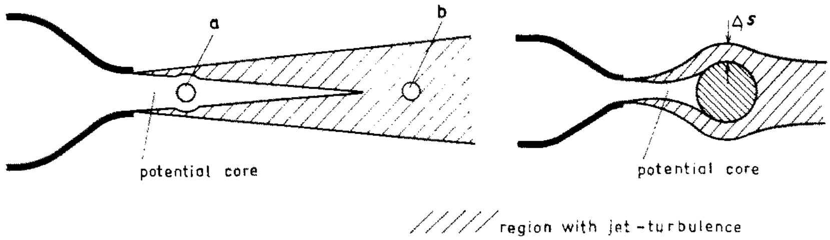

FIG. 7. (Left) A cylinder in a jet of a height larger than the cylinder diameter (schematic).
FIG. 8. (Right) Coanda-type flow of a jet around a cylinder (schematic).

and is in the turbulence-free core of the jet as in position *a* of Fig. 7, the pressure distribution does not differ qualitatively, but only quantitatively from that in unlimited parallel flow. Similar considerations apply also further downstream in position *b* of Fig. 7, but here the turbulence in the jet affects the boundary layer flow on the cylinder.

A different behaviour can be expected if the jet is small in comparison to the cylinder diameter. Depending on the distance from the nozzle, a small jet is already turbulent on coming into contact with the cylinder or becomes so soon afterwards. Under such conditions the jet has a tendency to adhere to the curved surface of the cylinder (Fig. 8); this phenomenon is well known by the name Coanda effect (for a survey see reference 2). Some distance downstream of the stagnation region all streamlines become concave with respect to the surface of the cylinder (Fig. 8); then the pressure difference Δp across each half of the jet is according to Fig. 8 approximately given by

$$\Delta p = p - p_\infty = - \rho \frac{\bar{u}^2}{R} \Delta s \qquad (3)$$

p is the pressure on the cylinder surface, p_∞ the ambient pressure, $\bar{u}$ and R are the respective mean values across the jet of the velocity and of the radius of curvature of the streamlines, and Δs is the jet height. The maximum size of Δp depends on the interplay of two influences: In flow direction the velocity $\bar{u}$ of the jet decreases and the height of the jet increases. Where Δp becomes largest, the pressure on the cylinder becomes a minimum.

At a sufficient distance from the nozzle even a small jet would have spread considerably so that conditions would resemble those of position b of Fig. 7.

In Figs. 9 and 10 the pressure distributions on the cylinder ($D = 20$ mm) are given; p_0 is the pressure at the stagnation point, L the distance from the nozzle exit plane to the stagnation point on the cylinder, H the jet height. For the largest jet heights (i.e. $D/H = 0{\cdot}4$ and 1) they resemble those of cylinders in an unlimited flow with a laminar boundary layer at the separation point, i.e. there is only a small pressure rise after the pressure minimum followed by a wide region with almost constant pressure such as is typical for a separation region. When a jet of 10 mm height has split into two equal halves at the stagnation point of the cylinder, each half appears to be sufficiently thin, so that it can adhere to the surface because of the Coanda effect. This is confirmed by the pressure distribution for $D/H = 2$ which is now markedly different in character. Compared with the two previous cases the pressure falls now to much lower values and after the pressure minimum the pressure rise is larger and extends over a much larger region. At large distances from the nozzle where the jet is comparatively thick the pressure falls to lower values than for small distances, but rises thereafter more quickly. Due to the intense turbulence in the jet, the boundary layer very likely becomes turbulent before the separation point and hence separation is delayed (see also curve C in Fig. 11). As the jet height decreases and considering small values of L/H, the stagnation region diminishes more and more in extent as is seen from the reduction of the region within which the non-dimensional pressure $(p - p_\infty)/(p_0 - p_\infty)$ falls from 1 to about

