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The OpenFOAM Calculation of Subsonic-Supersonic Shear Mixing Layer

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Introduction

Subsonic-supersonic shear mixing flow is one of important research field in turbulence research. In the rocket ramjet combustion chamber, the mixing of main rocket gas and air is a typical large gradient subsonic-supersonic shear mixing flow, which has characteristics of high convective Mach number (Mc) and large flow parameter gradient. It is of great significance to study the development rule and flow structure of the large gradient subsonic-supersonic shear mixing flow, which is of great significance to enhance the blending and enhance the working performance of the ramjet engine.

Numerical simulation

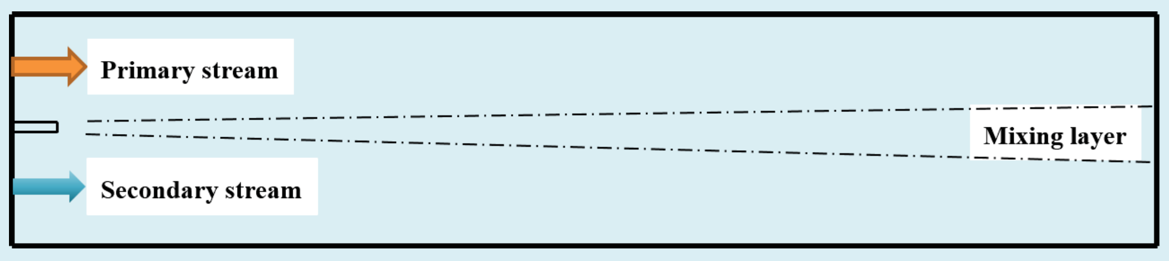


Figure 1: Schematic diagram of flow area

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.

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.

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

In this paper, the range of convection Mach number (Mc) was 0.39-0.69. The subsonic-supersonic shear mixing flow of normal temperature is studied. Keeping the other parameters constant and changing Ma of the secondary flow of Case1-Case3, study the effect of Mc on compressibility of shear mixing layer.

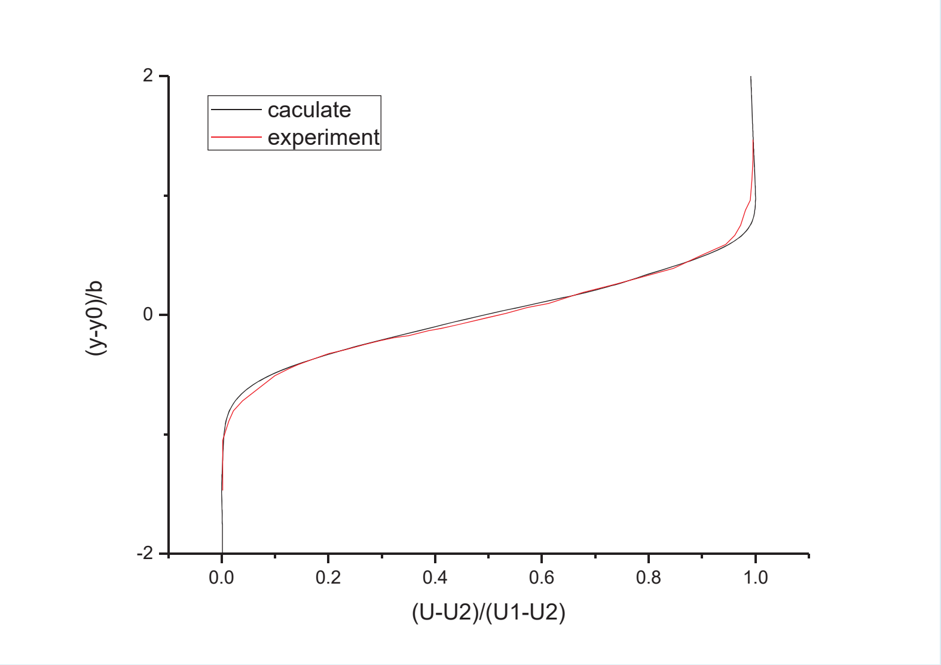
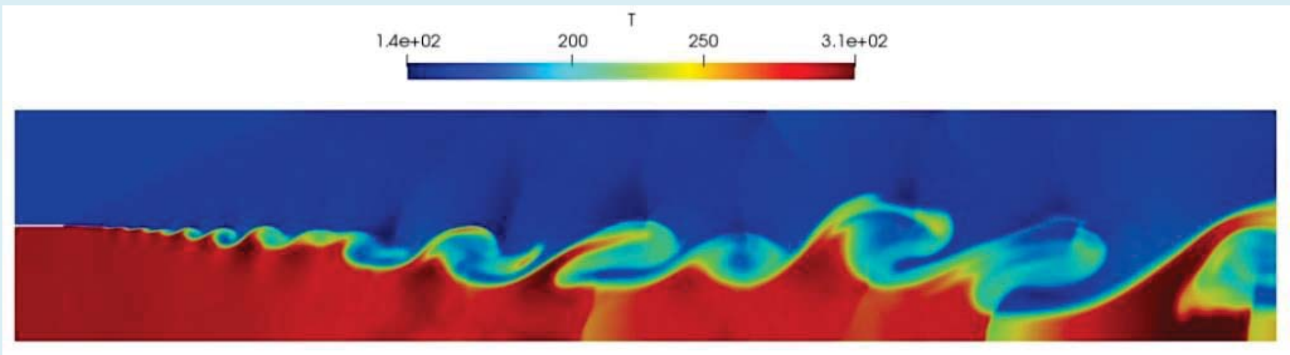


