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REATTACHMENT OF A PLANE TURBULENT JET TO A WALL UPON INJECTION AND SUCTION

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In propagating a plane immersed turbulent jet near a solid surface, the so-called Coanda effect [1-3] is observed. This effect is caused by the ejecting properties of the jets. The presence of the closely located wall hinders fluid entrainment into the plane jet which leads to the formation of a rarefaction zone between the jet and the wall. As a result, a pressure difference occurs, and the jet curves and attaches to the wall at a certain point with the X_R coordinate. In a two-dimensional system, such a state is steady.

The Coanda effect occurs and often influences the mass- and heat-transfer processes in mixing chambers and furnace devices, in jet heating and cooling of solid bodies, in jet-type vapor cleaning of heating surfaces, as well as in pneumonics and venting systems. For example, in attachment of a coal-fired jet to the wall of a furnace chamber, the wall screens are intensely slugged, and underburning of the fuel particles, which deteriorates sharply the operational characteristics of the boiler, can occur.

Jet reattachment to the wall has been fairly well studied theoretically in the case where the jet flows parallel or obliquely to a plane surface [1-3]. Many works deal with technical applications. For example, in pneumatics one needs to know only the current position (of two possible ones) of the jet under the action of a control signal [4]. At the same time, the flow structure is not described. The vicinity of the reattachment point where the hydrodynamic and thermophysical parameters change sharply and the mass- and heat-transfer processes proceed most intensely [5, 6] is of primary importance.

In the present work, we study the characteristics of an attaching turbulent jet under the action of various control flows for the first time. New data on the flow structure in the vicinity of the critical point (reattachment point) have been obtained owing to the use of double electrodiffusive friction microprobes.

To investigate the fundamental regularities of the attachment of turbulent jets to a wall upon injection and suction, we designed a special hydrodynamic stand. The working section (Fig. 1) is a Plexiglas vertical rectangular channel 1 whose inner dimensions are $86 \times 162 \times 1600$ mm. A plane jet 2 issues from a rectangular contoured nozzle 3 of width $2h$ and length 86 mm. The length of the nozzle is equal to the width of the channel and, hence, a two-dimensional flow is realized at least at not too large distances from the nozzle.

Since jet reattachment to the wall is caused by the transverse pressure difference, it is natural to use injection (or suction) into a rarefaction zone 4 in order to control such a system. It is also clear that the resulting effect should depend on the method of injection. In the experiment, we used three types of control flow which are fundamentally different from each other (Fig. 1). Type 0 corresponds to diffusional injection through a perforated plate 5. In this case, the injected momentum flux is negligible, which corresponds to the concepts of an integral approach [2, 3]. The control flow of type 1 is arranged through a slit nozzle 6 perpendicular to the basic jet. Here the momentum fluxes in the basic and control jets can already be comparable in absolute magnitude but are mutually perpendicular in directions. The control flow of type 2 is formed also as a near-wall jet directed along the basic flow.

In studying reattaching flows, the wall-pressure distributions and the position of the reattachment point are usually measured. Another important hydrodynamic parameter is a shear stress on a solid surface which is associated with the mass- and heat-transfer processes and is extremely important for determination

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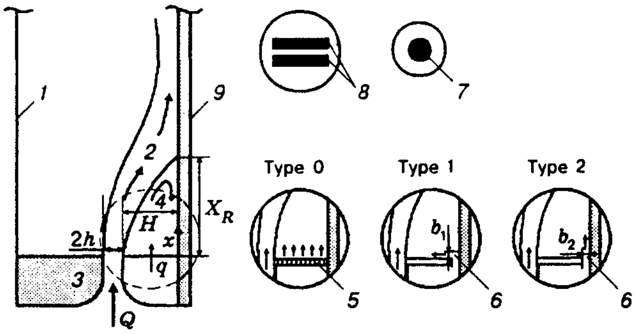

