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TURBULENT FLOW AND HEAT TRANSFER BEHIND A BACKWARD-FACING STEP. EFFECT OF INJECTION AND SUCTION

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ABSTRACT. The paper presents the results of numerical simulation of the flow structure and heat transfer in the turbulent separated flow in the channel with sudden expansion at porous injection or suction. Simulation was based on two-dimensional averaged equations of Navier - Stokes, energy and v2-f turbulence model. It is shown that an increase in intensity of the cross-flow on the wall downsizes the separation zone at suction and increases its length in the case of injection until boundary layer edging. At that, dependence of the maximal heat transfer coefficient on permeability parameter is well described by the asymptotic theory of turbulent boundary layer.

INTRODUCTION

Investigation of separated flows is of great fundamental and practical interest. A great number of experimental and numerical works deal with this issue. Some conclusions about the laws of vortex formation and heat transfer in the turbulent vortex flows can be found in the monographs and reviews, for example Ota [2000]. The most important and insufficiently studied issue is the possibility of efficient control of flow separation and its suppression or intensification depending on the specific conditions.

Among the large number of methods for controlling heat transfer and hydraulic resistance, one of the most effective is the use of porous injection and suction. It is widely used in continuous flows, and at a relatively low energy costs for gas pumping through the porous surface it results in significant changes in surface friction and heat and mass transfer. The theory of boundary layer on the permeable surface without flow separation is worked out thoroughly by Kutateladze [1972], but at flow separation there are few experimental and numerical studies [Abu-Hijleh [1997, 2000], Yang et al. [1996] and the problem is far from solution.

PROBLEM STATEMENT AND MATHEMATICAL MODEL

Plane channel with initial height h_1 expands suddenly to height h_2; at that, uniform substance supply or removal is organized through the heated bottom wall of the channel after expansion. The turbulent flow from left to right separates from the step edge and attaches to the bottom wall at distance x_R. The length of separation zone depends on the ratio of channel heights before and after expansion $ER = h_2/h_1$, Reynolds number Re_H, and intensity of injection (suction) through the bottom wall, which will be shown below. The flow is incompressible and has constant physical properties.

In this work, we use the approach based on the solution of averaged Navier-Stokes and energy (RANS) equations supplemented with the v^2-f turbulence model. Preliminary analysis showed that under the

conditions of ongoing simulation and experiments, used for comparison, the flow has almost two-dimensional and stationary character; therefore, the two-dimensional equations were solved.
The above system of equations was solved by the method of control volume on the structured joint grid. The convective terms were approximated by the QUICK scheme, diffusion terms were approximated by the central-difference scheme, variables from the center of control volume to the edge were interpolated by the Rhie-Chow method. The equations were solved through iteratively successive semi-implicit algorithm SIMPLEC with lower relaxation. Convergence of solutions was assumed, when the residual values of all variables less than 10^{-6} were achieved.
To verify the above mathematical model and its numerical implementation, a series of calculations and comparisons with data of direct numerical simulation of Le [1992] and experimental data of Yang [1996] were carried out. The first stage of verification consisted in selecting the computational grid: it was a series of calculations, using the finer grids, until the solution independent on the grid size with maximal local deviation of 0.1% was achieved.

SIMULATION RESULTS

Calculations have been carried out within the Reynolds number $Re_H = 5{\cdot}10^3 \div 5{\cdot}10^4$ and relative injection/suction rate $F = 0 \pm 0.05$. Without injection, a typical vortex zone of a reverse flow with well-defined point of flow attachment to the wall is formed on the wall behind a step. At intense injection, the zone of reverse flows behind a step is not formed. However, immediately behind a step, the joint effect of separation and injection results in formation of the area of negative shear stresses, which then turns into the region of positive stresses. Therefore, the coordinate with zero shear stress cannot be considered as a point of separated flow attachment, as it occurs at separation without injection.
At porous suction, the length of reverse flow zone decreases, and the angular vortex on the impermeable surface disappears in the presence of suction.
Thus, injection and suction strongly affect formation of the flow after its separation from the step edge. Accordingly, the value of cross-flow on the surface and its direction will affect the main flow parameters such as the coordinate of attachment point, friction and heat transfer. This can be seen in Fig. 1, where the data on distribution of surface friction coefficient and heat transfer are presented for different injection and suction rates.

