Numerical study on the influence of slit shapes and sizes between the lower wall and the plate on turbulent flow and heat transfer characteristics

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Abstract. The results of numerical study of flow structure and heat transfer in turbulent flow of air over a flat plate at \( q_w = \text{const} \) with a rectangular rib with slit channel of different shapes: confusor, diffusor and const cross-section are presented. The slit channel is located between the plate and the lower wall of the rib. Numerical simulation is performed for an incompressible fluid in the framework of three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations with a Kato-Launder \( k-\epsilon \) turbulence model for turbulence closure. The parameter effects, including the slit channel sizes and shapes (confusor, diffusor and plane-parallel), on turbulent flow structure and normalized local heat transfer coefficients on the heat transfer surface are examined. It is established that the rib with a slit, especially with a confusor, substantially reduces the size of the recirculation region behind the rib due to the effect of the generated near-wall jet on main flow. In addition, in the presence of a slit between the wall and the rib, in transverse direction, a pair of symmetrical extended spots with high values of heat transfer coefficients relative to the middle of the plate is observed. Rib with a confusor slit having a longer confusor part (Case B2) provides the best overall heat transfer performance.

1. Introduction

It is an extremely urgent problem to design and create a highly efficient and compact cooling system, which is often and successfully solved with the use of the methods of heat transfer enhancement. Many studies have focused on methods of enhancing heat transfer by affecting the flow and primarily the boundary layer by means of various intensifiers – ribs of different geometry [1]. As every additional turbulization of the flow is bound to associate with additional energy loss, the selection of location and the method of the additional turbulization of the flow are crucial in the development of effective methods for heat transfer intensification. The most effective method is the intensification of flow, which may affect the near-wall layers of the fluid at a distance, which is of the order of \( y^+ < 30...100 \) from the wall, without affecting the flow core [2-4]. It can be assumed that such a method of heat transfer intensification can significantly increase the heat transfer coefficient together with a moderate increase in the friction coefficient, i.e. to achieve an increase in heat transfer faster than the growth of friction resistance. The interest in ribs, which are immersed in a boundary layer and somewhat larger than the height of the laminar sublayer has increased.

As is known, when flowing around a solid rib, in front of it and behind it, low-speed separated zones are formed, leading to a significant deterioration of heat transfer in its vicinity. As shown in [5], reduction or elimination of these zones can be achieved through perforation of the rib with plane-
parallel slit channels. Comparison of the thermal-hydraulic efficiency of the slit rib (horizontal and vertical slit) and the perforated rib in a turbulent channel flow was studied in [6]. It is shown that such a slit rib is able to eliminate separation zones due to the throttling effect [7]. The studies of [8-10] under the guidance of Panigrahi P. K. are devoted to experimental studies of the processes of flow around permeable ribs with different slit geometries. In addition, in many experimental and numerical studies [11-14] much attention is paid to the study of the flow features of the detached ribs located at a small distance from the heating surface. The study of [11] presents experimental results of the distribution of local heat transfer coefficients in a rectangular tube with detached ribs. The influence of the distance between the pipe wall and the rib, as well as the angle of its installation on the separated flow structure and heat transfer are numerically studied in [12, 13]. In [14] it is shown that the organization of near-wall jets formed by the flow of air from the external flow to the bottom region of the rib can be used to control hydrodynamic and thermal processes in flow around the rib.

Recently, an experimental study of turbulent flow around transverse slit ribs located on a flat plate was carried out in [4]. The confusor, diffuser and constant cross-section slits of finite length between the plate and the lower wall of the rib are considered. It is noted that the structure of the vortex zones before and after the slit rib significantly depends on the shape of the slit. Based on this, in this paper, a detailed numerical study is conducted to investigate the influence of three shapes of a slit (confusor, diffuser and constant cross-section slit) and different slit sizes on the turbulent flow and heat transfer.