Fig. 1

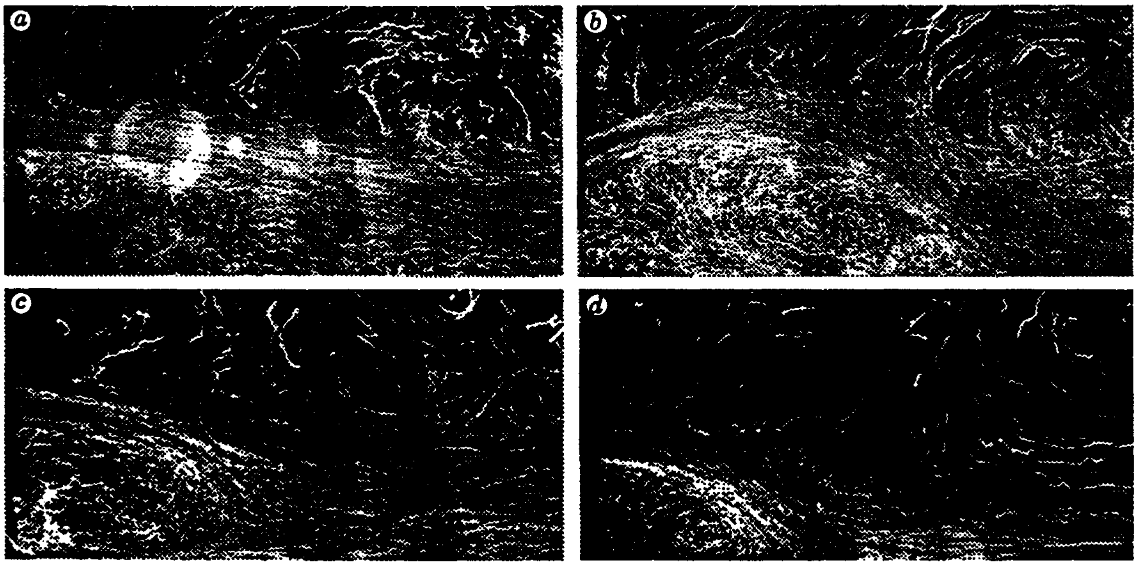

Fig. 2

of the near-wall structure of attached turbulent flows. However, since it is difficult to measure this quantity (especially in strongly turning turbulent flows), relevant data are practically absent in the literature.

In this study, we measured the local values of the wall shear stresses using the electrodiffusive method [7]. To do this, we employed single friction microprobes 7 of diameter 100 μm along with double probes 8 with a 30-μm size of each sensitive element over the flow and with a 15-μm gap between them. The small dimensions of the microprobes allow us to measure the local flow structure and also the turbulent characteristics. The electrodiffusive friction gauges and the static-pressure holes were located on the right-hand wall of a channel 9 which could move in the vertical direction with a 0.1-mm step.

A key feature of our experimental technique is the use of double probes that are sensitive to the flow direction. In the vicinity of the reattachment point, owing to turbulent pulsations, the flow changes its direction chaotically (in the given case, longitudinal pulsations dominate). Therefore, the mean friction and the turbulent characteristics can be measured correctly only with the use of a double probe that is sensitive to the flow direction, and only in this way is it possible to find exactly the reattachment (critical point) where the mean friction is zero. The details of the electrodiffusive method are given in [7].

Figure 2 shows typical patterns of the reattaching flow, depending on the type of control flow: diffusive injection (type 0) and $q/Q = 0.25$ (Fig. 2a), transverse injection (type 1) and $q/Q = 0.25$ (Fig. 2b), longitudinal injection (type 2) and $q/Q = 0.25$ (Fig. 2c), and suction and $q/Q = -0.15$ (Fig. 2d). The flow was visualized

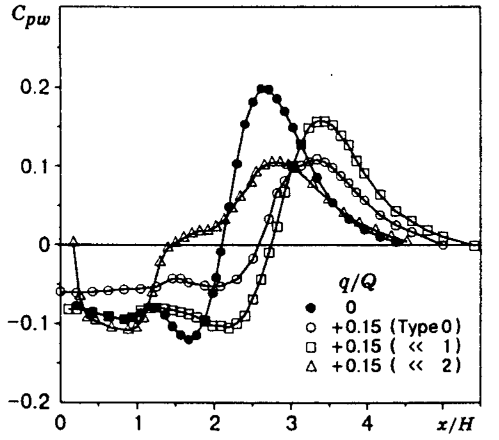

Fig. 3

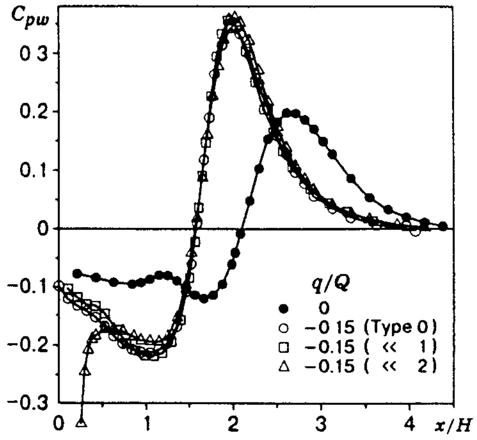

Fig. 4

by small air bubbles which were illuminated by a light knife in the central cross section of the channel. Here q is the volumetric flow rate of the liquid in the control flow, Q is the flow rate in the basic flow, and the nondimensional quantity q/Q is an injection parameter whose positive and negative values correspond to injection and suction, respectively.

