Reseach on the reduction of rocket motor jet noise by water injection

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Abstract: Injecting water in the mixing layer of rocket motor jets is a means to reduce jet noise. The calculation of the sound pressure signals at the prescribed receivers was performed by FW-H acoustics model under the condition of water injection and without water injection. The calculation results show that the jet noise is with obvious directivity. The total sound pressure levels are obviously much higher in 10°to 30°direction than that in other direction. The sound pressure levels at the condition of water injected are lower than that of without water injection at the all receiver points, which indicates that water injection can reduce jet noise effectively.

1 Introduction

When Rocket engine is at work, Propellant combusting in chamber generates high temperature and high pressure combustion gas. And then the gas inject into the surrounding environment through the laval nozzle at a supersonic speed. The high speed jet mix sharply with relatively static medium around, which will form the violent turbulence pulsation in the jet boundary layer, and spread to all around in the form of compressing wave. It will produce violent jet noise to the surrounding. The jet noise not only do harm people at the auditory organs and the upper respiratory tract around the rocket emission but also damage to the load and structure of the aircraft and ground facilities.

The research on jet noise reduction has made great progress so far. Such as microjet noise reduction technology[1], it makes microjet and engine plume generated strong coupling action. The coupling action makes the jet flow field, especially the structure of the turbulent mixing region, change obviously, which change the structure of the jet noise field and achieve the purpose of noise reduction. Based on the sound source, jet noise can be reduced by two methods[2], reducing the jet velocity and changing the structure of the jet field. At present, noise is reduced mainly by lobe nozzle and water injection. Lobed nozzle reduces noise by increasing the contact area of the wake flow with the outside atmosphere, so as to enhance the gas mixture to achieve noise reduction target. In this way, the mixing of airflow is enhanced, the goal of noise reduction is achieved. However, this method will cause the negative effects like the loss of engine's thrust, the increasing resistance, the increasing mass of aircraft and so on while reducing noise. It is proved by practice[3-5] that injecting water in the jet flow field of engine is an effective way to reduce noise. Low temperature water rapidly vaporizes and absorbs noise when it is contacted with high temperature gas. For example, in order to minimize effect of jet noise resulted from the rocket ignition on the aircraft structure, a lot of water would be used to suppress overpressure when the rocket ignition. Krothapalli[6] inject the fine atomization water droplets directly into the gas jet shear layer, with the help of particle image velocimetry, draw a conclusion that water injection reduces the turbulence intensity and shear stress in the jet. NASA and the European space agency claimed that it reduced the jet noise by 8 to 12 db to use the water spray at the plume when rocket was launching. Xu Yue, etc[7]. applied the modified finite volume method to study the effect of water injection on the jet noise. They obtained that the influence of water mass flow rate on the effective gas parameters.

Above all, a lot of researches on jet noise reduction have been carried out. Of them, experimental and numerical study on the water injection to reduce noise are also carried out. But the numerical calculation is based on the equivalent jet parameter method to estimate the size of the noise. In order to eliminate the error caused by the method of equivalent parameter. In this paper, CFD method will be applied to calculate the near field flow field and sound source, combined with the method of solving the wave equation and the far field acoustic field distribution, to research rocket engine jet flow and gas dynamic field noise characteristics, and calculate the

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effect of water injection on jet flow field and sound field. It provides numerical reference for water injection to reduce noise of the rocket engine.

2 Computing method

Lighthill[8] modified navier-stokes equation into the following form:

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial \tau_{ij}}{\partial x_i \partial x_j} \tag{1}$$

The left side of the equation is a classic acoustic wave operator, the right is a source term associated with turbulence mostly, known as Lighthill stress tensor. Lighthill equation of sound source is quadrupole source and also the source of turbulence noise, which is unknown and needed to get through computing the flow field. This equation is mainly suitable for the condition that high speed and turbulence as the main noise sources, such as high speed jet. On the basis of the Lighthill equation, Ffcows Williams and Hawkings[9] develop FW-H equation.

$$\frac{\partial^2 p'}{c_0^2 \partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i \partial x_j}\{T_{ij} H(f)\}$$
$$-\frac{\partial}{\partial x_i}\{[\tau_{ij} n_j + \rho u_i (u_n - \nu_n)]\delta(f)\}$$
$$+\frac{\partial}{\partial_t}\{[\rho_0 \upsilon_n + \rho(u_n - \nu_n)]\delta(f)\} \tag{2}$$

Where, T_{ij} is the Lighthill stress tensor, defined as

$$T_{ij} = \rho u_i u_j + P_{ij} - a_0^2(\rho - \rho_0)\delta_{ij} \tag{3}$$

τ_{ij} is the compressive stress tensor, u_i is the fluid velocity component in the x_i direction, u_n is the fluid velocity component normal to the surface ($f = 0$), v_i is the surface velocity components in the x_i direction, v_n is the surface velocity component normal to the surface, $\delta(f)$ is Dirac delta function, and $H(f)$ is Heaviside function.

