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ENGINEERING APPLICATION OF GAO-YONG RATIONAL TURBULENCE MODEL TO AN INTER-COOLED DUCT

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Abstract

GAO-YONG rational turbulence model utilizes no empirical coefficients. The CFD 3d calculation program is developed with the joint application of the model and the OpenFOAM. Two calculation samples are simulated using the program. First, the simulations of backward step flow in different conditions are used to testify the accuracy of GAO-YONG model simulations as for the separation and reattachment flow. And then, GAO-YONG model and Spalart-Allmaras turbulence model are used to simulate an inter-cooled duct. To forecast the separation flow in the inter-cooled duct the results demonstrate that, the higher accuracy of the GAO-YONG model compared with the Spalart-Allmaras model which is not able to predict the separation in the duct.

1 General Introduction

GAO-YONG rational turbulence model is based on mass partial-weighted average method which is different from Reynolds average method. In this research, flow simulations under different conditions are conducted with the joint usage of GAO-YONG turbulence model and OpenFOAM, an open source software. Flow over a backward step and flow in an inter-cooled duct are simulated using GAO-YONG model.

A turbulence model is a crucial element of CFD, which influences the accuracy of simulations. The RANS turbulence models are wildly used in engineering applications for years. But the disadvantages of RANS models are obvious. Firstly, empirical coefficients are adopted in these turbulence models, which limit the ability of the models to simulate flow in different conditions. Secondly, the Reynolds average method erases the fluctuation information of flow, which loses lots of flow characteristics. In some cases, the RANS models without careful rectification are helpless, such as the flow with large adverse pressure gradients and large separations. Based on the mass weighted partial-average scheme, GAO-YONG turbulence model retains the first order turbulence fluctuations, and the fluctuant equations are induced from the Navier-Stokes equations. With no empirical coefficient being introduced in the GAO-YONG model, it can be used under different flow conditions without adjustments. Thereby, the GAO-YONG model is named a rational model.

OpenFOAM is an open source field operation and manipulation C++ libraries, which provides the base operations of CFD. The GAO-YONG CFD program used in this research is compiled with OpenFOAM.

Firstly, flow over a backward step is simulated to verify the accuracy of the GAO-YONG CFD program [1]. Secondly, this program is used to simulate flow in an inter-cooled duct. Both of the two cases are compliant with the experiments.

2 The Theory Of GAO-YONG Rational Turbulence Model

GAO-YONG turbulence model is jointly developed by Professor Ge Gao and Professor Yan Yong. This model has several characteristics which are different from RANS models. First of all, GAO-YONG turbulence model is based upon the mass weighted partial-average scheme and retains the fluctuation information of flow. Secondly, the cascade down property of kinetic energy and momentum of turbulence is used to model the correlation terms and close the whole set of equations. Thirdly, none empirical coefficient is adopted in GAO-YONG turbulence model, which implies that the GAO-YONG model can be used in different cases without any modulation. The derivation of GAO-YONG turbulence model equations is given in Gao [2].

Governing equations of compressible GAO-YONG turbulence model is shown below.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{1}$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p + \nabla \cdot \sigma + \nabla \cdot \sigma^{turb} \tag{2}$$

$$\begin{aligned} &\frac{\partial (\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \nabla (\rho U h_{tot}) = \\ &-\nabla \cdot (q + q^{turb}) + \nabla \cdot ((\sigma + \sigma^{turb}) \cdot U) \end{aligned} \tag{3}$$

The Eq. (1) ~ Eq. (3) are the continuity, momentum and energy equations of mean flow, respectively. ρ, p and U represent the density, pressure and velocity. σ designates the Reynolds stress.

$$\nabla \cdot (\rho \tilde{U}) = 0 \tag{4}$$

$$\begin{aligned} &\frac{\partial (\rho \tilde{U})}{\partial t} + \nabla \cdot (\rho \tilde{U} U) \\ &= -\nabla \tilde{p} + \nabla \cdot (\tilde{\sigma} + \tilde{\sigma}^{turb} - \sigma - \sigma^{turb}) - \nabla \cdot (\rho U \tilde{U}) \end{aligned} \tag{5}$$

The Eq. (4) and Eq. (5) are the continuity and momentum equations of fluctuation flow.

$$\begin{aligned} &(\sum_{n=1}^{\infty} \frac{(L \cdot \nabla)^n U}{n!}) \cdot (\rho \tilde{U}) \\ &= L \cdot (-\nabla(\rho U \tilde{U} + \tilde{p} I) + \nabla \cdot (\tilde{\sigma} + \tilde{\sigma}^{turb} - \sigma - \sigma^{turb})) \end{aligned} \tag{6}$$

The Eq. (6) is the mechanical energy equation of fluctuation flow. L represents the turbulent length.

