Hypersonic CFD Analysis for the Aerothermodynamic Design of HOPE

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ABSTRACT

Numerical study of hypersonic flow around HOPE (H - II Orbiting Plane) is performed, using upwind TVD Navier-Stokes CFD code. Parametric computations are made to investigate the aero and aerothermodynamic characteristics of HOPE. In our calculations, NWT(Numerical Wind Tunnel) at NAL (National Aerospace laboratory) is used. NWT is the parallel vector super computer system, which enlarges the applicability and data productivity of CFD in practical aerodynamic design. Numerical results are compared with the experimental data obtained at Calspan's shock tunnel. These works have been done as the joint research of NAL and NASDA

1. Introduction

With the increase of our computational ability, computational fluid dynamics (CFD) becomes an important tool for the design of hypersonic vehicles. Through many comparisons with the experimental data, it has become clear that CFD now has the accuracy and reliability in analyzing hypersonic flow phenomena and can give detailed information of complex flows, such as three dimensional separations due to compression surfaces and shock-shock interactions etc. Moreover, aerodynamic heating which greatly influences the aerodynamic design and TPS requirements of hypersonic vehicles, can also be predicted with great accuracy. The need to support aerodynamic design has driven the use of CFD. However, for these design purposes, there is a problem in data productivity. From the design point of view, a great number of parametric studies are needed to determine the optimum configuration of hypersonic vehicles and current super computers are not powerful enough to perform those parametric calculations. To resolve these problems, NWT (Numerical Wind Tunnel) at NAL plays now an important role. NWT, introduced at NAL in 1993, is a parallel vector supercomputer having 140 Processing Elements (PEs). Each PE has 1.7 GFLOPS peak performance and 256 MB main memory. This new computational environment changes significantly the applicability and utility of CFD for aerodynamic design.

We introduce here numerical calculations of the flow around HOPE (H - II Orbiting plane) ¹⁾ using this new parallel machine.

Computation were made by the flux-split TVD Navier-Stokes code ²⁾ at the flow conditions of Calspan's shock tunnel ($M_\infty=12.0\sim19.0$, $\alpha=30, 35, 40\text{deg}$, $Re_\infty=3.15\times10^4\sim1.88\times10^6$) and two typical re-entry flight conditions. In flight conditions, parametric configuration study are made and the effects of angles of attack(α), side slip angle(β) are investigated. Also, real gas effects are analyzed by using chemically non-equilibrium flux difference-splittig code ³⁾ and the decrease of aerothermodynamic heating on the HOPE TPS surface is estimated. In the present study, total of 80 flow cases were computed.

2. HOPE Geometry and Grid

HOPE geometry and typical computational mesh used for the comparison of Calspan's shock tunnel experiments are shown in Fig 1. Present HOPE has tip fin controllers attached to the wing. It's total length is 16.5m from the nose to the fuselage base. Three dimensional basic grids around this configuration are generated by using hyperbolic partial differential equations. Then, computational mesh is constructed, depending on the angles of attack and Mach numbers, because the outer inflow boundary adjusted to the bow shock wave in order to use the grid points efficiently. The clustering of grid point near the body surface is also made to resolve viscous effects. Cell Reynolds number is maintained about 2.0. In the final computational mesh of the basic symmetrical flow case, 91 points are distributed streamwise along the body,

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Fig.1 HOPE Computational Grids

93 points circumferential and 60 points between the body and outside of the bow shock wave. For the side slip flow case, number of mesh points is doubled.

Figures 2 and 3 show HOPE configurations calculated parametrically for the aerothermodynamic configurations design. Model 1000 series are double delta wing type geometry and model 2000 series represent power delta one. For each series of configurations, slight modifications were made and its effects on aerothermodynamic heating are investigated in detail.

3. Numerical Method

Basic equations used in the present analysis, are Navier-Stokes equations with thin-layer assumption. The differencing used for perfect gas flow calculation is upwind TVD flux-split method.²⁾ and real gas computations were made by flux-difference splitting method using 7 species chemically non-equilibrium model³⁾ Detailed description of the numerical algorithm is presented in Ref. 2 and Ref. 3, respectively.

4. Parallel Algorithm

NWT (Numerical Wind Tunnel) system at NAL is used in our parametric calculations for the aerodynamic design of HOPE. NWT is the parallel vector super computer having 140 Processing Elements (PEs). In the present parallel computations, a simple parallel algorithm has been developed; i.e., computational region are equally divided into 6 - 12 zones circumferentially and parallel computations using 6 - 12 PEs are performed for each computational flow regions. In

the present numerical analysis. 10 parametric parallel processes can be performed simultaneously. This means that 10 cases of the different flow conditions are computed in each computational cycle and a total of 60 - 80 PEs of NWT system are used at the same time.

Computational speed using 6 PEs are 5 times faster than that of 1 PE calculation. A 50 - to 100 -fold improvement in computational speed has been attained in the present numerical analysis. Multiple parallel processing now enable us to perform several hundred numerical computations and produce sufficient numerical data for hypersonic aerodynamic design.