FW-H equation, containing a monopole, dipole and quadrupole, can describe all of the aerodynamic noise problem in theory. The complete solution consists of surface integrals and volume integrals. The surface integrals represent the contributions from monopole and dipole acoustic sources and partially from quadrupole sources, whereas the volume integrals represent quadrupole (volume) sources in the region outside the source surface. This paper adopts the FW-H equation to compute the noise flow field.

For Lagrange discrete phase model, fluid phase is treated as the continuous phase and the discrete phase is dealt by computing a large number of particles and bubbles or droplet movement in the flow field. Between dispersed phase and fluid phase, exchange can be exist in momentum, quality and energy, The requirements of volume ratio for the second phase as dispersed phase is very low. The volume rate of injection water droplet in this paper is less than 10%, therefor a discrete phase model can be used.

3 Computing model

A small experimental engine was the object of study. Its nozzle is an axisymmetric laval nozzle. The export is of 22 mm in diameter, and the throat is of 10 mm in diameter. The structure is shown in figure 1.

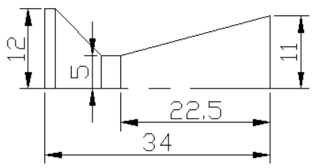

Fig. 1 Rocket engine nozzle structure

The engine combustion Chamber is of 3600K in total temperature and 10Mpa in total pressure. The pressure ratio of outlet to inlet is 0.01013, which is lower than the critical pressure ratio of the jet gas (the critical pressure ratio of air is 0.582). Tthe jet expand completely and can be simply described by the inlet pressure of jet, outlet pressure of jet is atmospheric pressure by default.

In this paper, computational domain selected is of 1000 mm at axial direction and of 220 mm at radial direction, as shown in Figure2. Nozzle entry is set as pressure entrance type of boundary. Nozzle wall is set as wall type of boundary. The rest boundary of the computational domain are set as export pressure. The divergent surfaces starting from the outlet of nozzle were took as sound source of FW-H integral surface. The sound source surface were divided into two parts. The first part starts with the nozzle exit, and 6D in axial length. The second part is of 3D for the initial diameter, 6D for the end diameter, 10D for axial length, where D is the nozzle diameter. A noise monitoring point is uniformly distributed at every 10 degrees in a circle at the center of the nozzle exit with 50d as the radius of circle from 10 ° to 90 °, as shown in figure 3.

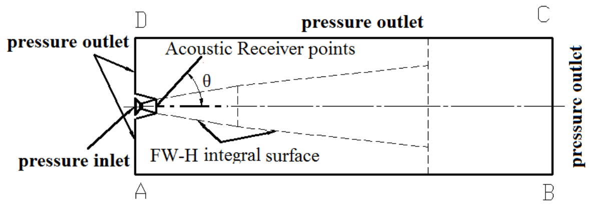

Fig. 2 Computational domain and the distribution of noise monitoring

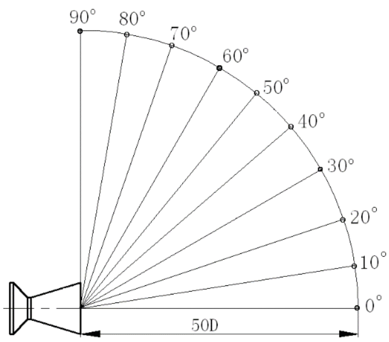

Fig.3 noise monitoring points distribution

To guarantee the whole calculation domain to be meshed structural grid, the whole region is divided into several sub-domains for meshing respectively. The nozzle and the sound source surface internal grid is refined, the number of grid is about 2 millions. The configuration of grid is shown in figure 4.

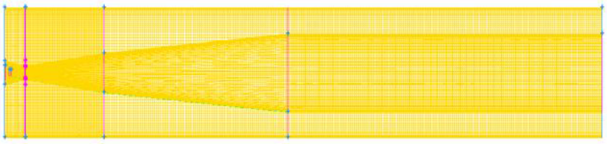

Fig.4 The axial cross-section grid configuration

Standard k-epsilon model, which most commonly used in engineering, is chosen as turbulence model. Without adding water, the medium attribute is set to the ideal gas, The medium is the mixture of air and water vapour after water injection. Water is injected into the flow field in the form of water droplets at a certain speed, then mixing with gas, and vaporized rapidly.

4 Calculation result and analysis

4.1 Flow field without water injection

In order to give a good initial boundary condition for the unsteady calculation, steady state is computed before the unsteady calculation. Under the condition of the steady state flow field, general calculation is exhanged to the condition of the unsteady, the time step is set as $\Delta t = 1 \times 10^{-5}$s. FW-H noise model is open. In order to reduce the influence of initial conditions on the unsteady calculation results, the unsteady calculation takes a long time until the flow field is stable and convergent and the noise of the total sound pressure level changes with time no longer.

