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Numerical Investigation of Heat Transfer Enhancement with Mist Injection

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Abstract. In the present work, computational simulations was made using ANSYS CFX to predict the improvements of internal heat transfer in rectangular ribbed channel using different coolants. Several coolants such as air, steam, air/mist and steam/mist were investigated. The shear stress transport (SST) turbulence model is selected by comparing the predictions of different turbulence models with experimental results. The results indicate that the heat transfer coefficients enhance in ribbed channel at injection small amount of mist. The heat transfer coefficients of air/mist, steam and steam/mist increase by 1.13, 1.57 and 2.07 times than that of air, respectively. Furthermore, comparing with droplets size, the proper size is from 6 to 10 μm. which had the best enhancement performance in ribbed duct.

Introduction

Modern gas turbines have to be heavily cooled because of the high turbine inlet temperatures. Because the allowable metal temperature is lower than the hot gas temperature, the blade material temperature has to be reduced by using internal cooling channels. The major advantage of an internal cooling channel is that it can eliminate the need for film cooling. By numerical predictions of the flow and heat transfer for internal flow have been conducted previously by several investigators: Kashmiri et al. [1], Ooi et al. [2], Taslim and Liu [3] ,Haasenritter et al. [4], Shui et al. [5] investigated the effect ribs on heat transfer coefficient using air or steam as coolant. There have been experimental and numerical studies of tubes and flat plate cooling with air/mist including those of Sikalo et al. [6], Oisin et al. [7] studied effect of fine water injection to air. These studies concluded that the heat transfer coefficient can be increased with introduction of a fine water mist. However the experimental and numerical validation of heat transfer results of mist/steam cooling in heated horizontal tube introduced by Gou et al. [8] and Dhanasekaran and Wang [9]. They found that the average cooling enhancement was 100% with 5% mist.

The pervious studies investigated air/mist cooling or steam/mist cooling in smooth tube or flat plate and have not studied effect of droplets size in ribbed channel. This paper aims to provide a comparison of heat transfer coefficient for four coolants (air, steam, air/mist and steam/mist). Also, this paper show the effect of droplets size in ribbed duct

Geometry and Numerical Model

Rectangular duct tested by Tanda [10] is adopted as the calculating object to verify the accuracy of calculation model and method. Figure 1 shows the geometry and the numerical grids for the one side ribbed duct. The ribbed side wall was denoted as the bottom surface. The other side walls were denoted as the smooth surfaces. A total of seven ribs were simulated. A multiple block structured grid is used. A grid size fell within the range of 1.2 million hexahedral elements. To accurately predict fluid behavior, the cells have been clustered towards the wall to obtain appropriate y+ value less than1.

The influence of turbulence models in predicting the heat transfer characteristics and flow have been tested for experimental conditions. The local heat transfer coefficient is:

$$h = [q / (T_w - T_b)] \qquad (1)$$

Where q is heat flux [W/m^2 K], T_w and T_b are wall temperature and bulk temperature [K], respectively. The local Nusselt number for the ribbed side wall is defined as

$$Nu = h\, D_h / k \quad (2)$$

Where h is heat transfer coefficient [W/m^2 K] and D_h hydraulic diameter [m]. The ribbed side wall friction factor is defined as following:

$$f = D_h\, \Delta p / 2L\rho u^2 \quad (3)$$

Δp, L and u are pressure loss [Pa] and test section length [m] and flow velocity [m/s], respectively. Where, k and ρ are thermal conductivity [W/m K] and density [kg/m^3], respectively.

Figure 2 shows the numerical result of average Nusselt number in the ribbed wall. The friction factor at the different Re number is illustrated in Fig.3. It is clear that, the prediction by SST turbulence model is comparable with experimental data than Kω and ωRS turbulence models. So the SST turbulence model is chosen for all simulations in our study.

Boundary Conditions

The air and steam are considered as continuous flow and mist is considered as a discrete flow in the model. The inlet mass flow rate is 0.0116 kg/s, inlet saturated temperature is 388 K and heat flux of 15000 W/m^2. The flow exit of computational domain is assumed to be a constant pressure of 1 atm. The non slip boundary condition is assigned at all the walls, ribs and unheated walls are assigned as adiabatic wall. Mist droplet size is 4, 6, 10 and 20 μm at mass fraction 6%. The boundary condition of droplets at walls is assigned as reflect [11], which means the droplets elastically rebound off once reaching the wall.

