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Influencing Analysis to Nozzle's Inner Flow Field of Different Pintle Radius and Shapes

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Abstract: The pintle controlled thrust regulating mechanism is an effective means to realize thrust real-time regulatation of solid-rocket engine. Factors of thrust regulating range and speed, thrust loss, reacting force on pintle section should be considered in pintle design. Basic equation of liquid motion and turbulence model of nozzle's inner flow flied are analyzed. Geometry model of nozzle is established. Numerical simulation on inner flow field of nozzle for different radius pintle, different head coning of pointed cone pintle and different head ellipticity of ellipsoidal pintle had been carried and the flow field changing was analyzed. The changing rule of thrust regulating under different conditions was gotten. These results provide theoretical guidance for pintle design.

Key words: Thrust regulating, pintle size and shape, inner flow field, numerical analysis, nozzle

INTRODUCTION

Pintle controlled thrust regulating mechanism can realize real-time thrust-regulating of solid-rocket engine effectively. The air stream in nozzle flows under the constraint of pintle face and nozzle inside wall and the real area and position of nozzle throat is changed by pintle. So different size and shapes of pintle will cause different effects to inner flow field of nozzle (Li *et al*., 2007).

Tang *et al*. (2013) study the performance of non-coaxial pintle control thrust nozzle and propose a method for calculating the nozzle equivalent throat area. Li *et al*. (2007) determine the relationship among configuration, position of pintle and throat area by means of the equivalent throat area calculation method and contrast the thrust regulating performances of the motors with different pintle configuration. Hua *et al*. (2008) simulate the flow field of the variable thrust motor nozzle with pintle, and optimize the throat pintle contour. Wei *et al*. (2009) design an experimental system of non-coaxial pintle solid rocket motor to analyze the performance of variable thrust pintle solid rocket motors and carry out the experiments that validate variable thrust principle.

Based on definite structure and size of nozzle, numerical simulation on inner flow field for different radius pintle, different head coning of pointed cone pintle and different head ellipticity of ellipsoidal pintle were done. Its main aim is to get the changing rule of thrust regulating under different conditions and to provide theoretical reference for design of pintle controlled thrust regulating mechanism.

MATHEMATICAL MODEL

Basic equation: The basic equations of liquid motion are mass conservation equation, momentum conservation equation and energy conservation equation. Their differential form can be expressed as follow:

Mass conservation equation:

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

Momentum conservation equation:

$$\frac{\partial \rho V}{\partial t} + \nabla \cdot (\rho V V) = \rho f_v + \nabla \cdot P \tag{2}$$

Energy conservation equation:

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho V E) = \rho f_v \cdot V + \nabla \cdot (P V) + \rho \hat{q} + \nabla \cdot (\kappa \nabla T) \tag{3}$$

In these equations, ρ is liquid density, V is liquid motion rate, f_v is volume force to liquid micellar, P is surface force to liquid micellar, E is the energy of liquid

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micellar, $\hat{q}$ is the heat of unit mass produced in per unit time, k is thermal-conductivity coefficient.

Turbulence model: Relative simple and mature S-A (Spalart-Allmaras) model is adopted to numerical simulation on inner flow flied. From experience and dimension analysis, S-A model is an equation model that considers the momentum transfer only. Compared with two-equation turbulence model, S-A model has many merits, e.g., little calculation, better stability and low requirement to computational grid granularity. To flow with fixed wall boundary conditions in gas dynamics, flow problems of calculating flow in boundary layer and large pressure gradient can be gotten better results by S-A model (Lai, 2002; Li *et al*., 2004).

GEOMETRY MODEL AND BOUNDARY CONDITION

According to design requirement, geometry model of nozzle was built. Quadrilateral mesh type was adopted and mesh was divided by Map. The mesh model of nozzle is showed as Fig. 1.