2. Computational investigation

2.1. Formulation of the problem

Spatial low-velocity turbulent air flow and heat transfer in the vicinity of a single transverse rectangular rib mounted on the plate in the presence and in the absence of a profiled slit are computed. The computational domain size corresponds to experimental section sizes in [4]. Figure 1 depicts the computational domain. The length of the computational domain in longitudinal, transverse and vertical directions is 195, 300 and 80 mm respectively. A square rib with the height of 3.2 mm is located at a distance of 35 mm from the inlet boundary. The ratio of the boundary layer thickness $\delta$ in the inlet section to the height of the rib is 4.2.

![Figure 1. Scheme of the computational domain. All dimensions are in millimeters.](image)

The present work considers ribs with a three-type slit (eight cases). The detailed configurations of different slit channels between the wall and the lower wall of the rib with the indication of the geometric dimensions are shown in Figure 2 and in table 1.

Case A1: a single transverse square rib of the height $h$ and the length $B = 300$ mm is mounted on the heated plate.

In Cases B1-B3, unlike a solid rib (Case A1), a confusor slit is made between the plate and the lower wall of the rib. The slit length in the central part of the rib is 50 mm. In Case B1, the slit consists of confusor and plane-parallel parts. In Case B2, the slit looks like a complete confusor. In Case B3, the inclination angle of the confusor slit is smaller. The vertical size at the slit outlet is somewhat larger than in Case B2 (Figure 2 and Table 1).
Cases C1-C2 are similar to Case A1 but have a diffuser slit between the plate and the lower wall of the rib. In Case C1, the slit consists of plane-parallel and diffuser parts. In Case C2, the slit looks like a complete diffuser.

Cases D1-D2 are similar to Case A1 but have a constant cross-section slit between the plate and the lower wall of the rib. In Cases D1 and D2, the gap between the plate and the rib wall is different; in Case D2, the gap is smaller than that in Case D1.

**Figure 2.** Location of square ribs with different-shape and different-size slits on the plate for all cases

| Case | Type of slit          | Rib height, $h$ (mm) | Slit size $h_1$ (mm) | $h_2$ (mm) | $b_1$ (mm) |
|------|-----------------------|----------------------|----------------------|------------|------------|
| A    | Absent                | 3.2                  | 0                    | 0          | 0          |
| B1   | Confusor              | 3.2                  | 2.2                  | 0.6        | 1.5        |
| B2   | Confusor              | 3.2                  | 2.2                  | 0.6        | 0          |
| B3   | Confusor              | 3.2                  | 2.2                  | 1.0        | 0          |
| C1   | Diffuser              | 3.2                  | 0.6                  | 2.2        | 1.5        |
| C2   | Diffuser              | 3.2                  | 0.6                  | 2.2        | 0          |
| D1   | Constant section      | 3.2                  | 1.0                  | 1.0        | 3.2        |
| D2   | Constant section      | 3.2                  | 0.6                  | 0.6        | 3.2        |

### 2.2. Numerical method and Boundary conditions

The Reynolds number calculated by $U_\infty$ and $h$ is taken to be 3000, which corresponds to the experimental conditions of [4]. The computational software package ANSYS Fluent 17.2 (license number: 339001) coupled with Kato-Launder $k$-$\varepsilon$ model with enhanced wall function [15] was applied in the analysis of the three-dimensional turbulent flow.

In the present study, the working medium (air with the temperature $T_\infty = 297.15$ K) and the flow thermophysical properties were assumed constant. Experimental obtained velocity and temperature profiles in [4] were assigned at the computational domain inlet. Turbulence kinetic energy and dissipation rate profiles were determined from velocity and temperature profiles with the use of the Plandtl mixing length hypothesis and the local equilibrium conditions [16].

Outlet boundary conditions are assigned at the computational domain outlet. At the lower wall and rib surface, the no-slip condition is satisfied and the constant heat flux of $q_w=350$ W/m$^2$ is assigned. The conditions of symmetry of governing parameters are satisfied at the upper and side boundaries of the computational domain.