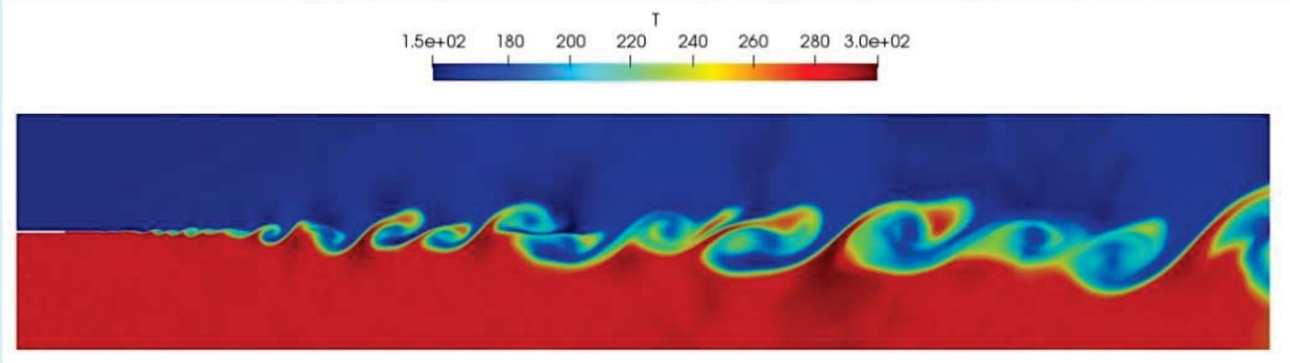
Figure 2: Comparison of shear mixing layer velocity profile between numerical result and experimental data.

Experimental data of normal temperature subsonic-supersonic shear mixing layer carried out by Goebel is adopted for numerical validation LES model using in this paper. Figure 2 shows the shear mixing layer velocity profile expressed in self-similar form, and it can be found that numerical result is in good agreement with experiment data.

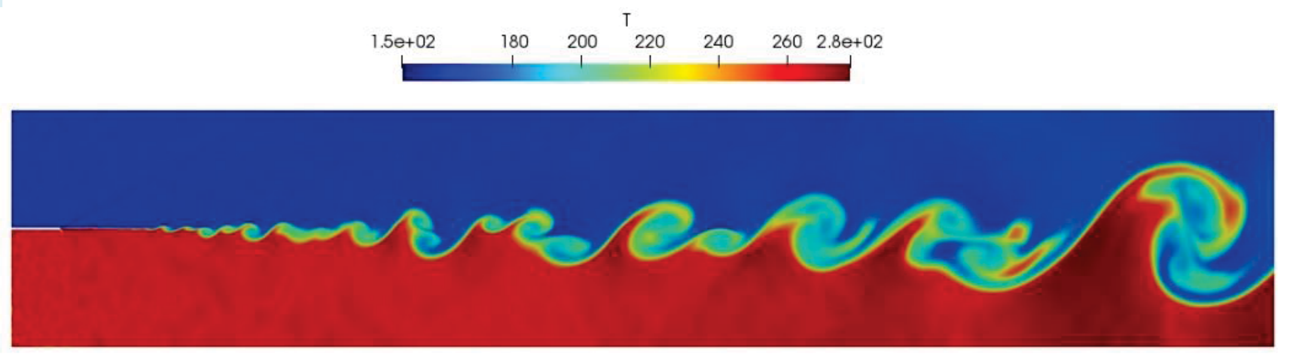
In the calculation process, when the shear mixing flow reaches the quasi-steady state, the data of a certain moment is selected to obtain the temperature contour. Figure 3 (a) - (c) is the temperature contour of each group of Case1-Case3.



