CFD ANALYSIS OF AERODYNAMIC HEATING FOR HYFLEX HIGH ENTHALPY FLOW TESTS AND FLIGHT CONDITIONS

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Abstract

HYFLEX (Hypersonic flight Experiment) was conducted in February 1996. In the present study, surface temperature history of HYFLEX C/C nose cap is analyzed by CFD-FEM coupling simulation.

With the rebuilding of the aerothermal environments of HYFLEX flight, CFD analysis of the post flight wind tunnel experiments are also made to compare the aerodynamic heating. In the latter half of the paper, real gas CFD computations, corresponding to ONERA F4 hot shot tunnel heat transfer measurements, are reported.

1 Introduction

HYFLEX flight experiment was conducted in February 1996. Figure 1 shows surface temperature history of HYFLEX flight, simulated by CFD-FEM coupling analysis [1]. In the figure, surface temperature change is demonstrated at ten seconds intervals with HYFLEX flight attitude. At the start of re-entry flight, constant temperature Twall = 300 K is assumed. In hypersonic flight range from flight time 50 to 200 sec, maximum nose heating is produced at the flight time of 130 sec and maximum temperature of 1450 K is caused on the C/C nose stagnation region at the flight time of 150 sec. CFD/FEM coupling method developed previously, can predict these phenomena and comparisons were made on ceramic TPS (thermal protection system) tiles with the laminar flow assumption. However, from the flight time of 120 sec, turbulent transition took place and rapid increase of aerodynamic heating was observed on the ceramic tile windward surface. So, computations of turbulent flow, using Baldwin-Lomax turbulence model, are made from the flight time of 120 to 150 sec. After the latter flight time, flow relaminalizations started. On the other hand, the processing of the temperature data on the HYFLEX C/C nose cap was made recently [2]. In this report, final comparisons of the temperature increase of C/C nose cap and turbulent heating are reported. Through these comparisons, a series complete aerothermal evaluation of HYFLEX TPS is accomplished by present CFD/FEM coupling method.

After HYFLEX flight experiment, various wind tunnel tests are being made, using NAL/1.27m and ONERA S4MA large cold hypersonic wind tunnels. Real gas effects are also investigated by using high enthalpy facilities such as HEK, the medium size free-piston shock tunnel at Kakuda Research Center of NAL and ONERA F4 hot shot tunnel. These wind tunnel experiments are conducted to re-simulate again the HYFLEX re-entry flight environments and to compare their data with the flight data by setting the nozzle exit flow conditions such as Mach and Reynolds numbers equal to the flight value. However, the capability of reproducing circumstances during re-entry is limited for the ground-based facilities. So, it is needed to construct the general extrapolation method from the ground to the flight conditions [3]. CFD plays a great important role to investigate the correlations between the wind tunnel experiments and the flight data. In the final part of Ref. [4], CFD analysis for HYFLEX wind tunnel experiments of HEK heat transfer measurements were reported. In this paper, CFD analysis for HYFLEX wind tunnel experiments is introduced and typical comparisons with ONERA F4 hot shot tunnel heat transfer measurements are reported.

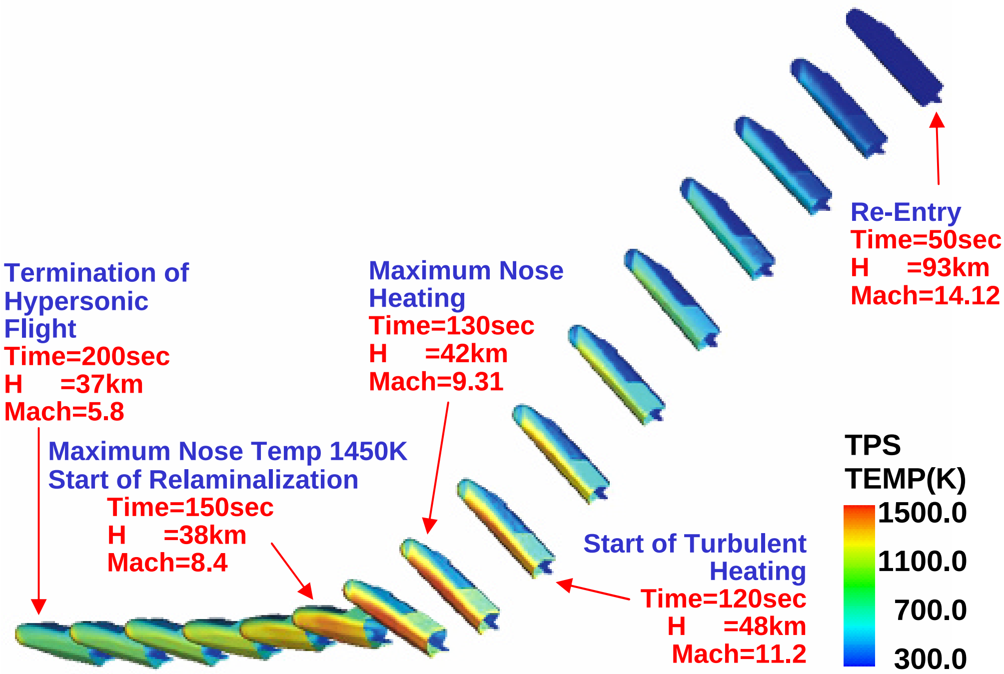


Fig. 1. HYFLEX Re-Entry Flight Simulation Representing TPS Surface Temperature Change at 10 sec Intervals in Hypersonic Speed Range

2 Numerical Rebuilding of Aerothermal Environments by CFD/FEM Coupling Method

2.1 Grid for Outer Flow CFD Computations

In Figs. 2 and 3, HYFLEX configuration and computational grids for outer flow calculations are shown. Hyperbolic grid generation method is applied for constructing the computational grids. On the surface, 101 points are distributed from the nose to the fuselage with 89 points in the circumferential direction. Outer boundary is determined to include the bow shock wave and 61 points are used from the body surface to the outer boundary.

