NUMERICAL INVESTIGATION OF LAMINAR AND TURBULENT FLOWS OVER RIBBED SURFACES

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ABSTRACT

A numerical study was conducted for the characteristics of the laminar and turbulent flow over the two surfaces with rib arrays. The dimensionless rib height were chosen as 0.03 and 0.05, and the initial streamwise Reynolds numbers as $2.7x10^5$ and $3.4x10^6$ which correspond to the laminar and turbulent flow, respectively. k─ε turbulence model with near-wall treatment method were adopted during the calculation. The results showed that the flow separations and reattachments occurred before and on the first ribs, in the cavities between the ribs and after the last ribs. The flow separation before the first rib and the reattachment behind the last rib occurred earlier in laminar flow than the turbulent flow.

KEYWORDS: *Flow Separation, Laminar Flow, Turbulent Flow, Ribbed Wall.*

I. INTRODUCTION

The analysis of laminar and turbulent flows on surfaces with ribs is very important for many engineering problems and designs due to reducing energy loss and enhancement of the energy transfer. Use of the ribbed surface is one of the passive methods that increase the heat transfer. In this method, flow separates from the surface due to the ribs and reattaches it again. Because of the separation and reattachment of the flow, the ribs create flow unsteadiness, pressure fluctuations, noise and vibration. But they also enhance the heat transfer by invigorating turbulent mixing, breaking the thermal and hydrodynamic layer and enlarging the heat transfer area. The ribbed surfaces are encountered in many applications, such as in the cooling of electronic systems, solar collectors, gas-cooled nuclear reactors, furnaces and chemical processing equipment.

In this paper, Reynolds-averaged Navier–Stokes equations are solved by a finite-volume method with the k─ε turbulence model and near-wall treatment. The investigations were carried out for the dimensionless rib height of 0.03 and 0.05, and the initial streamwise Reynolds numbers ($Re_x=ux/\nu$) of $2.7x10^5$ and $3.4x10^6$ to brightened the effects of rib height and Reynolds number on the laminar and turbulent flows.

The rest of the paper is structured in following manner. In section II a brief background to the related work is provided. The simulations, geometry, governing equations and turbulence modeling, boundary conditions, numerical procedures and mesh structure are explained in section III. The results are given in section IV and the conclusion of the paper and the progressive studies in the V and VI sections, respectively.

II. RELATED WORK

Numerous numerical investigations on ribbed surface flows have been reported in the literature such as, Braun et al. [1] carried out an experimental and numerical investigation of turbulent heat transfer in a channel with periodically arranged rib roughness elements. A numerical study on the flow and forced-convection characteristics of turbulent flow through parallel plates with periodic transverse ribs was carried out by Luo et al. [2] who found that the standard k─ε model had superiority over the

Reynolds stress model. Ryu et al. [3] indicated that the block arrangements significantly affected flow characteristics and increased heat transfer. The two-dimensional forced convection in a channel containing short multi-boards mounted with heat generating blocks was studied numerically by Tsay and Cheng [4] who indicated that heat transfer increased with increasing block height. Miyake et al. [5] offered that the major effect of the roughness element was to enhance the turbulent mixing and heat exchange. The turbulent flow in a channel with transverse rib roughness was investigated numerically by Cui et al [6] who reported that the rib roughness elements imposed their own characteristic length scales on near-wall flow structures. Mushatet [7] was studied on a simulation for a backward-facing step flow and heat transfer inside a channel with ribs turbulators, and reported that the Reynolds number and contraction ratio have a significant effect on the variation of turbulent kinetic energy and Nusselt number. The effect of thermal boundary conditions on numerical heat transfer predictions in rib-roughened passages was investigated by Iaccarino et al. [8]. Tsai et al. [9] studied on the computation of enhanced turbulent heat transfer in a channel with periodic ribs. A numerical investigation of convective heat transfer between a fluid and three physical obstacles mounted on the lower wall and on the upper wall of a rectangular channel was conducted by Korichi and Oufer [10]. Beig et al. [11] were performed an investigation in a blocked channel for heat transfer enhancement. A numerical investigation in a channel with a heater was carried out by Alves and Altemani [12].