In response to parameter condition of given pressure, the boundary condition of left entrance and right outlet were defined individually as pressure entry and pressure outlet. Static pressure can be set by total pressure relational equation of compressible flow in the process of parameter setting. As showed in Eq. 4:

$$P_{total} = P_{static}\left(1+\frac{k-1}{2}Ma^2\right)^{k/(k-1)} \tag{4}$$

In Eq. 4, Mach number can be estimated by Eq. 5:

$$\frac{A}{A_*} = \frac{1}{Ma}\left(\frac{1+\frac{k-1}{2}Ma^2}{\frac{k+1}{2}}\right)^{\frac{k+1}{2(k-1)}} \tag{5}$$

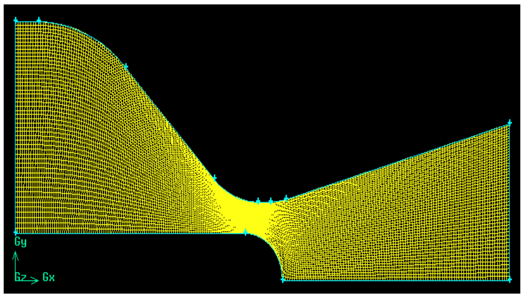

Fig. 1: Mesh model of nozzle in GAMBIT

The air flow in outlet section of nozzle is supersonic flow, so any boundary conditions needn't be given.

NUMERICAL SIMULATION AND RESULTS ANALYSIS ON INNER FLOW FIELD OF NOZZLE

Analysis on inner flow field of nozzle for different radius pintles: At the same position of nozzle, actual throat area is different because of different radius of pintle. Regulating ability of throat is different when pintle position changes.

Figure 2-4 show mach number distribution that pintle radius are 12, 15 and 20 mm.

Known from the result, the bigger pintle radius is, the farther distance between outlet surface and collision location generated by shock wave and nozzle wall is and the Mach number distribution in nozzle radial distribution is higher. The reason is that the bigger turning of gas paths is, the high Mach number in radial distribution is and the more generating loss is. Therefore, the smaller pintle radius is, the less flow loss is and the bigger thrust force is at the same condition.

According to theory of pintle thrust regulating, the regulating range is $0 \sim \pi R^2$. So the bigger thrust radius is, the bigger regulating range is. While pintle moves the same distance, big radius pintle generates big area-changing amount and regulating speed is relatively fast. Therefore, big radius pintle should be used in big-range and rapid regulation. From another point, the bigger pintle radius is, the bigger sectional area is and the bigger axial resistance force of pintle is. This will bring higher requirement to control system. Not only regulating performance but also reaction force in pintle section and economy should be considered when pintle radius is chosen (Liu *et al*., 2007; Hua *et al*., 2008).

Analysis on inner flow field of nozzle for different pintle head shapes: Different pintle head shapes generate different thrust regulating results. According to the relationship between actual throat area of nozzle and moulding surface of pintle, typical pintle head shapes--cone pintle and ellipsoidal pintle are chosen to analyze inner flow field's change of nozzle and effecting rule to regulating performance.

Analysis on inner flow field of nozzle for different head coning of pointed cone pintle: Under the unchanging precondition of nozzle size, pintle radius (15 mm) and pintle position (final regulating position), head coning is selected as 2:1, 1.5:1, 1:1 and the same pressure entrance