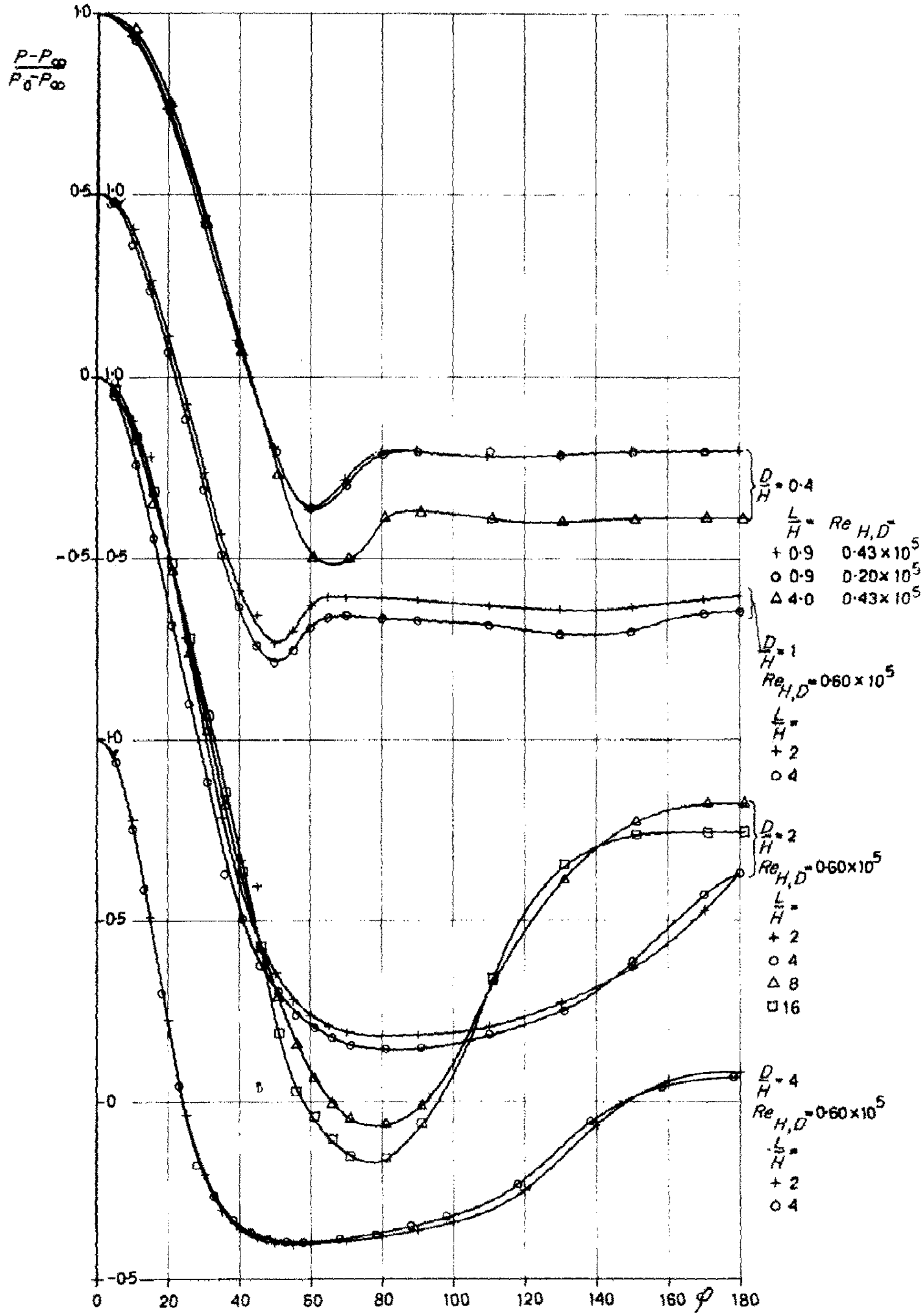

FIG. 9. Pressure distributions on cylinder in jets of different heights.

