16èmes Journées Internationales de Thermique (JITH 2013)
Marrakech (Maroc), du 13 au 15 Novembre, 2013

RANS conjugate heat transfer predictions in two-dimensional ribbed ducts

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Abstract: The turbulent flow with heat transfer in a periodic ribbed duct passage is investigated numerically up to Reynolds number up to 10^6. The objective of the present work is to study the effect of the geometrical features effect *P/D* and *e/D* on turbulent heat transfer. The standard k-ε, the shear stress transport k-ω and the second moment closure *RSM* models are used to close the governing steady RANS equations. The effect of the thermal boundary conditions is investigated by simulating an insulated rib, a solid–fluid coupling, constant heat flux at the base of the rib and a constant heat flux at the rib surface. The numerical results obtained show a decrease trend of the averaged heat transfer with the roughness parameter and a fairly invariance with the duct pitch to rib-height ratio. It is also demonstrated that the constant heat flux at the walls and convective heat transfer and the conductivity solid/fluid ratio modify mainly the recirculation bubbles upstream and downstream of the ribbed duct and have different effects on the local heat transfer.

Keywords: conjugate heat transfer, rib, thermal boundary conditions, RANS.

1. Introduction

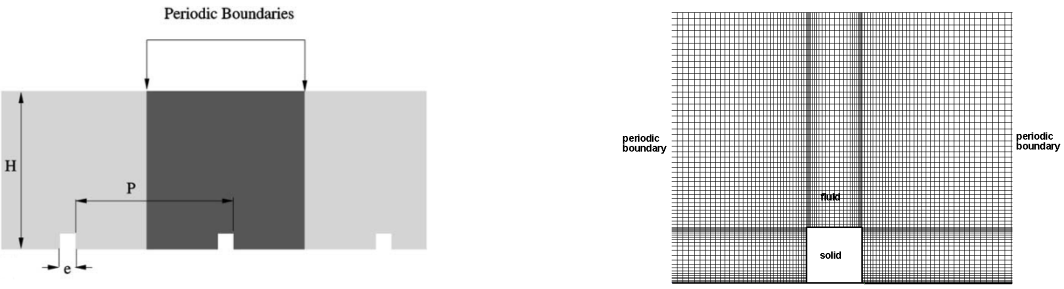
Flow inside a ribbed duct has a high industrial interest. The internal cooling channels of turbine blades usually have such geometry. Big amount of measurements were carried out investigating integral quantities (pressure drop and averaged Nusselt number) and fewer on detailed flow and heat transfer characteristics. On the other hand, the majority of industrial fluid dynamics cases are turbulent; and resolved by the Reynolds Averaged Navier-Stokes equations involving less computational resources. Nowadays, this technique is being used to predict heat transfer in complex passages. Numerical studies conducted by Liou et al. [1] have evaluated the accuracy of some of the more commonly used turbulence models by comparing numerical predictions with the experimental data of Bredberg and Davidson [2], Rau et al. [3] and Han et al. [4]. Iacovides and Raisee [5] have found that the numerical studies concluded to accurate near-wall modelling of turbulence transport is crucial to ensure good predictions.

To improve the accuracy of the heat transfer prediction, the effect of the thermal boundary conditions at the walls of the ribs and the conduction heat transfer in the walls should be taken in account since in real passages; the heat transfer process that occurs is always a combination of forced convection and heat conduction. Therefore, it might be more appropriate to assess the accuracy of the numerical model by performing conjugate heat transfer calculations. This is suggested in the experimental works cited above as, depending on the technique used and on the materials and the experimental set-up, very different values of heat transfer are measured [6].

In the present investigation, the standard k-ε, the shear stress transport k-ω and the second moment closure *RSM* turbulence models are used to predict the flow and the heat transfer in two-dimensional ribbed passages. The predicted averaged heat transfer is compared with experimental correlations to illustrate that the average heat transfer is related to the large scale flow field motion. Several aspect ratio of the geometry are also examined. Three thermal conditions are tested: insulated rib, solid–fluid simulation, constant heat flux at the base of the rib and constant heat flux at the rib surface. At the end, the conjugate heat transfer predicted is studied as the main focus will be on how the predicted heat transfer data is influenced by the rib wall thermal conditions.