(a) Static temperature distribution contour of Case1.



(b) Static temperature distribution contour of Case2.



(c) Static temperature distribution contour of Case3.

Figure 3: Static temperature distribution contours of Case1-Case3.

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

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

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

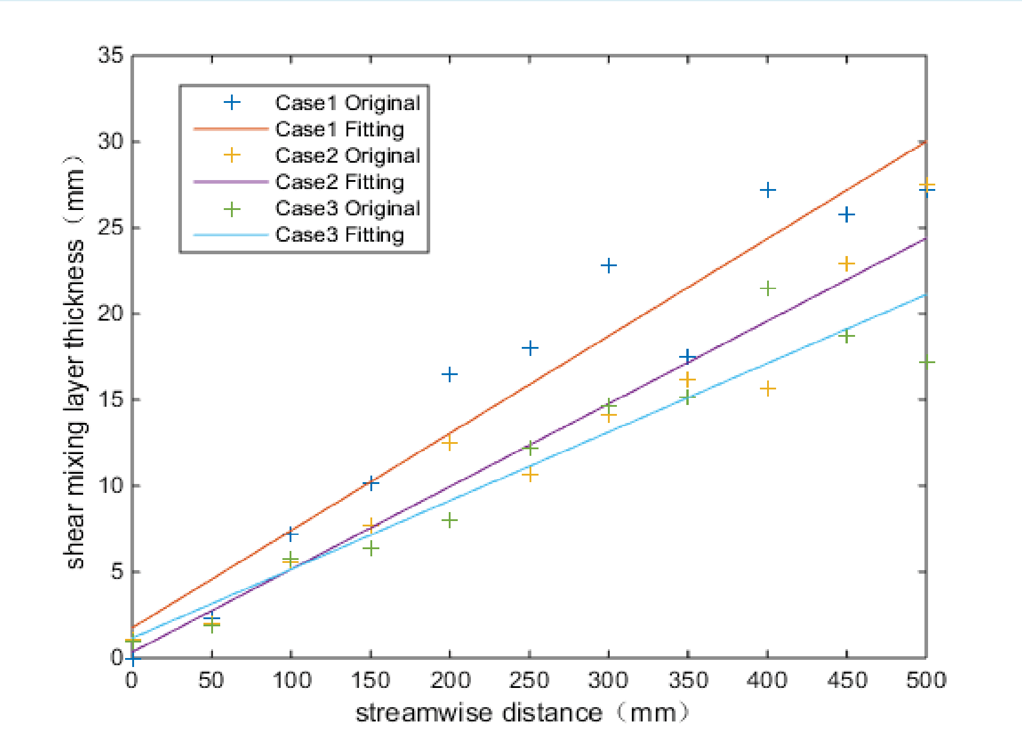


Figure 4: Thickness of shear mixing layer of Case1-Case3.

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.

	Case1	Case2	Case3
δ'	0.0565	0.0481	0.0399
δ_0'	0.2078	0.1433	0.0948
δ'/δ_0'	0.2720	0.3356	0.4209
Mc	0.69	0.53	0.39