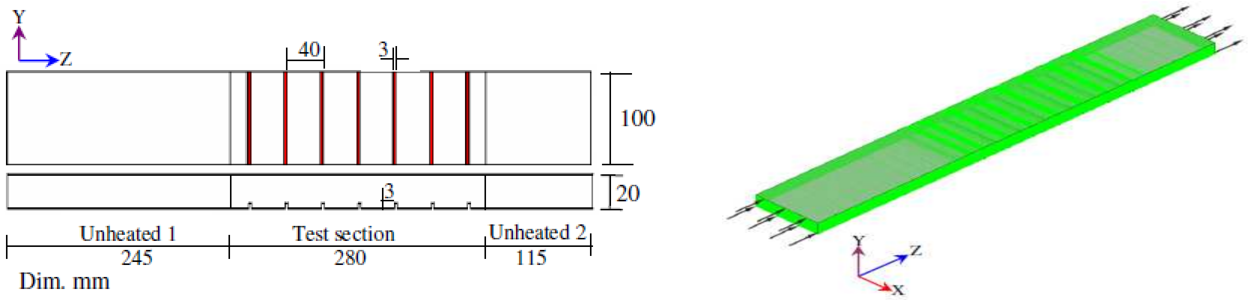

Fig. 1 Geometry and numerical grid

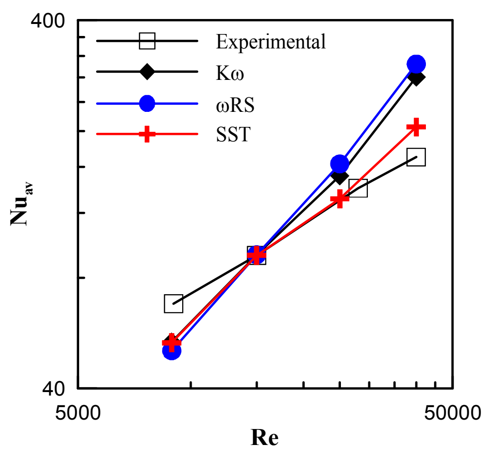

Fig. 2 Turbulence model with average Nu number

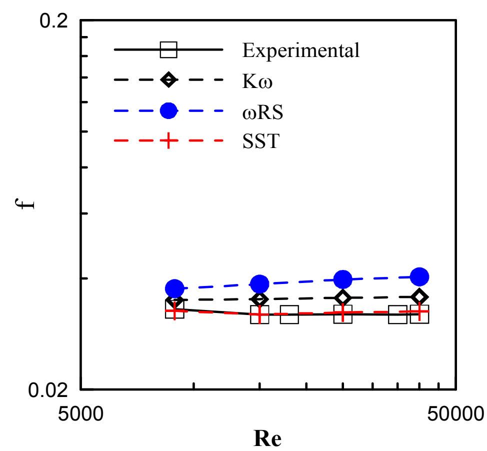

Fig. 3 Friction factor with turbulence model

Result and Discussion

Comparison between different coolant types

To compare the flow characteristic of different coolant at the same condition, the same entry static temperature and mass flow rate and outlet static pressure are employed. A uniform heat flux of 15000W/m^2 is given in the wall boundary. Two kinds of different operation conditions are selected in the calculation for mist case whose droplet diameter and mist fraction**.** Figure 4 presents the local heat transfer coefficient distribution along the centerline of the ribbed side wall. The steam and air /mist have higher local heat transfer coefficient by about 1.57 and 1.13 times than that of air. It is because that Pr number reflects the relative magnitude of the flow boundary layer thickness divided by the heat transfer boundary layer thickness and the larger it is the better the heat transfer will get. Moreover, the steam has large thermal capacity. The steam/mist has higher local heat transfer coefficient than that of air and air/mist by about 107% and 84%, respectively.