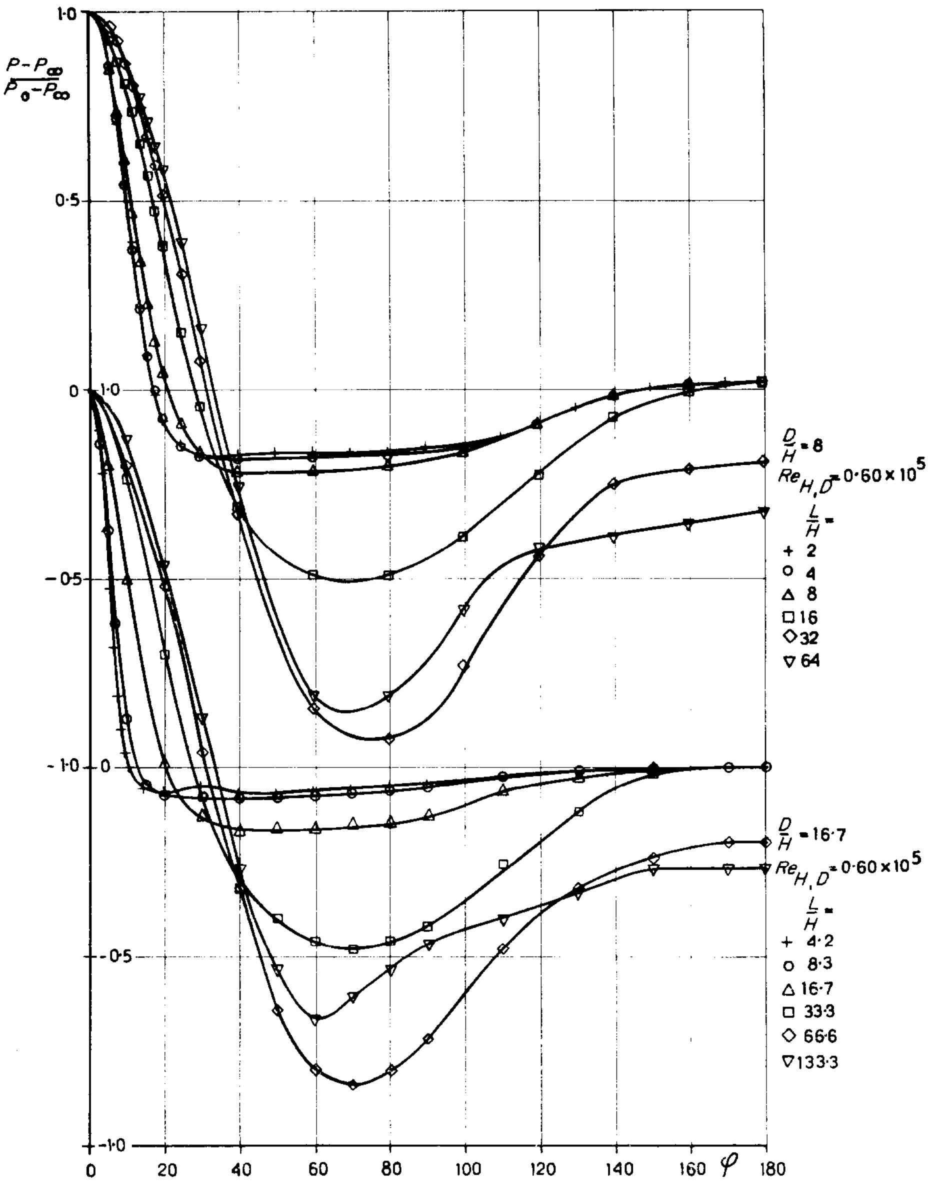

FIG. 10. Pressure distributions on cylinder in jets of different heights.

zero; further, the deviations from the ambient pressure become less in the region of negative pressures. According to equation (3) the latter fact is due to the jet height Δs being small. Further downstream from the nozzle where the jets become thicker ($L/H \geqslant 30$), the pressure distributions become similar for all ratios of D/H and are of a type discussed previously.

In Fig. 11 a comparison is made between five cases of pressure distributions on cylinders: A, B, C are taken from reference 3 and refer to measurements in a wind tunnel (i.e. real viscous flow around a cylinder in unlimited parallel flow), E refers to potential flow and D to the present measurements in a free jet with $D/H = 2$ and $L/H = 8$ as taken from Fig. 9. Cases A and

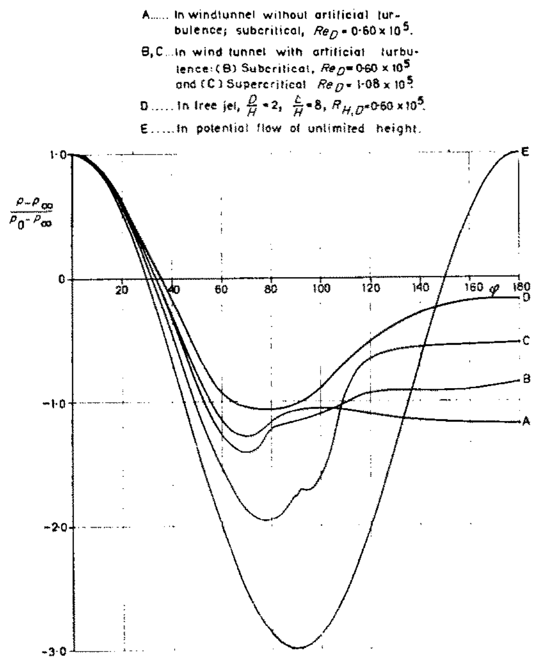

FIG. 11. Comparison between typical pressure distributions on a cylinder under different flow conditions.