The parameters without superscript ‘ ~ ’ belong to mean flow. And the parameters with superscript ‘ ~ ’ belong to pulsant flow. The terms with superscript ‘ *turb* ’ represent parameters caused by eddy viscosity.

3 Results

Gao [3] has simulated many 2D and 3D cases to show the accuracy of GAO-YONG turbulence model. All of the cases show that this model can properly simulate flow in different conditions. In this research, firstly, the flow over a backward step is simulated to check the accuracy of GAO-YONG program based on OpenFOAM. Secondly, this model is used to simulate flow in an inter-cooled duct. The results from GAO-YONG model are compared with the experimental results.

3-1 Flow Over A Backward Step

The structure and boundary conditions of the flow over a backward step are the same as Qi [4]. The geometry is depicted in Fig 1.

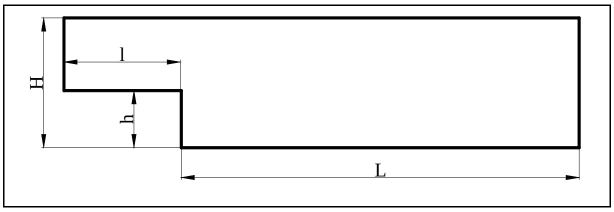

Fig 1 The sketch map of the backward structure

h is the height of the step; H, the height of the duct after step, equals twice h; l is the length before step; L is the length after step.

Two conditions with different Reynolds numbers are calculated. $Re_{in}=U_{in}h/\nu$ (ν is the dynamic viscosity). One case is laminar flow with $Re_{in}=320$. And another case is turbulent flow, with $Re_{in}=3200$.

The transition (laminar flow with $Re_{in}=320$ is shown in Fig 2 and turbulent flow with $Re_{in}=3200$ is shown in Fig 4) simulations of backward step flow coincide with the topology structure in PIV tests (laminar flow is shown in Fig 3 and turbulent flow is shown in Fig 5).

The transition laminar flow develops a series of vortex and the vortex dissipates with flow before the reattachment point. A stable vortex appears on the top of the reattachment point in time-average results. The transition turbulent flow also develops a series of vortex. The turbulent vortex breaks off the series and dissipates with flow. No vortex appears on the top of the reattachment point in average results.

Different cases with Reynolds numbers ranging from 250 to 4000 are simulated by GAO-YONG model. All the reattachment lengths of cases including laminar and turbulent flow (Fig 6 represents the time-averaged laminar flow and Fig 7 represents the time-averaged turbulent flow) are pointed out in Fig 8 and are consistent with the experimental results except for the $Re_{in}=500$ case. The backward step cases prove that GAO-YONG model can simulate separation and reattachment flow correctly.

