SPACE-TIME STRUCTURE OF SEPARATED FLOW BEHIND AN OBSTACLE IN LAMINAR STREAM

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Introduction

Recently interest towards laminar separated flows has considerably risen. On the one hand it can be attributed to the fact that behavior of these flows has not been sufficiently studied. Thus, after the flow separation the disturbances may increase with subsequent transition to turbulence even at low Reynolds numbers corresponding to nominally laminar flow [1]. However, detailed flow structure and mechanisms of transition to turbulence for such conditions are not clear. On the other hand this interest is caused by solving a practical problem of developing compact and ultra-compact heat exchangers with channels of small hydraulic diameter in which a laminar flow is usually realized. Discrete roughness elements used for heat transfer enhancement often initiate flow reattachment regions near channel walls. Clear idea of flow structure and heat transfer in these regions at nominally laminar flow regime is so far absent. Mean heat transfer coefficient in the region of laminar flow reattachment is calculated by up-to-date numerical methods with uncertainties of dozens of percents. Besides, the ranges of regime and geometrical parameters variation at which discrete roughness elements initiate transition to turbulent flow in heat exchanger channels are unknown.

In this paper some experimental results concerning space-time structure of flow separation in a channel behind a single obstacle (rib) at nominally laminar flow regime are presented.

Experimental setup and methods of investigation

Scheme of the experimental setup is shown in fig.1. The setup included a hermetic case 1 looked like a metal tube with the internal diameter of 150 mm. A test section with a smooth inlet 3 was located in the case. The test section had a rectangular cross section with width of 50 mm and height of 20 mm. Walls of the test section were made of plexiglas.

Air flow through the duct of the experimental setup was generated by vacuum pumps 6, and kept constant (during a series of experiments) using a set of critical nozzles 4 installed on a flange 5 of the case. Pumps were connected with an outlet adjutage 8 of the test section with the aid of a flexible tube 7.

Flow regimes corresponding to low Reynolds numbers were provided by generating the required rarefaction in the duct of the experimental setup. The rarefaction was provided by a combination of critical nozzles 9 mounted in the outlet adjutage 8 at the outlet of the test section and critical nozzles 4 (at the inlet of the test section).

There were two transparent hermetic windows with flanges at the lateral side of the case with an angle of ninety degrees between them. A window 10 was necessary for flow illumination which was organized according to the method of a light sheet using a lamp 11. A window 12 was used for observations and video recordings with the help of a camcorder 13. The rib stretched across the whole width of the test section and ranged from 2,3 to 4 mm in height. Two identical test sections were used in experiments. One of them was used for visual studies, another one was used for quantitative measurements. The smoke wire visualization was provided using five nichrome wires 14 (each of them had a diameter of 0,2 mm) mounted near the inlet of the test section.
Simultaneous measurements of velocity (at the test section inlet and downstream of the rib) and instantaneous local values of streamwise component of the skin friction vector behind the rib were conducted (fig.2).

The visualization was made in x0y plane (the symmetry plane of the test section) and in x0z plane located parallel and near the wall of the test section where the rib is mounted. The video records were obtained using a digital video camera.
The flow velocity was measured using hot wire probes. The diameter of a wire was 5 μm. The length of a wire was 2 mm. Longitudinal component of the skin friction vector was measured with the aid of a 3-wire near-wall probe [2]. New hot-wire apparatus IRVIS-TA5 developed by the authors [3] was used for data acquisition. The apparatus has a capability to measure instantaneous temperature difference between two wires. The sign of the difference determines the direction of a near-wall flow.

The Reynolds number calculated using the test section height $H$ and the inlet velocity $U_\infty$ varied in the range of $Re_H=94...4240$. At the same time the Reynolds number calculated using the rib height $h$ and mean-flow-rate velocity above the rib was $Re_h=24...1060$ for $h=4$ mm and $Re_h=12...550$ for $h=2,3$ mm.

**Results**

Experimental results demonstrate that in a wide range of the Reynolds number the flow in the recirculation region is three-dimensional and unsteady with low-frequency variations of the inner structure of the region. Three stable horizontal structures can be recognized near the wall behind the rib. Freeze-frames of a flow visualization are shown in fig.3 for one of the flow regimes.