B correspond to the same Reynolds number as in the present experiments and then laminar separation occurs. B and C differ from A by artificially introduced turbulence in the main stream. For C the Reynolds number is higher ($Re_D = 1{\cdot}08 \times 10^5$) and here the boundary layer becomes turbulent before the separation point is reached and therefore separation is delayed and significant changes in the pressure distribution occur. The pressure distribution D corresponds to a Coanda-type flow around the cylinder; its form is smoother than for the curves A and B and the pressure minimum lies slightly above the values for these curves, while the pressure at the rear side of the cylinder is higher than in cases A–C.

(c) *Heat-transfer measurements*

As mentioned previously, all heat-transfer coefficients h are average values for the whole surface of the cylinder. In Fig. 12, h is given as a fraction of $h_{\infty,H}$ which is a heat-transfer coefficient one would obtain in case of unlimited and turbulence-free parallel flow with an undisturbed speed equal to that at the nozzle exit. $h_{\infty,H}$ as well as $h_{\infty,L}$ to be introduced later on have been calculated according to Hilpert [1]. The abscissa is the ratio of the distance L of the stagnation point of the cylinder from the nozzle exit plane to the height H of the nozzle at its exit. The figure also shows the maximum speed in the cross section of the jet, u_m, divided by the speed in the nozzle exit u_H. At the smallest distance of the measurements, $L/H = 2$, the flow in the middle region of the jet is still free of turbulence, because there the same speed as in the nozzle exit prevails. Hence for the largest nozzle h is smaller than $h_{\infty,H}$, because the pressure field cannot develop fully due to the limited size of the jet. This is so even for the nozzle coming next in decreasing size. As is already known from the pressure distributions, a Coanda-type flow exists for $H = 10$ mm. In this case turbulent regions of the jet come close to parts of the surface on the cylinder and this yields an increase in h. With decreasing values of H, but still at $L/H = 2$, larger parts of the surface of the cylinder come under the influence of jet turbulence; there is also an increase in the pressure gradient at the stagnation point and hence also in h, because the jet height decreases. The maximum value of h is reached for $H = 2{\cdot}5$ mm. An increase in L/H from 2 to 4 yields almost no change in h for the largest nozzle for which the cylinder still appears to be entirely in the turbulence-free core of the jet. With decreasing jet height the heat-transfer coefficient increases, first sharply, when the jet turbulence begins to influence the heat transfer, then more gradually as the increase in the area of the cylinder surface which is affected by the jet turbulence becomes less. For the smallest jet height ($H = 1{\cdot}2$ mm) the speed in the attached jet on the rear parts of the cylinder is already much reduced and hence h is less than for $H = 2{\cdot}5$ mm; for the smallest jet height the maximum value of h is at $L/H = 2$ and 4 and h falls for larger distances, first slowly later on more rapidly.

At around $L/H = 6$ the turbulence spreads to the middle of the jet as can be seen from the velocity distribution; then even the stagnation region of the cylinder is exposed to the severe turbulence of the jet. At around $L/H = 8$ the heat-transfer coefficient reaches its maximum for the nozzles with $H = 2{\cdot}5$ to 20 mm; at this

