THE EFFECT OF POROUS BLOWING AND SUCTION ON AERODYNAMICS AND HEAT TRANSFER IN SEPARATED LAMINAR FLOW IN DUCT BEHIND OF BACKWARD-FACING STEP

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Being a powerful intensifier of friction and of heat transfer in gas and liquid flows the flow separation plays a vital part in kinetics of exchanging processes in nature and in technical applications. The porous blowing and suction are also powerful factors that determine the characteristics of these processes. In present work the influence of these factors on friction and on heat transfer in separated laminar flow in duct behind of backward-facing step is investigated in numerical experiment.

Consider a steady-state two-dimensional flow of incompressible liquid with constant properties in parallel-sided channel having an abrupt expansion in the form of rectangular backward-facing step with height s. The height of the channel up to the expansion and behind of it is equal to s and $2s$ respectively; its length behind of the step is equal to $50s$. The channel's down wall siding to the step is porous and the liquid having a constant velocity throughout the whole channel's length is blown/sucked through it. The ratio of blowing/suction velocity $V_{blowing/suction}$ to the average stream velocity u_s in the step's cross-section is used as the blowing parameter $F = \frac{V_{blowing/suction}}{u_s}$. The positive values of F correspond to blowing and the negative ones to suction. Considering the heat transfer task the channel's down wall is heated and is kept with constant temperature; the other walls are adiabatic. The Reynolds number is defined by the average velocity in the step's cross-section and by the step's height $\mathrm{Re}_s = \frac{u_s s}{\nu}$.

The task is solved in two stages. As first the steady-state velocity distribution throughout the region is obtained from the solution of unsteady Navier – Stokes equations that were solved by the method of temporal establishment. For that a finite-difference scheme of the alternating direction implicit method is used. The scheme has a first order accuracy by spatial variables steps for convective terms and a second order accuracy for diffusive ones. As second using the obtained velocity distribution the temperature field is found as solution of energy equation. To simplify the problem the flow previous history is modeled by set of parabolic velocity profile with fully developed boundary layer in the step's cross-section. The correctness of the numerical model's use for separated laminar flow modeling has been checked in [1] and a good agreement to experimental result [2] has been shown.

The flow's calculation has been carried out for Reynolds numbers Re_s in range from 10 to 400 and the blowing parameter F has been taken from 10^{-4} to 10^{-1} for blowing and from -10^{-4} to -10^{-2} for suction respectively. The results are presented for the same absolute

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Abstract

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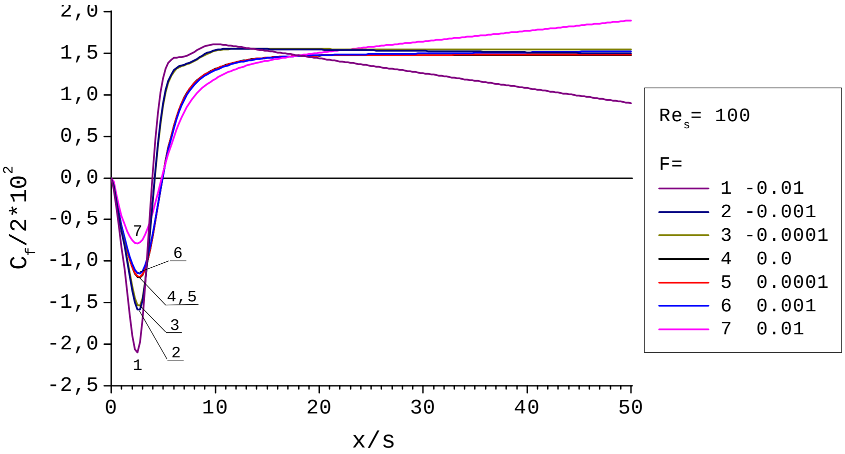


Fig.1. The friction coefficient on the channel's porous wall for $\mathrm{Re}_s = 100$ and for different blowing parameters F .

values of blowing parameter comparing to the case when the channel has an impermeable down wall $(F = 0)$.