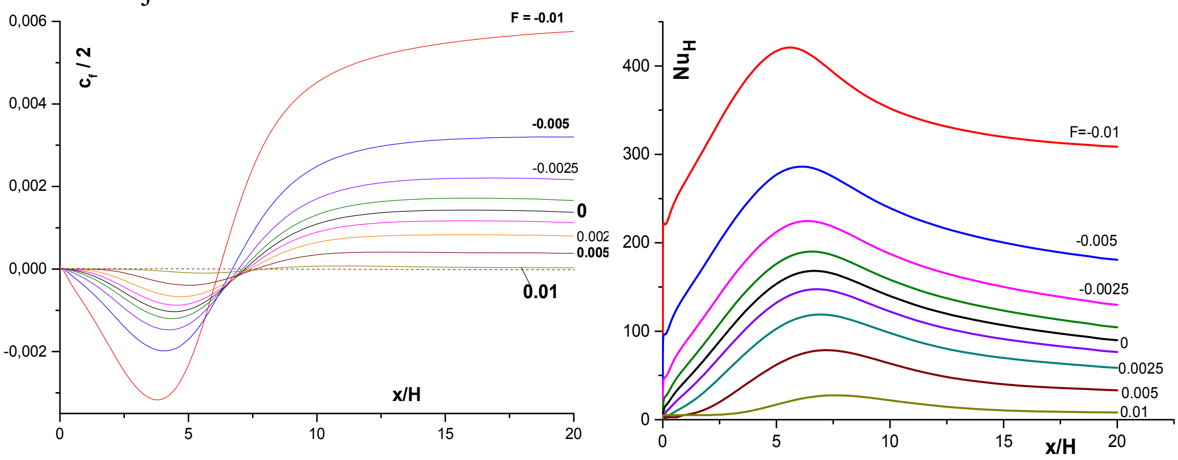

Figure 1. Effect of suction/injection on the skin friction coefficient (left) and Nusselt number (right). $Re_H = 5{\cdot}10^4$.

When flowing around a step, injection, as it can be expected, leads to friction reduction both in the area of reverse flow and behind the point of flow attachment. At intense injection ($F \sim 0.01$), friction on the plate is everywhere close to zero, indicating the approach to the regime of boundary-layer displacement. Suction, on the contrary, leads to the friction increase in the separation zone and after flow attachment. At intense suctions, as it follows from, friction increases in the area of reverse flow and behind the point of flow attachment. At that, the absolute values of shear stresses on the wall in the two specific areas are close to each other. The similar character of the effect of the cross-flow is observed for the heat transfer rate. Variations of the velocity value and direction on the wall can lead to a very large change in convective heat transfer. The effect of injection/suction on the position of attachment point and coordinate of maximal heat transfer coefficient is shown in Fig. 2. The coordinate, where the shear stress on the wall was zero (τ_w=0), was taken as the coordinate of the attachment point. At boundary layer suction, we observed a gradual halving in the length of separation zone in comparison with separation on the impermeable wall. At injection, on the contrary, the length of the separation zone increases at first, and then sharply decreases until the complete flow edging from the porous wall.

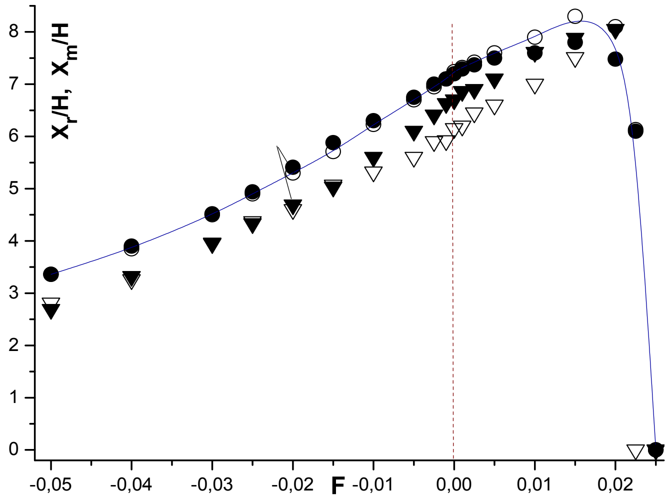

Figure 2. Position of attachment point (circles) and coordinate of maximal heat transfer coefficient (triangles). Open symbols - Re_H= 5·10^3, solid symbols - Re_H= 5·10^4