2.2 CFD Analysis of Outer Flows

In the preset study, Navier-Stokes CFD code based on flux-split type upwind scheme is used for outer flow computations. Parallel computations made by using 8 PE units of NWT systems (Numerical Wind Tunnel systems at NAL). Heat transfer data is calculated by using the wall temperature distributions given by the FEM analysis.

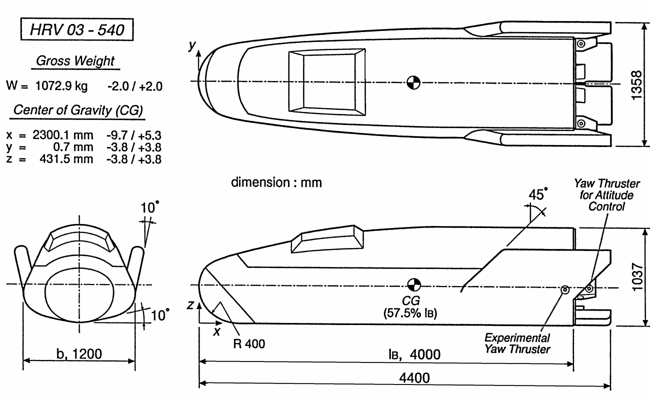


Fig. 2. HYFLEX Vehicle Configuration

2.3 FEM Thermal Analysis

Basic equations are three dimensional unsteady heat conduction equations. Numerical scheme is based on CGM methods and 8 iso-parametric elements are used for the present FEM analysis. For time integrations, Crank-Nicolson implicit method is applied. In the present study, FEM analysis was also made by 6 PE parallel computations using NWT.

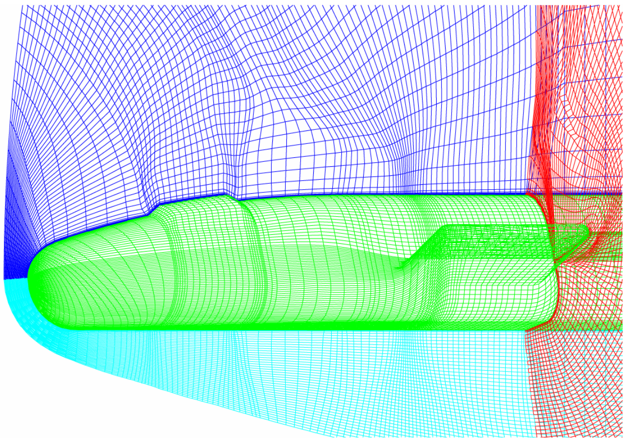


Fig. 3. CFD Grids for Outer Flow Calculations (101x89x61)

2.4 Numerical Results for TPS Aero-Thermal Environment

HYFLEX main TPS systems are composed of 4 mm thick C/C nose cap and 25 mm thick ceramic tiles, as shown in Fig. 4. In the figure surface temperature measurement locations are also indicated. There were 21 sensors, 8 in C/C TPS region (nose cap and body flap surface), 11 in ceramic tiles (from TA21 to TA44) and 2 in flexible insulation surface (TA46, 48). In FEM analysis, the effects of temperature dependence of thermal properties of each TPS are included and directional dependence of specific heat and thermal conductivity for C/C nose cap is also evaluated. Radiation effects from the outer TPS surface are computed by assuming the constant emissivity of *e* equal to 0.85 for both C/C and ceramic TPS.

For these TPS aero-thermal structures, CFD/FEM coupling simulations are performed at 10 seconds intervals along the HYFLEX trajectory listed in Table 1. Inner FEM TPS mesh coincides with the outer flow CFD mesh on the surface and totally 150,000 nodes are used. Detailed coupling procedures are described in Ref. [1].

