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Analysis on numerical results for stage separation with different exhaust holes ☆

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ABSTRACT

The flow field for thermal stage separation is carried out and predicted by unsteady numerical simulation with the dynamic moving grids in this work. The overset grids are applied to simulate the relative separating motion of multi-stage rocket. The flow problems and effects of different exhaust holes within the interstage under considering the design of thermal stage separation are systematically computed, discussed and also analyzed.

1. Introduction

Multistage rockets propelled by solid rocket engines employ generally the thermal separating technology for the interstage in the densely populated regions of the atmosphere to separate the upper and lower rockets to a suitable driven height. While under the effect of the separating process, besides the over-expanded nozzle in the upper rocket engine, which produces itself substantially the jet effects, at the same time there exists a short overlapped working time between an operation in the upper and lower rocket engines generally. The hot jet flow within the interstage, which is produced by the upper rocket engine, affects in this case on the nose head of the lower rocket stage, under such an operating process, this jet flow is partly discharged directly through the exhaust holes and therefore is combined and mixed together with cold outer flow.

The enclosed space of the interstage, which is arranged from the nozzle exit of the upper rocket stage up to the nose head of the lower rocket stage, affects another partial jet flow. Such a jet flow will affect directly on the curved nose head of the lower rocket engine. These jet and back flow motions are caused by a thermal stage separation, whose complicated moving process is a temporary change and there exist three-dimensional unsymmetrical flow effects. The construction of such process of thermal stage separation is focused on the following points of emphasis:

- The flow with high pressure and high temperature, which is arisen by the jet flow of the upper rocket engine. How we can reduce such a flow up to permitted ranges of stress in the interstage structure between the two rocket stages?
- How the cold external flow would affect on the thermal flow field in the interstage. Dealing with this should be considered.
- An accelerating collision by the lower stage with the upper stage should be avoided during the separating process.

The above separating phenomena of multi-stage rocket under conditions of high speed and compressible flow motions of aero-thermodynamics still present many unsolvable difficulties in research fields for numerical flow problems. In this paper, the process of thermal stage separation, which affects under the above-mentioned over-expanded nozzle, whose flow field problems are carried out and predicted by an unsteady numerical computation and simulation. This is done with the structural dynamic moving grid and with the so-called overset grid to simulate the relative separating motion of multi-stage rocket at the same time.

2. Computational methods

In this paper we apply the conservation equations solved by the compressible unsteady Navier–Stokes equation based on a coupling density [3,4,8], to simulate and analyze the jet flow problems for the thermal stage separation of multi-stage rocket [6,7,9,10,2].

For the numerical discretisation [5,8], we use the finite volumes method based on a coupling density to solve above-mentioned conservation equations. In the spatial discretisation, the approximated estimation algorithms of upwind flux after Roe are applied by a precision differential format in second order [5]. In the same time we use the MUSCL method of approximation with a limiter after Minmod to treat the following: the numeric flux, the problem of viscosity term, the pressure gradient and the velocity gradient in conservation equations

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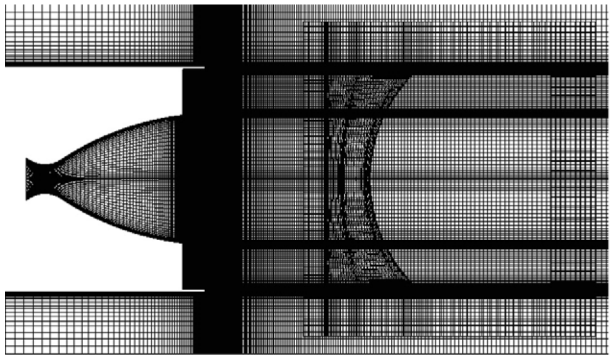

Fig. 1. The structural overset grids of the upper and lower rocket stages (the structural multi-block grid is applied).

with the compressible high Mach-numbers. In this way the intensity and the displacement of shock waves can be captured by the computation of separating flow and the computation accuracy can be also improved. For the temporal discretisation, we use the so-called backward Euler implicit algorithms to treat the unsteady term in conservation equations.

