THE OPENFOAM CALCULATION OF SUBSONIC-SUPERSONIC SHEAR MIXING LAYER

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1 Introduction

Subsonic-Supersonic shear mixing layer flow is one of the important flow types. In the combustion chamber of the rocket-ramjet combined propulsion system, the rocket jet flow and inflow air is a typical subsonic-supersonic shear mixing layer flow. To achieve the high efficient mixing in a finite length combustion chamber and improve the performance of the propulsion system, it is very essential to carry out research on the development rule of the subsonic-supersonic shear mixing layer.

OpenFOAM (Open Field Operation and Manipulation) is an open source CFD software under Linux platform, and its essence is a C++ library based on object-oriented programming. The software has many advantages of using finite volume method, many kinds of schemes, the superior design architecture, excellent portability, containing abundant physical model and numerical solver, good interface with other software, can and it can write specialized for specific problem solver. Its computing power has got the recognition and application, so it is widely popular with the CFD developers, and gets the wide attention from researchers. The numerical simulation work of subsonic-supersonic shear mixing flow is carried out based on OpenFOAM computing platform, and using rhoCentralFoam compressible solver, which is a compressible density solver, based on Kurganov&Tadmor center windward format, and has good adaptability for compressible flow.

2 Main results

In this paper, three groups of large eddy simulation were carried out, and the range of convection Mach number (Mc) was 0.39-0.69. The subsonic-supersonic shear mixing flow of normal temperature and normal pressure state is studied. The numerical calculation parameters are shown in table 1.

Table 1: Numerical calculation parameters.

	U1(m/s)	U2(m/s)	Ma1	Ma2	Mc
Case1	517.61	103.24	2	0.3	0.69
Case2	517.61	201.22	2	0.6	0.53
Case3	517.61	289.90	2	0.9	0.39

Keeping the total temperature constant and changing Ma of the secondary flow of Case1-Case3, study the effect of Mc on compressibility of shear mixing layer.

In this paper, the classical plane shear flow configuration is adopted, as shown in figure 1. In the flow area of the cube, the upper part is supersonic flow (primary flow), and the lower part is subsonic flow (secondary flow). The left side is the entrance, and the right side is the exit. The upper and lower surfaces are walls.

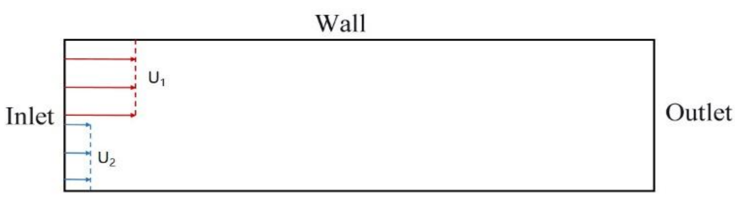
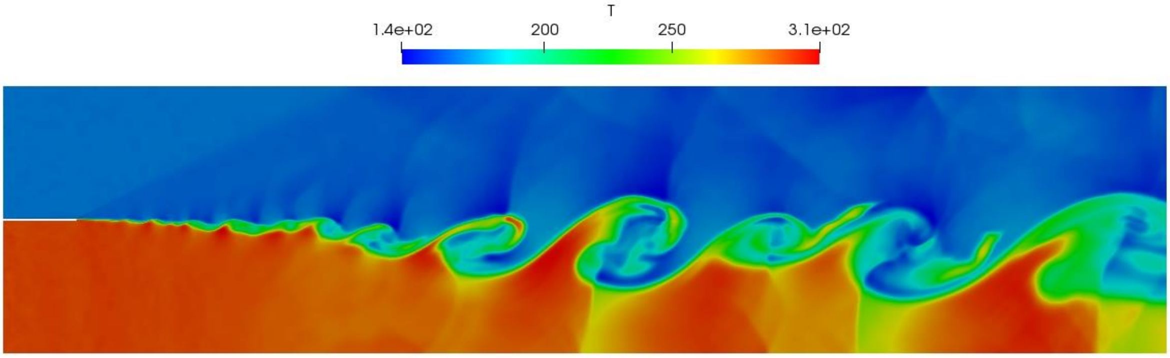


Figure 1: Schematic diagram of flow area.