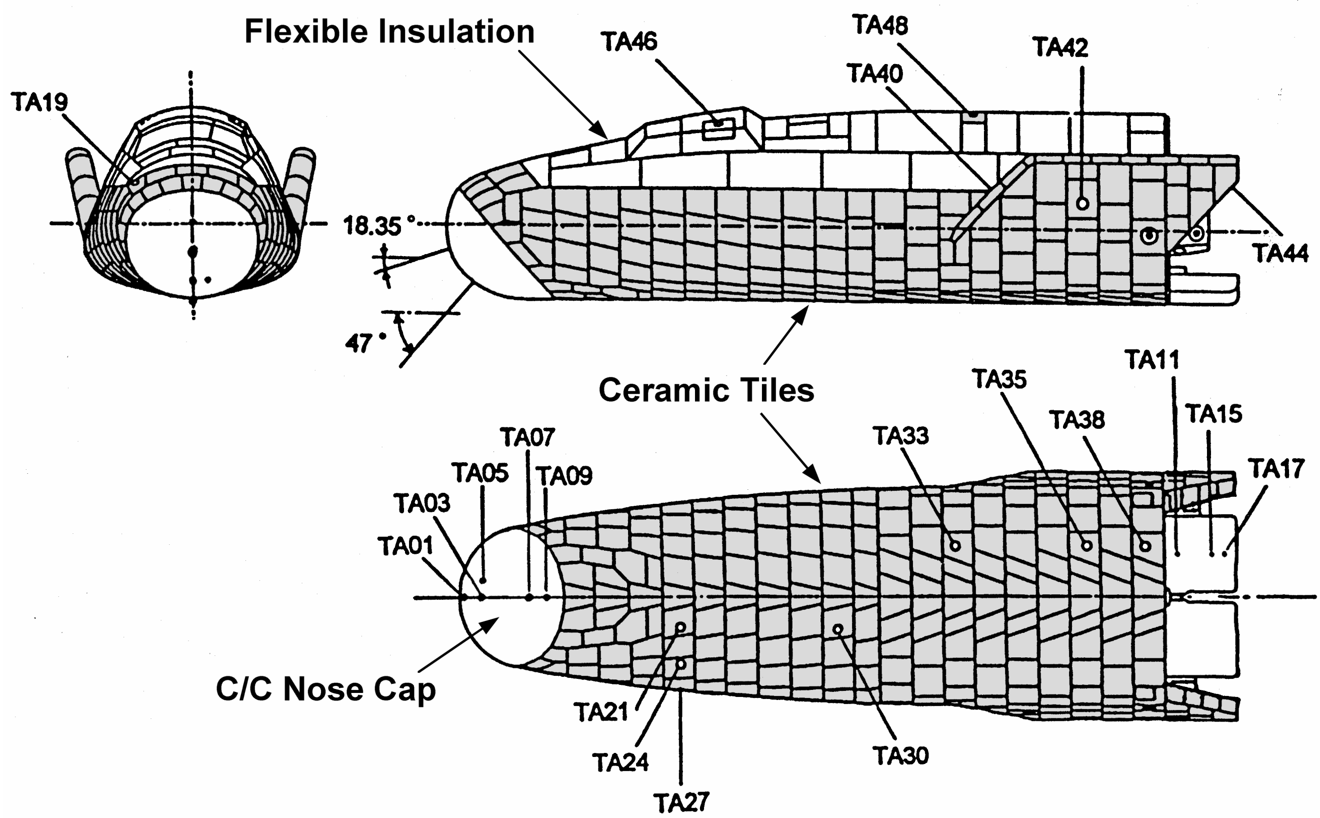


Fig. 4. HYFLEX TPS and Temperature Measurement Locations

Table 1. HYFLEX Flight Trajectory

Time t [sec]	Altitude H [m]	Velocity U_∞ [m/sec]	Temp. T_∞ [K]	Pressure P_∞ [Pa]	Density ρ_∞ [kg/m^3]	Mach M_∞	AoA α [deg]
50.44	93043	3932.4	194.82	0.10982	1.90E-06	14.12	48.914
60.44	88167	3932.5	194.39	0.25266	4.65E-06	14.276	49.395
70.44	82701	3933.3	200.23	0.63898	1.20E-05	14.109	48.327
80.44	76564	3919.2	211.21	1.7277	3.15E-05	13.643	50.519
90.44	69822	3918.8	223.44	4.8786	8.49E-05	13.177	49.959
100.44	62632	3895.9	238.28	13.821	0.000222	12.55	49.044
110.44	55103	3840.6	252.61	38.69	0.000561	11.87	48.902
120.44	47963	3690.1	262.82	97.676	0.001323	11.189	48.793
130.44	42502	3348.5	258.14	197.5	0.002788	10.414	46.76
140.44	39575	2947.5	252.63	290.48	0.004251	9.3145	39.236
150.44	38670	2650.4	250.95	327.94	0.004858	3.4178	32.899
160.44	38075	2436.6	249.77	355.44	0.005307	7.7647	28.992
170.44	37625	2259.3	248.6	377.78	0.005676	7.2183	29.362
180.44	37411	2093.1	247.98	388.97	0.005862	6.6953	29.414
190.44	37173	1939.1	247.21	401.74	0.006075	6.2112	29.401
200.44	37175	1800.1	274.31	401.55	0.006073	5.7658	29.462
220.44	36514	1606.1	245.63	439.38	0.006711	5.1638	29.593
240.44	35697	1400.6	242.78	294.13	0.007602	4.5246	29.689
260.44	34756	1219	239.93	561.87	0.008789	3.9598	29.834
280.44	33585	1040.3	235.72	663.67	0.010553	3.4026	30.097
300.44	32435	893.72	231.36	783.52	0.012659	2.9434	30.25
320.44	31268	730.56	227.5	930.41	0.015158	2.4147	34.911
340.44	29851	584.97	224.02	1150.2	0.018838	1.9395	35.19

2.5 C/C Nose Cap

Aerodynamic heating was measured at five locations on the C/C nose cap. In the symmetry cross section, four measurement points are arranged as shown in Fig. 5. Point TA03 is located near the nose stagnation point during the initial stage of HYFLEX re-entry flight, where HYFLEX flew at a constant angle of attack of α = 49 deg. until the flight time of 120 sec.

Comparisons of temperature increase at these measurement points are presented in Fig. 6. Flight data are recently derived from the measured temperatures by the procedures described in Ref. 2. Inferred flight temperatures are reported up to the flight time of 120 sec. As shown in the figure, present CFD/FEM coupling method simulates well with these inferred flight temperature increase. Also, temperature data obtained by using ANSYS thermal analysis software are plotted in the figure. Agreements between numerical and ANSYS results are excellent. Using the same heat transfer distributions derived by the CFD/FEM coupling identification analysis makes predictions by ANSYS.

