Vortex shedding behind an obstacle in a channel under transition to turbulence in steady and pulsating flows

V M Molochnikov\textsuperscript{1,3}, E I Kalinin\textsuperscript{2}, A B Mazo\textsuperscript{2}, A V Malyukov\textsuperscript{1}, D I Okhotnikov\textsuperscript{2} and O A Dushina\textsuperscript{1}

\textsuperscript{1} Kazan Scientific Center of RAS, Kazan, 420111, Russia
\textsuperscript{2} Kazan Federal University, Kazan, 420008, Russia
\textsuperscript{3} Kazan National Research Technical University, Kazan, 420111, Russia

e-mail: vmolochnikov@mail.ru

Abstract. Experimental research and DNS of separated flow over a spanwise semicylindrical rib mounted in a rectangular channel have been performed for the cases of steady and pulsating flow with transition to turbulence. Spiral motion of fluid behind the rib directed from the channel walls towards the channel symmetry plane has been shown to govern the formation of large vortices in the mixing layer starting from some critical Reynolds number. The mechanism of origination of such motion has been hypothesized. The effect of frequency and amplitude of forced freestream pulsations on the vortex pattern behind the rib has been described.

1. Introduction

Large vortices play a crucial role in heat transfer enhancement caused by near-wall turbulence promoters. However, there are only a few attempts at studies of the formation of these vortices in conditions of laminar-turbulent transition and they are mainly focused on evolution of instabilities in a separated laminar flow with small perturbations \cite{1}.

The majority of researchers attribute the formation of large quasiperiodic vortices in an obstacle wake in unbounded freestream to the global instability of flow on the scale of entire separation region (instability to periodic vortex shedding) \cite{2, 3}. The mechanism of large vortex generation in wall-bound flows at transitional flow regimes is different. In a rectangular channel, the sidewalls significantly influence the separated flow pattern downstream of the obstacle. This issue has been recognized for the first time ever when the data on the reattachment length obtained by 2D simulation had been observed to deviate from the experiment \cite{4}. The reason for such deviation was shown to be the secondary spiral motion of fluid from the channel sidewalls towards its symmetry plane. With the increase in the Reynolds number, the intensity of this flow grows in the laminar region and falls at transitional and turbulent flow regimes \cite{5}. DNS of a backward-facing step flow \cite{6} showed that when the channel width increases, the Reynolds number corresponding to the onset of instability in the separated shear layer decreases. The loss in stability is accompanied by the transition to essentially three-dimensional behavior of velocity and temperature fields. Some regularities in the spiral motion from the channel sidewalls towards its symmetry plane for the case of backward-facing
step flow were shown in [7]. Only the results for Re = 400 are given, although the authors state that they can be extended to the Reynolds number range Re = 100–400. The already cited paper [5] showed that the discrepancy between the reattachment lengths obtained experimentally and computationally (2D model) was initiated when the spiral motion from the channel sidewalls reached the channel symmetry plane. Despite a large number of research papers studying 3D effects in transitional separated flows in rectangular channels, the mechanism of formation of large 3D vortices in such flows has remained beyond the scope of these studies.

Understanding of physical mechanisms of quasiperiodic vortex formation behind the obstacles makes it possible to control the processes in heat exchangers and cooling systems. Forced pulsations of the oncoming flow are a promising control method. However, there are almost no published data on the effect of pulsations on the formation of vortices behind the obstacles in the channels under transitions to turbulence.

In the present paper, the flow over a spanwise rib mounted on the wall of a rectangular channel has been studied experimentally and by direct numerical simulation (DNS) for the case of low Reynolds numbers in the steady and pulsating oncoming flow. The mechanism of laminar-turbulent transition and large vortex formation in the shear layer behind the rib has been studied, the vortex pattern control using the forced periodic freestream pulsations has been considered.

2. Experimental setup and procedure

The experiments were conducted in a rectangular test section (height $H = 20$ mm, width $B = 50$ mm) with a smooth inlet attached to it (figure 1). The spanwise rib (height $h = 3$ mm, radius $R = h$) was mounted at the distance $l = 106$ mm from the test section inlet. The air flow rate through the test section was provided by a vacuum pump. The experiments were carried out in the Reynolds number range Re = $U/h$/$\nu = 58.5–439.5$ based on the average velocity in the test section, $U$, the rib height, $h$, and kinematic viscosity of air, $\nu$. Here, the average velocity, $U$, varied between 0.28 and 2.12 m/s. Hot-wire measurements revealed no turbulent fluctuations of flow velocity at the channel inlet. The boundary layer thickness exceeded the obstacle height in all the considered regimes. Smoke-wire visualization of flow was performed. The flow pattern was recorded in a light sheet in the channel symmetry plane ($z = 0$) and in the planes parallel to the bottom wall at the distance $y = 1$ and 3 mm from the latter. The frame rate was 800 frame/s. In addition to flow visualization, PIV measurements of instantaneous velocity vector fields were obtained downstream of the rib in the channel symmetry plane. PIV measurements were processed using an iterative algorithm for the calculation of velocity fields with particle displacement compensation. 32×32 pixel interrogation windows with 50% overlap were considered.

