Flow structure behind a spanwise rib in channels of different geometry at moderate Reynolds numbers

V M Molochnikov¹, A B Mazo², A V Maluykov¹ and E I Kalinin²
¹Institute of Power Engineering and Advanced Technologies of FRC Kazan Scientific Center of RAS
²Kazan Federal University, Kazan, 420008, Russia

E-mail: vmolochnikov@mail.ru

Abstract Experimental study of laminar-turbulent transition in a rectangular channel with a semicircular rib has been carried out. The study comprised the flow visualization as well as direct numerical simulation of some flow configurations. The paper investigates the effect of the channel geometry (width and height), aspect ratio of the rib and blockage ratio on the mechanisms of transition to turbulence, formation of large vortical structures in the mixing layer behind the rib and on the critical Reynolds number at which the transition to turbulence occurs.

1. Introduction
It is well known that local imperfections (obstacles) mounted on the channel walls trigger earlier (compared to smooth channels) transition to turbulent flow. These processes are accompanied by considerable augmentation of heat transfer. Large amount of experimental studies of integral flow parameters in such channels has been accumulated for different geometries of local imperfections. However, there is clearly a shortage of data on flow evolution and mechanisms of transition to turbulence in enhanced channels. Transition to turbulence behind two-dimensional obstacles located on surfaces in unconfined flows is well understood. When the obstacle is relatively high, the laminar-turbulent transition is dominated by self-excitation of the separation region of the boundary layer, which is manifested through large-scale quasi-periodic vortical motion [1]. Authors of [1] note that oscillations excited by the separation bubble can combine with convective disturbances due to the separated shear layer [2, 3].

Transition to turbulence in the channel with obstacles is strongly influenced by three-dimensionality of the flow induced by the side walls of the channel. Numerical simulation of laminar and transitional flows past spanwise ribs (backward-facing steps) revealed the spiraling motion of the flow from the side walls towards the channel center [4, 5]. Our earlier experiments and direct numerical simulation of the flow past a semicircular rib in a channel allowed us to describe the mechanism behind formation of large vortical structures in the case when channel geometry provides merging of spiraling fluid at the channel center behind the rib [6, 8]. Mechanisms of laminar-turbulent transition in wider channels when spiraling fluid does not merge at the channel center are unexplored.

The present paper elaborates on the mechanism of transition to turbulence behind a semicircular spanwise rib installed on a channel wall and studies the effect of the channel width (aspect ratio of the rib) and channel height (blockage ratio) on this mechanism. The experiments include flow
visualization and measurements of instantaneous vector fields of velocity. Direct numerical simulation (DNS) of a number of cases has been performed.

2. Experimental setup and procedure

The experiments were carried out in a rectangular test section with transparent walls. It was equipped with a smoothly shaped inlet.

Three geometries of the test section (channel) have been considered. When the channel height was $H = 20$ mm, its width, $B$, was either 50 mm (case I) or 150 mm (case II). Besides, at $B = 150$ mm the channel height varied from 20 to 10 mm (case III). In all cases, a semicircular spanwise rib was installed at the distance $L_1 = 100$ mm from the channel inlet. The rib height was $h = 3$ mm (radius $R = h$), aspect ratio $B/h = 16.6$ (case I) and 50 (cases II and III) while the blockage ratio, $h/H$, varied from 0.15 (cases I and II) to 0.33 (case III). The air flow through the channel was generated by a vacuum pump. A set of critical flow nozzles placed downstream of the test section maintained constant flow rate with the uncertainty of max. 0.25%.

Smoke visualization technique was employed in experiments. Case I was studied both experimentally (SIV measurements [7] of the instantaneous vector fields of velocity) and numerically (direct numerical simulation, namely three-dimensional incompressible unsteady Navier-Stokes equations [6, 8]). Computational domain matched the configuration of the test section. No-slip condition was set on the solid walls; uniform profiles of unit velocity and zero pressure were assigned at the inlet; soft boundary conditions were specified at the outlet.

The Reynolds number range was $Re = 59 – 440$ (based on the average flow velocity, $U_0$, rib height, $h$, and kinematic viscosity of air, $\nu$) both in experiments and simulation.

3. Results and discussion

Simulation procedure has been verified for the case I of the channel geometry. Flow patterns, including the size of separation region, configuration of vortex clouds and vortex shedding frequency, profiles of flow velocity and its RMS fluctuations were compared with experimental data of flow visualization and PIV measurements in [6]. Satisfactory agreement of numerical and experimental results was obtained.

Flow visualization behind the rib revealed spiraling motion of fluid from the side walls towards the channel center when the channel width was $B = 50$ mm (case I). This motion was manifested through the pairs of corner vortices in visualization pictures (fig.2, a). In this case (when the rib height was fixed), the spiraling fluid merged at the channel center forming a closed steady recirculation region at $Re < 190$. At $Re = 170$, convective disturbances were documented in this region at the external boundary of the shear layer. They were observed in the form of oscillations of smoke plumes. Their amplitude increased with the Reynolds number, and eventually, the plumes were shaped like mushrooms. At Reynolds number $Re = 190$, in the region of merging the spiraling jets, three-dimensional large-scale vortical structures (vortex clouds) emerged and were swept periodically in streamwise direction (fig.2, b). The shedding frequency grew with the Reynolds number, while the clouds disintegrated into several vortices when moving further downstream.