Fig.2 HOPE Geometry (Model 1000 Series)

Fig.3 HOPE Geometry (Model 2000 Series)

5. Numerical Results

Computations were made at the flow conditions of the Calspan's shock tunnel. Flow conditions are listed in Table 1. Figure 4 shows the comparisons of heat transfer distributions between numerical results and Calspan's shock tunnel data. Numerical results represent maximum heat transfer plots of each cross sectional plane and experimental results present the heat transfer along the wing leading edge windward point, where local maximum heat transfer may be caused at $\alpha = 40$ deg. Excellent quantitative agreements are obtained except for the wing root area. Validations of present flux-split CFD code were made through the comparisons of Calspan's shock tunnel data and it may be indicated that our CFD code can be used for the aerothermodynamic design of HOPE basic configurations. Then, our validated CFD code are further applied for more improved aerothermodynamic configuration design. Parametric calculations for model 1000 and model 2000 series geometries are made at two flight conditions of Table 2. Angles of attack were taken $\alpha = 30, 35$ and 40 deg for the basic model 1000 and model 2000 geometry. For the other models with slight modifications, angles of attack are fixed to 35 deg. For all the numerical test cases, the effect of side slip angle ($\beta = 5$ deg) are also investigated. Fig.5 shows oilflow patterns of the windward and leeward surfaces of model 2000 at $\alpha = 35$ deg, $\beta = 5$ deg. In a series of parametric computations, it must be denoted that slight change of wing sweep angle and tip fin controllers has a great influence on heat transfer distributions of double delta type models (model 1000 series), whereas no noticeable effects are observed for the power delta type models (model 2000 series). Detailed results will be presented later.

Real gas effects at high Mach numbers are investigated by non-equilibrium flow calculations. In Fig 6, the comparison of maximum heat transfer distributions between the perfect and real gas computations are shown at the two flight conditions for Model 1000 geometry. Constant wall temperature of 1200K and non-catalytic wall condition are assumed. In the high Mach numbers ($M_\infty = 26$) and altitude (80Km) case, local peak heating on the nose, wing and tip fin leading edges is simultaneously decreased for the real gas flow results. However, low Mach number ($M_\infty = 17$) and altitude (65Km) case, local peak heating on the wing leading edge has almost the same between two codes. This may be caused due to the difference of freestream density and velocity of each altitude. Finally atomic oxygen mass fraction contours are presented in Fig.7 for the power delta type model at an altitude of 65 Km .

6. Conclusions

In summary, we conclude;

- 1) For aerothermodynamic heating, present flux-split Navier-Stokes CFD code gives excellent quantitative agreements with Calspan's shock tunnel data and it is indicated that CFD can be used as the reliable tool for the aerothermodynamic design of HOPE
- 2) Parallel computations using NWT system at NAL can now produce as many numerical results as the current HWT can do, and CFD becomes a highly efficient tool for the design of HOPE geometries.
- 3) Through a series of parametric calculations by NWT, it is shown that slight change of configuration has a considerable effect on aerothermodynamic peak heating for double delta type HOPE configurations
- 4) In order to simulate the actual re-entry flight conditions of HOPE, chemically non-equilibrium flux difference splitting code has been applied, using 7 species, one temperature model. Real gas effects appear in decreasing aerothermodynamic peak heating on the nose, wing and tip fin leading edges. However, these effects depend on the flight velocity, altitude, and wall catalicity. Therefore, more careful and precise analysis are needed through the considerable number of validation process of the real gas CFD code.

References

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	Model	Case	M -	α (deg)	U - (m/sec)	T - (K)	P - (Pa)	Re - (/Total Length)
WING I	Wing LE sweep $\Lambda = 48$ deg Basic Model	1	15.34	30	2083.3	45.86	60.2	1.18×10^6
		2	15.34	35	2083.3	45.86	60.2	1.18×10^6
		3	15.34	40	2083.3	45.86	60.2	1.18×10^6
		4	13.51	35	4303.8	252.3	20.9	3.15×10^6
		5	18.92	35	2367.7	38.96	29.8	9.22×10^6
WING II	Wing LE sweep $\Lambda = 48$ deg Cylindrical Wing LE	6	15.34	35	2083.3	45.86	60.2	1.18×10^6
WING III	Wing LE sweep $\Lambda = 60$ deg Cylindrical Wing LE Tip Fin Forward	7	12.12	30	2226.3	83.9	298.4	1.88×10^6
		8	12.06	35	2221.7	84.3	302.4	1.88×10^6
		9	12.04	40	2236.6	85.78	303.4	1.835×10^6
		10	18.36	35	2362.5	41.17	36.8	1.02×10^6

Table 1 HOPE06 Computation Case (Comparision with Calspan's Shock Tunnel Data)

Fig.4

Comparison of Heat Transfer Distributions near the Wing Leading Edge

- Calspan's Shock Tunnel Data (along the Wing Stagnation Line $\theta = 40^\circ$)
- Numerical Result (Maximum Heat Flux at Each Cross Section)

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Flow condition A	Altitude 80km $M_{\infty} = 26$ $U_{\infty} = 7346 \text{ m/s}$ $T_{\infty} = 198.6 \text{ K}$ $P_{\infty} = 1.053 \text{ Pa}$ $T_{\text{wall}} = 1200 \text{ K}$ $Re_{\infty} = 1.409 \times 10^6$
Flow condition B	Altitude 65km $M_{\infty} = 17$ $U_{\infty} = 5205.3 \text{ m/s}$ $T_{\infty} = 233.3 \text{ K}$ $P_{\infty} = 10.93 \text{ Pa}$ $T_{\text{wall}} = 1200 \text{ K}$ $Re_{\infty} = 8.059 \times 10^5$

Table 2

Altitude 80km, $M_{\infty} = 26$, $V_{\infty} = 7346.0 \text{ m/s}$
 $T_{\infty} = 198 \text{ K}$, $P_{\infty} = 1.053 \text{ Pa}$, $T_w = 1200 \text{ K}$

Fig.5 Oil Flow Patterns of HOPE Power Delta Model (Model 2000)

(Model 1000) at $M_{\infty} = 26$, $\alpha = 35 \text{ deg}$

Fig.6

Real and Perfect Gas Comparison of Maximum Heat Transfer Distributions at Each Cross Section of HOPE (Model 1000) at $M_{\infty} = 17$, $\alpha = 35 \text{ deg}$