Direct numerical simulation (DNS) of flow was performed using ANSYS Fluent 14.5 software. The computational domain matched the test section configuration with the semicylindrical rib. 3D unsteady Navier-Stokes equations were solved in dimensionless physical variables for incompressible fluid in the Reynolds numbers range $165 < Re< 480$. All dimensions of the computational domain were normalized by the rib height, $h$, the time was normalized by $h/U$, and the pressure was normalized by $\rho U^2$, where $\rho$ is the air density. No-slip condition was set at solid walls; uniform streamwise unit velocity profile and zero excess pressure were set at the inlet; “soft” boundary conditions were set at the channel outlet. The computational grid was built using a locally-structured approach [8]: the domain was filled with a set of structured grid segments, which were connected by non-structured insertions. The grid was refined near the solid walls and in the obstacle wake. In the case of steady flow past the rib, the grid contained $1.5 \times 10^6$ cells, the dimensionless spacing of the grid in refinement areas was 0.01, in the middle wake it was 0.3, the time step was
The total number of grid cells in pulsating flow was $10^6$, minimal dimensionless grid spacing in the refinement areas was 0.02, in the middle wake it was 0.15, in the boundary layer on the channel walls it was 0.01, and the time step was 0.05. Calculations on twice finer grid did not reveal any noticeable changes in computational result. The computational results were visualized by the simulation of passive particles released from virtual “smoke wires” located near the rib.

3. Results and discussion

3.1. Steady flow over the rib

Flow visualization downstream of the rib demonstrated a laminar flow with a stable closed recirculation region behind the rib at Re < 165 (figure 2 a). The flow pattern in horizontal plane includes a circular motion of fluid from the channel sidewalls towards its center, i.e. corner vortex pairs (figure 2 b). As soon as a critical Reynolds number, $\text{Re} = \text{Re}_* \approx 196$, is attained, large 3D vortices (vortex clots) are formed near the channel symmetry plane. In $x0y$ plane they look like spanwise vortices (figure 3 a). Corner vortices persist at this regime, they are clearly visible at the distance $y = 3$ mm from the ribbed wall as well (figure 3 b).

When the Reynolds number increases, the region of vortex clot generation onset shifts towards the rib, and the area occupied by these clots grows in transversal direction. The process is accompanied by fragmentation of large vortices into smaller ones. The wake flow downstream of the reattachment line takes the features of turbulent flow.

![Figure 2. Flow visualization behind the rib at Re = 135: (a) – channel symmetry plane; (b) – horizontal plane at $y = 1$ mm](image)

![Figure 3. Flow visualization behind the rib at Re = 233: (a) – channel symmetry plane; (b) – horizontal plane at $y = 3$ mm](image)

More detailed 3D flow pattern and its quantitative estimation were obtained by DNS. The latter was tested by the comparison of flow patterns, average velocity profiles and fluctuations obtained numerically and experimentally. Good agreement between DNS results and flow visualization together with PIV measurements (figure 4 and 5) was obtained.

Formation of large vortices in the mixing layer at Re $\geq \text{Re}_*$ is accompanied by essentially 3D flow in the boundary layer downstream of the obstacle in the channel. Corner vortex pairs shown in figures 2 and 3 appear to represent complex spiral flow directed from the channel sidewalls towards the channel center. The entrained fluid is shown in figure 6. This figure demonstrates the formation of 3D vortex clots near the channel symmetry plane and their shedding.

Thus, corner vortex pairs observed in the experiments include the spiraling fluid visible in the light sheet and stagnation regions not involved into the ascending spiral motion. The part of fluid involved in the spiral motion enters the recirculation region and is periodically shed to the free stream in the form of vortex clots at Re $\geq \text{Re}_*$.
In calculations, the increase in dimensionless (normalized by the velocity head) static pressure, \( p(x) \), in the channel symmetry plane started upstream of the reattachment point. For example, at \( \text{Re} = 270 \) the pressure growth started at \( x/2h \approx 4.4 \) (figure 7), and flow reattachment corresponded to \( x/2h \approx 4.75 \) [9]. Considerable increase in pressure pulsation amplitude was observed in the region of the adverse pressure gradient \( (5 < x / 2h < 7.5 \text{ at } \text{Re} = 270) \). This is the region of large vortex (vortex clots) generation onset.