III. MATERIAL AND METHODS

3.1. Simulations

A two dimensional flow over ribs has been analyzed numerically. A two dimensional, steady and incompressible flow has been modeled numerically with the FLUENT code based on the finite-volume method. The thermophysical properties of air have been assumed to be constant.

3.2. Geometry

Two different surfaces were used with an array of 9 and 7, and dimensionless rib height (h/H) of 0.03 and 0.05 with the plate length of 600 and 480 mm, respectively. The ribs width (w) and the cavities between the ribs (s) were fixed as 30 mm. The geometry and computational domain is shown in Fig. 1. The unheated plate length of 2000 mm in laminar and 4000 mm in turbulent flow was used, while the leading edge length, domain height (H) and trailing edge length is 100, 500 and 500 mm respectively.

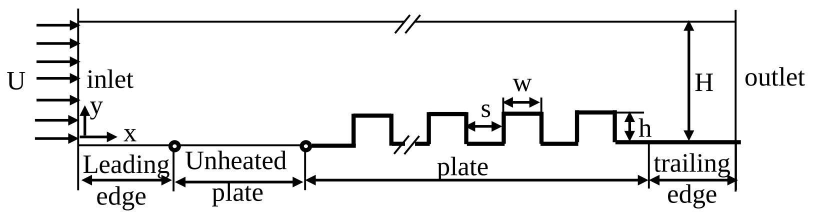

Figure 1. Geometry and computational domain.

3.3.Governing Equations and Turbulence Modeling

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\rho \frac{\partial u_i u_j}{x_j} = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \rho \frac{\partial}{\partial x_j}\left(-\overline{u_i' u'_j}\right) \tag{2}$$

In Eq. (2), $\left(-\overline{u_i' u'_j}\right)$ is the Reynolds stress term, and it is related to the local velocity gradients and turbulent viscosity μ_t (Boussinesq Hypothesis [13]).

$$-\overline{u_i' u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{3}$$

Standard $k-\varepsilon$ model

The standart $k-\varepsilon$ model (Launder and Spalding [13]) used to determine the turbulent viscosity (μ_t) as $\mu_t = \rho C_\mu k^2/\varepsilon$, where k is the turbulence kinetic energy and ε is its rate of dissipation. These variables are obtained from the following transport equations:

$$\rho \frac{\partial}{\partial x_i}\left(k u_i\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{4}$$

and

$$\rho \frac{\partial}{\partial x_i}\left(\varepsilon u_i\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{5}$$

In these equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients and is calculated as $G_k = \mu_t S^2$, where $S = \sqrt{2S_{ij}S_{ij}}$ and $S_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)$. The model constants are $C_{1\varepsilon}$=1.42, $C_{2\varepsilon}$=1.92, C_μ=0.09, σ_k=1.0 and σ_ε=1.3.

In this study standard wall function is used for near wall treatment to act as a bridge between the wall and the fully turbulent region.

3.4. Boundary Conditions

The conservation equations are solved with the following boundary conditions:

1. The air entered the channel with a uniform velocity (u=U, v=0).
2. No-slip boundary conditions were enforced at all walls and rib sides conditions (u=0 and v=0).
3. Zero streamwise gradients of velocity components in the axial direction were applied at the exit plane of the channel ($\partial u/\partial x = 0,\ \partial v/\partial x = 0$).

3.5. Numerical Procedures and Mesh Structure

The SIMPLE-C algorithm was preferred for the pressure-velocity coupling. The pressure staggering option was applied for the pressure discretization and the momentum equations were discretized by a second order interpolation scheme. In each case, convergence was assumed when the normalized residual errors were reduced by factors of 10^{-7} for all equations. A 2-D quadrilateral structured mesh was used, as shown in Figure 2. The cell number ranged from the 38.000 to 48000.

