Influence of forced flow pulsations on heat transfer behind a rib in a channel in transitional flow regimes

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Abstract
Direct numerical simulation of flow and heat transfer behind a spanwise rib in a pulsating flow in a channel has been performed at the Reynolds numbers that correspond to transition to turbulence in the separation region behind the rib in a steady flow case. Good agreement between the calculations and experimental data has been demonstrated. The effect of forced unsteadiness parameters on heat transfer behind the rib has been analyzed. It has been shown that forced flow pulsations are able to augment heat transfer. The correlation between the heat transfer level and the vortical structure of flow behind the rib has been demonstrated.

1. Introduction
Local surface non-uniformities in the form of spanwise ribs are often used to enhance heat transfer in the channels of power systems. Near-wall heat transfer enhancement in ribbed channels is much more pronounced at low Reynolds numbers that correspond to the laminar flow regime in a smooth channel. In this case, ribs lead to earlier onset of turbulence in the flow. The mechanism of laminar-turbulent transition in a rectangular channel with a semicircular rib has been studied in detail in experiments and calculations performed in [1]. It was established there that spiral motion of fluid from the channel side walls towards its center plays a decisive role in transition to turbulence. If this motion reaches the channel symmetry plane, quasi-periodic vortices are formed in the channel center triggering the transition to turbulence in the rib wake. The vortex formation starts as soon as the Reynolds number reaches some critical value of Re ≈ 180 (based on the rib height).

Vortex formation and flow turbulization in the channel are accompanied by local heat transfer enhancement. Additional augmentation of heat transfer behind an obstacle is possible through targeted forcing of the vortical structure by flow velocity pulsations. The efficiency of such an approach in the case of turbulent flow past the obstacles was demonstrated in [2]. In a pulsating flow at the frequencies corresponding to the Strouhal number Sh ~ 1 (based on the reattachment length in a steady flow), the heat transfer coefficient averaged over the reattachment length increased by approximately 60%, while the reattachment region became approximately half of its initial size.

DNS of flow and heat transfer behind an obstacle in a pulsating channel flow are presented in this paper. Calculations have been verified. It has been shown that forced flow unsteadiness is able to...
further enhance heat transfer behind the obstacle. The correlation between heat transfer enhancement and vortical structure of the flow has been revealed.

2. Computation procedure

Mathematical statement of the problem of a channel flow past a semicircular rib includes the solution of three-dimensional unsteady Navier-Stokes equations in dimensionless natural variables for an incompressible fluid and the solution of convective heat transfer equation. The governing system of equations was integrated in Ansys Fluent 14.5 software using the second-order finite volume approach. No-slip boundary conditions and the wall temperature were set on solid walls, while a uniform profile of a unit streamwise velocity and zero gauge pressure were adopted at the channel inlet. The dimensionless temperature of flow at the inlet was assumed to be zero, while the dimensionless wall temperature was equal to one. In the pulsating flow case, a uniform unit velocity profile with forced pulsations with a given frequency and amplitude was set at the channel inlet. “Convective” (non-reflecting) boundary conditions were imposed at the channel outlet.

The computation domain geometry is shown in figure 1. The channel height was $H = 20$ mm, width $B = 50$ mm, and length $L_1 + L_2 = 250$ mm ($L_1 = 106$ mm). The rib height (radius), $h$, was 3 mm. Direct numerical simulation of the pulsating flow past a rib implies generation of a computational grid and solution of the system of original equations without any additional semiempirical models and parameters. The computational grid was built using locally-structured approach [3]: the domain was filled with a set of structured grid segments, which were connected by non-structured insertions. A total of $10^8$ cells were generated with significant refinement near the solid walls and in the vortical wake (figure 2). Minimal dimensionless cell size along the direction normal to the rib surface was 0.02. The cell size in the middle wake region was 0.15. To resolve the wall boundary layer, the minimal cell size along the wall normal direction was 0.01. The time step was 0.05.