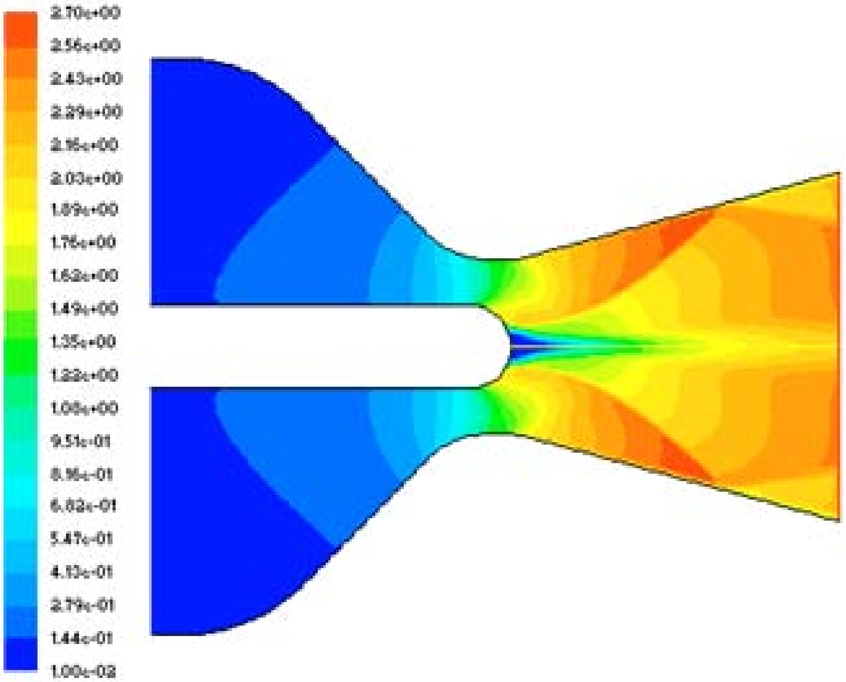

Fig. 2: Mach number distribution of inner flow field for nozzle while pintle's radius is 12 mm

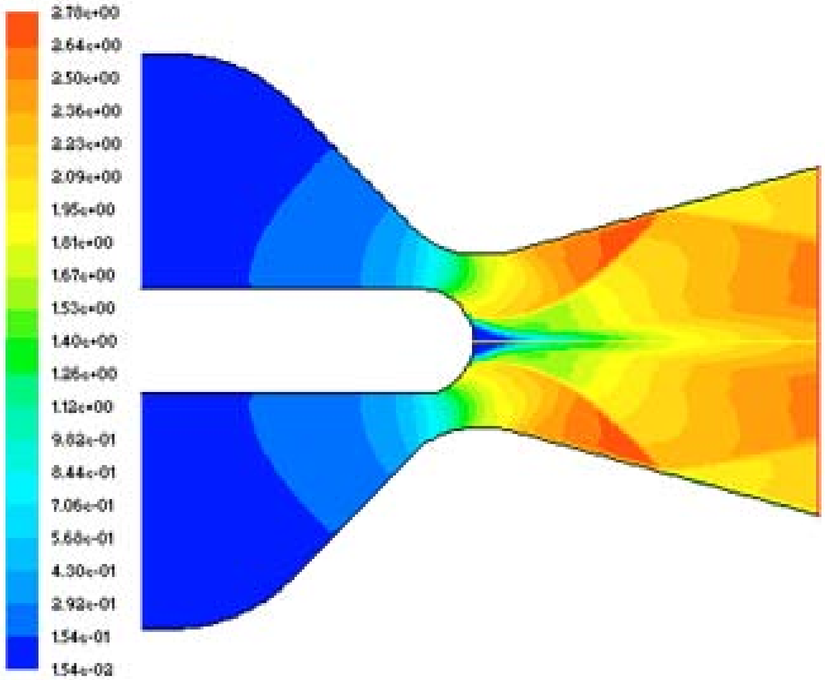

Fig. 3: Mach number distribution of inner flow field for nozzle while pintle's radius is 15 mm