After the flight time of 120 sec, it is remarked that inner radiation effect becomes significant from the back surface of the C/C nose cap. The flexible insulator attached to the bulkhead is heated up and a strong reflection comes to the rear surface of the C/C nose the bulkhead insulator. To take this phenomenon into account, analysis using ANSYS thermal software has been made with and without the computations of the inner radiation. Typical ANSYS results are presented at the flight time of 150 sec, where maximum temperature revealed on the C/C nose cap during HYFLEX re-entry flight. In Fig. 7, temperature contours are depicted for the cases with and without the inner radiation. The difference of the maximum nose stagnation temperature becomes more than 100 K. Temperature of the bulk head insulator increases about 1200 K by this radiation effect.

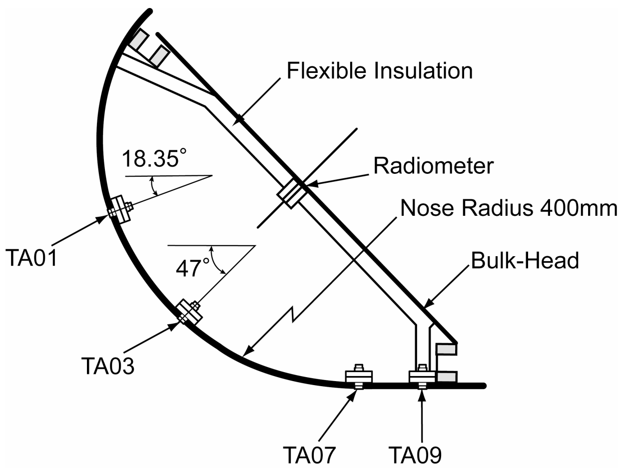


Fig. 5. C/C Nose Cap Temperature Measurements Points

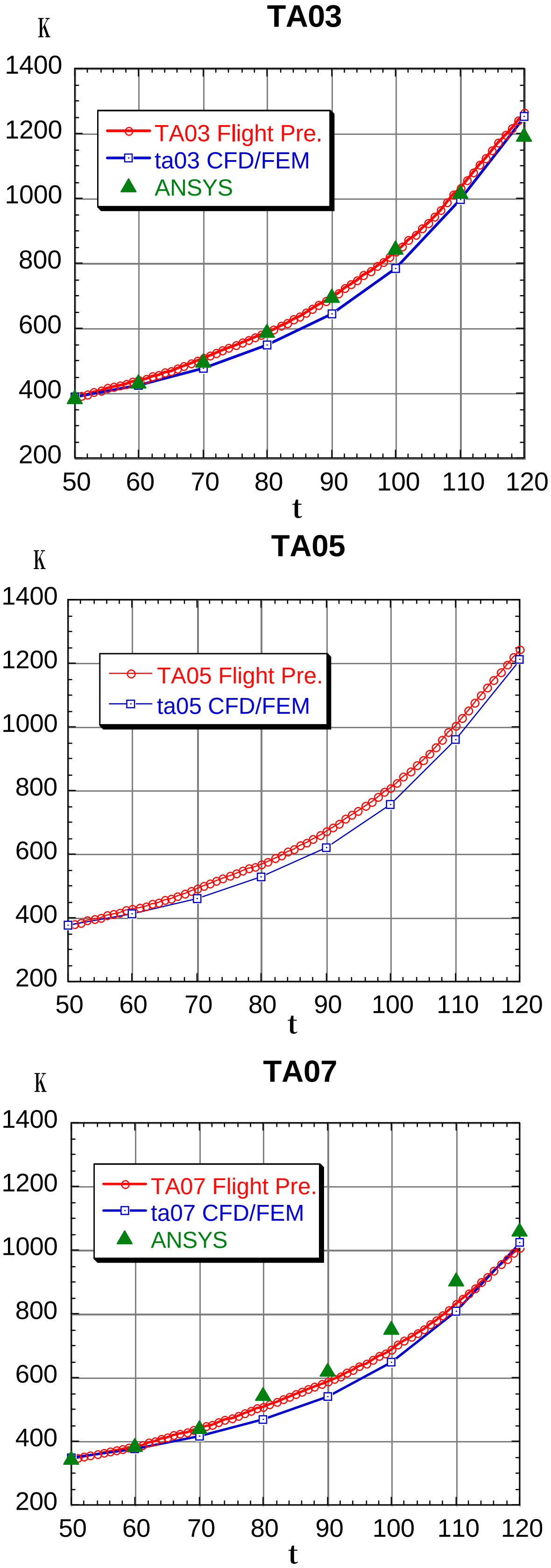
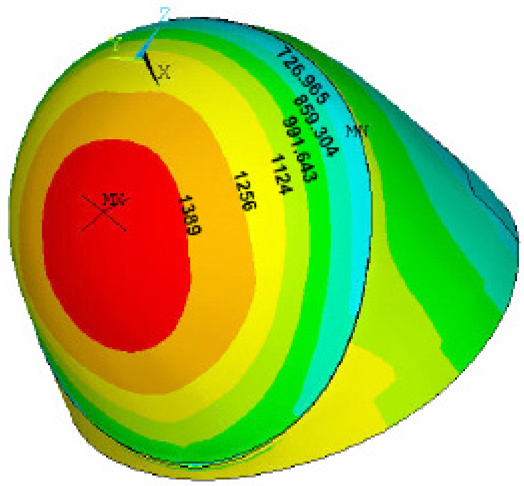
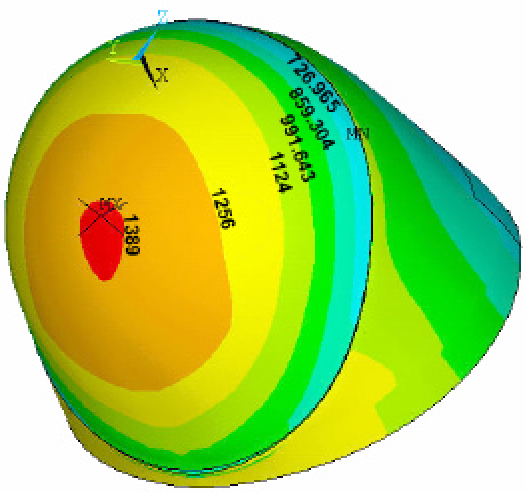