The obtained experimental and numerical results revealed the main features of the mechanism of large vortex formation in the rib wake in the channel under transition to turbulence. The core flow above the recirculation region behind the rib develops in conditions of adverse pressure gradient. The reverse flow in the recirculation region is the strongest near the channel symmetry plane due to spiral

Figure 4. Experimental (a), (c) and computational (b), (d) flow patterns at \( \text{Re} = 270 \): (a), (b) – channel symmetry plane; (c), (d) – horizont. plane at \( y = 3 \text{ mm} \)

Figure 5. Comparison of experimental and computational profiles of statistical characteristics of flow behind the rib at \( \text{Re} = 439 \), \( x/h = 4 \): 1 – experiment; 2 – calculation

Figure 6. Spiral motion of fluid from the channel sidewalls to its center at \( \text{Re} = 439 \)

Figure 7. Averaged (1) and instantaneous (2) pressure behind the rib at \( \text{Re} = 270 \)
flow from the sidewalls to the channel center. At low Reynolds numbers the circulation energy of fluid in the closed region behind the rib dissipates to the free stream due to viscous forces at the external boundary of this region and friction forces on the wall; the flow remains stable in this region, separation region is closed, and no vortices are observed. At \( Re \geq Re_\ast \), viscous forces are unable to remove fluid circulation energy accumulated in the separation region, the flow in the adverse pressure gradient region becomes unstable, 3D coherent vortices form inside the separation region near the channel symmetry plane, and they are periodically shed to the main flow. The increase in Reynolds number leads to reduction of the scale of corner vortices and displacement of vortex generation onset in the upstream direction. This process is accompanied by fragmentation of large vortices into smaller ones and augmentation of velocity fluctuations; the obstacle wake downstream of the reattachment line acquires the features of turbulent flow.

The onset of spiral motion (pairs of corner vortices) in the obstacle near wake obviously results from the development of viscous boundary layer in dihedral angles between the bottom horizontal and vertical walls of the channel and from the interaction of this layer with the spanwise rib. According to [10], for the case of flow inside dihedral angles under the adverse pressure gradient, considerable reduction of skin friction is observed when approaching the dihedral angle edge in transversal direction. And it is the region of the pressure growth onset (figure 7) where the most intense displacement of flow from the channel walls is observed (figure 4 and 6).

3.2. Pulsating flow over the rib

In the present work we applied periodic forced flow pulsations to the flow over the rib in order to control the vortex pattern of the flow. The experiments were conducted in the same test section (figure 1), and forced pulsations were generated in a receiver tank 3 mounted at the channel outlet (one wall of the receiver was replaced by a speaker 4) (figure 8). The speaker was controlled by a pulse generator through a signal amplifier to generate the required frequency and amplitude of pulsations. Forced flow pulsations frequency, \( f \), and relative amplitude \( E = A/U \) (here \( A \) is the amplitude of pulsations) varied in the experiments. The dimensionless frequency and amplitude changed in the ranges \( Sh = f h/U_0 = 0.07 – 0.51, E = 0.07 – 0.3 \) for each Reynolds number \( Re = 58.5 – 439 \). In steady flow \( Sh = 0.06 \) at \( Re = Re_\ast \) and grows up to 0.13-0.16 at \( Re = 228 – 439.5 \). For the considered \( Re, Sh \) and \( \beta \), the flow pulsations were shown to significantly alter the flow pattern typical of the steady flow at the same Reynolds numbers. “Starting vortices” are formed behind the rib in the flow acceleration phase. The origination frequency of these vortices is determined by the period of forced flow rate pulsations. The spatial scale of starting vortices depends on the Reynolds number and the parameters of forced unsteadiness: at low frequency of pulsations the linear scale of these vortices is approximately twice the rib height (figure 9) and decreases with the pulsation frequency growth. New pattern behind the rib was revealed in the pulsating flow at low Reynolds numbers and relatively high frequency of pulsations: a closed recirculation region with small starting vortices at its outer edge is formed behind the rib (figure 11).

The spiral motion of fluid from the sidewalls towards the channel center, while governing the formation of large vortices behind the rib in the steady flow, does not usually reach the channel symmetry plane in the pulsating flow. For this reason, initially, the starting vortices are cylinder-shaped and their transversal dimension depends on the Reynolds number, frequency and

\[Figure 8.\] Test section intended for the study of pulsating flow over the rib: 1 – smooth inlet; 2 – rib; 3 – receiver tank; 4 – speaker
Figure 9. Pulsating flow over the rib at Re = 194, Sh=0.07; β =0.15: (а) – channel symmetry plane; (b) – horizontal plane at y = 1 mm

Figure 10. Pulsating flow over the rib at Re = 58.5, Sh=0.51; β =0.15: (а) – channel symmetry plane; (b) – horizont. plane at y = 1 mm

amplitude of forced pulsations.

4. Conclusions
With the growing Re, the “span” of these vortices grows, and the region of spiral motion reduces. The increase in forced pulsation frequency has similar effect on the pattern of starting vortices. Having been shed, each starting vortex disintegrates into several 3D vortex clots, the number of which grows with Re and Sh. The revealed regularities can lay the foundation for active control of the intensity of large vortices formed behind the rib. However, this requires further theoretical studies and laboratory experiments.

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