As follows from Fig. 2, the reattached-flow structure depends strongly on the method of injection. In the case of diffusive injection, the jet trajectory becomes straighter in comparison with the variant where injection is absent, the reattachment point shifts downward, and the intensity of the eddy motion in the recirculation zone decreases sharply. On the contrary, transverse injection leads to a strong curving of the jet and promotes the formation of a large-scale vortex. Longitudinal injection forms a flow structure that is similar to the case of two interacting parallel jets [2, 3, 8]. Figure 2c shows distinctly the near-wall jet and the free stagnation point. In [2, 3], the authors have shown that the character of interaction of two jets is affected by the ratios of both the flow rates and the momentum fluxes.

Whatever the method of arrangement, suction leads to a more significant curving of the jet and also to the formation of an intense vortex near the reattachment point (Fig. 2d).

Figures 3–7 show the effect of the type and magnitude of the control flow on the distribution of the local pressure coefficient $C_{pw} = (P_w - P_0)/(\rho U_0^2/2)$ (P_w and P_0 are the static pressures on the wall and in the flow core, respectively, ρ is the density of the liquid, and U_0 is the velocity of the liquid at the nozzle exit). The values of the longitudinal x coordinate which are referred to the distance H between the nozzle edge and the wall (Fig. 1) are plotted as the abscissas. Experiments were performed in a regime that is self-similar in terms of the Reynolds number: $\mathrm{Re} = U_0 2h/\nu = 4.65 \cdot 10^4$ ($2h = 12$ mm is the width of the nozzle and ν is the kinematic viscosity). We used the following geometric parameters of the system: $H = 48$ mm and $b_1 = b_2 = 3$ mm.

Figure 3 shows the data on the static-pressure distribution along the wall, depending on the type of control flow. In the absence of injection ($q = 0$), the experimental curves are of a characteristic shape with a local maximum at the reattachment point and with weak variation in the recirculation zone. Both the diffusive and transverse jet methods of injection lead to shifting the maximum pressure downstream by approximately the same distance. The distribution curves remain similar in shape, but the maximum pressure differences are appreciably different. Longitudinal jet injection markedly transforms the pressure distribution, which is due to the complicated character of interaction between the basic jet flow and the near-wall jet. Here the magnitude of the maximum pressure decreases by a factor of two, while the reattachment point does not shift. Unlike injection, the method of arrangement of suction does not effect the pressure distribution, as seen in Fig. 4, except for the vicinity of the side wall.

We shall consider separately the effect of various types of control flow on the bottom pressure. Diffusive