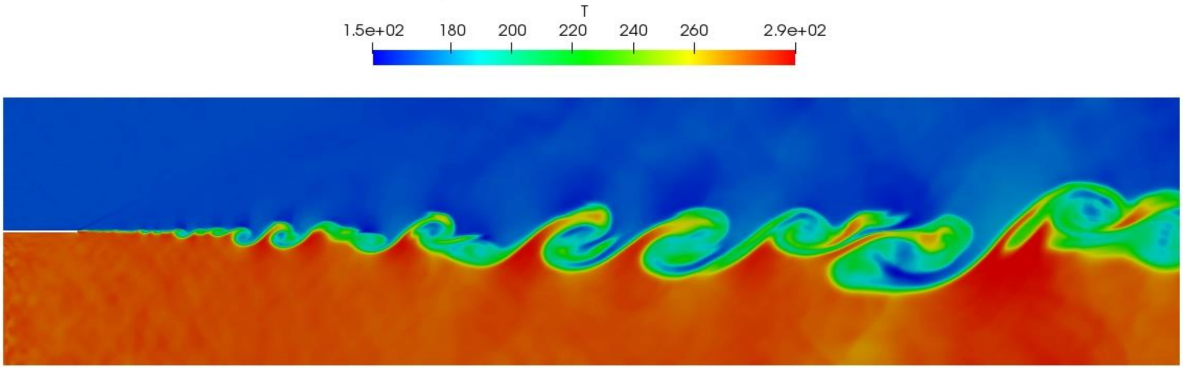
The length of the flow area is 300mm, the height is 80mm, and each of the primary and secondary flow is 39.75mm, the thickness of the split board is 0.5mm. The minimum grid scale is 0.1mm and the grid amount is about 170,000.

Velocity and static temperature are given at high speed and low speed inlet. Given static pressure at the high speed inlet, the low speed inlet pressure is obtained by extrapolation. The export condition is zero-gradient boundary condition. The split board is non-slip boundary condition, and the upper and lower wall is sliding wall surface.

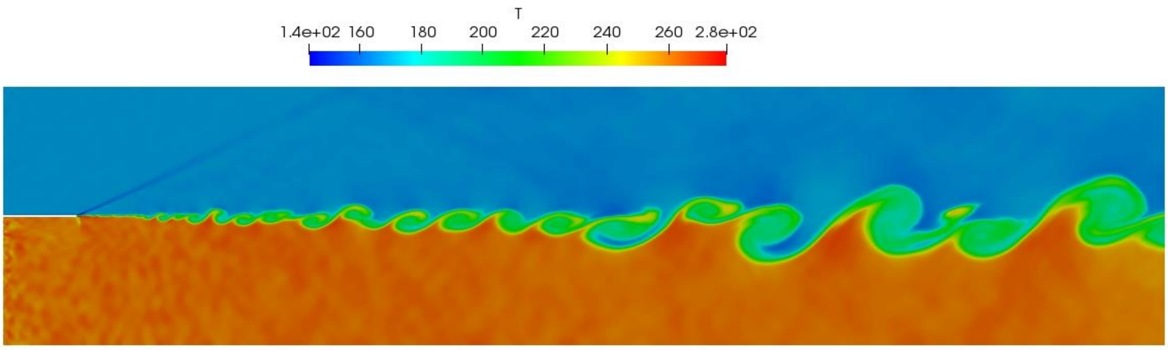
In the calculation process, when the shear mixing flow reaches the quasi-steady state, the data of a certain moment is selected to obtain the temperature contour. Figure 2 (a) - (c) is the temperature contour of each group of Case1-Case3.



(a)Static temperature distribution contour of Case1.



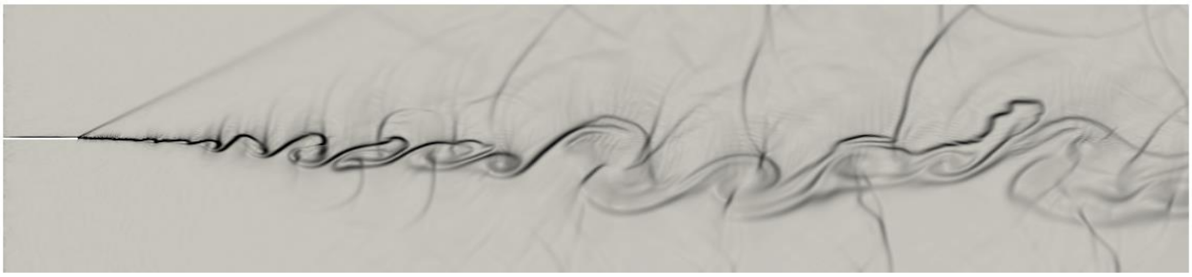
(b)Static temperature distribution contour of Case2.



(c)Static temperature distribution contours of Case3.