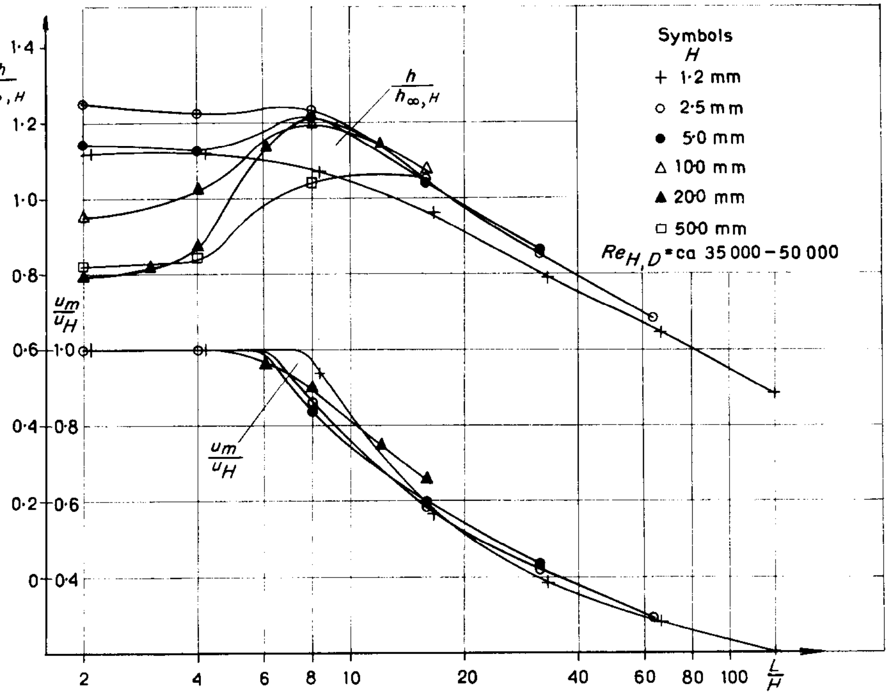

FIG. 12. Heat-transfer coefficient of a cylinder of 19·5 mm diameter in a jet of height H; reference value $h_{\infty, H}$.

ratio of L/H, the increase in heat transfer due to the increase of the turbulence in the jet core has reached its maximum and for larger distances the losses due to the decrease in the jet speed lead to a decrease in the heat-transfer coefficient. For large values of L/H the ratio of the heat-transfer coefficients for all jets tend to lie on one curve, because the jet becomes larger than the cylinder diameter and flow conditions do not differ much for different nozzles as has already been observed in the pressure distributions. The heat-transfer measurements of Fig. 12 are replotted in Fig. 13 where h is referred to $h_{\infty, L}$ which is again a heat-transfer coefficient for unlimited and turbulence-free parallel flow, but calculated with an undisturbed speed equal to the maximum local speed in the undisturbed jet at a distance L from the nozzle exit. For large values of L/H the local heat-transfer coefficients tend to be roughly the same for all nozzle heights except for the smallest and are about equal to $1{\cdot}5 h_{\infty, L}$.

The Reynolds number was varied to a large extent in only one set of measurements and this was for the largest jet for which $H = 50$ mm and with the cylinder placed at $L/H = 0{\cdot}8$. The Reynolds number variation was from 6000 to 35000 (see Fig. 14). With decreasing Reynolds number the deviations from the heat-transfer coefficient for unlimited parallel flow become less; this is tentatively explained by the larger share of the front part of the cylinder in the total heat transfer at lower Reynolds numbers [4].

There are two comments on the heat-transfer measurements: First, measurements for the larger nozzles have not been made at such large values of L/H as for the smaller nozzles; because of the limited width of the jets (250 mm) the jet flow for the large nozzles would not be two-dimensional at large distances from the nozzles. Even at the largest distances where measurements have been made for the large nozzles, some reservation must be made for deviations from the two-dimensional character of the flow. Secondly, the turbulence of the air in the nozzle has not been measured; due to that turbulence there may be some increase in the heat-transfer coefficients on the cylinder when placed in the

