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External forced convection around a circular cylinder near a plane boundary

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Abstract—The flow and the external forced convection around an isothermal circular cylinder, placed at various heights above a plane surface, has been investigated experimentally over the subcritical Reynolds number range 1.4×10^4–4×10^4, Reynolds number being based on the cylinder diameter. The influence of the presence of a plane boundary on drag and lift coefficients, and on both local and global Nusselt numbers, was examined. It was found that the formation of closed recirculation regions upstream and downstream of the cylinder is responsible for the occurrence of small values of the local heat transfer coefficient, especially at the rear of the cylinder. In all cases studied, the drag and global Nusselt number reached a minimum when the cylinder touched the wall; for this situation, particular attention was given to the influence of the boundary layer's thickness on the flow and on the external convection around the cylinder.

1. INTRODUCTION

THE CIRCULAR cylinder is one of the shapes most studied by the fluid dynamicist. Nevertheless, there seems to be a limited understanding of the flow around a circular cylinder near a plane boundary and, to our knowledge, external convection has never been investigated in such a condition. These problems are of fundamental interest and are important in many engineering applications.

Bearman and Zdravkovich [1] investigated the flow around a circular cylinder near a wall at two Reynolds numbers: $Re = 2.5 \times 10^4$ and 4.8×10^4. The thickness of the boundary layer on the wall at the position of the cylinder, but with it removed from the tunnel, was 0.8 diameters and the free stream turbulence level was less than 0.8%. Pressure distributions around the cylinder showed that, in the presence of a plane surface, the frontal stagnation point moved towards the gap, while the separation point on the cylinder nearest to the wall, moved as far downstream along the cylinder shoulder as the upper separation point was displaced upstream of the upper shoulder. In their experiments drag decreased as the plate was approached, and reached a minimum when the cylinder touched the plate. For all distances H/D (cf. Fig. 1) there was always a mean force on the cylinder, repelling it from the wall. This force decreased very rapidly as the cylinder was moved away from the plane surface. Also Goktun [2] investigated the flow around a circular cylinder near a wall at Reynolds numbers between 0.9×10^5 and 2.5×10^5. In his experiments the wall was represented by a plate parallel to the flow and the cylinder was positioned at 2, 4 and 8 diameters downstream of the leading edge. In these three positions, for a given value of H/D, he found no differences in the values of the lift and drag determined by measurements of pressure distributions. The thickness of the boundary layer in the absence of the cylinder was not reported but we presume it must have been small.

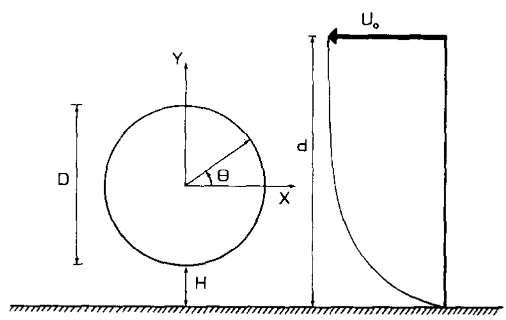

FIG. 1. Arrangement of the models and symbols.

Buresti and Lanciotti [3] investigated vortex shedding from circular cylinders in cross-flow near a plane surface at Reynolds numbers between 0.85×10^5 and 3.0×10^5. From their results and those of Bearman and Zdravkovich it is apparent that, at least in the case of thin oncoming boundary layers, a very important modification appears in the flow for small values of the gap-to-diameter ratio, H/D: regular vortex shedding is completely suppressed on both sides of the cylinder for all distances $H/D < 0.3$. The flow-visualization experiments of Bearman and Zdravkovich demonstrated that at all the H/D ratios, where vortex shedding was suppressed, closed recirculation regions formed on the plate upstream and downstream of the cylinder and when the cylinder was touching the plate they attached themselves to the cylinder.