The dependence of friction coefficient $C_f/2$ on the channel's down wall on the longitudinal coordinate x for $\mathrm{Re}_s = 100$ and for different blowing parameters F is presented in Fig. 1. First of all regarding the figure one can conclude that blowing has an opposite influence on friction inside of and outside of the recirculation zone. In the zone's inner part the blowing leads to diminution of absolute value of friction coefficient and in the outer part the blowing leads to its augmentation comparing to the case of impermeable down wall. The mentioned behavior of friction coefficient may be explained by combined action of two factors that are the consequence of porous blowing. The first factor is the repulsion of streamlines from the channel's wall and the second one is the augmentation of average stream velocity to channel's length. The first factor leads to diminution of friction coefficient and the second one to its augmentation. The first factor prevails inside of the separation zone and the second one begins to prevail according to progress by the channel's length behind of the point of reattachment. As it is seen from Fig. 1 the similar argumentation and conclusion taken quite the contrary is true for suction.

Besides one can find from Fig. 1 that the friction coefficient in the recirculation zone is more sensible to suction than to blowing. Regarding the curves corresponding to $|F| = 0.01$ one can notice that the friction coefficient's absolute maximal value inside of the separation zone is as 75% higher for suction and is as 30% lower for blowing comparing to the case of impermeable wall.

The point of reattachment has been determined by the zero value of friction coefficient. The dependency of reattachment length r as a function of Reynolds number Re_s for different blowing parameters F is presented in Fig. 2. One can see that up to $\mathrm{Re}_s = 50$ the blowing and the suction do not exert remarkable influence on the length of separation zone and all the lines coincide with the curve corresponding to the case of impermeable wall. However in further augmentation of Reynolds numbers the curves' family divides into two branches: upper and

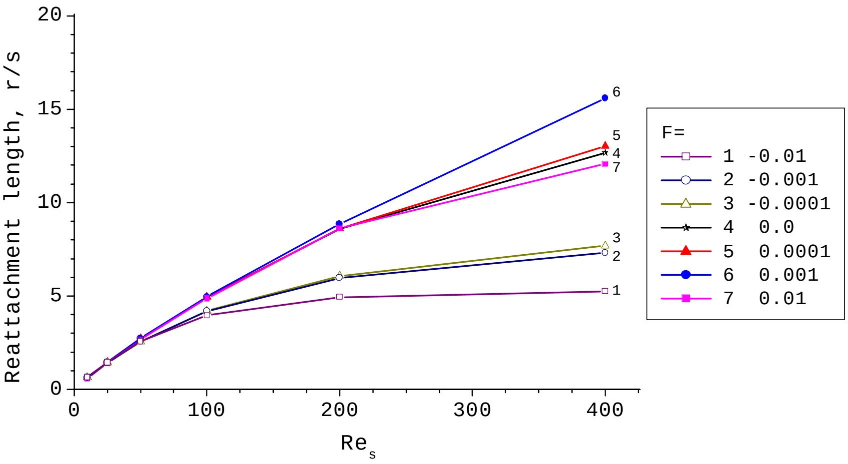
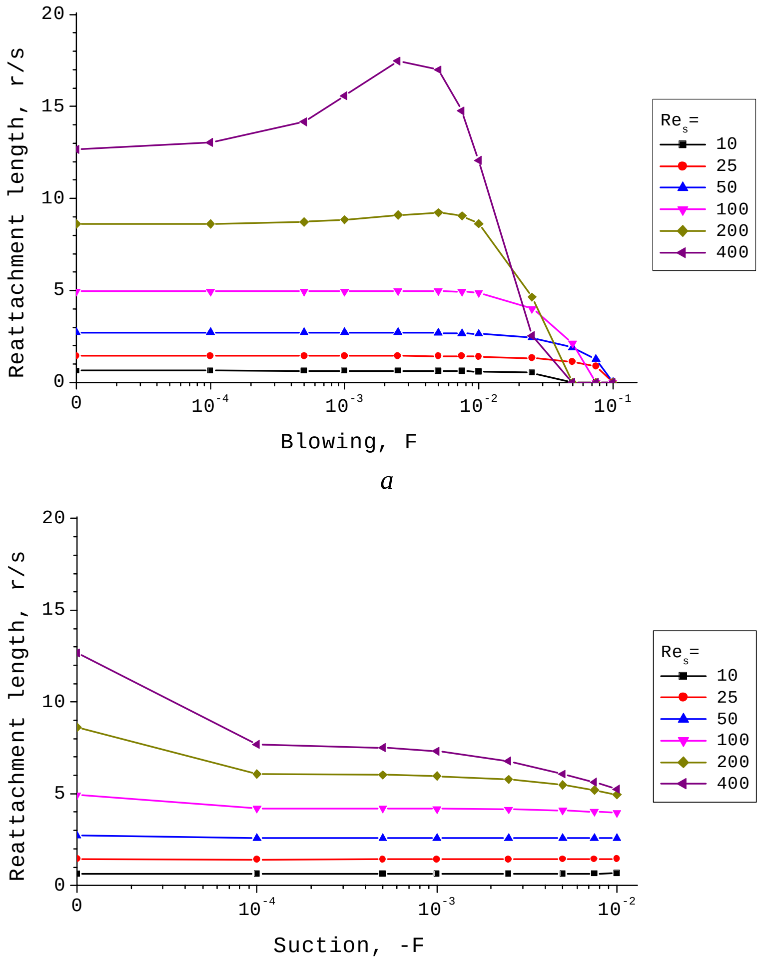