### 3. Results and discussions

Figure 3 shows the flow structure in the vicinity of the longitudinal-vertical ($x$-$y$) plane along the middle of the plate as well as the predicted dimensionless field of the longitudinal velocity component and the streamlines. In flow around the solid rib (Case A) behind it there develop an extended recirculation zone ($0 \leq x/h \leq 8$) and a secondary vortex characteristic of it. The attached flow providing the high heat transfer intensity is observed in the sections (from $x/h = 8$ to $x/h = 10$).
The flow structure undergoes change in the presence of a profiled gap between the plate and the lower wall of the rib. The presence of a near-wall jet significantly changes the structure of the recirculation zone. Figure 3 illustrate that the stagnation and recirculation zones in front of and behind the rib with a slit are suppressed in comparison to the solid rib. In the case of the rib with a confusor slit (Cases B1 and B2), a very thin separation zone is seen \( (4 \leq x/h \leq 6) \). When the gap between the plate and the back wall of the rib (Case B3) is increased, the separation zone disappears due to a larger flow rate of the accelerated near-wall flow issuing from the slit. Also, in Cases B1, B2 and B3, behind the rib \( (h - h_2) \) the backflow zone develops. It represents a pair of vortices rotating towards each other and their scale decreases a little at \( h_2 = 1 \) mm (Case B3).

\[ U/U_0 \]

Figure 3. Dimensionless longitudinal velocity component field and streamlines around the rib in the longitudinal-vertical \((x,y)\) plane along the middle of the plate for different cases

In the case of the rib with a diffuser slit (Cases C1 and C2), some part of the near-wall flow rushes into the slit where it slows down in the expanding part of the slit. A small recirculation zone is seen within the range \( (1 < x/h < 7) \). Its size appears to be significantly smaller in comparison to the similar zone for the solid rib (Case A). When the size of the expanding part of the slit between the wall and the rib is increased, the separated bubble grows in size. It should be noted that in this case, only one vortex is observed directly near the back wall of the rib \((h_1 - h_2)\). Behind the rib with a constant cross-section slit (Cases D1 and D2), flow is a lot like flow around the rib with a confusor slit and a pair of vortices is also observed behind the rib \((h - h_2)\). However, at \( h_2 = 0.6 \) mm (Case D2) the separated bubble forming within the range \( (2 < x/h < 7) \) significantly increases in size and at \( h_2 = 1 \) mm (Case D1) the separation zone behind the rib disappears as in Case B3. From the aforesaid it follows that in the case of the rib with a confusor slit the accelerated near-wall jet flow entrains the flow separated from the upper surface of the rib and more effectively suppresses the recirculation zone in comparison to ribs with a diffuser slit and a constant cross-section slit.

Figure 4 shows the distribution of the relative heat transfer coefficients \((St/St_0)\) in front and behind each type of the rib on the lower ribbed wall. Here the parameter \( St_0 \) describes heat transfer in the developed turbulent boundary layer in flow around a flat plate at \( q_w = \) const \[17\].

The classical pattern of heat transfer is observed in flow around a solid rib (Case A) - the region with an extremely low heat transfer coefficient appears immediately behind the rib \( (0 \leq x/h \leq 2) \). Then, in the process of the flow movement, there is an area \( (2 \leq x/h \leq 12) \) with a moderate increase in the heat transfer level \((St/St_0 \approx 1.1)\) as a result of recirculation and reattachment of the flow, respectively. Further, the heat transfer gradually decreases to the level of a flat wall.

