Numerical simulation on supersonic shock wave/turbulent boundary interaction

Bei Yang[1,a] , Ge Li[1,b], Chenyu Zhang[1,c]

[1] School of Aircraft Engineering,Nanchang Hangkong University, Nanchang 330063, China

[a]peipeiyang99@sina.com, [b]1985075484@qq.com, [c]70599@nchu.edu.cn

Keywords: turbulence model; numerical simulation; supersonic; shock wave; turbulence; heat transfer

Abstract. Supersonic shock wave/turbulent boundary layer interactions were simulated by employing three popular engineering turbulence models, namely Spalart-Allmaras(SA), k-ω, shear stress transport(SST) over a 24ºcompression ramp at Mach 2.84 and a 11º×11º double-sharp fin plates at Mach 2.91. Comparisons of pressure distributions and skin friction coefficient on the wall with experimental results show that, for the compression ramp, SA model is superior to other models for calculating pressure distribution, the friction coefficient given by SST model is closest to the experimental results. For double fin plates, the pressure distributions of three turbulence models are all close to the experimental results at the centerline, except peaking value, SST model is more accurate for skin friction distributions than SA model and K-ω model. In summary, SST model is more accurate for calculating wall pressure and skin friction coefficient distributions, improvements must be made for simulating supersonic shock wave/turbulent boundary layer interaction to the three turbulence models.

Introduction

In recent years, Scramjet is of importance in hypersonic research field internationally. Inlet is a key part of scramjet and is significant for re-search. The core in inlet research is high-speed turbulent flows and flowfield of shock wave/turbulent boundary layer interaction. Predicting the complex flow formed by inlet accurately is of great significance to aerodynamic characteristics of aircraft.

Panaras summarized shock wave/turbulent boundary layer interaction of single fin and double fin inlet [1]. Numerical simulations by Thivet etc demonstrated inlet flow field, the wall pressure, the coefficient of friction characteristics [2]. Shock wave characteristics and flowfield structure features of sidewall compression inlet was analyzed by Gruhn and Guelhan[3]. Much other re-search was performed to demonstrate complex flow characteristics formed by the inlet, Numerical results show it is necessary to make an intensive study of the complex flow of the inlet.

In this paper, SA[4],K-ω[5] and SST[6] models were used to simulate supersonic compression corner and double fin, and the distribution of wall pressure, friction coefficient and flow structure of symmetrical surface were demonstrated, Numerical results might provide reference for supersonic inlet design.

Mathematical Formulation and numerical methods

Under Cartesian coordinate system, the compressible mass averaged N-S equations were chosen, First-order time accuracy was adopted for time terms in the turbulence mode and N-S equations for steady state flow in this paper. The convection terms were discretized with a Roe scheme [7]. An implicit second-order central difference scheme was introduced for the diffusion terms.

The calculation results and analysis

Two-dimensional supersonic compression ramp test case. The Settles experiments were selected to carry out numerical simulations. Angle of the compression corner is $24^{o[8]}$, Mach number of flow-field is 2.84, total flow temperature 262 K, and the Reynolds number is 1.57×106 with boundary layer thickness $\delta = 23$mm. The number of grid points is 273×105 along the stream wise and vertical directions respectively and 105, respectively. The smallest mesh scale in the vertical direction is $3 \times 10\text{-}7$m, and the smallest grid scale near the leading edge is $2 \times 10\text{-}4$m in the stream wise direction.