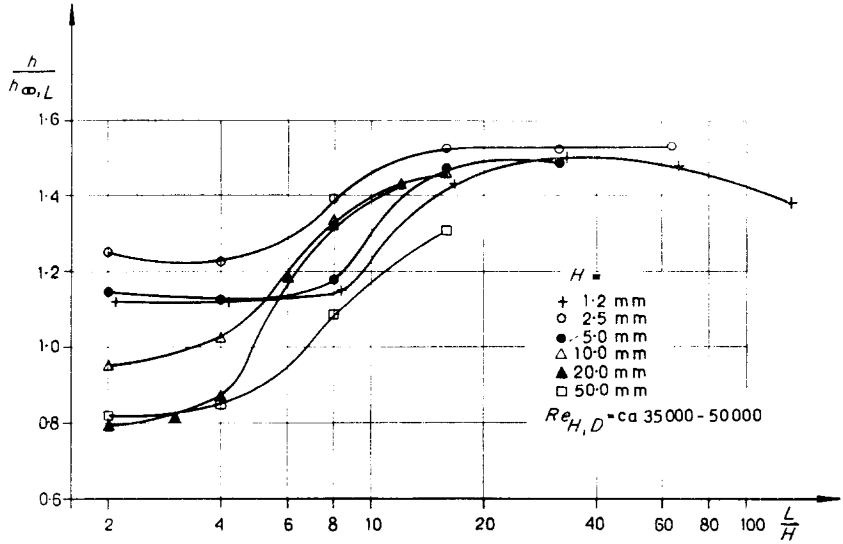

FIG. 13. Heat-transfer coefficient of a cylinder of 19·5 mm diameter in a jet of height H; reference value $h_{\infty,L}$.

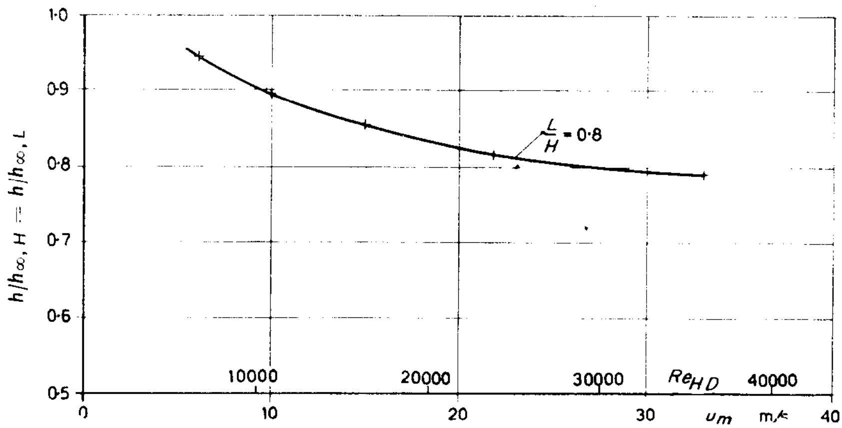

FIG. 14. Influence of Reynolds number variation on heat-transfer coefficient for largest nozzle.

core of the jet which is free of jet-turbulence. If this increase in h is subtracted, the curve in Fig. 14 would possibly lie somewhat lower, because the reference values $h_{\infty,H}$ and $h_{\infty,L}$ were taken from Hilpert [1] and hence refer to an almost turbulence-free air flow.

From Figs. 12 and 13 there emerges the fact that a jet of a height of about 0·12 cylinder diameter gives an average heat-transfer coefficient on the cylinder about 20 per cent higher than in unlimited parallel flow without turbulence in the main stream. The Reynolds number was $Re_{H,D} = 35000$ to 50000 and as mentioned previously the fluid outside the jet was at rest and at the same temperature as the jet. This remarkable result is due to the following effects: one reason for obtaining large heat transfer in the present case appears to be that the jet adheres to the surface of the cylinder (Coanda effect). As the jet height decreases and becomes small in comparison to the cylinder diameter, the velocity gradient at the stagnation point increases. As is well known, the local heat-transfer coefficient at the stagnation point in a laminar boundary layer with turbulence-free external flow is proportional to the square root

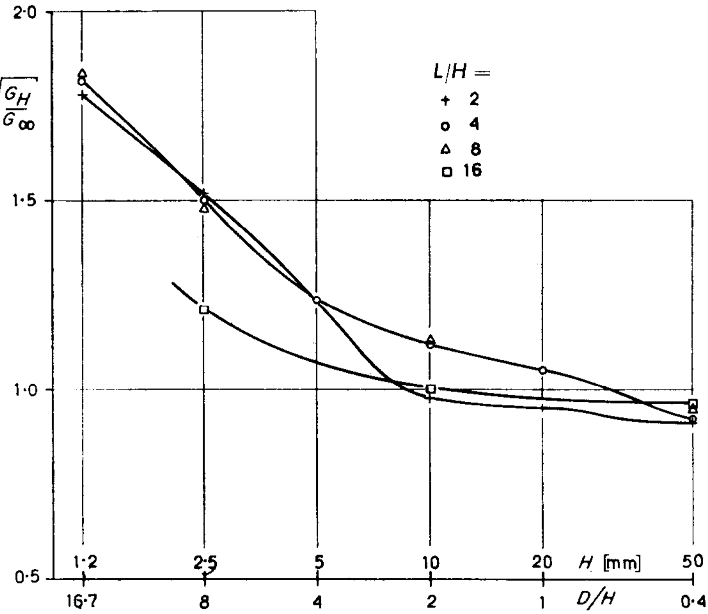

FIG. 15. Ratio of the stagnation-point heat-transfer coefficient in a jet to that in unlimited parallel flow. Assumed laminar boundary layer and turbulence-free external flow.