In this paper two new aspects of the problem are presented: the influence of the presence of a plane surface on external convection around the cylinder at

NOMENCLATURE

D	diameter	p_∞	free stream static pressure
d	oncoming boundary layer thickness	Re	Reynolds number, $U_\infty D/\nu$
C_p	pressure coefficient, $(p-p_\infty)/\frac{1}{2}\rho U_\infty^2$	U_∞	free stream velocity.
H	cylinder-to-plate distance		
k	thermal conductivity of fluid		
$h(\theta)$	local heat transfer coefficient	Greek symbols	
h	average heat transfer coefficient	θ	circumferencial angle on cylinder
i	free stream turbulence intensity	ν	kinematic viscosity of fluid
Nu	Nusselt number, hD/k	ρ	density of fluid.

various H/D ratios, and the effects of the upstream boundary layer characteristics on the values of drag, lift and heat transfer coefficients, when the cylinder touches the plane surface.

2. EXPERIMENTAL SETUP

2.1. *Pressure distributions*

The experiments were performed in the Laboratory of Fluid Mechanics, University of Coimbra. Two subsonic wind tunnels were used. The smaller one had a test section area of 0.45×0.45 m^2 and was 1 m long. The free stream turbulence level was about 1.6% at the top speed of 28 m s^{-1}, and could be modified by placing grids between the nozzle and the test section. An aluminium cylinder with a diameter of 25.0 mm spanned the working section horizontally, thus having a length-to-diameter ratio of 18. The cylinder was pressure tapped at the mid-span and by rotating it, pressure measurements could be made at any angular position. An aluminium plate, 0.45 m wide, 0.72 m long and 2 mm thick was placed horizontally in the working section. The gap between the cylinder and the plate was varied over the range 0–0.4 cylinder diameters. The cylinder was situated at 14.4 cylinder diameters from the sharp leading edge. The plate was pressure tapped at the mid-span. A central tapping was fitted under the axis of the cylinder and the others were positioned at 0.4, 0.8, 1.6, 2.4, 4 and 6 diameters upstream and downstream of it.

Experiments were also carried out in a 4 m long suction wind tunnel with a test section area of 1×1 m^2. The free stream turbulence level was about 6% at the top speed of 14 m s^{-1}. Three PVC cylinders of diameters 50, 90 and 160 mm were utilized in the experiments. All the models were pressure tapped at the mid-span. An aluminium plate 1 m wide, 1.3 m long and 4 mm thick was placed horizontally in the working section, and the gap between the cylinders and the plate could also be varied. For all runs, the axis of the cylinder was situated at 0.7 m from the leading edge and at 3.2 m from the entrance of the working section.

The dimensions of this wind tunnel enable the simulation of thick boundary layers on the bottom of the working section using Counihan's method of vortex generators [4]. The characteristics of the boundary layers were measured with a DISA 55M constant-temperature hot-wire anemometer, with the plate and the cylinders removed from the tunnel. In the test section the thickness of the boundary layers were 150, 330, and 550 mm, and the exponent of the mean velocity profile was 0.14 which means that they were good approximations of the open-country atmospheric boundary layer. The boundary layer developed on the bottom of the tunnel without vortex generators was also analysed and the values of the thickness and the exponent were 60 mm and 0.13. The boundary layer thickness-to-diameter ratio varied between 0.38 and 11.

In all experiments pressure measurements were carried out with a Betz micromanometer with an error smaller than 0.02 mm of the water column. Drag and lift were evaluated from pressure distributions around the cylinders and corrected for blockage effects according to the procedure of Maskell [5]. In the case of the bigger model, the maximum corrections for drag were about 24% of the measured values. In a second method of correction [6], the effective flow velocity past the cylinder was taken as $U_\infty + \Delta U_\infty$ where ΔU_∞ was the increase caused by blockage effects. The results obtained by both methods were always in good agreement (less than about 4%).

The contribution of skin friction to the total drag and lift was not taken into account in the present results. In fact, for a cylinder in cross-flow and for Reynolds numbers of the order of those investigated here, the results of Achenbach [7] show that this contribution is only about 1%.