Figure 5, figure 6 and figure 7 show the pressure, temperature and Mach number distribution at the axial across section without water spray respectively. From these figures, it is known that the complex expansion shock wave system exist in supersonic jet flow field of rocket engine. As the nozzle exit pressure is greater than the ambient pressure, gas expands at the exit, which makes the pressure and temperature of gas flow decreasing, and the Mach number increasing at the central region. When the air flow reaches the free boundary, the pressure is reduced to the ambient pressure. The gas flow is compressed under the action of the free boundary. The pressure and temperature at the center of the flow increase, and the Mach number decreases gradually until intersection with the free boundary again. And it will generates a new expansion wave system. The supersonic jet flow field of rocket engine is the alternating flow field of the expansion wave and the compression wave until the shock wave vanishes under the action of viscous dissipation.

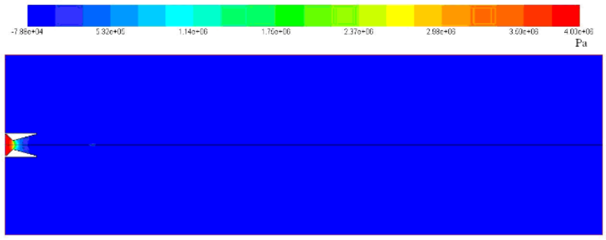

Fig. 5 (a) Full scale pressure distribution at the axial cross section

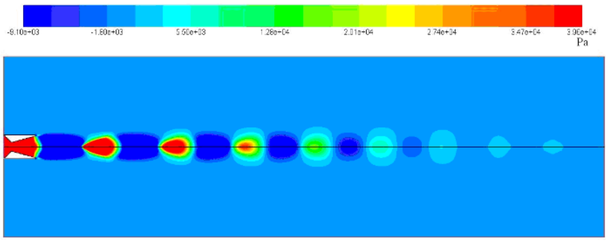

Fig. 5 (b) Narrow the range pressure distribution at the axial cross section

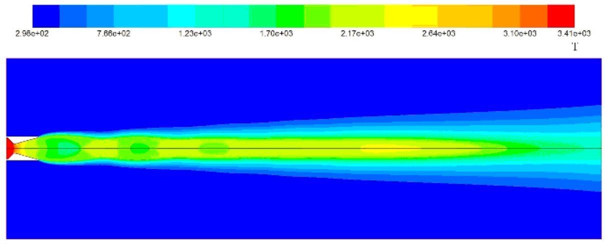

Fig.6 The axial cross section temperature distribution temperature distribution at the axial cross section

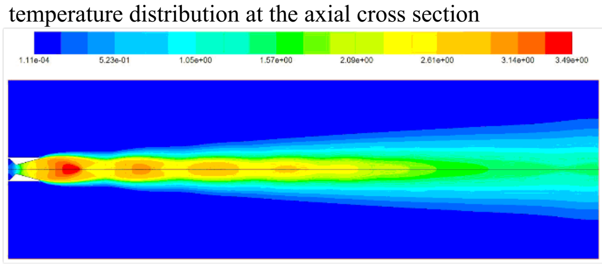

Fig.7 Mach number distribution at Tthe axial cross section speed of Mach number distribution

4.2 fluid Flow field with water injection

Water spray to the jet flow with the angle of 45°to the axis, and the spray point is at the position of 2D far from the nozzle outlet port (where, D is nozzle outlet port diameter). The mass flow rate of the water is 0.88kg/s. The calculation results of flow are shown in figure 8 to 11. These figures show the H_2O mass fraction distribution, Water particles concentration distribution, temperature distribution and Mach number distribution after water injected respectively.

From these figures, it is known that water evaporates after being fixed with high temperature combustion gas, the maximum H_2O mass fraction reaches to 0.466. The maximum concentration of water particles is only 10kg/m^3, the most of water sprayed into the jet flow was vaporized, which make high temperature region of jet flow became small. Due to the evaporation of liquid water, and energy exchange with gas flow, the temperature of flow field at downstream of the nozzle

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exit decrease obviously, the highest temperature of flow field at downstream of the nozzle exit is less than 1300 k. And the Mach number of flow was decreased. To compare figure 7 and figure 11, it would be found that the Mach number after the water spray was 0.04 smaller than that of without water, and the high Mach region became small too, only a small part of the area, the highest Mach number is up to 3.45 Ma . the supersonic flow does not exist in the downstream flow field area.