Fig. 1 compares the numerical results of the pressured distribution in the ramp flow using the selected three turbulence model. It is seen that the three turbulence models cannot demonstrate the characteristics of the separation zone. In the ahead of the separation zone of the compression corner, the SST model shows the increased pressure of the wall surface ahead, while the increased pressure predicted by K-ω model is slower than experimental pressure. Although the increased pressure is slow, in contrast to the former models, the result of the SA model is more closed to the experiment. Between the separation zone and the reattachment point, the pressure recovery predicted by K-ω model is usually bigger, while the result of SST model is smaller, but the result of the SA model is closed to the experiment. In front of the compression inflection point, the friction predicted by the three models is all smaller than the experiment. However, at the back of the inflection point, the friction predicted by K-ω model is bigger than the experiment, while the result of the SA model is smaller. From Fig.1, It can be seen that the SST model demonstrate good simulation performance.
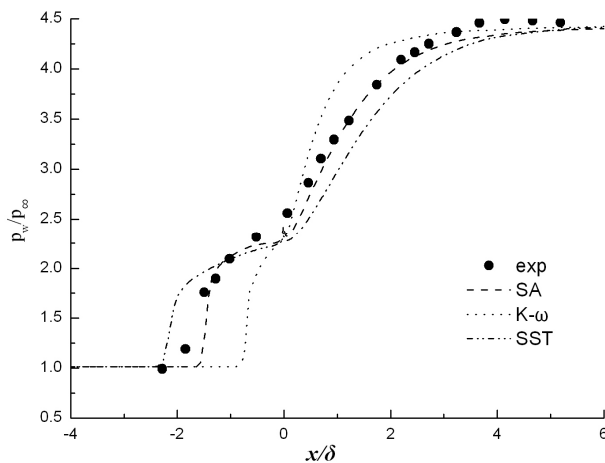
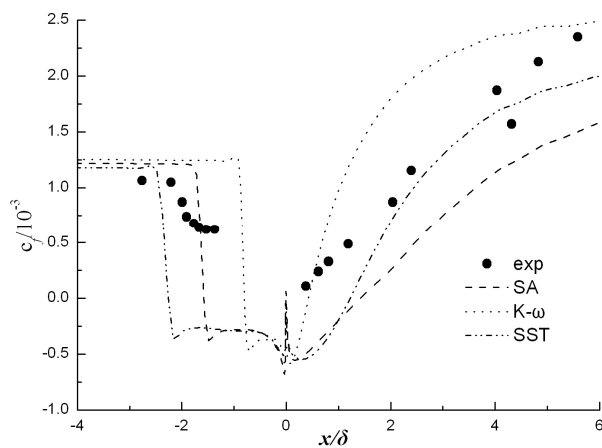

Fig.1 Pressure distributions over the compression ramp

Fig.2 Local fiction coefficient distributions over the compression ramp

Three-dimensional supersonic inlet test case. A fin type structure was selected as test case for supersonic condition, sidewall compression angle is $11^{o} \times 11^{o}$ and narrowest width is 4.65cm, the expansion angle is 30° afterwards. Other simulating parameters could be found in literature[9].

For symmetrical characteristics of the configuration, half-module was adopted in the follow analysis and simulation. The length of the calculation region in flow direction is 0.2 meter from the fin leading edge, and 51 grid points was as-signed in that direction. The grid points in flow, normal and spanwise directions are $153 \times 105 \times 65$, respectively, with a total of 1.04 million grids approximately. The flow grid is fine near the leading edge of the fin and the narrowest width; the normal mesh is dense near the wall. The smallest grid scale is $5 \times 10\text{-}7$ m in the wall normal direction, and is $2.5 \times 10\text{-}5$m ~ $5.0 \times 10\text{-}5$m near the fin wall.

The simulation conditions[8,10] are: the Mach number is 2.91, the incoming total temperature 295K, the wall condition can be approximated as adiabatic wall, the thickness of the boundary layer is 3.02 mm, Re/ $m = 6.2 \times 10^{7}$. Fig.4 shows the wall pressure distribution on the center line of the