2. Geometry and grid

The ribbed duct simulations are carried out using a 2D grid with periodic boundary conditions in the streamwise direction. Hence, as shown in Fig. 1(a), only one section of the actual ribbed passage will be considered. The mean velocity field is assumed to be fully developed which will allow the use of periodic boundary conditions in the streamwise direction. The duct pitch to rib-height ratios, *P/D*, ranging from 1 to 3 and the roughness parameter, *e/D*, is varied by 0.1, 0.2 and 0.3. The duct width to the rib-height *H/D* is fixed to 3. Such configurations illustrate the grooved tip cross-section of a turbine blade. Structured hexahedral grids with high quality are used to allow for normal to the wall clustering on all the wall sides of the passage (Fig. 1(b)). Grids used consists of 13 400 hexahedral cells enclosing 13 716 nodes.



(a)

(b)

Figure 1: Computational domain (a) and mesh (b) for the periodic flow in a ribbed duct

3. Numerical Model

The segregated solver of the commercial code Fluent 6.3.26 is used to solve the two-dimensional incompressible RANS in one pitch length. Turbulent fluctuations are accounted for using the Boussinesq eddy-viscosity assumption (the standard *k-ε* and the shear stress transport *k-ω* models) and also the second moment closure *RSM* model. The mathematical formulation of the turbulent flow with the heat transfer completed with the turbulence models can be found easily in the literature and the guide of Fluent. In the transport equations, the second order upwind method with cell based gradient formulation and traditional slope limiter is used for the interpolation of convective fluxes, the pressure in the momentum equations is interpolated using the standard method. The algorithm SIMPLE is used to couple the pressure–velocity fields. The flow and the heat transfer simulations are carried out for a range of Reynolds numbers based on the rib-height, *D*, and the mean velocity giving the appropriate mass flow rate. In the streamwise direction, periodic boundary condition is used for velocity and pressure to ensure the required mass flow rate.

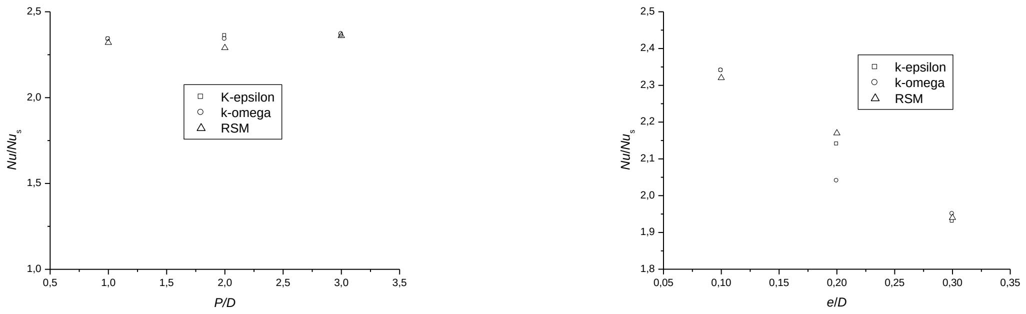
Different variations of thermal boundary condition on the ribs are considered in this study. These simulations are meant to assess the effect of uncertainty in the experimental conditions (which can be due to the measurement technique, the rib and channel wall material properties, the presence of unsteady effects, etc.) on the predicted data. The first case considered in this paper is where the rib is insulated (Fig. 2(a)). For conjugate heat transfer calculations (Fig. 2(b)), both the conduction and convection heat transfer is simulated where the base of the rib is heated with a constant heat flux. Constant heat flux is simulated by specifying the temperature gradients at all walls (see Fig. 2(c)). This is opposite to the real operative condition, where the fluid is hot and heat is removed by the passage walls. The Nusselt number is normalized with its corresponding value for a smooth tube evaluated by:

$$Nu_s = 0.02\,\mathrm{Re}^{0.8} \qquad (1)$$

4. Results and discussion

4.1. Averaged heat transfer predictions

The Turbulent flow simulations were carried out for a Reynolds number *Re* =12600 with *P/D* ranging from 1 to 3 and with various values of roughness parameter *e/D* ranging from 0.1 to 0.3. The predicted averaged Nusselt number is shown in Fig. 2. The data are obtained for *e/D* = 0.1 and *P/D* =1 in Fig. 2(a)–(b) respectively. The results obtained using the various turbulence models tested are consistently closer for the most pitch, *P/D* and the most roughness *e/D* ratios. The averaged heat transfer enhancement seem to be unaffected by the duct pitch to rib-height and inverse relationship with the roughness parameter *e/D*. The largest discrepancy between the k-omega and the RSM turbulence models predictions is about 6% for the case *e/D* = 0.2 otherwise all the other simulations predict commonly the same Nusselt number.