Fig. 2. The length of separation zone r as function of Reynolds number Re_s for different blowing parameters F.

lower that correspond to blowing and suction respectively. It is necessary to notice that the speed of growth for separation zone's length r in augmentation of Reynolds number Re_s is not monotone function of blowing parameter F.

The length of separation zone r as function of Re_s and F is presented in detail in Fig.3a and 3b where the blowing parameter F is appearing as a variable and the Reynolds number Re_s is conversely appearing as a parameter. For blowing when $F = 10^{-4}$ the values of r coincide with high precision to similar values for the case of impermeable wall. The results presented in Fig.3a confirm that the length of reattachment r is non-monotone function of its variables. There is a maximum on the curves corresponding to $\mathrm{Re}_s = 200; 400$ which exceeds value for impermeable wall for 7% and 35% respectively. At the same time the separation zone's length decreases for any Reynolds number when $F > 10^{-2}$. There is some value F^* of blowing parameter, which is individual for any value of Re_s when $r = 0$. But when $F = 10^{-1}$ $r = 0$ for any Reynolds number. It means that the point of flow reattachment to down wall disappears. The detailed study of stream structure shows that the reattachment point is forced out to step's surface by the stream injected through the porous wall. Therefore the zone of recirculation fully separates from the down wall and entirely reattaches the step.

The dependency of reattachment length r on the blowing parameter F for different Reynolds numbers Re_s is presented in Fig. 3b. One can see that r monotonically decreases for suction during the augmentation of F absolute value. But it does not become equal to zero, which contrasts to the situation for blowing. The possible explanation is that in the case of suction the range of F parameter is more restricted by physical reasons than in the case of blowing. The channel's length and the quantity of substance in main stream determine the range of F in current task performance. Besides a remarkable influence of blowing parameter F on the separation zone's length takes place only for relatively high Reynolds numbers $\mathrm{Re}_s = 200; 400$.



a

b

Fig. 3. The reattachment length r as a function of blowing parameter F for different Reynolds numbers Re_s in the case of a) blowing and b) suction.

For lower values of Re_s the changes are negligible. However at the same time it is necessary to notice that for suction the separation zone's length r values are remarkably lower than in the case of impermeable wall for Reynolds numbers $\mathrm{Re}_s = 100; 200; 400$ when the blowing parameter is equal to $F = -10^{-4}$. It means that the reattachment length is more sensitive to suction than to blowing.

Consider the results of heat transfer calculation on the channel's porous wall. The dependency of determined by the step's height local Nusselt number Nu_s on the longitudinal coordinate x for $\mathrm{Re}_s = 100$ and for different blowing parameters F is presented in Fig. 4. One can see that the porous blowing and the porous suction leads to remarkable diminution and augmentation respectively of local heat transfer either in the separation zone or behind of the reattachment point comparing to the case of impermeable wall. Besides the heat transfer maximum almost coincides to the point of reattachment either for blowing or for suction but nevertheless it lies slightly closer to the step. While $|F| = 10^{-2}$ the Nu_s maximum for suction is as 50% greater and for blowing is as 30% less than in the case of impermeable wall. This means that inside the separation zone the heat transfer is more sensitive to suction than to blowing.