symmetric fin by the three turbulence models, which the calculated pressure was dimensionless with the incoming pressure. The origin of the x-axis is taken as the leading edge point of the fin, and d =3.5mm. According to the equations of oblique shock wave of the non-viscous ideal gas, the angle of the oblique shock wave from the front fin is 29º and two oblique shock waves intersect at the centerline with x/d = 24.2. However, as can be seen from Fig.2 to Fig.3, the pressure rises rapidly at x/d = 15 at the centerline, which shows that the thickness of the boundary layer drastically increases at x/d = 15. In the range of 25 < x/d <35, the increase of the boundary layer thickness slows down and the pressure rise is slow. After the center line with x/d > 35, the pressure reaches maximum value due to the reattachment of the boundary layer, and the pressure of the center line decreases gradually after the reattachment point. This means that some improvements can be performed in the calculation of the wall pressure distribution for strong shock wave/turbulence boundary layer interactions.
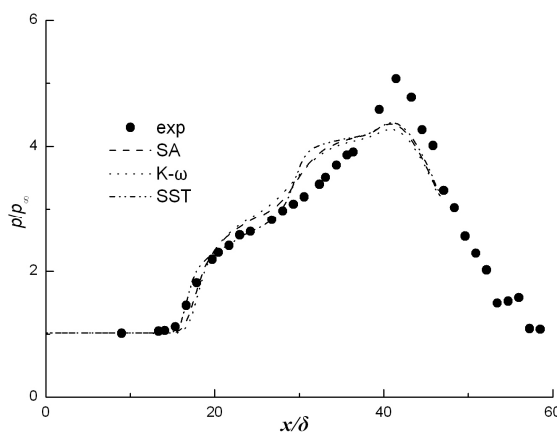

Fig.3 Pressure distributions over the centerline of the double fin at the centerline

The distribution of the friction coefficient on the center line of the symmetric fins by the three turbulence models is in Fig.4. It can be observed from the figure the friction coefficient decreases gradually when x/d <30, which indicates that the velocity profile in the boundary layer is changed by pressure gradient, leading to the decrease of velocity gradient within the boundary layer. The friction coefficient decreases therefore. After that, the velocity profile becomes thicker due to shock wave/boundary layer interaction, so friction coefficient increase. It can be seen from Fig.5, difference of friction coefficient by SA model and K-w is small, when x/δ>35, the calculated friction coefficient is smaller than the experiment. In 18 < x/d <33, the results of SA model and K-w agrees with the experiment, the results of SST model is favorable in other regions. This is similar to the pressure distribution on the center line demonstrated in Fig.4. In the shock wave/turbulent boundary layer interaction region (35 < x/d <45), the difference of friction coefficient exists compared with the experiment.
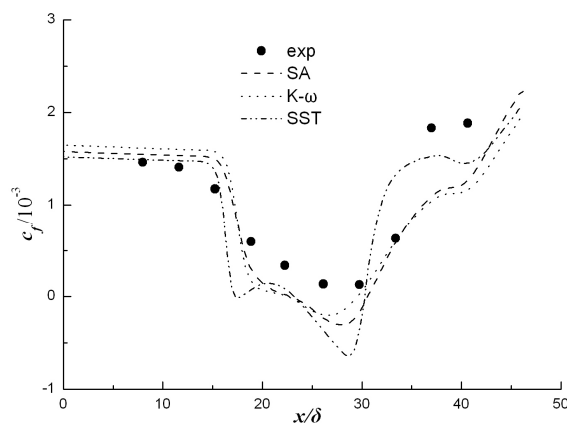
Fig.4 Local fiction coefficient distributions over the centerline of the double fin

The simulation results of the friction coefficient in the $x/\delta=29.8$、$x/\delta=37$ can be seen in Fig.5 and Fig.6 by three turbulent models., friction coefficient are increases first, and then decreases from the center line to the fin wall, the peaking position of friction coefficient at the different sections with different centerline distance are also different. The design of sidewall compression inlet should take this factor into consideration.