Figure 2: Static temperature distribution contour of Case1-Case3.

The density distribution contour can be obtained as the temperature distribution contour does, then get the gradient of the density distribution, and numerical schlieren contour can be obtained, as shown in figure 2.



(a)Numerical schlieren contour of Case 1.

(b) Numerical schlieren contour of Case 2.

(c) Numerical schlieren contour of Case 3.

Figure 3: Numerical schlieren contours of Case1-Case3.

It can be seen from figure 2 and figure 3 that the compressibility of shear mixing layer is weak, and large scale coherent structures can be observed, and coherent structure is very clear and regular, while the Mc is low.

For shear mixing layer thickness, the average velocity thickness is used here. The average velocity thickness can be defined as the longitudinal distance of the normalized velocity of 0.1 and 0.9. And the normalized velocity is defined as:

$$U^*(y) = \frac{U(y) - U_2}{U_1 - U_2} \quad (1)$$

Then: $\delta_v = y_{U_1 - 0.1\Delta U} - y_{U_2 + 0.1\Delta U}$.

Figure 4 shows the thickness of shear mixing layer along the flow direction of Case1-Case3. The points are the original data, and the lines are the linear fitting data. It can be found that the original data is very close to the linear fitting data and the thickness of shear mixing layer varies greatly in the calculated working conditions.

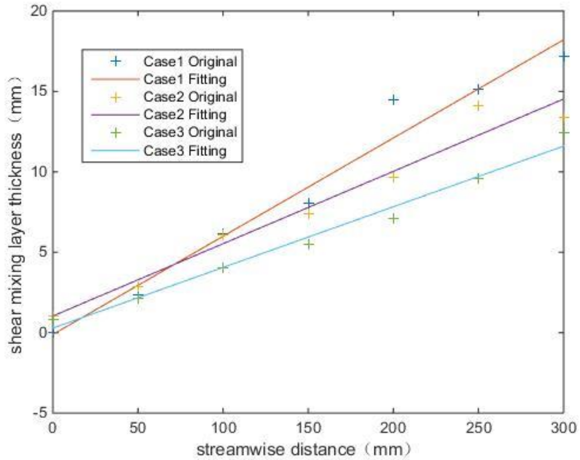


Figure 4: Thickness of shear mixing layer of Case1-Case3.

For decoupling the effect of compressibility, speed ratio and density ratio on the shear mixing layer growth rate, the growth rate of the normalized compressible shear mixing layer concept is put forward, which is the ratio of compressible shear mixing layer with the incompressible shear mixing layer growth rate under the condition of same speed ratio and density ratio under, as shown in equation (2).

$$\delta_{nor} = \frac{(d\delta/dx)}{(d\delta/dx)_{inc}} = f(M_c) \tag{2}$$

Dimotakis (1986) proposed the calculation formula for the incompressible shear mixing layer growth rate:

$$\left(\frac{\mathrm{d}\delta}{\mathrm{d}x}\right)_{inc} = C_\delta \frac{(1-r)(1+\sqrt{s})}{2(1+r\sqrt{s})}\{1-\frac{(1-\sqrt{s})/(1+\sqrt{s})}{1+2.9(1+r)/(1-r)}\} \tag{3}$$

Here: $0.25 < C_\delta < 0.45$, $r = U_2/U_1$, $s = \rho_2/\rho_1$.

Using the incompressible shear layer thickness growth rate δ_0' to make the compressible shear layer thickness growth rate δ' nondimensionalize, then get the shear layer thickness growth rate δ'/δ_0', and give the corresponding Mc, shown in the following table.

Table 2: Shear layer thickness growth rate and corresponding Mc of Case1-Case3.

	Case1	Case2	Case3
δ'	0.0611	0.0450	0.0377
δ_0'	0.2078	0.1433	0.0948
δ'/δ_0'	0.2940	0.3138	0.3977
Mc	0.69	0.53	0.39

It can be seen from the above table, the dimensionless thickness growth rate of shear mixing layer decreases with the increase of Mc.

3 Conclusions

In view of the subsonic-supersonic shear mixing flow, this paper uses the software of OpenFOAM to carry out large eddy simulation study, and the results show that the development process of the subsonic-supersonic shear mixing layer has the following rules:

(1) With the increase of compressibility, the dimensionless thickness growth rate of the shear mixing layer decreases.

(2) The shear mixing flow with weak compressibility and the incompressible shear flow have similar rules in the shear mixing layer growth rate et al. It shows that the flow rules of the two kinds of shear mixing flow are similar.