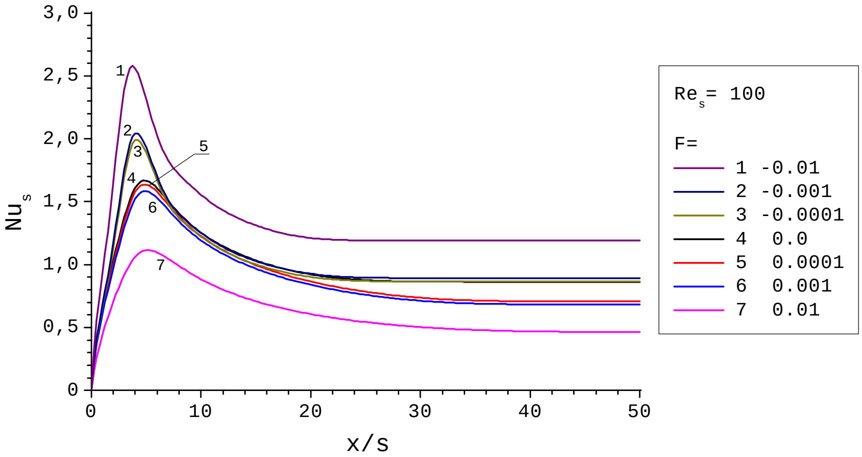


Fig. 4. The local Nusselt number Nu_s on porous wall for $\mathrm{Re}_s = 100$ and for different blowing parameters F.

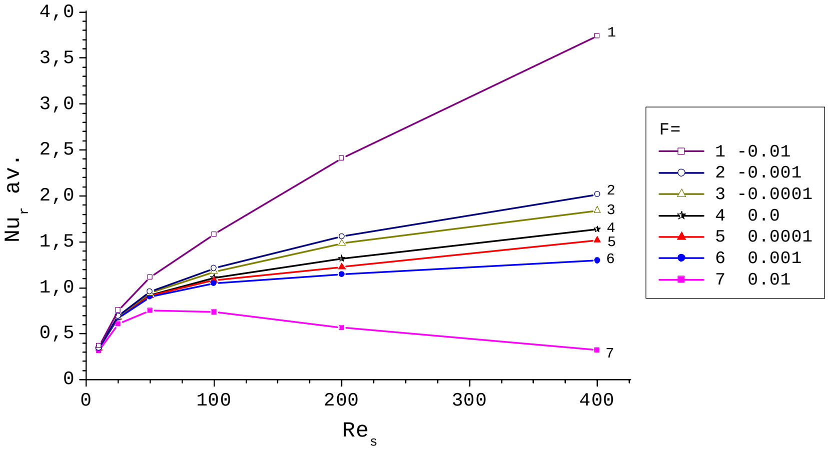


Fig. 5. The Nusselt number Nu_r *av.* on porous wall averaged by the length of separation zone r as a function of Reynolds number Re_s for different blowing parameters F.

Consider the Nusselt number $Nu_r\ av.$ averaged by the length of separation zone r. The graphs corresponding to dependence of $Nu_r\ av.$ on Reynolds number Re_s for different blowing parameters F are presented in Fig.5. One can see that all curves for blowing lie lower and all curves for suction lie upper than the line corresponding to the case of impermeable wall. All the curves form a figure similar to a fan. One can also find that the more absolute value of blowing parameter F the greater curves' divergence is. Besides the curves' divergence increases on the Reynolds number growing up. On the whole the increase of absolute value of blowing parameter and of Reynolds number for suction leads to augmentation of averaged heat transfer comparing to the case of impermeable wall and for blowing the dependence is inverted.

Summing up the entire mentioned above one can conclude the following. The blowing and the suction are powerful factors affecting on friction and heat transfer inside of the recirculation zone. The porous blowing leads to diminution of friction and of heat transfer inside of the separation zone comparing to the case of impermeable wall and the porous suction quite the contrary leads to their augmentation. The local characteristics of friction and of heat transfer in separation zone are more sensitive to suction than to blowing. The blowing and the suction exert intricate influence on the separation zone's length. The increase of absolute value of blowing parameter leads to monotone diminution of average heat transfer inside the separation zone for blowing comparing to the case of impermeable wall and for suction this leads vice versa to its augmentation.

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