2.2. *External convection measurements*

An aluminium cylinder 45 mm in diameter was used in the tests. Figure 2 shows some construction details. As is seen, data concerning local heat transfer was taken from a heated test strip made of silver imbedded in an insulating block of bakelite. The test strip was heated by an electrical resistance on the back surface and thermal control of the main cylinder A was obtained with ten resistances placed inside the cylinder and parallel to its axis. Power input to the resistances

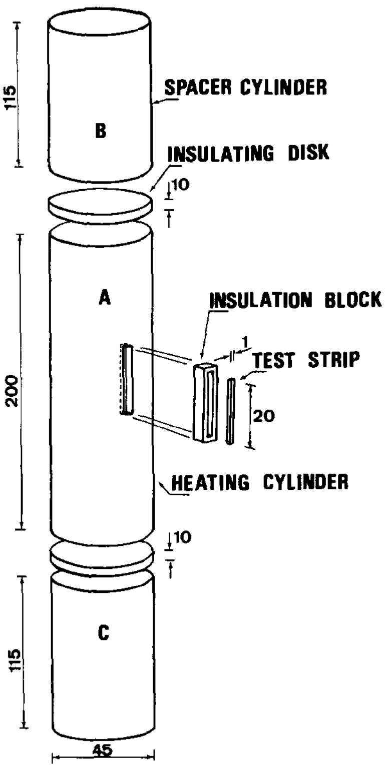

FIG. 2. Details of 45 mm diameter heated cylinder.

was adjusted to assure isothermal conditions on the cylinder surface. A chromel–alumel thermocouple was placed at the mid-point of the test strip and similar thermocouples were positioned on the main cylinder, at a depth of about 1 mm from the surface. Both cylinders B and C were heated and the power input was adjusted until their temperature was equal to the main cylinder surface temperature to prevent axial heat conduction losses from it. The temperature difference between the cylinder and the free stream was usually of the order of 20–35°C. At each angular position, the power input to the test strip was adjusted until its temperature was equal to the main cylinder surface temperature. It was assumed that all the power supplied to the test strip was transferred to the flow from the surface of the test strip. The effective heat-transfer area was supposed to be equal to the area of the test strip plus half the area of the gap. Thus, after correcting the data for radiation losses, the local heat-transfer coefficient was calculated directly by knowing the power input to the test strip, the effective test strip surface area, and the temperature difference between the cylinder and the free stream. The value of power supplied to the heating resistances of the main cylinder allowed the calculation of the average heat transfer coefficient. This coefficient could also be evaluated from the distribution of the local heat transfer coefficient around the cylinder by integration. The values obtained by the two methods were always in good agreement (< 5%).

This model spanned the test section of the smaller

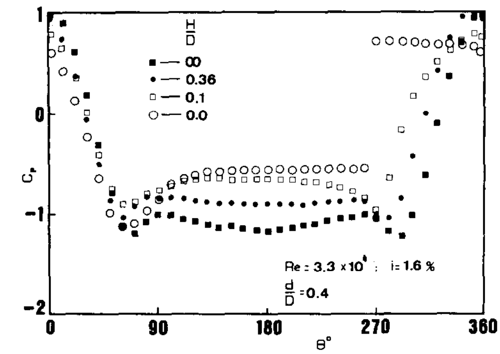

FIG. 3. Distribution of pressure coefficients around the cylinder at several cylinder-to-plate distances and the same Reynolds number.

wind tunnel and was provided on both sides with two aluminium spacer cylinders to span the test section of the bigger wind tunnel.

3. EXPERIMENTAL RESULTS

3.1. *Pressure distributions*

Time-averaged pressure distributions around the cylinder are shown in Fig. 3. Pressures are presented nondimensionally in the form of pressure coefficients C_p, at a Reynolds number $Re = 3.3 \times 10^4$ and for H/D ratios between 0 and 0.4. The same figure shows a pressure distribution obtained in uniform cross-flow at the same Reynolds number. It agrees very well with the results of Roshko [8] and shows typical features of the subcritical flow around a cylinder: symmetrical development of two laminar boundary layers that separate on both sides at about 80° and the formation of a large wake downstream of the cylinder. The results obtained when the cylinder is in the presence of a wall agree with those of Bearman and Zdravkovich, and Goktun, and show modifications in the positions of the frontal stagnation point and of the separation points. Nevertheless, for values of the distance $H/D < 0.1$ both separation points shift downstream: this effect reveals that an important modification in the behaviour of the boundary layer occurs in this range of cylinder-to-plane surface distances: there is an intermediate separation of the laminar boundary layers forming separation bubbles probably followed by turbulent reattachment to the cylinder wall.