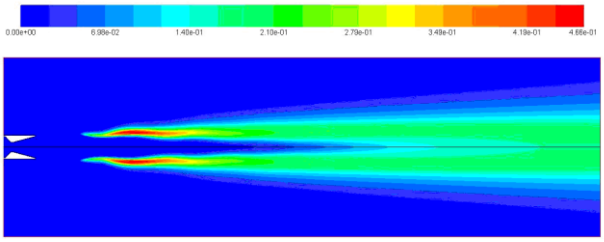

Fig.8 H_2O mass fraction distribution

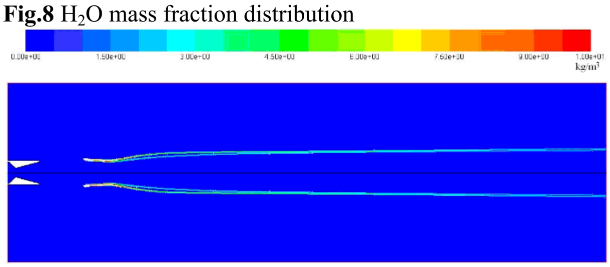

Fig.9 Water particles concentration distribution

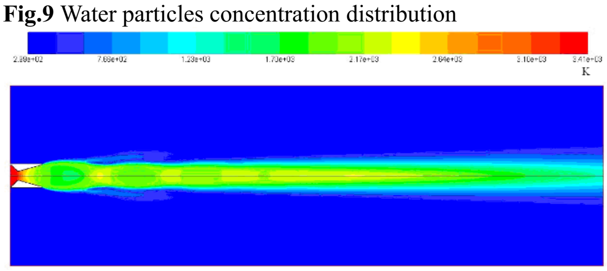

Fig.10 Temperature distribution after water injected

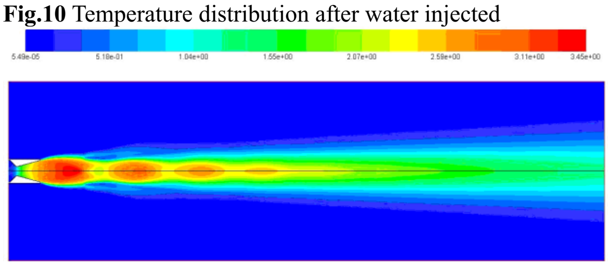

Fig.11 Mach number distribution after water injected

4.3 Analysis of water spray influence on noise reduction

The calculation of the sound pressure signals at the prescried receivers was performed by FW-H acoustics model. And the sound pressure signals were transformed with the Fourier transformation. The total sound pressure level of the monitoring points were obtained. The results are expressed as the function of the angle for the monitoring point, as shown in figure 11.

In figure 12, the solid curve shows the total sound pressure level change with the azimuth angle induced by jet flow field at the condition without water injection, while the dotted line shows that induced by jet flow field with water injection.

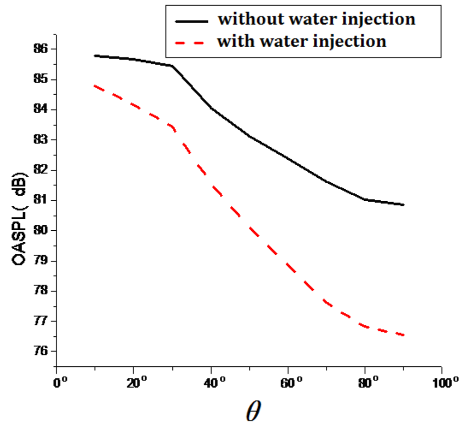

Fig.12 Change of the total sound pressure level with the azimuth angle

From the figure 12, jet noise is not evenly distributed in the circumference direction, but of obvious directivity. The total sound pressure levels are obviously much higher in 10°to 30°direction than that in other direction. The maximum total sound pressure level is 85.78db. According to the overall trend of the curve, from upstream direction to downstream direction total sound pressure level gradually decreases. This is because the rocket jet noise is dominated by the turbulent jet flow away from the nozzle exit. Throughout the 10° ~ 90°direction, within the scope of the dashed curve are located in below the solid curve, and the closer to the 90° direction, the greater the gap is, which indicate that the overall sound pressure levels at the condition of water injected are lower than that of without water injection. The maximum total sound pressure level is 84.78db after water is injected. Water injection at the nozzle exit have effect of noise reduction, the closer to upstream direction, the more effective noise reduction is.

5 Conclusion

1) Under the same initial conditions, the highest temperature of flow field at downstream of the nozzle exit is less than 1300 k after water was injected. Meanwhile, the Mach number with water injection was less than that of without water. And the construction of flow field was changed obviously.

2) The jet noise is with obvious directivity. The total sound pressure levels are obviously much higher in 10°to 30°direction than that in other direction.

3) The overall sound pressure levels at the condition of water injected are lower than that of without water injection, which indicates that water injection can reduce jet noise effectively.

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