(a) (b)

Figure 2: Averaged heat transfer improvement: (a) effect of the pitch, *P/D*; (b) effect of the roughness *e/D*

The Reynolds number effect is examined in figure 3 showing a net decrease of the normalized heat transfer with the increase of the Reynolds number for all the turbulence models tested. The difference in the averaged heat transfer predictions is related to the large scale motion of the flow field (separation lengths, etc.). This is can be seen from the flow patterns computed at Re = 10 000 using the *RSM* model, shown in Fig. 4. It can be seen a large recirculation bubble downstream and upstream the rib. The results obtained with the other turbulence models, not presented here show fairly the same hydrodynamic behavior. Lower turbulence levels in the recirculation bubble account for the lower value of predicted *Nu* number. The velocity vectors passing up to the height rib are more accelerated and seem to be not perturbed by the presence of the obstacle.

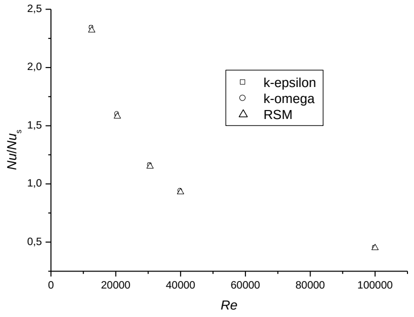


Figure 3: Effect of the Reynolds number on the averaged heat transfer

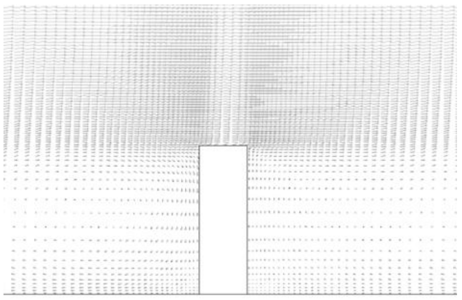


Figure 4: Velocity vectors around the rib for *Re* = 10 000

4.2. Local heat transfer predictions

The local *Nu* distribution obtained numerically for *Re* = 12600 and using the standard k-ε model turbulence model is shown in figure 5. The effect of the thermal boundary condition of the rib is well explained and the overall agreement is satisfactory in terms of the heat transfer level attained away from the rib. When the rib is heated, the predicted value of *Nu* is very close to zero, directly upstream of the rib. When the rib is insulated, the model predicts large values of *Nu* in that region. In order to obtain a better understanding on how heat is transferred from the ribs, conjugate heat transfer calculations were carried out. These additional computations show that the predicted heat transfer is very sensitive to the type of thermal boundary conditions used in the simulations. The recirculation regions upstream and downstream of the rib have opposite effects on the conjugate heat transfer. In the upstream bubble, cold flow impinges on the rib side wall and then moves towards the floor of the channel. If the rib material has high conductivity this fluid is heated before it reaches the floor. If the rib has low conductivity, the impinging flow cools the lower wall at the base of the rib. In the downstream bubble, the flow is reversed and heated fluid is convected toward the rib side wall, then up and away from the floor.

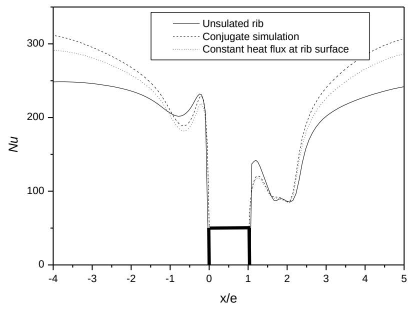
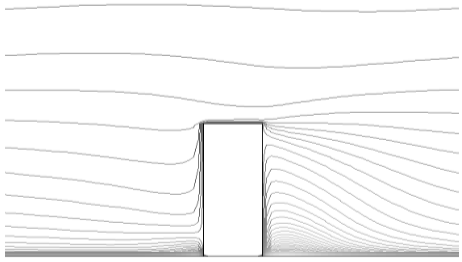
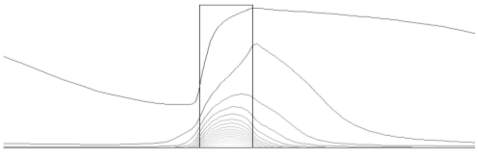