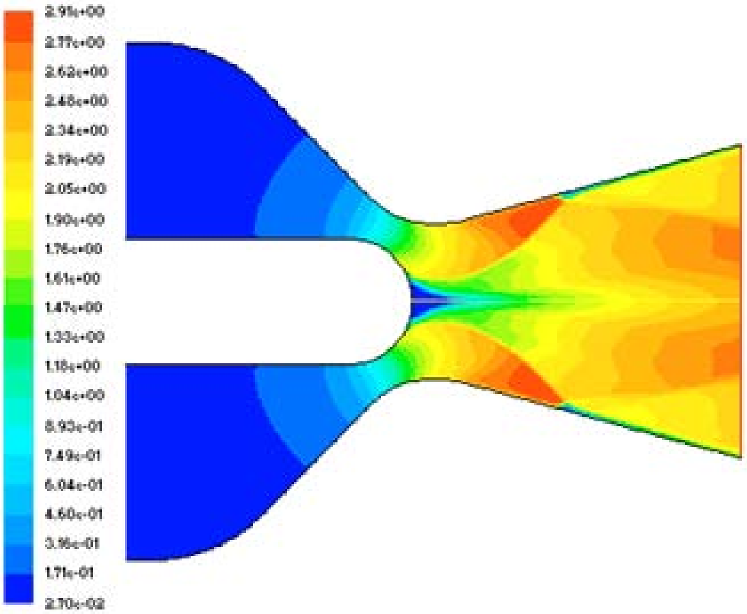

Fig. 4: Mach number distribution of inner flow field for nozzle while pintle's radius is 20 mm

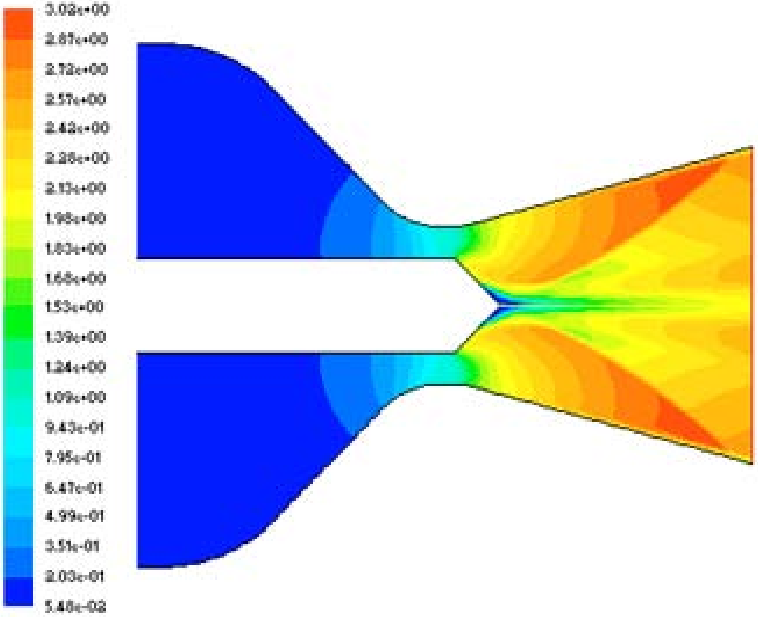

Fig. 5: Mach number distribution of inner flow field for nozzle while head coning of pintle is 2:1

condition is defined. Analysis on inner flow field of nozzle was done and Mach number distributions of nozzle are showed as in Fig. 5-7.

Known from the above results, with the increasing of head coning, the inhomogeneity of flow will be weak gradually, the collision location between shock wave and