The friction coefficient at the cross section by SA and SST model is favorable with the experiment, the maximum error of the friction coefficient by K-ω model is 20％ compared with the experiment. SA and SST model are more accurate for skin friction distributions than K-ω model at $x/\delta=29.8$、$x/\delta=37$ cross-section region.
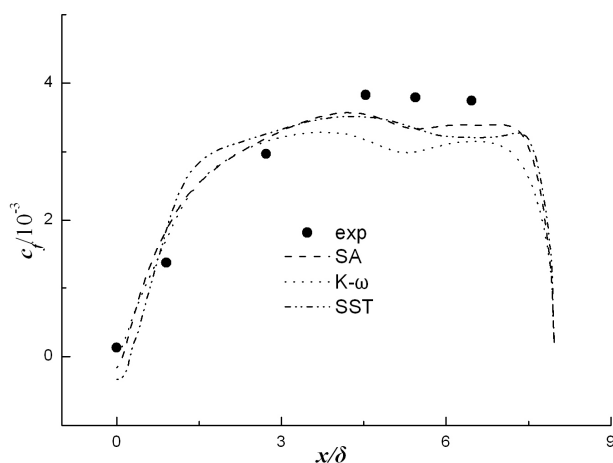
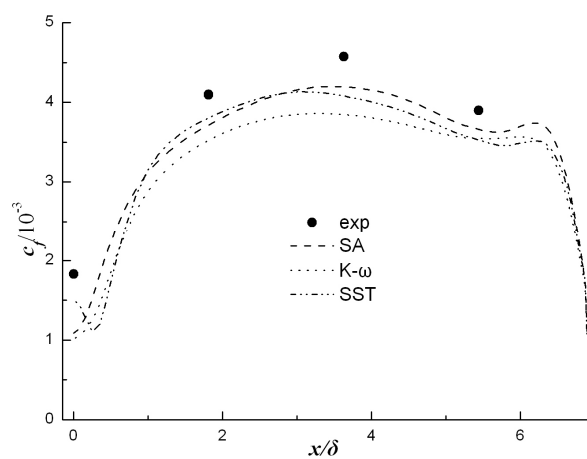Fig.5 Local fiction coefficient distributions over the double fin at section $x/\delta＝29.8$

Fig.6 Local fiction coefficient distribution over the double fins at section $x/\delta＝37$

Conclusions

Supersonic shock wave/turbulent boundary inter-actions are critical in study of sidewall compression inlet. In this paper, the three turbulence models were used to simulate the supersonic compression corner flow and 11°×11°double fin. Through the comparison between simulations and

the distributions of wall pressure and skin friction with the experiment, the following conclusion can be drawn:

1) On the simulation of compression pressure distributions, the SA model is better than K-ω model and the friction coefficient distributions by the SST model is superior to the other two models.

2) There exist no significant differences except the maximum pressure predicted in the symmetry plane, the numerical results in others area are in favorable agreement with the experiment, in the double fin plates symmetrical line wall pressure distributions demonstrated by the SA, K-ω, SST turbulent models. The results show that It can be improved in the three turbulent models for predicting shock wave/turbulent boundary interaction.

3) Numerical results of friction coefficient, by the SA and SST turbulent models are close to the experiment on the base plate of the fin, how-ever the results of K-ω model demonstrate large discrepancy compared with experiment.

4) On the whole, the SST model is better than SA and K-ω models in the prediction of the super-sonic compression corner and the double fin.

Acknowledgements

References

[1] A.G.Panaras: Progress of Aerospace science, Vol. 32 (1996), P. 173-244.

[2] F. Thivet, D.D. Knight, A.A. Zheltovodov and A.I. Maksimov:Aerospace Science & Technology, 6.1(2002), P. 3-17.

[3] P. Gruhn and A. Guelhan: Journal of Propulsion & Power, Vol. 27 (2011-05), P. 718-729.

[4] P.R. Spalart and S.R. Allmaras: *A One-Equation Turbu-lence Model for Aerodynamic Flows*. AIAA-92-0439.

[5] D.C. Wilcox: AIAA Journal, Vol. 26 (2012), P. 1299-1310.

[6]   F.R. Menter: AIAA Journal, Vol. 32 (1994), P. 1598-1605.

[7] P.L. Roe: Journal of Computational Physics, 1981,Vol43:357-372.

[8] G.S. Settles and L.J. Dodson: *Hypersonic shock/boundary-layer interaction database*. NASA-CR-177577, 1991.

[9] T.J. Garrison, GS Settles, N. Narayanswami and D. Knight: AIAA Journal, Vol. 31 (1993), P. 2204 - 2211.

[10] T.J. Garrison, GS Settles, N. Narayanswami and D. Knight: AIAA Journal, Vol. 32 (1994), P1234 - 1241.