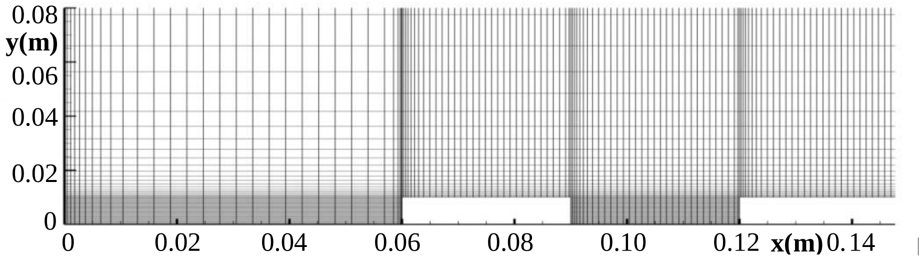

Figure 2. Mesh structure.

IV. RESULTS AND DISCUSSION

In the computation, the initial streamwise Reynolds number and the dimensionless rib height varied from $2.7x10^5$ to $3.4x10^6$ and 0.03 to 0.05, respectively. The streamwise patterns in laminar flow with the dimensionless rib height of 0.03 and 0.05 are shown in the Figs. 3 and 4, respectively. The streamline started deflection at about 1.3h downstream from the first rib on the both flow surface. The higher velocities were determined at the beginning corners of the 1st ribs due to high momentum and impact effects, as explained by Morris and Garimella [14]. The flow separated at the ending corner of the 1st rib for h/H=0.03, while the flow separation with 1.1h streamwise length occurred on the first rib for h/H=0.05. Recirculation regions that approximately covered all the gap existed in the cavities between the ribs for the dimensionless rib height of 0.05, while the smaller regions occurred for h/H=0.03. The flow structure in the cavities was coherent with another periodically for all surfaces. Once the accelerated fluid could not afford enough axial momentum to overcome the pressure lift, a big recirculation region formed behind the last rib. The reattachment length of this separation region was found about 6.0h and 4.5h for h/H=0.03 and 0.05 respectively, which is in accord with Kim and Anand [15]. The results showed that the reattachment length and the vortex velocity and depth of the cavities increased with rib height.

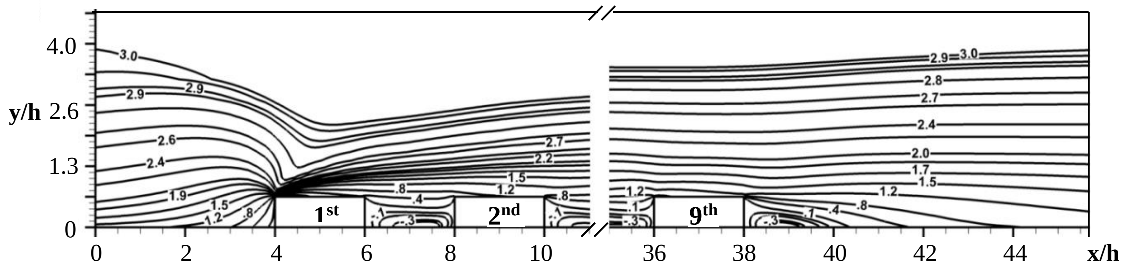

Figure 3. Velocity profiles with streamwise distance at $Re_x=2.7x10^5$ and h/H=0.03.

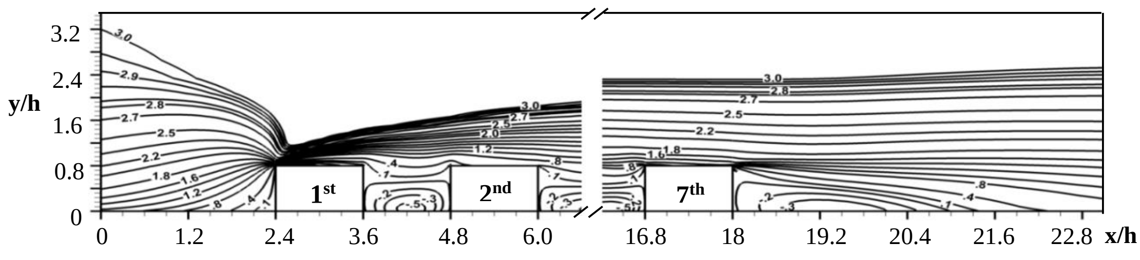

Figure 4. Velocity profiles with streamwise distance at at $Re_x=2.7x10^5$ and h/H=0.05.