Fig. 6. Comparisons of Temperature Increase of HYFLEX C/C Nose Cap with Flight Data



(a) Without Inner Radiation



(b) With Inner Radiation Effects

Fig. 7. Comparisons of Nose Temperature with and without Inner Radiation Effect

3 CFD Analysis of HYFLEX Tests at ONERA F4 Hot Shot Facility

In this section, CFD analysis of aerodynamic heating of HYFLEX model at ONERA F4 hot shot facility is summarized.

3.1 Summary of ONERA F4 Tests

ONERA F4 hot shot tunnel is impulsively arc heated high enthalpy facility and one of the most reliable test facilities in evaluating real gas flow phenomena with its high level intrusive measurement systems. HYFLEX 10 % scaled model was tested as shown in Fig. 8 and three test conditions are selected for CFD computations. Test conditions are listed in Table 2. For case 1, Reynolds and Mach numbers of the F4 test agree with the HYFLEX flight condition at flight time of 107 sec. For case 2 and 2' free stream velocity, temperature and pressure coincide with those at the HYFLEX flight. In the latter case, Reynolds number in F4 test is about one order lower than the flight. In F4 test conditions, compared with the HEK experiments, Mach number is high and total enthalpy is low. In Fig. 9 shock wave geometry are compared with the schrielen photographs in F4 test.

3.2 Numerical Method for Real Gas Analysis

Numerical scheme is based on Roe-type flux difference splinting method. Chemically non-equilibrium one temperature Navier-Stokes code developed by Wada [5] is applied with Park's 7 species 24 chemical reaction model. In the present computations, full-catalytic wall is assumed at the constant surface temperature of 300K.

Present real gas code is compared with the other two temperature Navier-Stokes codes at the HEK test conditions and reliability of the present code with Park's chemical reaction models are confirmed through the comparisons of the temperature and mass fraction distributions near the stagnation point stream lines [6].

3.3 Comparisons of Heat Transfer Distributions

In Fig. 10, comparisons of heat transfer distributions are shown for ORERA F4 hot shot tunnel test conditions. For all test cases, angle of attack is fixed at α = 49 deg. Numerical results show good agreements with ONERA F4 test data on the nose region. However, downward from the nose, discrepancy with the experimental data is revealed. In experimental data, corrections of the conical flow effect on the nozzle exit are not made. It is noted that through these corrections, experimental data becomes higher and close to the numerical results. Also, lower value of the experiments may be due to that measurement points on the windward fuselage are located slightly of the windward symmetry line, whereas numerical results are plotted along the symmetry line.

Table 2. HYFLEX Computational Cases of ONERA F4 tests and Flight

Case	F4/ Flight	Time [sec]	U_∞ [m/sec]	T_∞ [K]	p_∞ [Pa]	ρ_∞ [Kg/m^3]	M_∞	R_∞	α [deg]	T_{wall} [K]
Case1	Shot982	0.1448	2867.83	129.41	125.508	3.3678x10^{-3}	12.23	3.9888x10^{5}	49.0	300
	Flight	107	3871.07	247.22	27.640	3.8793x10^{-4}	12.26	3.7861x10^{5}	48.932	575.61 at TA03
Case2	Shot973	0.0928	3755.99	288.18	83.478	9.8801x10^{-4}	10.78	8.3940x10^{4}	49.0	300
	Flight	118	3739.41	261.10	78.857	1.0479x10^{-3}	11.52	9.4561x10^{5}	48.924	721.88 at TA03
Case2'	Shot982	0.1348	3474.48	234.54	171.999	2.5464x10^{-3}	11.02	2.3518x10^{5}	49.0	300
	Flight	128	3444.56	259.57	170.084	2.2736x10^{-3}	10.64	1.8987x10^{6}	47.983	883.51 at TA03