In order to treat the boundary viscosity sufficiently, the so-called model of Sutherland is therefore used by the treating of dynamic viscosity μ. This formula is generally affected directly by the effect of temperature T, the coefficients μ_∞ and T_∞ are 1.79×10^{-5} kg/m s and 273.1 K respectively.

Because the considered flow field problems in this paper, which are caused by the phenomenon of thermal stage separation of multi-stage rocket under conditions with compressible supersonic flow, the developing shock waves have substantially a crucial role within this range. For this reason, we apply the Baldwin–Lomax turbulence model [1] in the computations of all simulation parameters.

3. Overset grid

The necessary physical models in the present paper refer to an unsteady relative separating motion, which is substantially realized under the effect of thrust during a thermal stage separation of a multi-stage rocket engine. In order to compute and simulate this phenomenon, we apply a so-called method of overset grid [3,7] and use the self-adaptive algorithms of Chimera [3,7] to treat the arisen relative motion from the moving mesh system, and to achieve the results of dynamic grid simulation.

Fig. 1 shows the upper and lower rocket stages are segmented by the separating structured grids respectively. In order to refine the local mesh well, additionally, we divide the suitable multi-block grids respectively to increase the accuracy of the computations. While two rocket stages disperse with the separation time, with an overset grid, one can get an appropriate effect of mesh refinement in different separation distances. In this way, the computation accuracy of relative motion is increased during the stage separation.

In the studied rocket stages in this paper there exists no substantial sufficient geometry (e.g. no clear sharp torpedo head… etc.). For this reason, we will initially simplify the separating motion in this paper and consider only the relative separating motion of the lower rocket engine and the external flow field of the upper rocket engine is presented by the zero attack angle.

Table 1
Computational conditions (c.c. = combustion chamber, Abb. = abbreviation)

Notation	Unit	Abb.	Data
Total pressure of c.c.	[kg/cm^2]	P_{to}	30
Gas molecular weight	[g/g-mol]	M	31
Gas constant	[–]	R	1.16
Ambit pressure	[kg/cm^2]	P_a	0.05
Separation height	[km]	H	15
Diameter of rocket	[m]	D	1

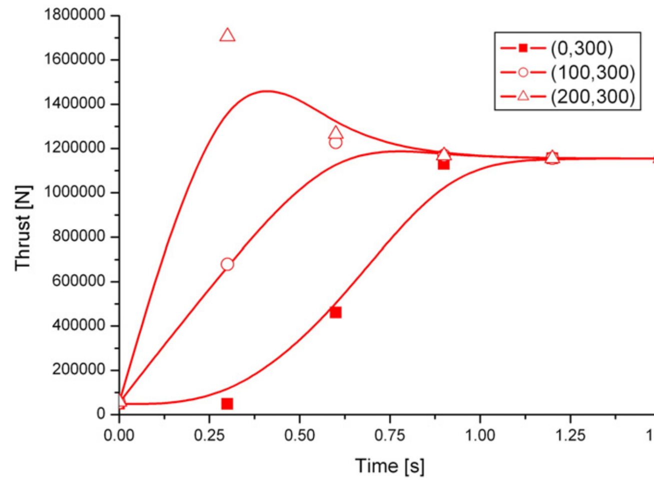

Fig. 2. Distributions of thrust integral for the upper rocket stage over the separation time for the exhaust holes $X=0$, 100, 200 mm and the axial distance of the interstage $Y=300$ mm.

4. Computational conditions and applied geometries

The space of the interstage is determined by the over-expanded nozzle of the upper rocket engine, the nose head of the lower rocket stage and the separation devices, in which on the separation structure of the lower rocket stage within the interstage distributes eight assistance skeletons with 15° angle along circumferential directions respectively. In this paper, we carried out a systematic study with three different simulation parameters of the exhaust hole with length sizes in the axial direction for $X=0$, 100, 200 mm respectively. The axial length of the enclosed space in the interstage has only a same value with $Y=300$ mm for all configurations. Some important conditions applied by the flow computations, are shown in the Table 1.