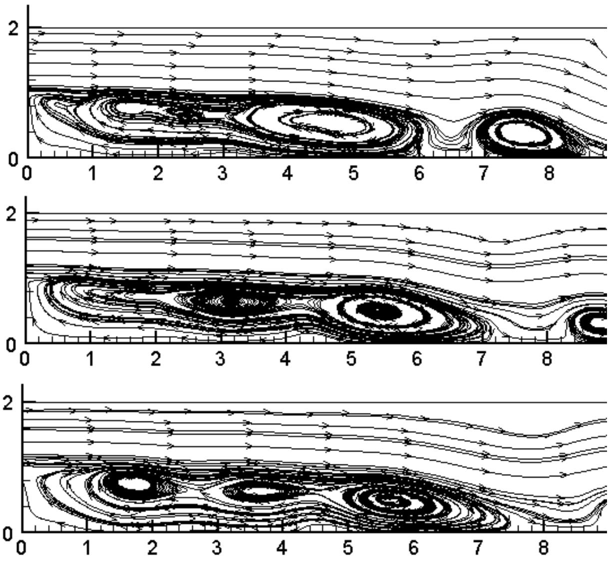

Fig 2 Transition laminar results in a period

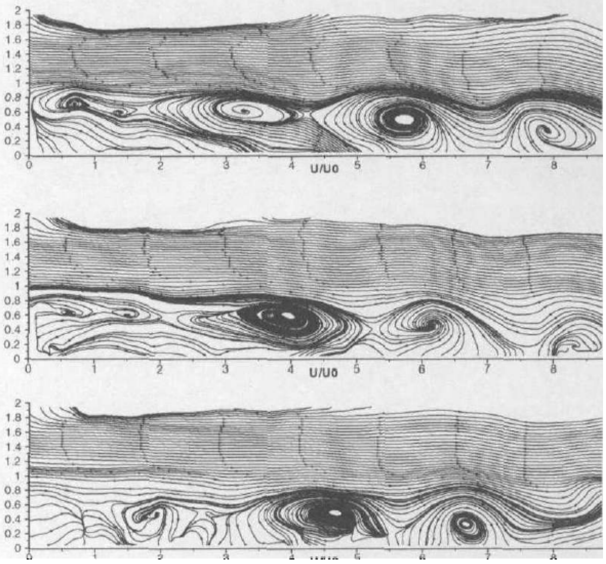

Fig 3 PIV topology of laminar flow result

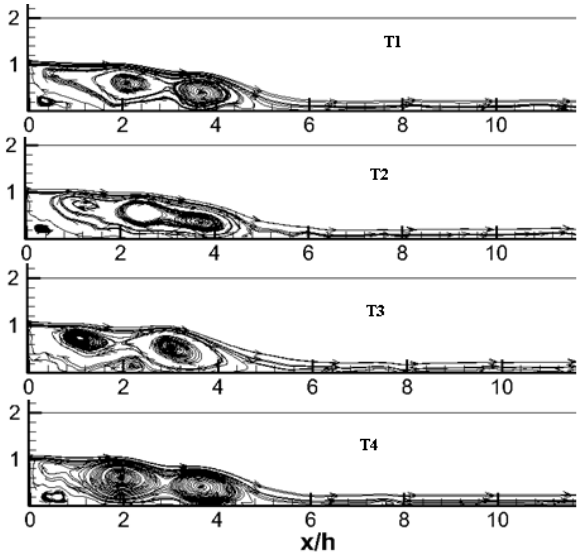

Fig 4 Transition turbulent results in a period

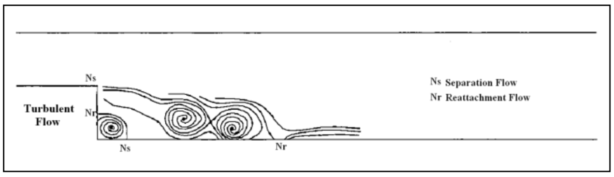

Fig 5 PIV topology of turbulent flow result

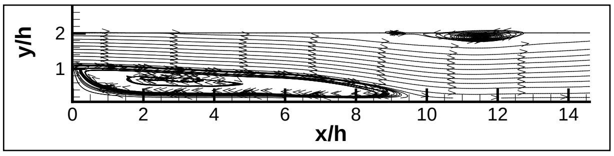

Fig 6 Laminar time-average result

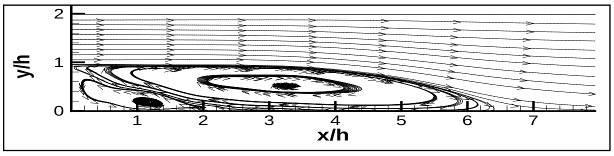

Fig 7 Turbulent time-average result

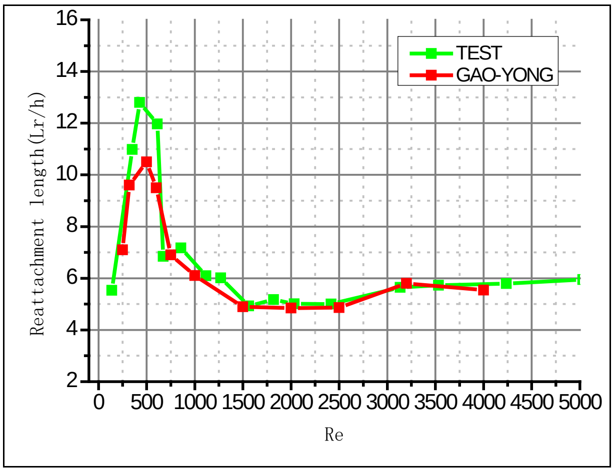

Fig 8 Reattachment lengths of cases with different Reynolds numbers

3-2 Flow In An Inter-Cooled Duct

In this part, the flow in an inter-cooled duct is simulated. The structure of the duct is shown in Fig 9. The outlet of low pressure compressors connects with the inlet of the duct and the air current from low pressure compressors flows through cross section S1, S2 and S3. The duct outlet connects with the cooler inlet. The inlet velocity is about 140m/s and the outlet velocity is about 50m/s. Flow direction changes from horizontal to vertical and back to horizontal again. The duct configuration has a large expansion ratio and great curvature.

The inlet BCs (short for boundary conditions) are given as: The pressure is set to a fixed total pressure. The temperature is set to a fixed total temperature. The velocity is set to a zero gradient.

The outlet BCs are given as: the pressure is set to a fixed static pressure. The temperature and velocity are set to zero gradients.

The experiment result shows that a separation occurring after the first turn of the inter-cooled duct causes 3 percentage drop of the total pressure recovery coefficient. In this case, the simulation with GAO-YONG turbulence model proves that this model is able to predict separation flows in the duct more accurately than RANS models including standard S-A (short for Spalart-Allmaras) model, standard k-Epsilon model and SST k-Omega model (the results using the last two models are not shown in this paper because both of them are similar to the result using Spalart-Allmaras model). The S-A turbulence model is not able to predict the separation in the adverse pressure gradient region after the first turn of the duct (shown in Fig 10). And the total pressure recovery coefficients (shown in Fig 13) of the simulation with S-A model are much bigger than the coefficients of experiment result. The stream lines calculated with the GAO-YONG turbulence model are shown in Fig 11 and the vortexes calculated with Q rule are shown in Fig 12. Both of the figures show a separation region caused by a great pressure gradient. Besides, the total pressure recovery coefficients agree with the experiment very well, which are shown in Fig 13.