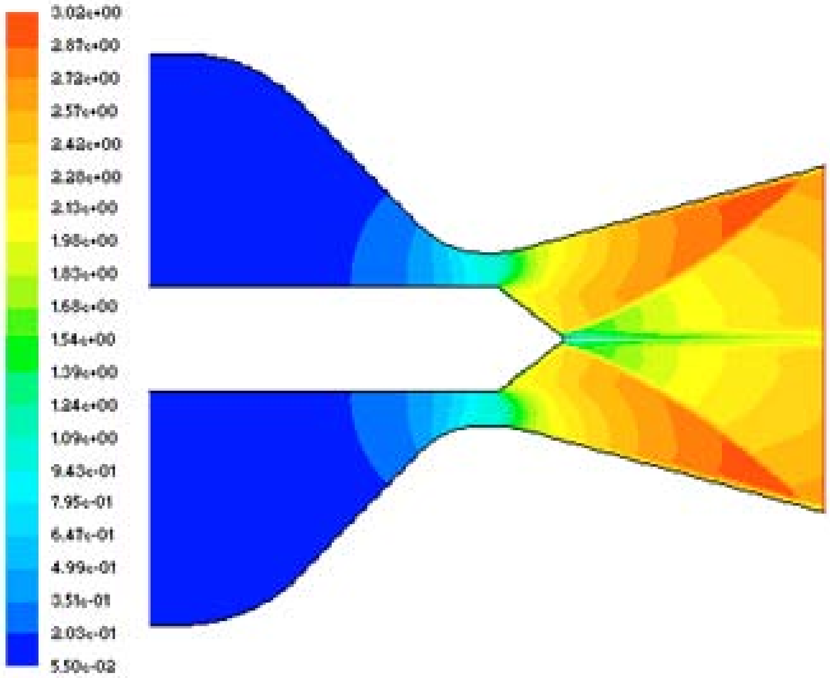

Fig. 6: Mach number distribution of inner flow field for nozzle while head coning of pintle is 1.5:1

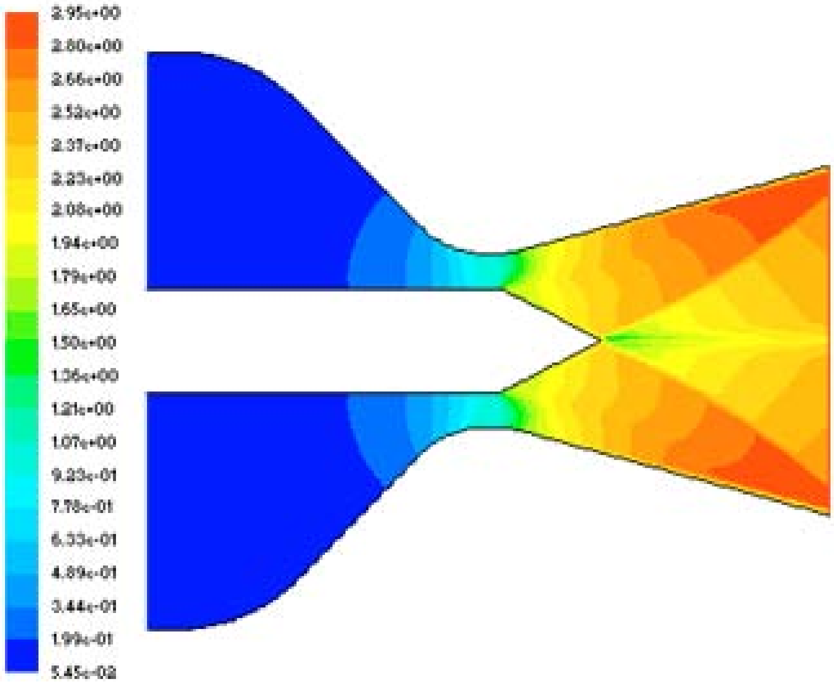

Fig. 7: Mach number distribution of inner flow field for nozzle while head coning of pintle is 1:1