The mechanism of vortex formation is evident in computer visualization of flow obtained from DNS (fig.3).
When the aspect ratio of the rib increased up to $B/h = 50$ (case II, $B = 150$ mm, $H = 20$ mm), the spiraling fluid behind the rib did not reach the channel center. At $Re \approx 300$ this fluid (corner vortices) occupied approximately 30% of the channel span, and the onset of the cell structure could be observed inside the recirculation region which is clearly seen in flow visualization pictures in the $xz$-plane at the distance of 1.5 mm from the ribbed wall (fig.4, b). Large-scale vortices formed in the mixing layer behind the rib starting from this particular regime (fig.4, a). The cell structure and large vortices were more pronounced with the increase in the Reynolds number (fig.5), while the region occupied by spiraling fluid shrank in spanwise direction.

When the blockage ration increased up to $h/H = 0.33$ (case III: channel width $B = 150$ mm, height $H = 10$ mm), the level of flow expansion grew, and hence, the streamwise adverse pressure gradient above the separation region was promoted resulting in reduction of the critical Reynolds number down to $Re \approx 110$ (the critical Reynolds number corresponds to the onset of cell pattern in the recirculation region across the channel and formation of large vortices in the mixing layer).

It should be noted that no transition to turbulence was observed in the smooth channel throughout the considered range of Reynolds numbers in all channel configurations.

![Image](image1.jpg)  
*Figure 2. Smoke visualization of flow in the $xz$ plane at the distance of 1 mm (a) and 3 mm (b) from the ribbed wall, Re = 190.*

![Image](image2.jpg)  
*Figure 3. Visualization of 3D flow structure behind the rib (DNS data).*
Figure 4. Visualization of flow behind the rib in the channel with $H = 20$ mm, $B = 150$ mm at $Re = 300$: $a$ – $xy$-plane; $b$ – $xz$-plane at the distance of 1.5 mm from the wall.

Figure 5. Visualization of flow behind the rib in the channel with $H = 20$ mm, $B = 150$ mm at $Re = 420$: $a$ – $xy$-plane; $b$ – $xz$-plane at the distance of 1.5 mm from the wall.

Conclusions
Flow separation behind the spanwise rib in the channel triggers earlier transition to turbulence if compared to the smooth channel. Transitional flow behind the rib features quasi-periodic large-scale vortices that are swept by the main flow. The mechanism behind the formation of these vortices and the critical Reynolds number of their onset are influenced by the aspect ratio of the rib and the blockage ratio, both of which are defined by the channel cross section dimensions, given the fixed rib height. Mechanism of transition to turbulence behind the rib in the rectangular channel is associated with the global instability of the whole separation region; however, the way it manifests itself depends on the channel geometry (aspect ratio of the rib, $B/h$, and blockage ratio, $h/H$) because the flow in the separation region is three-dimensional.

At $B/h = 16.7$, the fluid spiraling away from the channel walls behind the rib merges at the channel center. Owing to this motion, the maximum reverse flow velocity in the recirculation region is observed at the channel symmetry plane. When the critical Reynolds number is achieved ($Re = 190$),
the recirculation region becomes unstable, and large-scale vortices (3D vortex clouds) emerge around the channel symmetry plane. These vortices are periodically swept downstream.

At $B/h = 50$, the spiraling fluid does not reach the channel symmetry plane. As soon as the critical Reynolds number is attained, the instability of flow within the recirculation region behind the rib in spanwise direction is observed. This instability results in cell structure of flow in this direction. Large quasi-periodic vortices formed behind the rib occupy almost the whole channel width in a non-uniform manner. Critical Reynolds number at the given aspect ratio of the rib is $Re = 300$.

When the blockage ratio increases up to $h/H = 0.33$, the mechanism of vortex formation remains the same, while the critical Reynolds number reduces to $Re = 110$ due to the streamwise pressure gradient augmentation above the recirculation region.

Acknowledgments

The research was financially supported in part by the Russian Foundation for Basic Research (project no. 19-08-00421). Direct numerical simulation was carried out with financial support from the government assignment for FRC Kazan Scientific Center of RAS.

References

[1] Boiko A V, Dovgal A V and Kozlov V V 2017 Thermophysics and Aeromechanics 24 (2) 167–73
[2] Dovgal A V and Sorokin A M 2001 Thermophysics and Aeromechanics 8 (2) 179–86
[3] Dovgal A V and Sorokin A M 2002 Thermophysics and Aeromechanics 9 (2) 183–90
[4] Iwai H, Nakabe K and Suzuki K 2000 Int. J. Heat and Mass Transfer 43 457–71
[5] Tylli N, Kaiktsis L and Ineichen B 2002 Physics Fluids 14 (11) 3835–45
[6] Molochnikov V M, Mazo A B, Malyukov A V, Kalinin E I, Mikheev N I, Dushina O A and Paereliy A A 2014 Thermophysics and Aeromechanics 21 (3) 309–17
[7] Mikheev N I and Dushin N S 2016 Instruments and Experimental Techniques 59 (6) 882–9
[8] Mazo A B and Okhotnikov D I 2016 Lobachevskii J. of Mathematics 37 (3) 360–7