of the local velocity gradient. Thus the ratio of this heat-transfer coefficient for jet flow to that for infinite parallel flow is equal to $\sqrt{(G_H/G_\infty)}$ and can be seen from Fig. 15; G_H and G_∞ are the respective velocity gradients at the stagnation point for a jet of height H at the nozzle exit and for unlimited parallel flow.* The local increase in the heat-transfer coefficient for jets of small height is of course gained at the expense of losses at the rear part of the cylinder where the speed is reduced. The presence of turbulence in the external flow around a cylinder is known to increase the heat transfer [5] and this increase must be particularly large in the turbulent regions of a jet where the turbulence intensity is high [6]. However a further discussion of these effects is difficult to make without a knowledge of the local distribution of the heat-transfer coefficient.

A number of complementary measurements have also been made. For comparison with known results heat-transfer measurements were made in a wind tunnel† whose cross section was large in comparison to the cylinder diameter and hence unlimited parallel flow could be assumed around the cylinder. The same equipment and measuring technique were used as for the measurements in the jets. The tunnel had a contraction ratio of 3·3 : 1, a test section of 35 × 60 cm and with two screens in the settling chamber a turbulence intensity in the working section of about 0·9 per cent of the mean speed which was 20 m/s.‡ The published results about heat transfer on cylinders in wind tunnels show considerable scatter; the most likely explanation is that the turbulence intensity of the tunnels used was unknown although it influences the rate of heat transfer to a large extent [5]. Compared with Hilpert's measurements [1], which have apparently been made in an air stream of very low turbulence, in the present measurements the turbulence intensity of the air stream was relatively high and the heat-transfer coefficient

* G has been calculated from the pressure distribution using Bernoulli's equation. This is correct for $L/H \leqslant 4$ for which distance the flow at the stagnation point is free of turbulence, but it is only approximately true for larger values of L/H.

† The author is indebted to Prof. S. Luthander for permission to use this wind tunnel.

‡ According to measurements made by G. Bévengut.

were higher by 6 to 9 per cent for speeds of 9 to 28 m/s than those of Hilpert. The difference agrees well with other published data in tunnels of unspecified turbulence intensity (see for instance [7]). Some contribution (a few per cent) to the above difference may also be due to heat radiation for which no correction has been made.

In air at rest an average heat-transfer coefficient of about 0·002 kcal/m^{2}s degC had been measured on the cylinder in the same surroundings where all other measurements except those in the wind tunnel have been made. These values are so low that even the lowest values of h measured in jets could not have been influenced by free convection by more than a few per cent.

For comparison it was thought interesting to measure also in a channel with fully developed turbulent flow. The channel mentioned in Section 2 was connected to the largest nozzle with $H =$ 50 mm. The velocity profile in the channel can be expected to be fully developed, because turbulence promoters have been used at the entry of the channel; its length was 60 channel heights and the velocity profile at the end of the channel could be represented by $u/u_m = (2\,y/H)^{1/8}$ for $Re_H = 10^5$. When the cylinder was placed symmetrically to the mid plane of the channel and at a distance $L/H = 0{\cdot}8$ from the channel exit, the heat-transfer coefficient were 10, 6 and 4 per cent higher for the respective Reynolds numbers* of 36000, 16000 and 7000 than corresponding values for the cylinder in the turbulence-free core of a jet of height $H = 50$ mm and at the same distance $L/H = 0{\cdot}8$ from the nozzle exit. However, in a jet of sufficiently large height and with fully developed turbulence the heat-transfer coefficients for cylinder Reynolds numbers of the order of magnitude of 10^4 were found to be about 50 per cent higher than those for turbulence-free and unlimited parallel flow (see Fig. 13). This seems to indicate that the free-jet turbulence is much more effective in increasing the rate of heat transfer than is the turbulence in the middle of the channel. Even the pressure distribution was but little influenced by the channel turbulence. The explanation for these differences is of course the difference in the intensity and—perhaps more important—in the structure of the turbulence in channels and jets. The difference in intensity and in the characteristics between the turbulence in a channel and in a jet is well known. It was demonstrated [5] that turbulence produced by a grid in the main stream outside the boundary layer of a body influences considerably the heat transfer on the body. A theoretical explanation of this phenomenon was given in reference 8, but the theory is rather complicated. Therefore an explanation about the influence on heat transfer on bodies by different types of turbulence in the main stream is not attempted here as this paper is mainly a report on experimental work.