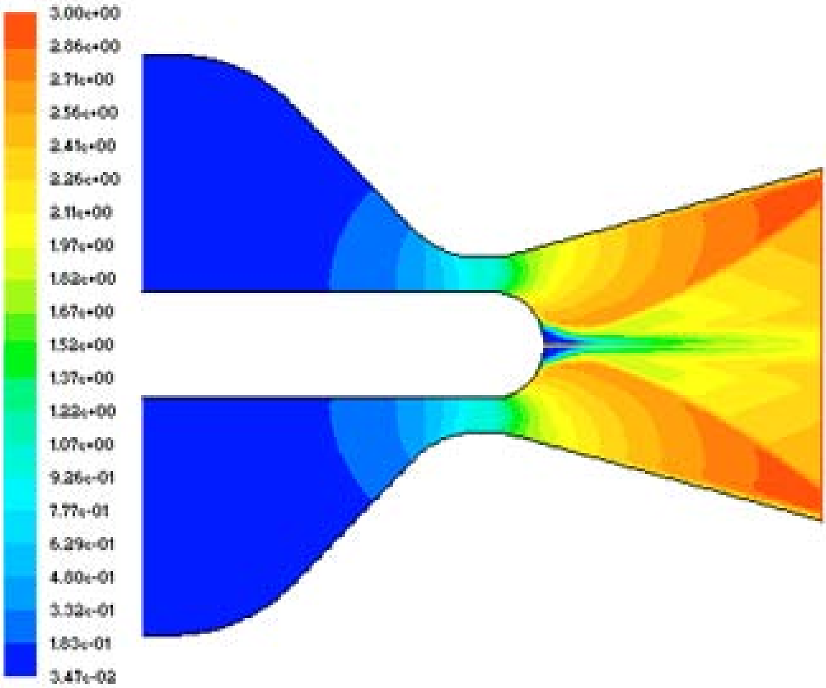

Fig. 8: Mach number distribution of inner flow field for nozzle while the ellipticity of pintle head is 1:1

nozzle wall moves outward and the downstream subsonic region of pintle head reduces continuously until disappears. The reason is that with the increasing head coning of pintle, turning degree of gas flow region between nozzle wall and pintle surface reduces. The radial distribution of Mach number and thrust loss reduce too. Thus better regulation can be achieved.

Analysis on inner flow field of nozzle for different head ellipticity of ellipsoidal pintle: Under the unchanging condition of structure size of nozzle and pintle, different head ellipticity of ellipsoidal pintle will generate different regulating result and response speed. Head ellipticity of pintle is selected as 1:1, 1.5:1, 2:1 and analysis on inner flow field of nozzle was done. Mach number distributions of nozzle are showed as in Fig. 8-10.

Known from the above results, the Mach number distribution is similar to that of the pointed cone pintle. With the increasing of pintle head ellipticity, turning degree of gas flow region between nozzle wall and pintle surface reduces and the inhomogeneity of flow will be weak gradually. The radial distribution of Mach number reduces and the downstream subsonic region of pintle head reduces too. Through theoretical analysis, we can know that the smaller head ellipticity is, the faster response of regulating is. Therefore, factors of regulating performance, turning loss and response time should be considered synthetically when head ellipticity of ellipsoidal pintle is determined.

Comparing analysis on regulating performance between cone pintle and ellipsoidal pintle: Comparing Mach number distribution of nozzle's flow field between cone pintle and ellipsoidal pintle, we can know that the inhomogeneity of flow increases because of intervention of pintle. On the outlet plane of nozzle, Mach number near axis region is smaller than that of nozzle wall. The high Mach number area in outlet plane of ellipsoidal pintle nozzle is relatively bigger and regulating performance of thrust is better. The reason is that radial distribution of Mach number of flow field for pointed cone pintle is relatively more because of different pintle shape and turning degree of flow channel and flow loss is greater. According to theoretical analysis, cone pintle can realize bigger throat area regulation and faster response through shorter moving distance. The smaller coning of pintle head is, the faster response speed is. Regulating performance, turning losses and response time should be