5. Flow effects within the interstage

In this study, we reduce all computations on a two-dimensional computational mesh and accomplish them with the unsteady Navier–Stokes equations in order to accelerate the computational convergent

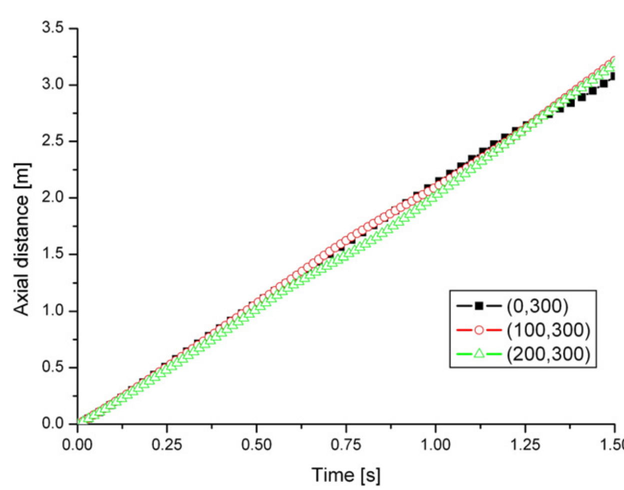

Fig. 3. Distributions of relative separation distance over the separation time for the exhaust holes $X=0$, 100, 200 mm and the axial distance of the interstage $Y=300$ mm.

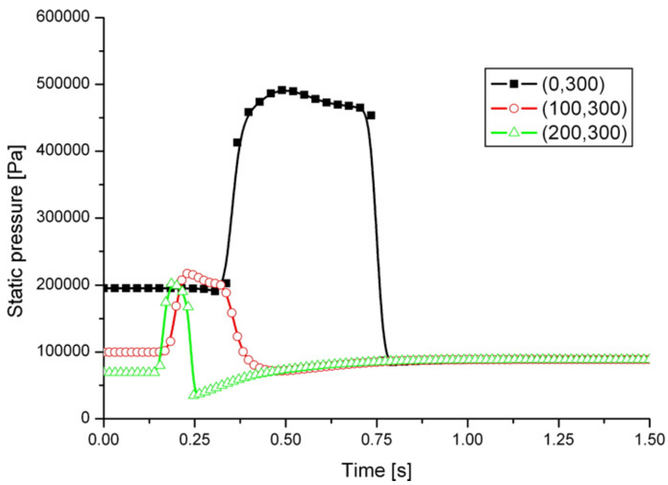

Fig. 4. Axial distributions of static pressure in the nozzle exit center of the upper rocket stage over the separation time for the exhaust holes $X=0$, 100, 200 mm and the axial distance of the interstage $Y=300$ mm.

speed and to predict some flow characteristics of the thermal stage separation at first. In this way we obtain the following computational results and show some important flow effects within the interstage.

5.1. Thrust of the upper rocket engine

Fig. 2 shows the distributions of thrust integral for the upper rocket stage over the separation time. From the obtained results in Fig. 2, one can find that the distributions are influenced by the size of exhaust holes, i.e. the thrust is increased substantially by the enlargement of exhaust holes (X), this tendency continued for approximately 1 s up to the separation time.

5.2. Distance of stage separation

Fig. 3 describes the separation distances of two rocket stages over the separation time under an effect from the thermal stage separation. The results show that the separation distance forms nearly a linear proportional relationship over the separation time. In addition, the separation distance in the interstage is reduced by the increased exhaust hole. But this tendency is not obvious. However, this tendency comparison showed in the computational results of solutions for the Euler equations [9] more obviously.

All studied configurations showed that the relative separation distance develops after the stage separation of two rockets up to the separation time 0.5 s at approximately 1 m. These results are strongly limited under the assumptions of unconsidered relative separation distance of the upper rocket stage with a flight velocity of Mach

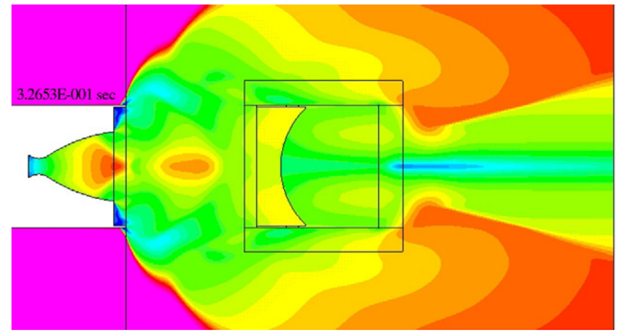

Fig. 6. Distributions of flow field for the Mach number after the iso-surface for the axial length of the exhaust hole with $X=100$ mm at the separation time $t=0.5$ s.

number 4 and in simplified geometry of two stages in this paper. Therefore the above separation distances are smaller than the reality.