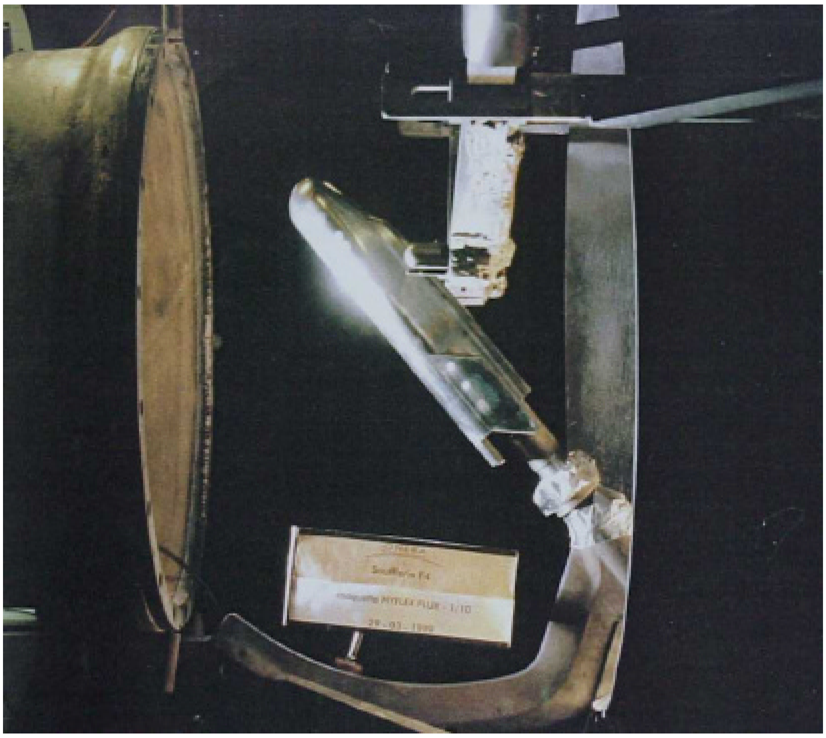


Fig. 8. HYFLEX 10 % Scale Model Setting in ONERA F4

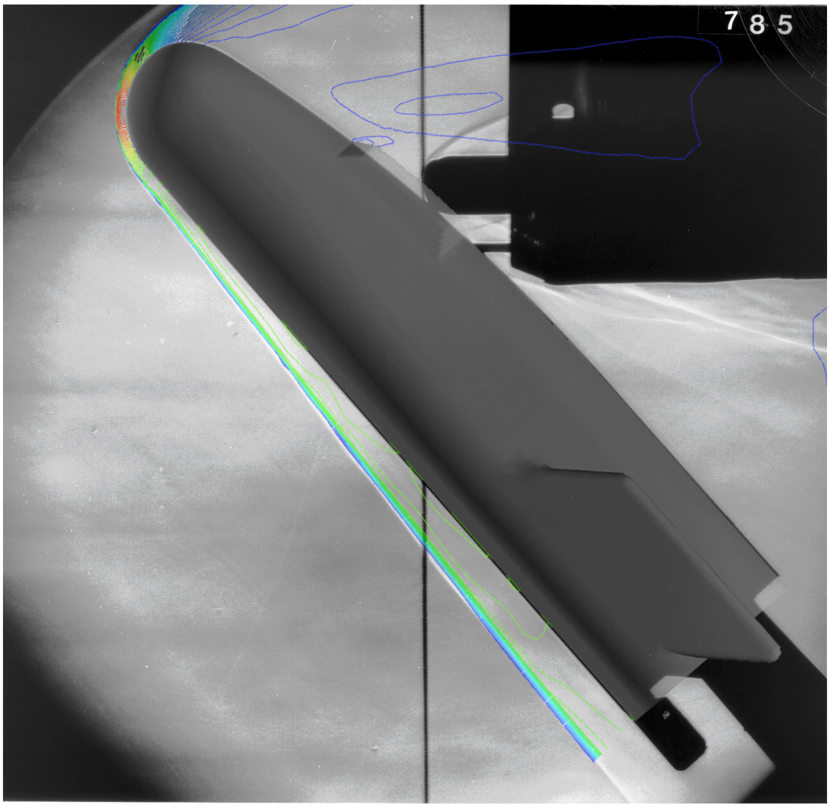
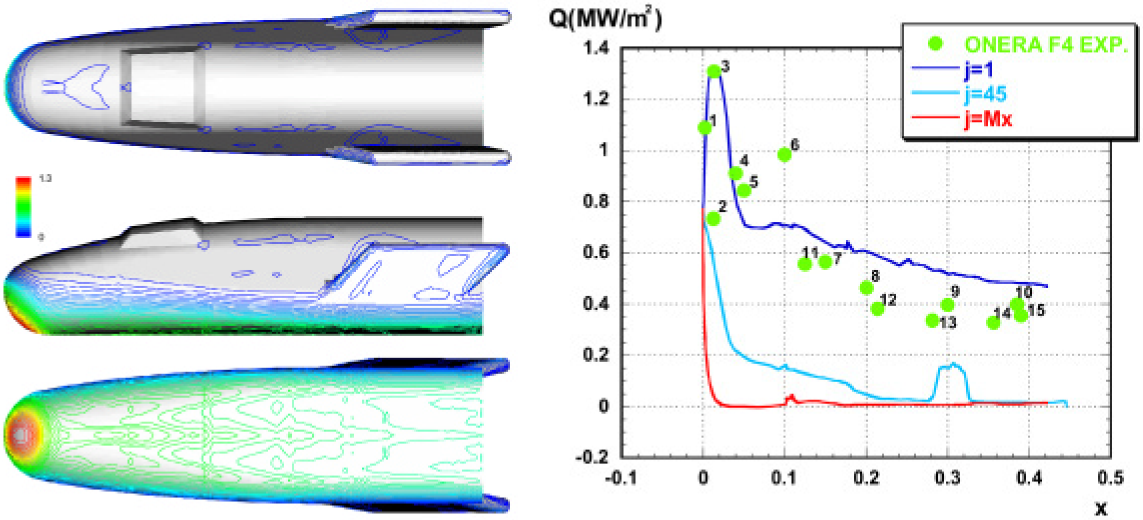
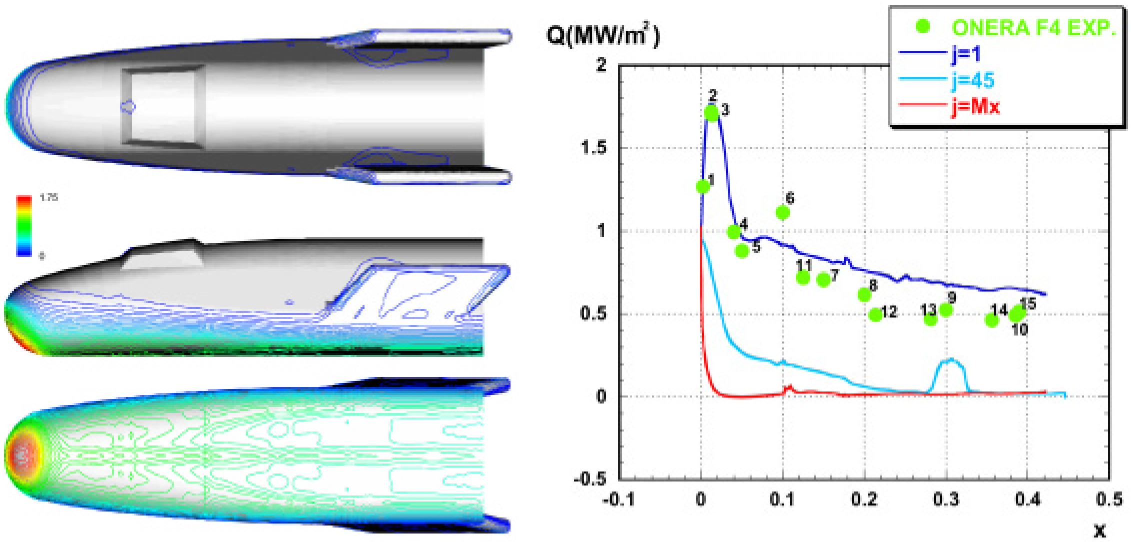