![Figure 1. Computation domain geometry](image1)

![Figure 2. Computation grid fragment](image2)

Calculation of flow was performed in the Reynolds number range $\text{Re} = U h/\nu = 69–480$ based on the mean velocity, $U$, and the rib height, $h$. The frequency, $f$, of forced velocity pulsations was varied so as to provide the range of Strouhal number variation $Sh = f h/U = 0.07–0.44$ at each considered Reynolds number. Normalized pulsation amplitude $\beta = A/U$ varied within the interval of 0.07–0.3. Heat transfer was calculated at $\text{Re} = 136, 233$ and 378, while the Strouhal number varied between 0.045 and 0.13, and the normalized amplitude of pulsations was equal to 0.15.

3. Results and discussion

3.1. Verification of calculations

The calculated flow pattern obtained using the tracers (weightless particles supplied to the flow) was compared with experimental smoke-wire visualization of flow. The experiments were carried out on a special setup. The test section geometry was identical to the computation domain of the considered flow. The only difference was in a smooth inlet attached to the test section in experiments. The inlet
was shaped according to Bernoulli lemniscates and provided the flow constriction of 6:1. The air was set in motion by a vacuum pump, and the required flow rate was provided and maintained by a set of critical flow nozzles. Forced flow pulsations were generated by a loudspeaker mounted at the test section outlet. It has been demonstrated that spatial scales and spacing of vortices obtained from numerical simulation and smoke visualization (figure 3) are in satisfactory agreement both at the Reynolds numbers corresponding to the onset of spanwise vortex generation and in the regimes of almost developed turbulence in the channel.

![Image](image_url)

**Figure 3.** Comparison between simulation (a, c) and experiments (b, d) at Re = 274, Sh = 0.12, β = 0.15: a, b – in the xOy plane; c, d – in the xz plane at the distance of 3 mm from the bottom wall

3.2. Results and discussion

Calculations showed that forced pulsations induce the formation of a “starting” vortex behind the rib. Initially, this vortex was almost two-dimensional. The span of the vortex across the channel is governed by the Reynolds and Strouhal numbers. In all the considered cases, the shedding frequency of “starting” vortices locked on to the forced pulsation frequency. The increase in Reynolds number or forced pulsation frequency resulted in increased span of the cylindrical part of the vortex while the span of the regions of spiraling motion of fluid decreased. Moving further downstream, the formed vortex split into two or three (depending on the forcing frequency) vortical structures, which subsequently disintegrated into smaller ones.

Maximum heat transfer coefficients and hence the highest heat transfer augmentation in the steady flow was observed at some distance from the obstacle. Heat transfer coefficient decreased with the distance from the obstacle. The highest augmentation of heat transfer coefficient across the channel was observed in the regions adjacent to the side walls, which was due to the spiral fluid motion transporting the heated fluid from the vicinity of walls to the channel center.

A “starting” vortex originates in the pulsating flow at some distance from the channel bottom wall, therefore no significant augmentation of heat transfer coefficient is observed near the rib. Once the cylindrical vortex has disintegrated into vortex clouds, the latter interact with the channel wall, enhance mass and heat transfer and promote the increase of local instantaneous and averaged heat transfer coefficient behind the rib (figure 4). There are 2 to 5-7 local peaks of the average heat transfer coefficient observed across the channel width depending on the Reynolds number.

It has been revealed that forced flow pulsations augment the average heat transfer from the channel wall downstream of the rib. The augmentation reaches 30-35% in the range of Reynolds numbers corresponding to the onset of large vortex generation behind the rib in the steady flow regime. Maximum enhancement of heat transfer in the pulsating flow in these regimes occurs at the forcing frequencies that are close to the shedding frequency in the steady flow case. However, the enhancement is highest (up to 70%) at lower Reynolds numbers which in the steady flow case correspond to the formation of a stable separation region behind the rib without any sign of vortices in the mixing layer.
Figure 4. Instantaneous (a) and average (b) heat transfer coefficient (Nusselt number) on the wall behind the rib at $Re=378$, $f = 80$ Hz, and $\beta = 0.15$.

Conclusions
Direct numerical simulation of heat transfer in the pulsating flow past a spanwise rib in a channel has been performed. The results have been verified and showed satisfactory agreement with experiments in terms of hydrodynamics at different stages of transition to turbulence in the rib wake. It has been demonstrated that forced flow pulsations are able to further enhance heat transfer behind the rib. Depending on the mean flow Reynolds number, the average heat transfer enhancement ranges between 30% and 70%. The highest augmentation of heat transfer has been observed in the rib near-wake.

Acknowledgments
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