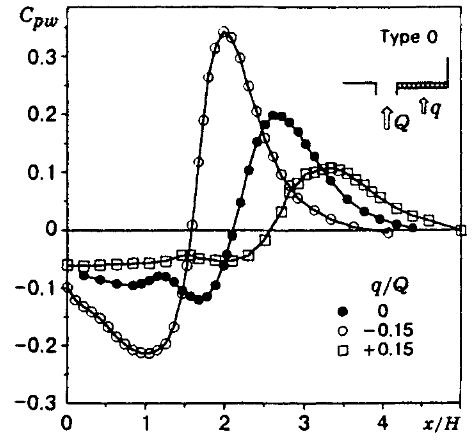

Fig. 5

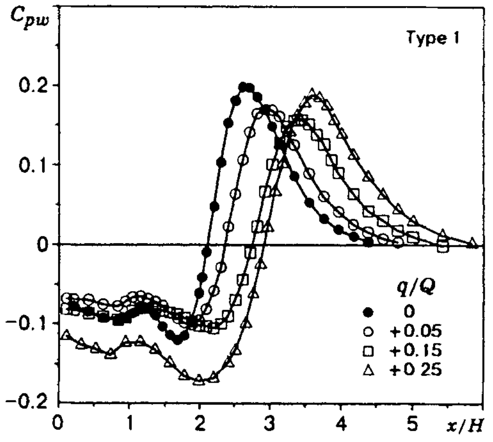

Fig. 6

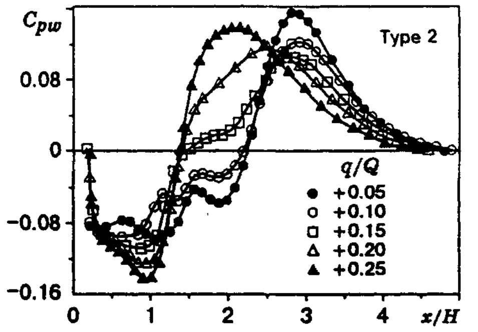

Fig. 7

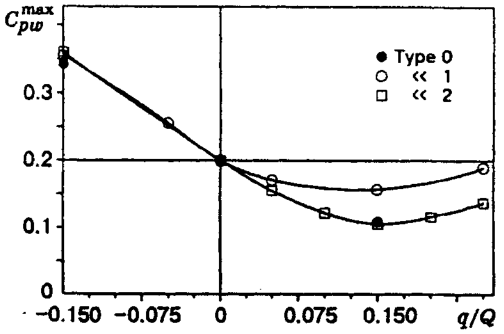

Fig. 8

injection transforms monotonically the pressure profiles with variation in the flow rate q of the control flow (Fig. 5). A similar behavior of the pressure distributions was observed also for a radial jet that is controlled by the transverse flow [9].

A more complicated evolution of the pressure profiles occurs if the jet is controlled by transverse injection (Fig. 6). As the flow rate q increases, the distance to the reattachment point always grows. However, the maximum pressure values have a local minimum at a certain value of q/Q (Fig. 8).

The behavior of the pressure profiles is even more complicated in the case of longitudinal jet injection (Fig. 7). The coordinate of the pressure maximum (which is identified here with the reattachment point) first grows with an increase in the relative flow rate q/Q up to 0.05 and then decreases sharply. Flow visualization shows that, for small values of injection ($q/Q < 0.1$), the control near-wall jet detaches from the wall in the recirculation zone, and the action of longitudinal jet injection is equivalent to the case of other control methods. However, for $q/Q > 0.15$ (Fig. 2d), the near-wall jet exists up to the vicinity of the reattachment point of the basic jet. Thus, the system of two interacting parallel-issuing plane jets in the presence of a solid wall is realized. Here the reattachment point of both jets (defined as the point of branching of the streamlines) is in the flow core. A certain equivalent point of reattachment of the basic jet to the wall can be defined as the point of maximum wall pressure. In [2], it is shown that even for two free parallel-issuing unequal plane jets, the reattachment point shifts nonmonotonically with variation in the ratio of the momentum fluxes. Figure 8 shows the effect of the type and magnitude of the control flow on the maximum value of the pressure coefficient.

The data on the wall shear stresses which were obtained by a double electrodiffusive probe are given

