Prediction of 3D Turbulence Induced Secondary Flows in Rotating Square Ducts

Suabsakul Gururatana[1], Vejapong Juttijudata[2], Ekachai Juntasaro[3] & Varangrat Juntasaro[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, Kasetsart University, Bangkhen, Bangkok 10900, Thailand, Email: fengvrj@ku.ac.th
[2]Department of Aerospace Engineering, Faculty of Engineering, Kasetsart University, Bangkhen, Bangkok 10900, Thailand, Email: fengvej@ku.ac.th
[3]School of Mechanical Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand, Email: junta@sut.ac.th

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Abstract: The cooling turbine blades are one of the challenging problems at present. This is because the characteristics of the flow field in the internal passage are affected by the combined effects of the secondary flows occurred in the passage and the rotation of the blades. These secondary flows have the great effect on the characteristics of the primary flow and the cooling rate. The accurate modeling of the flow in the near wall regions is therefore necessary. The Reynolds-averaged Navier-Stokes (RANS) turbulence models are more suitable than the large-eddy simulation (LES) in this case especially for the design optimization. There are currently three popular near-wall turbulence models: the enhanced wall function, the non-equilibrium wall function and the k-ω SST model. This paper aims to find the most suitable linear base model for the explicit algebraic Reynolds stress models (EARSM) and the non-linear turbulence models in predicting the combined effects of the rotating and secondary flows especially near the wall. From the results, it can be concluded that the k-ε turbulence model with the enhanced or non-equilibrium wall function is more suitable to be further developed for the EARSM or non-linear turbulence models.

In the aircraft industry, one of the major concerns is the gas turbine engine. The increase in the efficiency of the engine causes the temperature of the gas raisen. Because the turbine blades are limited to the material manufacturing, the cooling turbine blades are necessary for heat reduction. The important flow characteristic in the cooling turbine blades is the combined effects of the rotating and secondary flows. The rotating square duct is used as a test case to represent this combined effect in the current work.

In the case of the rotating square ducts, the structure of the secondary flows is modified by the effect of the Coriolis force due to the rotation. The cross-sectional area that is perpendicular to the steamwise direction is constituted of four counter-rotating vortices instead of eight vortices as found in the non-rotating square duct. Recently, Martensson et al. (2005) has discussed that the cross-stream flows become more asymmetric and the vortex near the top walls (pressure side) increases as the rotating number increases. The magnitude of the secondary flows grows approximately linearly with the rotating number.

The modeling of the turbulent flows in rotating square ducts is still not satisfactory even for the advanced Reynolds-averaged Navier-Stokes (RANS) turbulence models like Reynolds stress models (RSM), explicit algebraic Reynolds stress models (EARSM) and non-linear turbulence models. Pettersson Reif and Andersson (2003) has pointed out that the Reynolds stress models cannot predict the turbulence quantities in rotating ducts correctly. Belhoucine et al. (2004) has proposed the new EARSM model for the rotating square ducts. However, the model still fails to predict the Reynolds stresses and the velocity profiles accurately especially in the near wall regions.

At present, the turbulence models that have been proved to be good at predicting the near wall regions are the k-ε model with the enhanced wall function (Kader 1993), the k-ε model with the non-equilibrium wall function (Kim and Choudhury 1995) and the k-ω SST model (Menter 1994). This paper aims to find the linear model that has higher accuracy than the other linear models in predicting the combined effects of rotating and secondary flows to be used as the based model for the non-linear turbulence models. The chosen test case for the evaluation is the turbulent flows through a rotating straight square duct at Reynolds number = 48,000 and rotating numbers = 0.0133, 0.0266 and 0.12 (Pallares and Davidson 2000).

The results of the enhanced wall function, the non-equilibrium wall function and the k-ω SST model are compared with the LES data of Pallares and Davidson (2000) and also with the result of the EARSM model of Belhoucine et al. (2004) in predicting the combined effects of the rotating and secondary flows. The comparison is made where the data are available for the mean streamwise velocity along the width of the duct from the suction side to the pressure side (z/h=0.5) at Ro = 0.0133 and 0.12, and along the corner bisector at Ro = 0.0266 in Figs. 1 to 3, respectively.

It can be seen in Fig. 1 that the velocity profile near the pressure side (y/h=1) using the EARSM model is closer to the LES data than the other models as expected. This is because there are the large secondary flows on this side and it is well known that the linear models cannot predict the secondary flows. However, the linear models can predict the velocity profile better than the EARSM model in the near wall region on the suction side (y/h=0) where there are the small secondary flows. Amongst the near-wall linear models, the k-ε model with the enhanced wall function shows the better results than the k-ω SST model.

The predicted streamwise velocity profiles by the EARSM and the linear models on the pressure side and the suction side at the higher rotating number (Ro = 0.12) are similar to those at the lower rotating number as can be seen in Fig. 2. The non-equilibrium and the standard wall functions are better than other linear models at the core of the duct in this case for the higher rotating number.

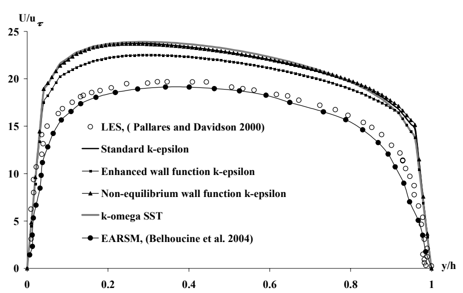

Fig. 1 Mean streamwise velocity at z/h=0.5 for Ro=0.0133

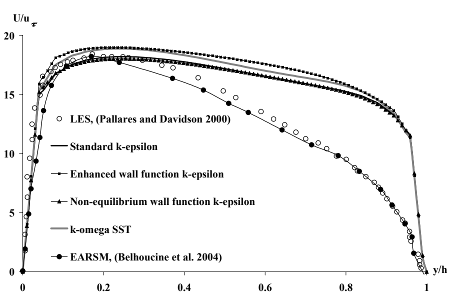

Fig. 2 Mean streamwise velocity at z/h=0.5 for Ro=0.12

In Fig. 3, it is clearly seen that the EARSM model cannot predict the streamwise velocity in the near wall region along the corner bisector of the duct. The non-equilibrium wall function, the enhanced wall function and the k-ω SST models perform much better in this case.

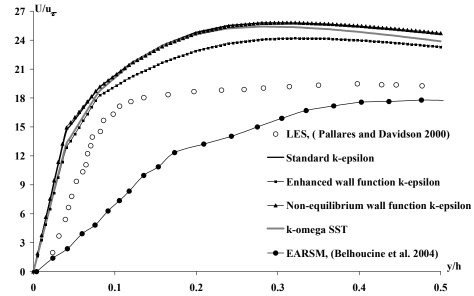

Fig. 3 Mean streamwise velocity along the corner bisector at Ro = 0.0266

The performance of the popular near-wall turbulence models to predict the combined effects of the rotating and secondary flows is assessed in this paper and compared with the result of EARSM model and the LES data for the rotating square ducts at three rotating numbers. The near-wall turbulence models even in the linear form perform better than the EARSM model in some cases especially in the near wall region. It is therefore important to have the suitable linear model as the base for the non-linear or EARSM models. It is found that the k-ε model with the enhanced or non-equilibrium wall function performs better than the k-ω SST model.

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