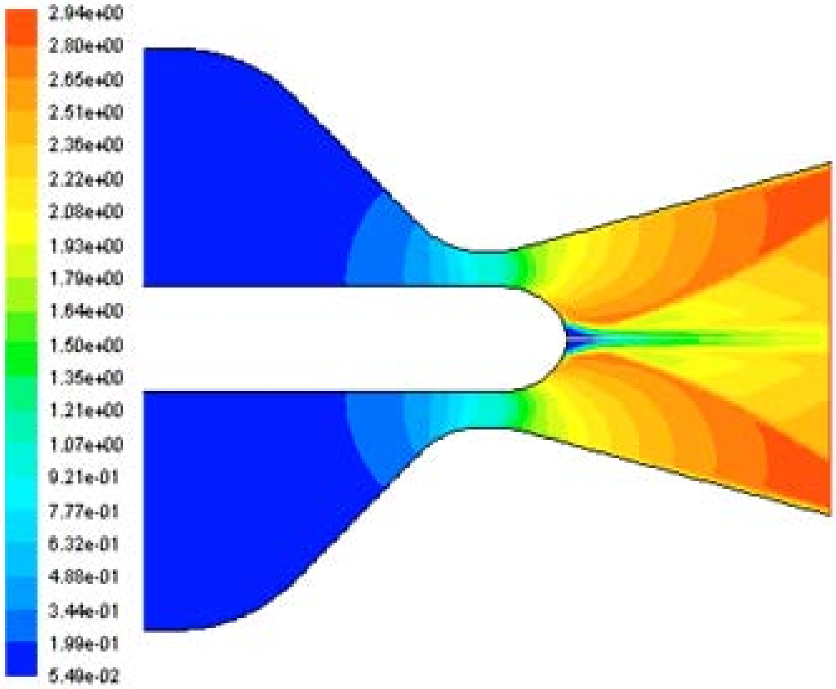

Fig. 9: Mach number distribution of inner flow field for nozzle while the ellipticity of pintle head is 1.5:1

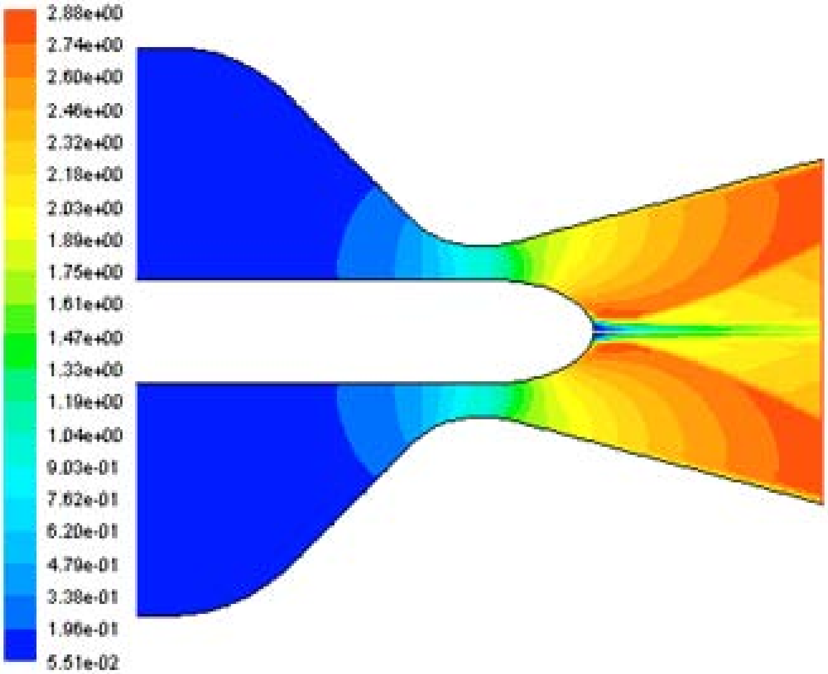

Fig. 10: Mach number distribution of inner flow field for nozzle while the ellipticity of pintle head is 2:1

considered synthetically when pintle shape is chosen (Tian *et al*., 2006; Zhang *et al*., 2007).

CONCLUSION

Through numerical simulation on inner flow field of nozzle, the effecting rules of different radius and shape pintle to thrust regulation were analyzed. The results provide theoretic guidance to the design of pintle controlled thrust regulating mechanism. When a pintle is designed, factors of regulating range, regulating response, loss and counterforce on pintle face should be considered synthetically. On the balance of performance and economy, the best pintle shape and size should be selected.

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