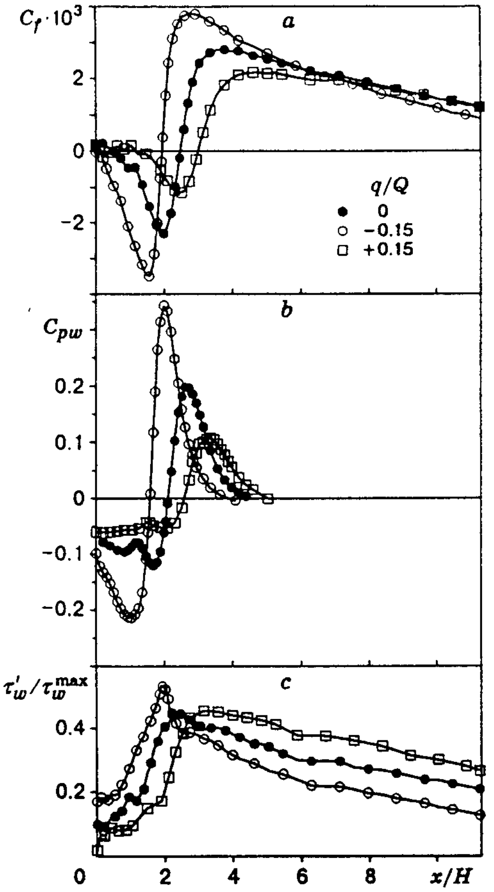

Fig. 9

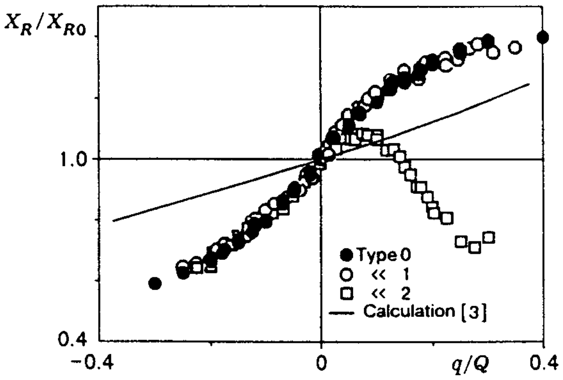

Fig. 10

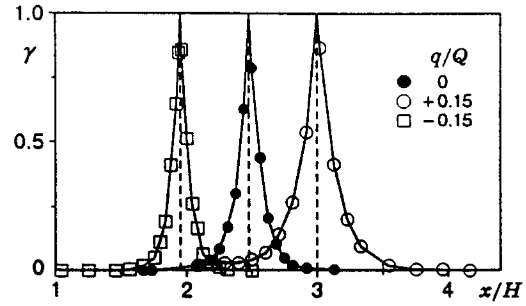

Fig. 11

in Fig. 9 for diffusive injection. Here the friction coefficient $C_f = \tau_w/(\rho U_0^2/2)$ (τ_w is the local time-averaged wall shear stress, τ'_w is the r.m.s. friction pulsations, and τ'_w is the maximum time-averaged friction). It should be noted that an exact value of the mean friction in the vicinity of the critical point of turbulent flow can be measured only by a double probe which allows one to determine the friction vector. The negative friction values in Fig. 9 correspond to the backward flow in the recirculation zone, and the zero value corresponds to the critical or reattachment point.

As seen from Fig. 9a and b, the effect of the control flow on the mean-friction profiles is approximately the same as that on the pressure profiles. The most remarkable fact is that the maximum and minimum values of friction is of the same order in modulus, although the reattaching jet divides into two strongly different flows. Hence, the generally adopted assumption [2] that the recirculation zone is a stagnation zone is not valid and should be corrected. Another important conclusion is that the maximum pressure does not coincide with the zero-friction point and lies downstream (up to 10%). A complete coincidence is observed only for impinging jets which are incident normal to the wall.

The maximum values of friction pulsations occur in the vicinity of the critical point (Fig. 9c). The level of turbulence decreases monotonically with the distance from the critical point.

Figure 10 shows the data on the reattachment distance X_R which were obtained based on pressure or friction measurements. Here X_{R0} is the coordinate of the reattachment point in the absence of the control flow. Clearly, the diffusive and transverse jet methods of control exert the same effect on the reattachment point whose coordinate varies monotonically with an increase in the control-flow rate. Longitudinal jet injection almost always leads to a decrease in the recirculation zone and is not convenient for control problems. However, since the near-wall jet tends to preserve its specific features, it can play the role of a near-wall jet screen and protect the wall against high-temperature reattaching jets in heat exchangers and combustion chambers.

The curve in Fig. 10 was plotted according to the integral theory [3] which takes into account diffusive injection (suction) to the recirculation zone. From this figure, it follows that for the time being we can only speak of a qualitative agreement between theory and experiment.

As noted above, the vicinity of the critical point is the most important and also the most difficult for investigation because of local detachments and unsteady-state backward flows. To characterize the structure of the turbulent near-wall flow in this region, we have introduced the backward-flow coefficient γ [7] which is measured by a double electrodiffusive friction probe and is defined as $\gamma = t_-/t_+$ (t_- and t_+ are the times of existence of the backward and direct flows near the wall, respectively).

The distributions of the coefficient γ as a function of the magnitude of diffusive injection are given in Fig. 11. These data allow one to establish the exact position of the critical point and to estimate the width of the region of existence of unsteady-state backward flows. Hence, for $q/Q = 0$, $H = 48$ mm, and width of basic nozzle $2h = 12$ mm, the dimensions of the region are approximately 8 mm. Note that the γ-distribution curves are symmetric, although the flow near the reattachment point is clearly asymmetric.

Thus, in the present paper, reattachment of plane turbulent jets to the wall under the action of the major types of control flow has been studied experimentally. Owing to the application of double electrodiffusive friction probes, new data on the structure of near-wall turbulent flows in the vicinity of the reattachment point have been obtained.

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