Figure 4 shows the variation of drag and lift with

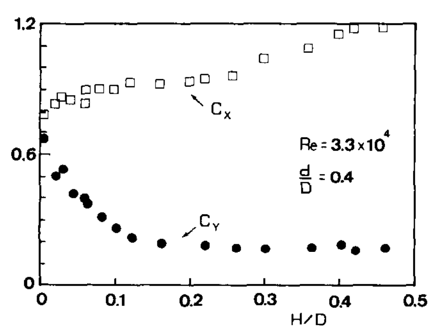

FIG. 4. Variation of drag and lift with H/D ratio at the same Reynolds number.

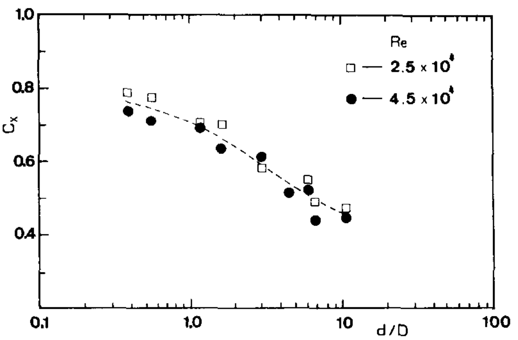

FIG. 5. Variation of drag with upstream boundary layer thickness at two different Reynolds numbers.

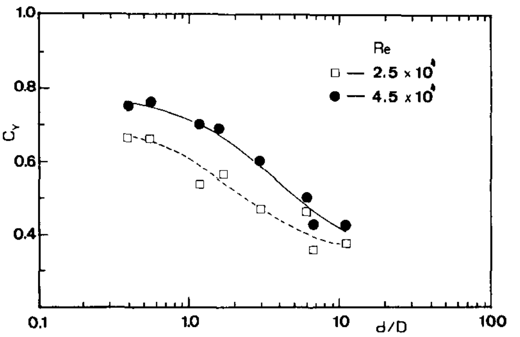

FIG. 6. Variation of lift with upstream boundary layer thickness at two different Reynolds numbers.

H/D ratio, at the same Reynolds number, $Re = 3.3 \times 10^4$. The influence of the presence of a plane boundary on drag is apparent all over the range $0 < H/D < 0.4$; it reaches a minimum when the cylinder touches the wall and is practically constant between 0.1 and 0.2. Lift increases very rapidly in the range $0 < H/D < 0.1$ and reaches a maximum of 0.68 at $H/D = 0$. Figures 5 and 6 show the influence of the thickness of the oncoming boundary layer on drag and lift, at $H/D = 0$. Both coefficients decrease with increasing d/D but the effect seems to be more pronounced in the range $1 < d/D < 4$ and weaker in the case of thin or very thick boundary layers. In the range of d/D investigated, the Reynolds number has a small influence on drag, but the lift increases with increasing Reynolds number especially when the upstream boundary layer is thin.