The position of heat transfer maximum behaves in a similar x_r way. The maximal heat transfer is always achieved at a certain distance (~ 1 step height along the step height) to the attachment point. This feature of the separated flows was mentioned by Sparrow [1987]. It is important to note that the behavior of the separated flow of these scales is very conservative relative to the Reynolds number. This is especially obvious at suction of the boundary layer.

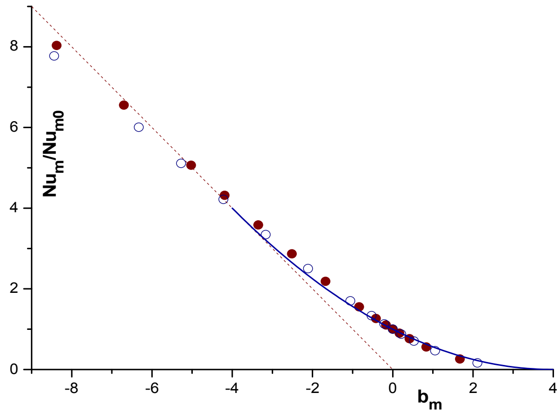

Figure 3. Maximal heat transfer dependence on permeability parameter. Open symbols - Re_H = 5·10^3, solid symbols - Re_H = 5·10^4. Dashed line – asymptotic suction law Nu_m/ Nu_{m0} = - b_m

When analyzing the processes of turbulent heat and mass transfer on the permeable surfaces, the conclusions of the asymptotic boundary layer theory by Kutateladze [1972] are very effective. Strictly speaking, they cannot be directly applied to the case of flow separation. At the same time, for such characteristic scales of heat transfer in the separated flow, its maximum value Nu_m or the value, averaged over the surface, can be evaluated depending on wall permeability parameter, using the relationships of this theory.

The results of such generalization of numerical calculation data area are shown in Fig. 3 in the form of dependence of the Nusselt number ratio at the point of Nu_m/ Nu_{m0} maximum on permeability parameter b_m. Here, Nu_m and Nu_{m0} are the maximal Nusselt numbers on the surface with and without injection/suction, respectively, and $b_m= F/St_{m0}$ is permeability parameter. The Stanton number here is calculated by the maximal value of Nusselt criterion at flow separation on the impermeable wall $St_{m0} = Nu_{m0} /Re_H \cdot Pr$. As it can be seen, the values obtained in a wide range of injection rates and Reynolds numbers are well generalized and coincide with the known dependence of heat transfer on the permeable surface (Kutateladze [1972]) $Nu_m/ Nu_{m0} = (1- b_m /4)^2$ (solid line, Fig. 3).
Surprisingly, all the data of numerical calculations for the maximal Nusselt number, as well as for values, averaged along the length, are well described by the presented ratio in the entire range of parameter F: from asymptotic suctions until critical injection parameters $b_m = 4$.
Thus, formula of Kutateladze [1972] allows calculation of the maximal (or average) value of heat transfer for different permeability parameters. The Nusselt number on an impermeable plate Nu_{m0} can be identified by the correlation relationships (Leontiev [1984], Ota [1987]), obtained through generalization of results of physical and numerical experiments. The calculation results of the current work coincide well with formulas and differ from the experimental data not more than by 20%.

CONCLUSIONS

Analysis of results of numerical simulation of the flow structure and heat transfer in the turbulent separated flow in a channel with an abrupt expansion in the presence of porous injection or suction showed that an increase in intensity of the cross-flow on the wall leads to reduction in the sizes of separation zone at suction and an increase in its length in the case of injection until the achievement of the regime of boundary layer edging. In this case, the heat transfer coefficients increase significantly with increasing suction intensity and reduce at injection. It is shown that dependence of the maximal heat transfer coefficient on permeability parameter is well described by the asymptotic theory of the turbulent boundary layer.
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