* Characteristic speed equal to u_m

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Résumé—Le coefficient moyen de transport de chaleur a été étudié sur un cylindre circulaire placé symétriquement dans un jet bidimensionnel de hauteur limitée. La température de la paroi du cylindre était constante et le nombre de Reynolds basé sur le diamètre du cylindre et sur la vitesse à la sortie de la tuyère était d'environ 20 000 à 50 000 pour la plupart des expériences. D'une façon surprenante, le maximum du coefficient de transport de chaleur était obtenu pour un jet avec une hauteur égale au huitième du diamètre du cylindre et avec le cylindre à une distance de la sortie de la tuyère égale à environ 2 à 8 fois la hauteur du jet; dans ce cas, le coefficient de transport de chaleur était environ 20% plus élevé que celui pour un cylindre dans un écoulement parallèle illimité avec une turbulence négligeable dans l'écoulement principal et avec une vitesse non-perturbée égale à celle à la sortie de la tuyère. Ce résultat est expliqué par la faculté des jets minces à adhérer aux surfaces courbes (effet Coanda) et par l'intensité élevée de la turbulence dans un jet. Les coefficients de transport de chaleur et les distributions de pression ont été mesurés pour des variations de la hauteur du jet de 2,5 à 0,06 du diamétre du cylindre.

Zusammenfassung—Es wurde der mittlere Wärmeübergangskoeffizient an einem kreisförmigen Zylinder untersucht, der sich symmetrisch in einer zweidimensionalen Düsenströmung begrenzter Höhe befand. Die Wandtemperatur des Zylinders war konstant und die Reynoldszahl, bezogen auf den Zylinderdurchmesser und die Geschwindigkeit am Düsenende, betrug 20 000 bis 50 000 bei den meisten Versuchen. Überraschenderweise wurde das Maximum des Wärmeübergangskoeffizienten für eine Düsenströmung erhalten, deren Höhe 1/8 des Durchmessers des Zylinders betrug und bei einer Entfernung des Zylinders vom Düsenende von ungefähr 2 bis 8 mal der Höhe der Düsenströmung; in diesem Fall war der Wärmeübergangskoeffizient etwa 20% höher als bei einem Zylinder in unbegrenzter Parallelströmung mit vernachlässigbarer Turbulenz in der Hauptströmung und mit einer ungestörten, gleich grossen Geschwindigkeit wie im Düsenausgang. Dieses Ergebnis wird erklärt durch die Fähigkeit dünner Düsenströmungen gekrümmten Oberflächen zu folgen (Coanda Effekt) und durch die hohe Turbulenz in einer Düsenströmung. Wärmeübergangskoeffizienten und Druckverteilung wurden bei verschiedenen Höhen der Düsenströmungen (2,5 bis 0,06 des Zylinderdurchmessers) gemessen.

Аннотация—Исследовался средний коэффициент теплообмена кругового цилиндра, помещенного симметрично в двухмерную струю определенной высоты. Температура стенки цилиндра была постоянной, а значение числа Рейнольдса, построенного по диаметру цилиндра и скорости в выходном сечении сопла, в большинстве экспериментов составляло приблизительно от 20.000 до 50.000. К удивлению, максимальный коэффициент теплообмена, полученный для струи высотой 1/8 значения диаметра цилиндра и на удалении цилиндра от выходного сечения сопла, в 2–8 раз превышающего высоту струи, был примерно на 20% выше значения, полученного для цилиндра в неограниченном параллельном потоке при малой степени турбулентности основного потока и при невозмущенной скорости, равной скорости во входном сечении сопла. Этот результат объясняется способностью тонких струй прилипать к искривленным поверхностям (эффект Коанда), а также большой интенсивностью турбулентности в струе. Коэффициенты теплообмена и распределения давления замерялись для струи, высота которой изменялась от 2,5 до 0,06 значения диаметра цилиндра.