3.2. *External convection*

Figure 7 shows local heat transfer coefficients around the cylinder at several H/D distances and at the same Reynolds number. Heat transfer coefficients are presented nondimensionally in the form of Nusselt numbers $Nu(\theta)$. Concerning the positions of the frontal stagnation point and separation points these results exhibit good agreement with pressure distributions presented in Fig. 3. The existence of a separation bubble in the boundary layer on the gap side of the cylinder at $H/D = 0.1$ is apparent with a sudden increase of local heat transfer between 150 and 160°. The same phenomenon occurs in the upper boundary

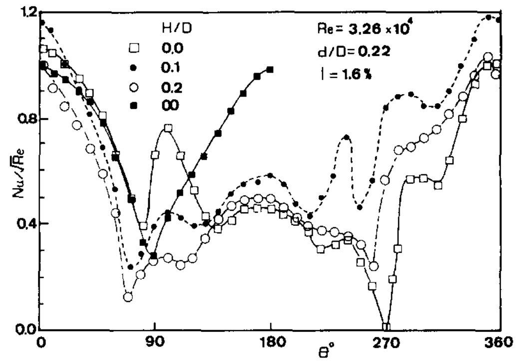

FIG. 7. Distribution of local Nusselt numbers around the cylinder at various H/D ratios and the same Reynolds number.

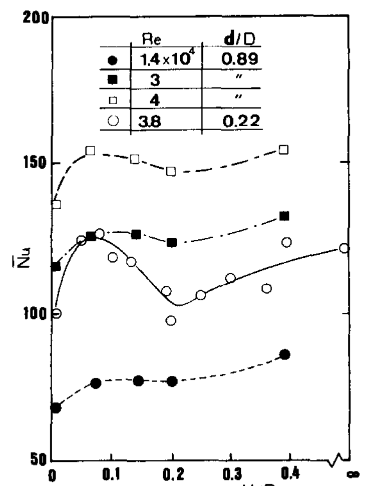

FIG. 8. Variation of average Nusselt number with cylinder-to-plate distance at various Reynolds numbers.

layer when the cylinder touches the wall. The most interesting characteristic of the interference between the flow around the cylinder and the flat plate at small distances, is the large decrease of heat transfer in the rear of the cylinder.

Figure 8 shows the variation of the average Nusselt number with cylinder-to-plate distance, at various Reynolds numbers. It is interesting to note that Nusselt number presents a behaviour quite similar to that of drag, plotted on Fig. 3. In the case of a very thin upstream boundary layer the average heat transfer coefficient presents a maximum at $H/D = 0.1$.

In Fig. 9 average Nusselt number is plotted against Reynolds number varying in the range $1.6 \times 10^4 < Re < 4.0 \times 10^4$, at two different values of the boundary thickness-to-diameter ratio: $d/D = 1.3$ and 12.2. It can be seen from this figure that global Nusselt number diminishes slightly with increasing thickness.

Figure 10 shows local Nusselt number distributions at several values of the thickness-to-diameter ratio and of the Reynolds number. It is apparent from the results that the formation of a separation bubble in the upper boundary layer depends on the value of Re

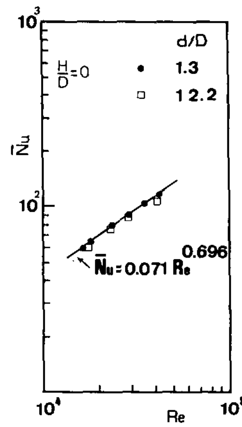

FIG. 9. Variation of average Nusselt number with Reynolds number for two different values of the boundary layer thickness-to-diameter ratio.

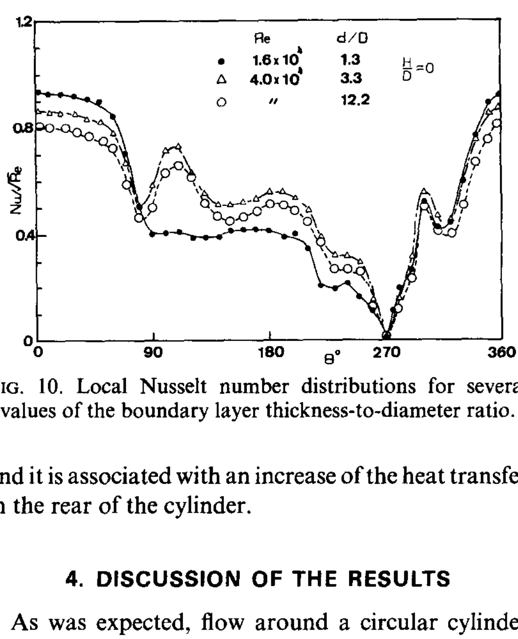

FIG. 10. Local Nusselt number distributions for several values of the boundary layer thickness-to-diameter ratio.

and it is associated with an increase of the heat transfer in the rear of the cylinder.