The calculated velocity profiles at Re_x of $3.4x10^6$ were shown in Figs. 5 and 6 for h/H of 0.03 and 0.05, respectively. As the fluid turned upward into the narrow gaps between the top faces of the 1st ribs and the upper walls, the fluid was drastically accelerated because of the contraction effect.

Meanwhile, due to the largely increasing adverse pressure gradient created by the accelerated fluid, the near-wall fluid could not afford to develop and separation occurred at 0.5h before the first ribs. These separating bubbles started at the front corner of the first ribs, extended along the top face of the ribs through streamwise lengths of 1.1h as already seen in the laminar flow, in a good agreement with the ratio of Chen and Wang [16]. The static pressure drastically increased due to the sudden expansion effect and the big recirculating bubbles occurred behind the last rib. The reattachment length values increased from 6.5h to 5.0h with rib height, similar to those of Ryu et al. [3]. The results showed that the vortex velocities of turbulent flow were bigger than the laminar values, the flow separations in the turbulent flow occurred later and the fluid moved the longer distance before the reattachment because of the highest momentum than those of the laminar flows.

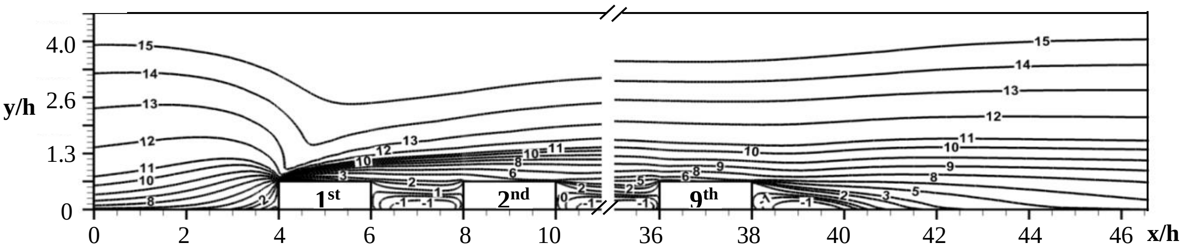

Figure 5. Velocity profiles with streamwise distance at Re_x=3.4x10^6 and h/H=0.03.

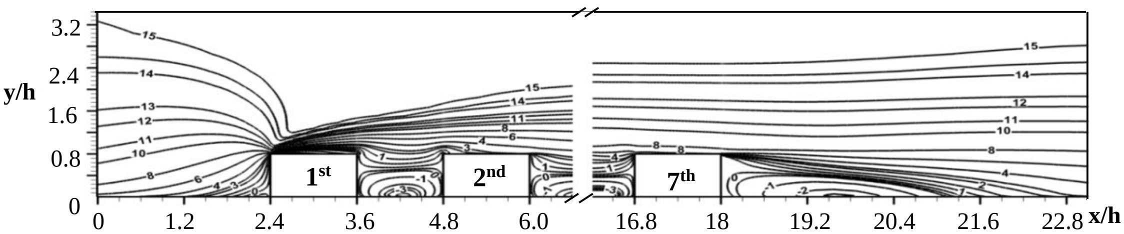

Figure 6. Velocity profiles with streamwise distance at Re_x=3.4x10^6 and h/H=0.05.

V. CONCLUSIONS

The laminar and turbulent flows with an array of ribs have been numerically studied under the effects of rib height and Reynolds number. The major conclusions are described as follows:

1. The presence of ribs changed the incoming flow considerably and caused recirculating zones on all rib walls.
2. The flow separated and reattached before the first rib, on the first rib, on the cavities between the ribs and behind the last ribs. The size and position of recirculating zones and the effects of Reynolds number and rib height on them were discussed.
3. The flow separation on the first rib didn't change with Reynolds number and the separation was not observed on the other ribs.
4. The flow separations before the first and the reattachments behind the last rib occurred later in turbulent flow than the laminar flow.
5. The reattachment lengths behind the last ribs and the vortex velocities of the cavities increased with rib height and Reynolds number.

VI. FUTURE WORK

In this paper the flow characteristics of the ribbed surfaces are obtained numerically in the laminar and turbulent flow. In the forthcoming work, the flow and heat transfer characteristics will be investigated together and the numerical analyses also will be supported with the experimental results.

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