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

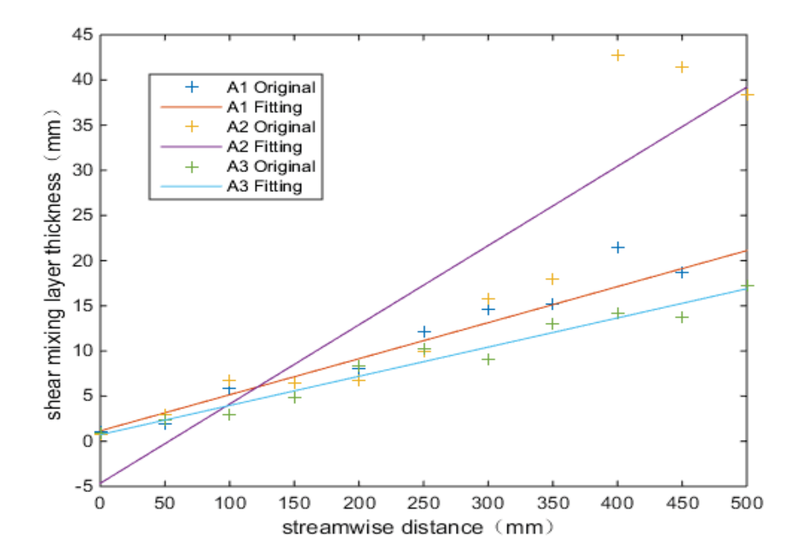
It can be seen from the above table, the dimensionless thickness growth rate of shear mixing layer decreases with the increase of Mc.

Calculation results of Changing parameters

Based on Case3, the boundary conditions of the upper and lower wall surfaces were changed to compare the thickness growth rate of subsonic-supersonic shear mixing layer under different boundary conditions.

	Ma1	Ma2	Mc	boundary conditions of the upper and lower wall surfaces
A1	2	0.3	0.39	Slid
A2	2	0.3	0.39	No slid
A3	2	0.3	0.39	Speed entrance

	A1	A2	A3
δ'	0.0399	0.0877	0.0323
δ_0'	0.0948	0.0948	0.0948
δ'/δ_0'	0.4209	0.9251	0.3407
boundary conditions of the upper and lower wall surfaces	Slid	No slid	Speed entrance

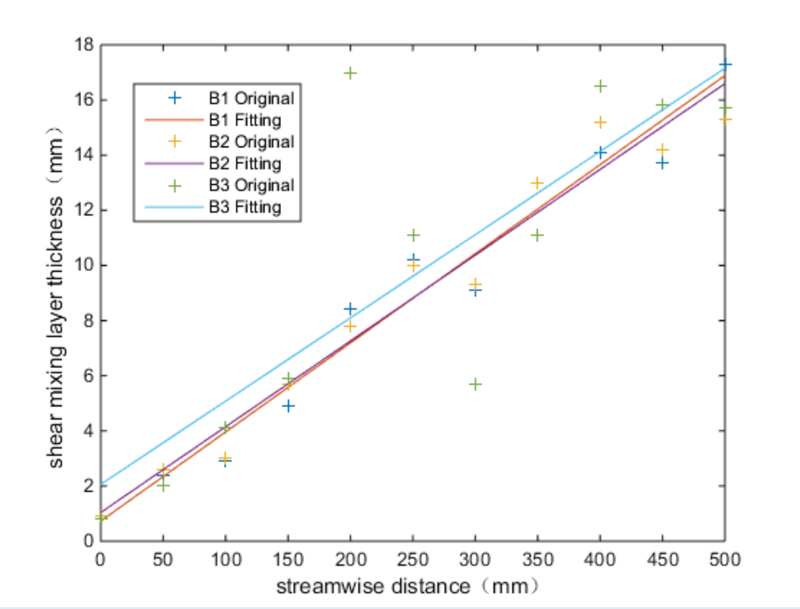


It can be seen from the above table that the dimensionless thickness growth rate and thickness growth rate of the shear mixing layer have great changes with the change of boundary conditions of the upper and lower wall surfaces.

Based on Case3, the static pressure of the incoming flow was changed to compare the thickness growth rate of subsonic-supersonic shear mixing layer under different static pressure conditions.

	Ma1	Ma2	Mc	static pressure (kPa)
B1	2	0.3	0.39	36
B2	2	0.3	0.39	60
B3	2	0.3	0.39	100

	B1	B2	B3
δ'	0.0323	0.0311	0.0302
δ_0'	0.0948	0.0948	0.0948
δ'/δ_0'	0.3407	0.3281	0.3183
static pressure (kPa)	36	60	100



It can be seen from the above table, both dimensionless thickness growth rate and thickness growth rate of shear mixing layer decrease with the increase of static pressure.

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) With the change of boundary conditions of the upper and lower wall surfaces, the dimensionless thickness growth rate and thickness growth rate of shear mixing layer have great changes.
(3) With the increase of static pressure, both dimensionless thickness growth rate and thickness growth rate of shear mixing layer decrease.