4. DISCUSSION OF THE RESULTS

As was expected, flow around a circular cylinder near to a wall depends on Reynolds number based on the cylinder diameter, the ratio of the gap between the cylinder and the wall to the cylinder diameter and the characteristics of the turbulent wall boundary layer. Bearman and Zdravkovich and Buresti and Lanciotti had reported that, at least in the case of thin oncoming boundary layers, and even with the flow remaining subcritical, regular vortex shedding was completely suppressed at a distance $H/D < 0.3$ and stable separated regions were established upstream and downstream of the cylinder. In our results, pressure and local heat transfer coefficients display typical features of the critical flow with formation of separation bubbles in the laminar boundary layers on both sides of the cylinder, for distances H/D between 0 and 0.2. Formation of those separation bubbles is probably associated with the greater level of free stream turbulence during our experiments, and depends on Reynolds number as it is apparent from Fig. 8. The immersion of the cylinder in the lower energy wall-boundary layer and the behaviour of laminar boundary layers on the cylinder surface explains the increase of the base-pressure coefficient at small cylinder-to-wall distances and the associated decrease of drag. On the other hand, the progressive inhibition of the gap flow with reduction in H/D and formation of a separation bubble in the laminar boundary layer on the upper shoulder of the cylinder introduces a stronger lack of symmetry on pressure distributions around the cylinder and explains the rapid increase of lift in the range $0 < H/D < 0.1$. This effect is similar to the occurrence of large values of lift on a cylinder in uniform cross-flow, at critical values of Re, caused by the formation of a separation bubble on only one side of the cylinder as was observed by Bearman [9], Farell and Blessman [10], Uzuki [11] and Schewe [12].

In the present work, particular attention was given to the influence of the oncoming boundary layer on the flow around the cylinder when it touches the wall. From the importance that the separation bubble in the laminar boundary layer has on lift, one could expect a greater dependence of this coefficient on Reynolds number which is confirmed by the results plotted on Fig. 6. One could expect that the results of Figs. 5 and 6 could be collapsed if drag and lift coefficients were based on velocity approaching the centre of the cylinder, instead of U_∞. In doing so, present results indicate however a slight but consistent decrease of drag with Reynolds number (0.9–0.82); this means that the values of Re investigated are close to the onset of the critical regime, which can be explained by the high level of turbulence induced in the flow by the vortex generators.

The most interesting feature of external convection around the cylinder at small distances from a plane boundary is the great influence of the upstream and downstream recirculation regions attached to the wall on local heat transfer coefficient. As expected, heat transfer increases around the frontal stagnation point with decreasing boundary layer thickness: in all cases the existence of a recirculation region downstream of the cylinder inhibits vortex shedding and is associated with a large decrease of heat transfer at the rear of the cylinder. When it touches the wall, recirculation regions attach themselves to the cylinder and are responsible for the occurrence of low values of local heat transfer, reducing the average Nusselt number to a minimum.

5. CONCLUSIONS

This study increased the understanding of the flow and external convection around a cylinder near a plane boundary. The following conclusions were obtained.

(1) The presence of a plane boundary introduces an asymmetry on the pressure and local heat transfer distributions around the cylinder.

(2) Both drag and average Nusselt number

decrease with decreasing cylinder-to-plane distance, and reach a minimum when the cylinder touches the wall. On the contrary, lift increases and has a maximum at $H/D = 0$.

(3) The influence of the presence of the wall on the values of drag and Nusselt number is apparent only for distances $H/D < 0.4$.

(4) Drag, lift and global Nusselt number decrease with increasing upstream boundary layer thickness, but the first two coefficients are more sensitive to this parameter.