5.3. Pressure within the interstage

Fig. 4 describes the axial distribution of static pressure in the nozzle exit center of the upper rocket stage over the separation time. Under the influence of three different configurations of exhaust hole, the static pressures appear to jump in each case by approximately 0.125, 0.2 and 0.3 s. However such a tendency reduces again these strong pressure intensities at about 0.25, 0.375 and 0.8 s respectively up to the ambient pressure.

In addition, it can be found in the figure that the intensity of pressure will be significantly reduced by an enlargement of the exhaust hole. In particular for the pressure distribution in this figure, i.e. the curve for $X=0$ mm, which results from a construction without an exhaust hole within the interstage. This remarkable pressure changes substantially after an ignition of the rocket engine. Such a high pressure flow field within the interstage arises from the jet flow of the upper rocket engine. A strong acceleration performance of a solid rocket engine results generally also in a faster motion of stage separation. In this case, for a short time period, the high pressure change arises substantially yet still has no direct influence on the device structure within the interstage. For this reason, this is also a viable structure construction.

The comparison results between the flow solutions for Euler and Navier–Stokes equations were shown in [9], which are not represented in this paper. On the construction configuration without exhaust hole within the interstage, the maximal pressure intensity of solution for Euler equations arises substantially a relatively weak value at the separation time 0.4 s.

This mainly delivers the above-described results. The pressure intensity within the interstage can be effectively reduced through a

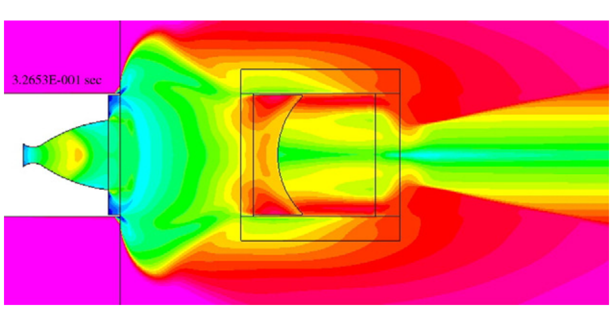

Fig. 5. Distributions of flow field for the Mach number after the iso-surface for the axial length of the exhaust hole with $X=0$ mm at the separation time $t=0.5$ s.

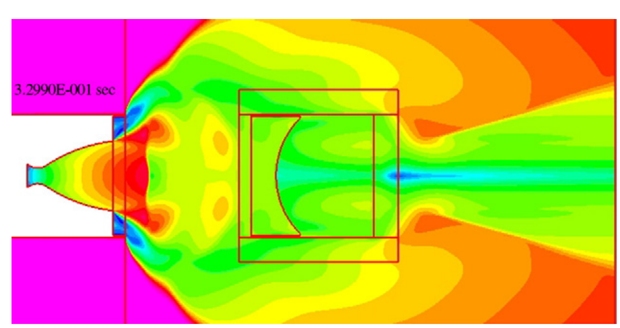

Fig. 7. Distributions of flow field for the Mach number after the iso-surface for the axial length of the exhaust hole with $X=200$ mm at the separation time $t=0.5$ s.

construction with an exhaust hole. Such a change tends to correspond substantially with the distributions of axial flow velocity in [9].