In the case of ribs with a confusor slit (Cases B1 and B2), a high-speed near-wall jet is formed in the gap between the plate and the rib, leading to a significant heat transfer intensification on the heat
transfer surface immediately in front \((x/h \approx -1)\) and behind \((0 \leq x/h \leq 2)\) the rib. Further downstream, for Cases B1 and B2 along the longitudinal direction \((2 \leq x/h \leq 6)\), the heat transfer deteriorates sharply in the zone of interaction of the near-wall jet with the recirculation region. For Case B2, due to the flow reattachment on the heat transfer surface, an extensive region \((6 \leq x/h \leq 20)\) of slight heat transfer intensification is observed \((St/St_0 \approx 1.05)\). Compared with Case B2, for Case B1, the value of the heat transfer coefficient in this zone is slightly lower. When the size of the near-wall jet (Case B3) increases, as in the Cases B1 and B2, a near-wall jet is formed, but with a greater intensity of injection. In so doing, the region \((0 \leq x/h < 4)\) of heat transfer intensification observed immediately behind the rib is bigger. Further downstream from the rib, the heat transfer rate decreases slightly and then slowly increases downstream.

**Figure 4.** Local relative Stanton number distribution on the heat transfer surface for different cases

In the case of ribs with a diffuser slit (Cases C1 and C2), a low-speed near-wall jet is formed. In doing so, immediately behind the rib, the area \((0 \leq x/h < 1)\) of heat transfer intensification is significantly reduced. However, further downstream, large differences are observed between Cases C1 and C2, and the heat transfer efficiency for Case C2 is significantly higher than that for Case C1. In the case of rib with a constant cross-section slit with a smaller gap size (Case D2), the heat transfer pattern on the heat transfer surface is largely similar to the pattern observed in the case of the rib with a diffuser slit (Case C1). With further increase of the gap size (Case D1), the heat transfer pattern in this case is largely similar to the case of the rib with a confusor slit having the same size at the outlet of the slit (Case B3). But behind the rib, the area of heat transfer intensification is slightly reduced.

It should be noted that in the presence of a gap between the wall and the rib, in the transverse direction, a pair of symmetrical extended spots with high values of heat transfer coefficients is observed, especially in the case of ribs with a confusor and diffuser slit (Cases B2 and C2), relative to the middle of the plate.

Figure 5 shows the averaged Nusselt number in spanwise direction (Z-axis direction) for each rib. Comparing with solid rib, ribs with a slit considerably improve the heat transfer upstream and immediately downstream from the ribs.

**Figure 6** illustrates the calculation results of the integral relative Stanton number \(St/St_0\) for different geometry ribs. It is seen that the ribs with confusor and diffuser slits (Cases B2 and C2) provide a higher mean value of the Stanton number than the solid rib. In Cases B1, B3, C1, D1 and D2, the heat transfer intensity appears to be somewhat less than that for the solid rib. A smaller value of the Stanton number is seen in flow around the rib with a diffuser slit (Case C1). Upstream of the rib in the selected region, the mean value of the Stanton noticeably increases for the rib with a slit, especially with a confusor slit (Cases B2 and B3) in comparison to the solid rib.
When considering the overall mean values of the heat transfer coefficient (Figure 6) a maximum value is seen in the case of the rib with a confusor slit (Case B2). So the overall relative value of St/St₀ is by 4% higher than in the case of the solid rib.

4. Conclusions
Hydrodynamics and heat transfer processes are numerically investigated in the case of turbulent air flow around the plate surface heated at qₑ₀ = const when rectangular ribs (δ/h ≈ 4) with confusor, diffuser and constant cross-section slits are mounted across the flow. It is shown that the near-wall jet forming in the slit substantially affects the separated flow structure behind the rib. Behind the rib with a slit, especially with a confusor slit, the separation zone is substantially smaller than that behind the solid rib. When intense jets are formed (Cases B3 and D1) separation zones do not develop on the plate. It is found that the rib with a confusor slit substantially enhances heat transfer directly behind it in comparison to the solid rib. A maximum heat transfer intensity is achieved in the case of the rib with a confusor slit having a longer confusor part (Case B2).

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