![Flow visualization](image)

*Fig.3. Structure of flow behind the obstacle at $Re_h=24$ (the air flows from right to the left): a – in vertical plane, b – in horizontal plane near the wall*

The separation region is isolated and its internal structure slightly changes at $Re_h<93$. Increase of the Reynolds number leads to formation of small amplitude disturbances in the reattaching shear layer. One can notice (according to the results presented later) that these disturbances do not cause oscillations of the flow velocity at the channel axis. The disturbances of the shear layer become greater and their starting point moves upstream with increase of the Reynolds number. Evidently, the shear layer becomes unstable at some distance $x_r$ from the rib ($Re_h=160$) and large-scale vortex structures formation starts. Later the vortex structures are transported downstream (fig.4,a). The initial point of these structures formation shifts towards the rib with increase of the Reynolds number (fig.4,b). Analysis of the visual data demonstrates that the Reynolds number calculated using the flow velocity and the distance from the rib to the region of unstable flow is constant: $Re_x=x_rU_0/\nu\approx710$. 


Fig. 4. Flow structure behind a rib of $h = 4$ mm in vertical plane at $l_x = 105$ mm: a – $\text{Re}_h=160$; b – $\text{Re}_h=922$.

The visual results are confirmed by measurements of streamwise component of the skin friction vector. Thus, in the range of $\text{Re}_h \approx 90...250$ average spanwise location of the flow reattachment point ($\gamma = 0.5$) varies from 4 to 5 rib heights (fig. 5). Here $\gamma$ is the flow reversal probability, i.e. time fraction of the whole measurement time, when flow direction near the wall was opposite to the outer flow.

The scattering of the reattachment point in the transversal direction mentioned above becomes smaller with increase of the Reynolds number (about 1 height of the rib at $\text{Re}_h=225$). Further increase of the Reynolds number leads to gradual disappearance of the scattering of $\gamma=f(x/h)$ distribution at the measuring cross-sections in the transversal direction (fig. 6).

Using the experimental data dependence of the reattachment length $X_R$ (the distance from the rib to the point where mean longitudinal component of the skin friction vector $\tau_x$ is equal to zero) on the Reynolds number $\text{Re}_h$ (fig. 7) is determined. These results agree well with the data [4].

Analysis of the velocity measurements at the axis of the test section shows that low-frequency oscillations of the flow velocity appear in the channel downstream the rib at $\text{Re}_h \approx 160$. Their frequency increases with increase of the Reynolds number. Oscillograms of the flow velocity for $h=4$ mm when the rib is located at the distance of $l_x=105$ mm from the inlet cross-section (fig. 2) are shown in fig. 7. Developed turbulent channel flow appears at $\text{Re}_h=1060$. It is proved by the following fact. In this case one may identify the so called inertial interval in a wave number energy distribution, i.e. the frequency range which corresponds to "$-5/3$ law" [5].

Fig. 5. Variation of flow reversal probability, $\gamma$, on the wall behind the rib at $\text{Re}_h=125$ (a) and 1060 (b): 1 – in the symmetry plane of the test section, 2 – 13 mm away from the symmetry plane in spanwise direction.
Conclusions

On the basis of visual investigations and hot-wire measurements of flow parameters in a nominally laminar separated flow behind a rib the following conclusions are made up.

The flow in the separation region is essentially 3D and nonstationary with apparent cellular structure and zones with transversal fluid movement. Internal structure of the region changes all the time, some low frequency oscillations of the flow take place. The reattachment line at $Re_h < 225$ is distorted. Amplitude of the reattachment point oscillations is small at these regimes.

Flow separation behind a rib initiates low frequency oscillations of flow velocity and the laminar-turbulent transition in the channel begins. The critical Reynolds number corresponding to the start of the channel flow instabilities development is $Re_h \approx 160$. The main features of a developed turbulent channel flow appear at $Re_h \approx 1000$ ($Re_H \approx 4000$).
Visualization results supplemented with data on simultaneous skin friction and flow velocity measurements clarified the idea about evolution of separated flow space-time structure behind the rib in a laminar stream in conditions of disturbances development.

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