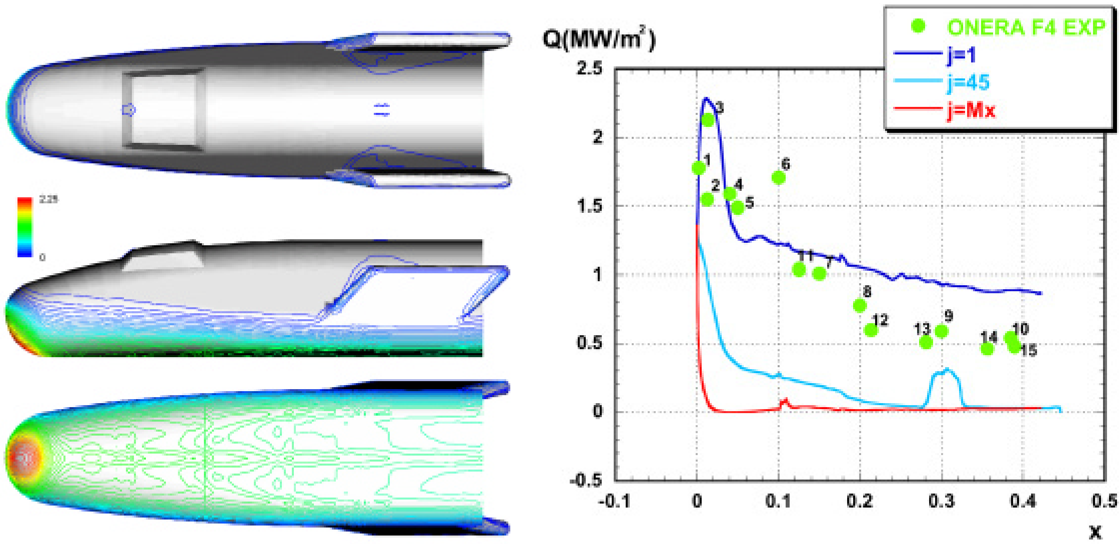
Fig. 9. Comparison of Shock Wave Shape with Schrielen Photograph in ONERA F4



(a) ONERA F4 case1



(b) ONERA F4 case2



(c) ONERA F4 case2'