Figure 5: Nusselt number distribution on the bottom of the ribbed duct

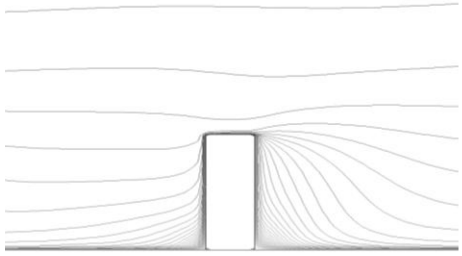
The temperature contours in the vicinity of the rib are reported in figure 6. The upper area in the figure corresponds to lower temperatures and, thus, to higher Nusselt numbers on the surface. The conjugate heat transfer calculation of Fig. 6(b) is for the same conductivity of the fluid and the solid ($k_f = k_s$). The qualitative and quantitative features of the solution corresponding to the solid–fluid coupled thermal field (Fig. 6(b)) are in between the adiabatic (Fig. 6(a)) and prescribed heat flux (Fig. 6(c)) cases. Data in Fig. 6 show that the region downstream of the rib is not dramatically affected by the various thermal boundary conditions. On the other hand



(a) Insulated rib

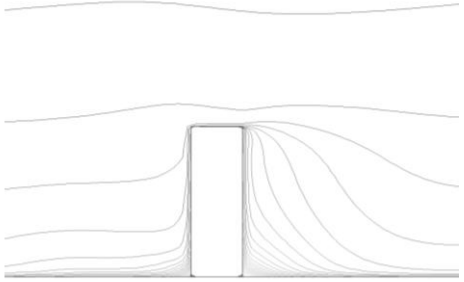


(b) Solid-fluid coupling (k_s/k_f=1)

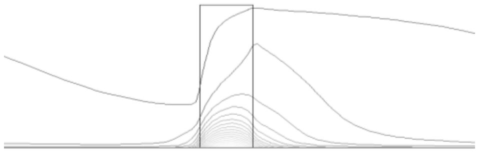


(c) Heated rib

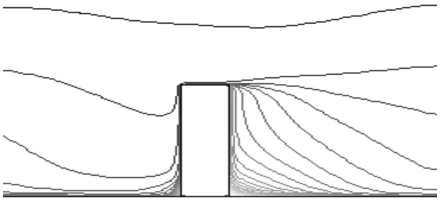
Figure 6: Effect of the wall thermal condition on the temperature distribution



(k_s/k_f=100)



(k_s/k_f=1)



(k_s/k_f=0.01)

Figure 7: Effect of the thermal conductivity of the rib on the temperature distribution

the area upstream of the rib shows large differences: when the rib side wall is heated, the fluid that impinges in the channel floor is approximately at the same temperature as the wall. When the side rib wall is adiabatic (see Fig. 6(a)), cold fluid reaches the floor and correspondingly high levels of *Nu* are predicted.

The effect of varying the rib thermal conductivity (k_s) is investigated in Figure 7. Temperature fields corresponding to high and low conductivity are reported in the figure. The upstream region does not show a strong dependency on (k_s) because the heat transfer is dominated by convection. The downstream region, on the other hand, is dramatically changed because, near the rib, heat is removed from the fluid mainly by conduction. The two limiting conditions of insulated and heated ribs show nearly the same levels of heat transfer in the downstream region. Upstream, as noted previously, cold fluid reaches the floor when the rib side wall is not heated. The analysis of the conjugate heat transfer predictions shows that conduction plays a major role in the downstream area. The level of the heat transfer away from the rib is only slightly altered by the rib boundary condition. On the other hand, the differences in the vicinity of the ribs are substantial.

Conclusion

In the present study, the effect of the the geometrical features effect *P/D* and *e/D* on turbulent heat transfer in a periodic ribbed duct passage is studied. The commercial code ANSYS Fluent 6.3.26 based on the finite volume technique is used to solve the equations of mass, momentum, energy and turbulent quantities. The standard k-ε, the shear stress transport k-ω and the second moment closure *RSM* models are used to close the governing steady RANS equations. The effect of the thermal boundary conditions and the conductivity solid/fluid ratio are investigated. In overall, the numerical tests show satisfactory agreement of the turbulence models tested with quietly similar Nusselt number predictions. It is shown that predicted averaged values of the Nusselt number decrease with the roughness parameter and a fairly invariable with the duct pitch to rib-height ratio. However, the local values of Nusselt number very close to the ribs are strongly affected by the wall thermal boundary condition on the rib. The numerical data show that the heat transfer is dominated by convection upstream and conduction downstream of the rib.

Nomenclature

D	height of the rib, *m*
e	thickness of the rib, *m*
H	width of the duct, *m*
k	thermal conductivity, w/m k
Nu	Nusselt number
P	pitch of the duct, m
Re	Reynolds number

indices

f	fluid
s	solid

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