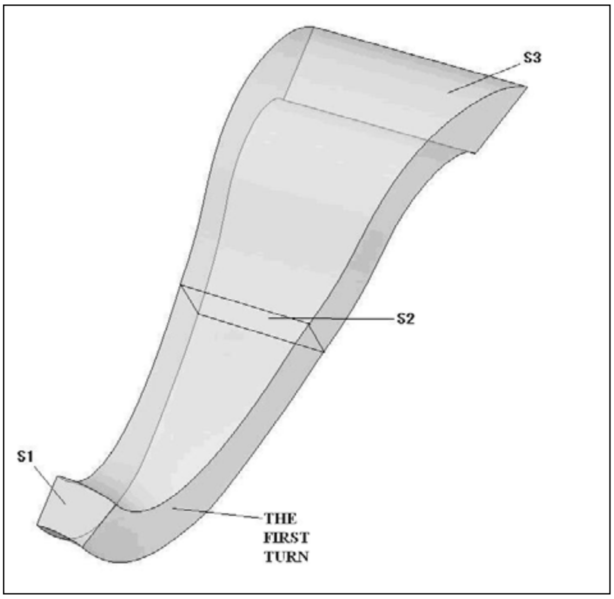

Fig 9 The geometry of the inter-cooled duct

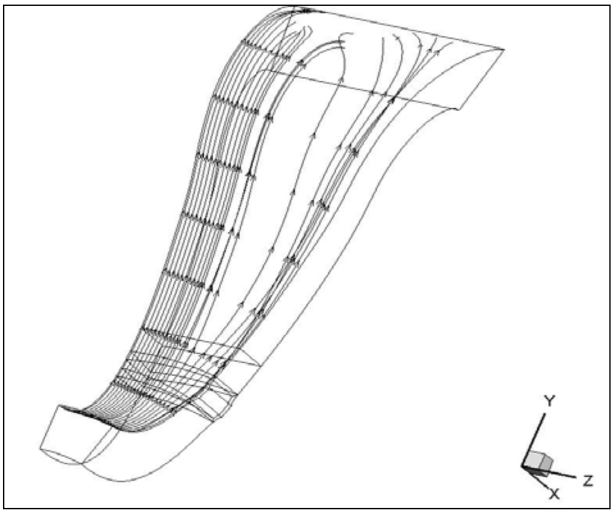

Fig 10 Result calculated with S-A turbulence model

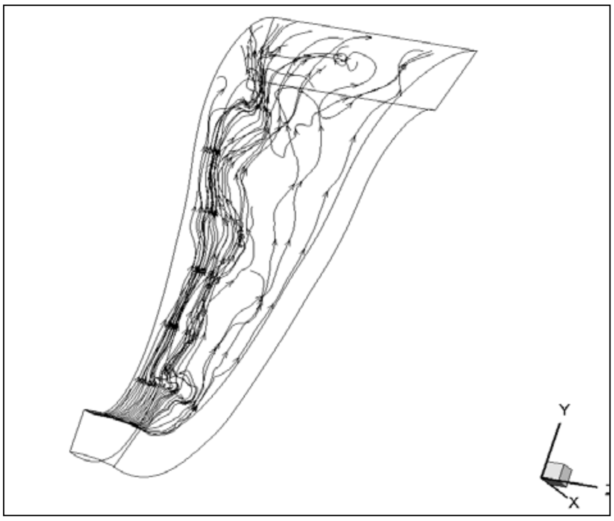

Fig 11 Result calculated with GAO-YONG turbulence model

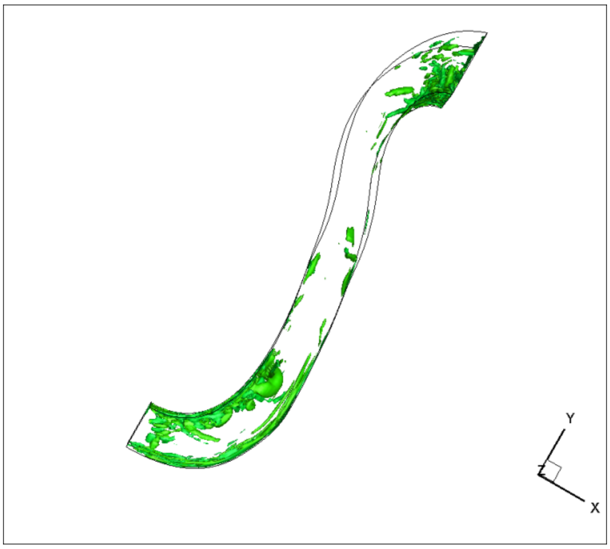

Fig 12 Vortex calculated with Q rule in the simulation using GAO-YONG model

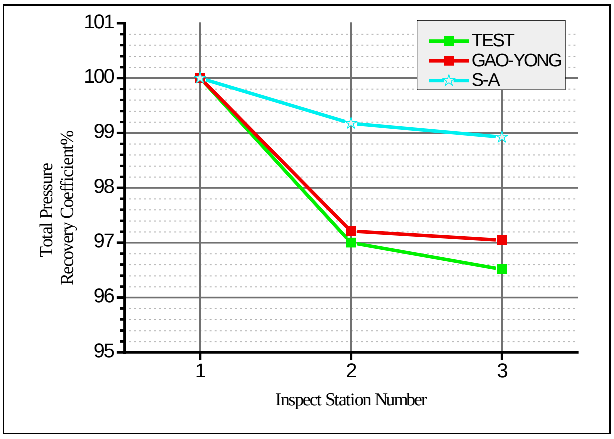

Fig 13 Total pressure recovery coefficients at different sections

4 Conclusions

In this research, the flow over a backward step and the flow in an inter-cooled duct are examined by GAO-YONG rational turbulence model.

As the transition simulations of the backward step flow match the PIV experiments and the reattachment lengths of time-averaged simulations agree with the lengths measured in tests, the backward step cases reveal the GAO-YONG program can properly simulate separation and reattachment flow.

The 3D inter-cooled duct case forecasts the separation at the first turn of the duct successfully. By comparing the total pressure recovery coefficients achieved by GAO-YONG and Spalart-Allmaras models, the result calculated by GAO-YONG model are more compliant with the test than Spalart-Allmaras model. GAO-YONG model also predicts the separation at the first turn of the duct, while the Spalart-Allmaras model is not able to simulate large separation flow.

Both the 2D and 3D cases demonstrate GAO-YONG rational turbulence model's ability to simulate flow with large adverse pressure gradients and separations.

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