Fig. 10. Heat Transfer Contours and Comparisons of Heat Transfer Distributions

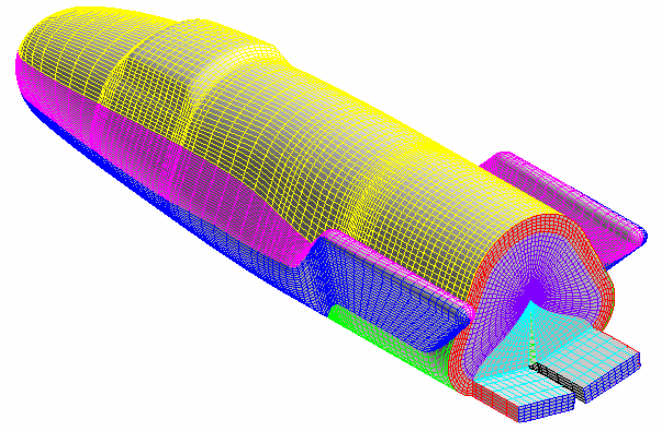


Fig. 11. Surface Mesh for Base Flow Calculation

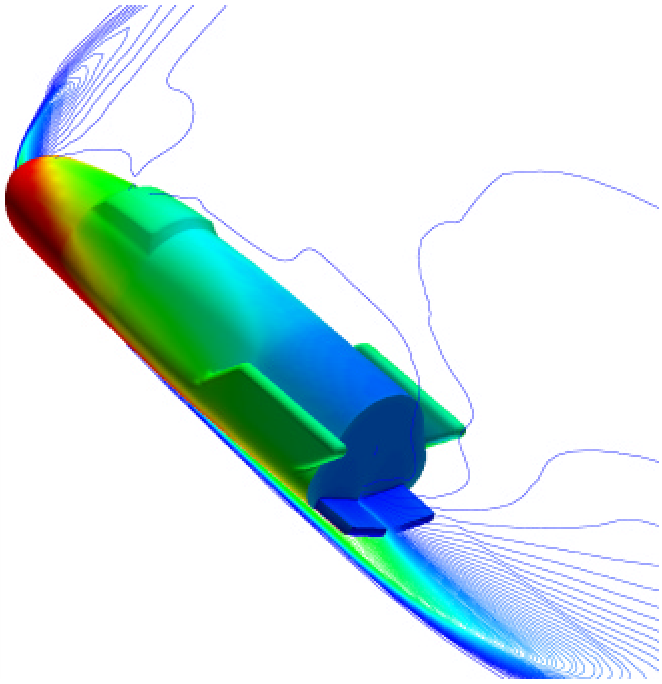


Fig. 12. Pressure Contours

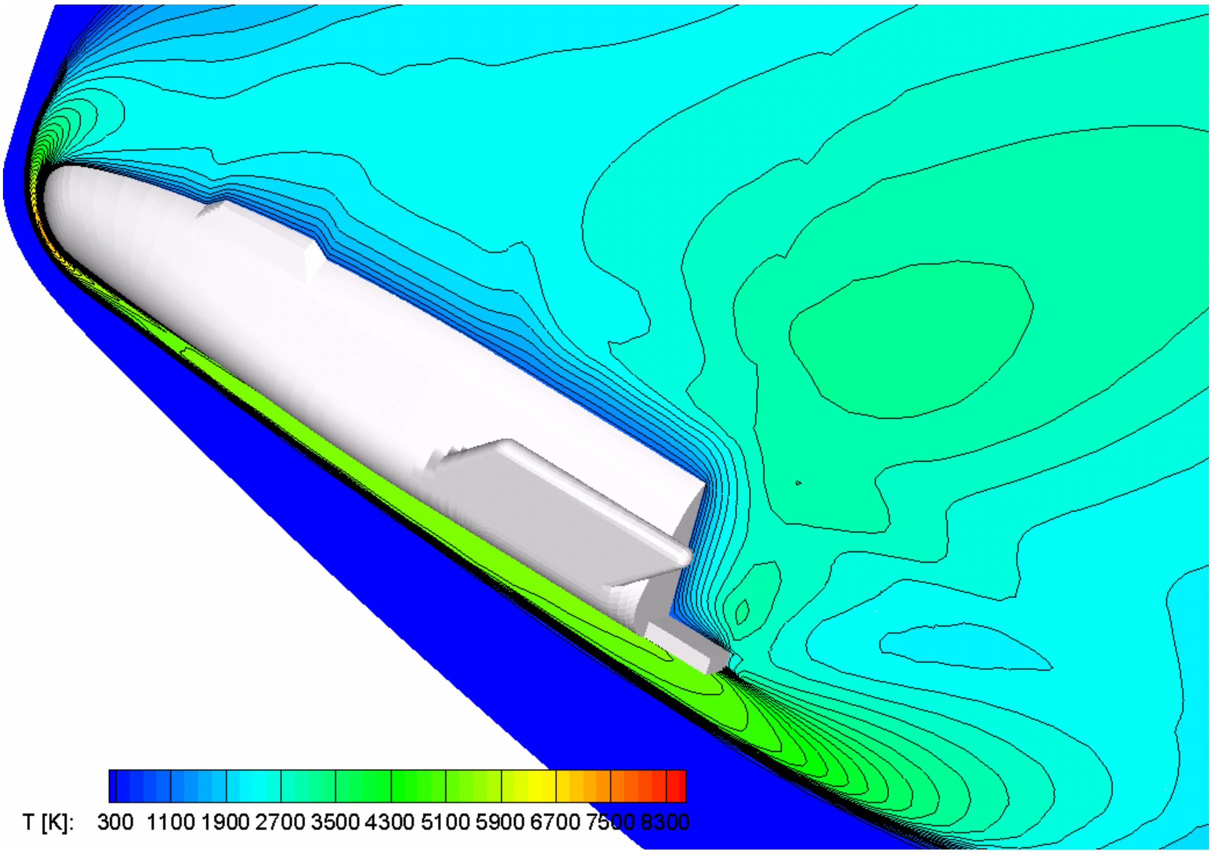


Fig. 13. Temperature Contours

3.4 Computation of Base Flow

The surface mesh for base flow calculation is shown in Fig. 11. In the figure, the body flap angle is fixed at 0 deg. In the present study, multi block code based on AUSMDV and Shock Fix [7] is used for base flow calculations, and computational domain is divided into 17 blocks. The total number of grid points is 287,285.

The result of perfect gas case at Mach number of 14.1 is shown in Figs 12 and 13. The free stream conditions are as follows: angle of attack is 48 deg, Reynolds number is 1.3428E+04 and free stream temperature is 200.2 K. Fig. 12 shows pressure contour on symmetric surface. It is known that shock wave gets near the body flap by real gas effects [1]. We will extend the present calculation to non-equilibrium real gas flow. From the temperature distributions shown in Fig. 13, high temperature gas flows along body and body flap, then flows into base region with strong expansion. Therefore, the aerodynamic heating of lower surface of body flap may become higher than upper surface even if body flap angle is 0 deg. The detail and quantitative calculations are underway. The non-equilibrium multi block code is also developing at this moment.

4 Conclusions

CFD/FEM coupling analysis and comparisons with the flight data have been conducted for the evaluation of the temperature increase on the C/C nose cap TPS. Results show good agreements with the available flight data.

For HYFLEX experiment, post flight wind tunnel tests have being made to compare the aerodynamic heating. In the present study, real gas flow analysis is made for the evaluation of ONERA F4 hot shot experiments. Heat transfer distributions can be predicted quantitatively well. Extension of the present computations to the base flow region is underway.

5 Acknowledgements

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