(5) The occurrence of small values of heat transfer at the rear of the cylinder seems to be related to the inhibition of vortex shedding for distances $0 < H/D < 0.3$. In this range there is formation of closed recirculation regions upstream and downstream of the cylinder.

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CONVECTION FORCEE EXTERNE AUTOUR D'UN CYLINDRE CIRCULAIRE PRES D'UNE FRONTIERE PLANE

Résumé—L'écoulement forcé et le transfert autour d'un cylindre circulaire isotherme, placé à différentes hauteurs au-dessus d'une surface plane, ont été étudiés expérimentalement, pour le domaine de nombre de Reynolds entre $1{,}4 \cdot 10^4$ et $4 \cdot 10^4$, ce nombre étant rapporté au diamètre du cylindre. On examine l'influence du plan sur les coefficients de trainée et de portance, et sur les nombres de Nusselt locaux et globaux. On trouve que la formation de régions de recirculation en amont et en aval du cylindre est responsable des faibles valeurs du coefficient de transfert thermique local, spécialement à l'arrière du cylindre. Dans tous les cas étudiés, la trainée et le nombre de Nusselt global atteignent un minimum quand le cylindre touche la paroi; dans cette situation, une attention particulière est portée à l'influence de l'épaisseur de la couche limite sur l'écoulement et sur la convection externe autour du cylindre.

ERZWUNGENE KONVEKTION AN DER AUSSENSEITE EINES KREISRUNDEN ZYLINDERS IN DER NÄHE EINER EBENEN BEGRENZUNG

Zusammenfassung—Die Strömung und die erzwungene Konvektion an der Außenseite eines isothermen kreisrunden Zylinders, der in unterschiedlichen Abständen über einer ebenen Fläche angeordnet ist, wurde experimentell im unterkritischen Reynolds-Zahl-Bereich von $1{,}4 \cdot 10^4$ bis $4 \cdot 10^4$ untersucht. Die Reynolds-Zahl ist auf den Zylinder-Durchmesser bezogen. Der Einfluß der ebenen Begrenzung auf die Koeffizienten für Strömungswiderstand und Auftrieb sowie auf die lokale und globale Nusselt-Zahl wurde untersucht. Die Ausbildung geschlossener Rezirkulationsbereiche stromauf und stromab vom Zylinder ist verantwortlich für das Auftreten von kleinen Werten des lokalen Wärmeübergangskoeffizienten. Dies gilt besonders für die Rückseite des Zylinders. In allen untersuchten Fällen erreicht der Strömungswiderstand und die globale Nusselt-Zahl ein Minimum, wenn der Zylinder die Wand berührt; für diese Konstellation wurde dem Einfluß der Dicke der Strömungsgrenzschicht auf die Strömung und die Konvektion an der Außenseite des Zylinders besondere Aufmerksamkeit gewidmet.

ОБТЕКАНИЕ КРУГОВОГО ЦИЛИНДРА ВБЛИЗИ ПЛОСКОЙ ПОВЕРХНОСТИ ПРИ ВЫНУЖДЕННОЙ КОНВЕКЦИИ

Аннотация—Проведено экспериментальное исследование обтекания изотермического кругового цилиндра, расположенного на различных расстояниях над плоской поверхностью, в условиях вынужденной конвекции в диапазоне докритических значений числа Рейнольдса $1{,}4 \cdot 10^4$–$4 \cdot 10^4$, рассчитанного по диаметру цилиндра. Анализируется влияниз плоской границы на коэффициенты сопротивления и подъемной силы, а также на локальные и интегральные числа Нуссельта. Показано, что малые значения локального коэффициента теплообмена, особенно за цилиндром, обусловлены образованием замкнутых областей рециркуляции вверх и вниз по течению от цилиндра. Во всех рассматриваемых случаях коэффициент сопротивления и интегральное число Нуссельта были минимальными, когда цилиндр соприкасался с плоской поверхностью. Основное внимание в этом случае уделялось влиянию толщины пограничного слоя на течение и конвекцию вокруг цилиндра.