Effects of mist droplet size

Figure 5 gives the local heat transfer coefficient along the centerline of the ribbed wall for several mist droplet size at mist fraction m_r= 6%. It is obvious that the air and steam have the similar trend with droplets size change. Between Z/D = 4.4 to Z/D = 5.3 the average heat transfer coefficients of air/mist are 72.33, 68.71, 68.29 and 66.91W/m^2 K for the droplets of 6, 4, 10 and 20μm, respectively. While for steam/mist the average heat transfer coefficients are 126.66, 122.16, 116.454 and 115.49 W/m^2 K for droplets of 6, 10, 4 and 20μm, respectively. It seen that, a droplets of 20μm has the lowest cooling effect because most droplets may not be evaporate and most of them can remain intact at the exit. For smaller droplets of 4μm, on the other hand, the relative velocity of droplets is high and which leave the test section without depositing on the liquid film. Droplet trajectories for droplets size of 4 and 20μm are shown in Fig.6, most of the 4 μm droplets evaporated before outlet while more of the 20μm droplets can survive till the outlet.

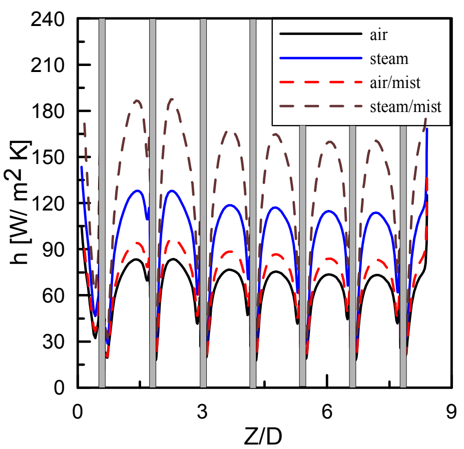

Fig. 4 Local heat transfer coefficients for different coolant fluids

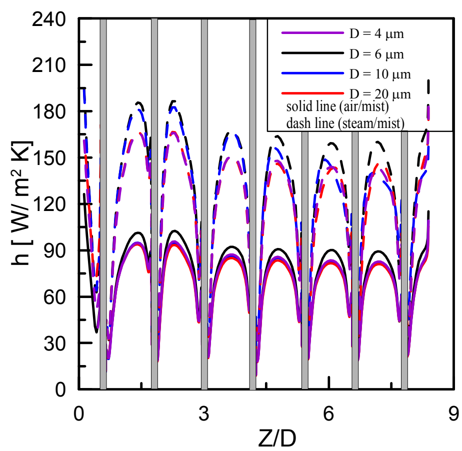

Fig. 5 Variation of droplets size with local heat transfer coefficient at m_r = 6%

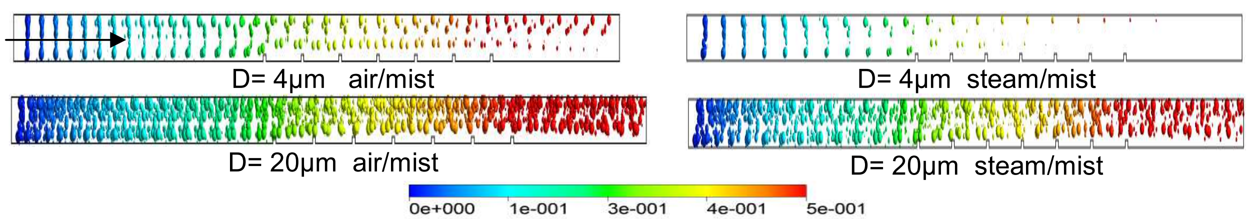

Fig 6 Droplets travel distance (m)

Summary

The cooling performances of different fluids are compared in this paper. The following conclusions are drawn:

- SST turbulence model is performed on 90deg ribbed duct. The numerical results are compared with the experimental data from Tanda [10]. It is suggested that the SST turbulence model could provide acceptable engineering accuracy to analyze the flow and heat transfer feature in the 90 deg ribbed duct.
- Internal rib cooling using steam and steam/mist as coolants save 57% and 107% compared to air, respectively to achieve the same cooling effect.
- A distributed size from 6 to 10 µm in internal ribbed duct will give an excellent enhancement on steam/mist and air/mist. The mist/steam enhancement of 6 and 10µm higher than that of air/mist by about 75% and 78.8%, respectively, at the same inlet conditions.

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