5.4. Flow fields of the Mach-number within the interstage

Figs. 5, 6 and 7 show the distributions of flow field of Mach-number after iso-surface within the interstage for all configurations of exhaust hole with $X=0$, 100 and 200 mm at the separation time $t=0.5$ s The figures show an unsteady flow motion under the effect of different exhaust holes. The normal shock wave, which arises in close proximity to the nozzle exit zone of the upper rocket engine, the position of such a shock wave displaces with an enlargement of exhaust hole substantially from the internal nozzle range to the upstream direction of the interstage. This position of the developing shock wave causes at the same time a discontinuity phenomenon, in which the reduction in the order of magnitude of the Mach number is intensified substantially by the influence from the configuration change of the exhaust holes. In addition, the shock wave structures will be therefore likewise explicitly complicated by the configuration changes of the exhaust hole on these discontinuity positions.

The before-described stage separation is carried out under the condition of high-speed flow with Mach number 4. The developing complicated shock wave structures within the interstage, whose zones of unsteady flow field are not only dependent on the jet flow from the upper rocket nozzle, but are also overreacted by the strong back flow from the nose head of the lower stage and at the same time are strictly repressed again by the cold outer flows with high-speed.

In addition, the wall between the nozzle exit wall and the outside diameter of the upper stage is visibly thick, wherefrom arise the explicit back flow fields in these ranges. Such back flows will be strictly repressed again by the jet flow and the cold external flow. They influence and deduce themselves continuously to the changes of the developing shock wave structures within the interstage. The figures show additionally still a differentiating change of high pressure reduction between the enclosed and the opened configurations of the exhaust hole clearly. Such results correspond substantially with the above distribution tendencies of static pressure.

6. Conclusions

In this paper, by the overset grids and the self-adaptive algorithms of Chimera all testing computations are carried out under the unsteady flow fields for the dynamic thermal stage separation with the restrictions of simplified geometry and some preconditions. The results of such computations are obtained clearly and then the constructions of exhaust hole can directly reduce the strong pressure intensity within the interstage effectively, however the length of the exhaust hole shows only a little of influence on this pressure intensity. When an entire geometry configuration of the upper rocket engine can be considered by the flow computation in the future and at the same time one can consider the relative separation distance and their influence effect on the relative separating motion of two rocket stages with a high flight speed. In this way, one can carry out some accurate unsteady flow simulations about the before-described flow problems within interstage clearly. In addition an un-symmetry flow phenomena can also be studied by three dimensional configuration of the interstage with the exhaust hole.

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References

[1] B. Baldwin, H. Lomax, Thin layer approximation and algebraic model for separated turbulent flow, AIAA Paper 78-0257, AIAA 16th Aerospace Sciences Meeting, 1978.
[2] Renjun Duan, Meng-Rong Li, Tong Yang, Propogation of singularities, The Boltzmann Equation Near Equilibrium, Mathematical Models and Methods in Applied Science, Vol. 18, No. 7, 2008, pp. 1093–1114.
[3] Jinsheng Cai, et al., An oversetgrid solver for viscous computations with multigrid and parallel computing, AIAA-2003-4232, 2003.
[4] C.H. Hirsch, CFD methodology and validation for turbomachinery flows, AGARD Lecture Series on Turbomachinery Design Using CFD, May to June, 1994, pp. 4.1–4.17.
[5] A. Jameson, W. Schmidt, E. Turkel, Numerical solution of the Euler equations by finite volume methods using Runge–Kutta time-stepping schemes, AIAA paper, 1981, p. 1981-1259.
[6] M. Mirzaei, et al., Numerical simulation of stage separation manoeuvre with jet interaction, Aircraft Engineering and Aerospace Technology: An International Journal, 78/3, 2006, pp. 217–225.
[7] R. Schwane, Y. Xia, Time-accurate CFD predictions and data validation for side load generation by flow-structure coupling in over-expanded rocket nozzles, J. Mathemat. Model. Algorithms Vol.4 (2005) 53–65.
[8] T.H. Shieh, M.R. Li, Numeric treatment of contact discontinuity with multi gases, J. Comput. Appl. Math. (2009) to appear.
[9] T.H. Shieh, T.M. Liou, C.H. Liu, et al., Investigation of 3D unsteady flow field for over-expanded nozzle of a solid rocket, Conference for National Defense of Science and Technology, Nov. 2006.
[10] R.A. Wasko, Experimental investigation of stage separation aerodynamics, NASA TN D-868, 1961.