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Aerothermodynamic Optimization and Design Analysis of a Novel Reusable Launch Vehicle using Numerical Techniques

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Presented By
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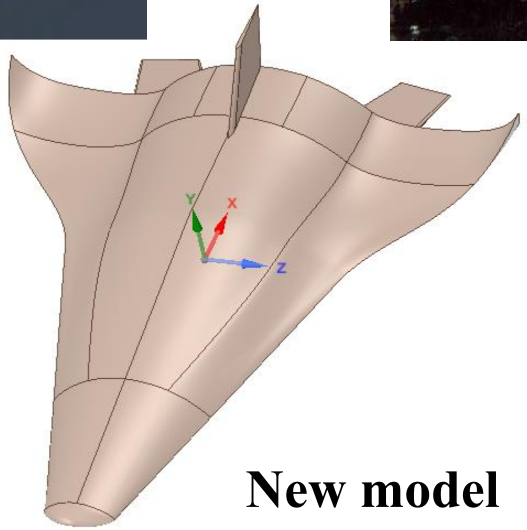
Introduction

HTV

Martin X-33



New model RLV

Literature Review

Title	Author names	Main Focus	Year	Numerical Or Experimental
Aerodynamic and Aeroheating Computations for Wind Tunnel and Flight Conditions XĐ33 Aerodynamic and Aeroheating Computations for Wind Tunnel and Flight Conditions	Brian R. Hollis, Richard Thompson, Kelly J. Murphy, Robert J. Nowak, Christopher J. Riley, William A. Wood and Stephen J. Alter	Hypersonic CFD studies validate essential technologies for experimental Single-Stage-to-Orbit craft.	1999	Both.
Aerothermodynamic Optimization of Hypersonic Vehicle TPS Design by a POD/RSM-Based Approach	P.C. Chen1, D.D. Liu2, K.T. Chang3, L. Tang3, X.W. Gao3, Amarshi Bhungalia4 Phil Beran5, Wei Shyy6	This paper describes TPS design using POD/RSM aerodynamic method.	2006	Both
Aerothermal Characterisation of a Typical Re-entry Module in Hypersonic Flow Regime	Devashish Bhalla2 , G. Vidya1 , Manoj T. Nair2	Thermal characteristics of a re-entry module flow field are analyzed.	2021	Both

Literature Review

A study on heat flux predictions for re-entry flight analysis	**Raman Balu, A.R.Arnalt Stalin ,Prince Raj L**	**analysis of heat transfer occurring at hypersonic and hyper velocity flow regimes over re-entry configurations**	**2012**	**Numerical**
Aerothermal environment definition for a reusable experimental re-entry vehicle wing	Francesco Battista1, Giuseppe C. Rufolo2, Marco Di Clemente3	A simplified methodology is developed to evaluate wing aerothermal environment.	2007	Both but mostly numerical
An aerothermodynamic design optimization framework for hypersonic vehicles	Simone Di Giorgio, Domenico Quagliarella, Giuseppe Pezzella, Sergio Pirozzoli	A highly integrated design environment is developed for aerothermodynamic optimization.	2018	Experimental

Literature Review

Constrained Optimization of Three-Dimensional Hypersonic Vehicle Configurations	**Scott G. Sheffer 1 and George S. Dulikravich 2**	**A constrained shape optimization procedure is presented.**	**1993**	**Both**
Multidisciplinary optimization of airbreathing hypersonic vehicles	Kevin G. Bowcutt	An MDO design system was developed combining propulsion, aerodynamics, mass properties, and modeling. optimization of a hypersonic cruise missile to maximize overall mission range	2001	Both
Rapid supersonic/hypersonic aerodynamics analysis model for arbitrary geometries	Marcus A. Lobbia	A unique implementation of supersonic/hypersonic analysis techniques is developed for automation.	2016	Experimental

Literature Review

Aeroelastic and Aero thermoelastic Analysis of Hypersonic Vehicles	**Jack J. McNamara∗ and Peretz P. Friedmann**	**the objective of this paper is to survey the** **status of research in the area of hypersonic aeroelasticity and aerothermoelasticity.**	**2006**	**Numerical**
Calculation of Heat Transfer and Drag Coefficients for Aircraft Geometric Models	Victor V. Kuzenov 1, Sergei V. Ryzhkov 1, and Aleksey Yu. Varaksin	An algorithm for heat fluxes and transfer coefficient calculations is developed.	2022	Numerical
Aerodynamic performance analysis of a winged re-entry vehicle from hypersonic down to subsonic speed	Giuseppe Pezzella, Antonio Viviani	phase-A design level of a reusable and unmanned flying laboratory designed to perform a high lift return from low Earth orbit	2016	Both
Design and CFD Analysis on the Reduction of Thermal Effect in Re-entry Vehicle by Using Retractable Aerospike	**Konstantin Volkov**	**The study's goal was to perform a thermos-structural analysis of the TPS of a re-entry module known as the Crew module**	**2022**	**Both**
AEROHEATING ANALYSIS FOR PLANETARY RE-ENTRY VEHICLES	Alvin Murray	A process for predicting the aero heating and thermal response of blunt re-entry configurations in high-speed flows	2003	Numerical

Literature Review

DRAG REDUCTION FOR HYPERSONIC RE-ENTRY VEHICLES	**G. Gopala Krishnan, Akhil and Nagaraja S R**	**A numerical study on re-entry vehicles with spikes from the point-of view of drag reduction**	**2017**	**Numerical**
Aerodynamic design exploration for reusable launch vehicle using genetic algorithm with Navier stokes solver	By Tomoaki TATSUKAWA1), Taku NONOMURA2), Akira OYAMA2) and Kozo FUJII2	A genetic algorithm with Navier-Stokes solver is used to analyze aerodynamic characteristics.	2012	Experimental
Hypersonic and High-Temperature Gas Dynamics	JOHN D. ANDERSON JR		2019	

Introduction

- With the growth of space exploration and commercial travel, the development of efficient and reliable reentry vehicles has become increasingly important to provide improved aerodynamic features, thermal protection, weight reduction, and cost minimization through enhanced blunt-nose designs, resulting in increased payload capacity and extended mission durations.
- The optimization of these designs is particularly vital for reusable spacecraft, as their lifespan and sustainability are extended.
- Numerical analysis, like CFD, accurately simulates real-life flight conditions by solving complex fluid flow, heat transfer, and pressure equations, allowing engineers to predict aerothermal and aerodynamic behaviors with precision, which informs the reliable design and optimization of flight vehicles across various scenarios.
- Therefore, in recent years, numerical studies have become very popular among researchers to experiment and develop more efficient RLV designs.

Objectives

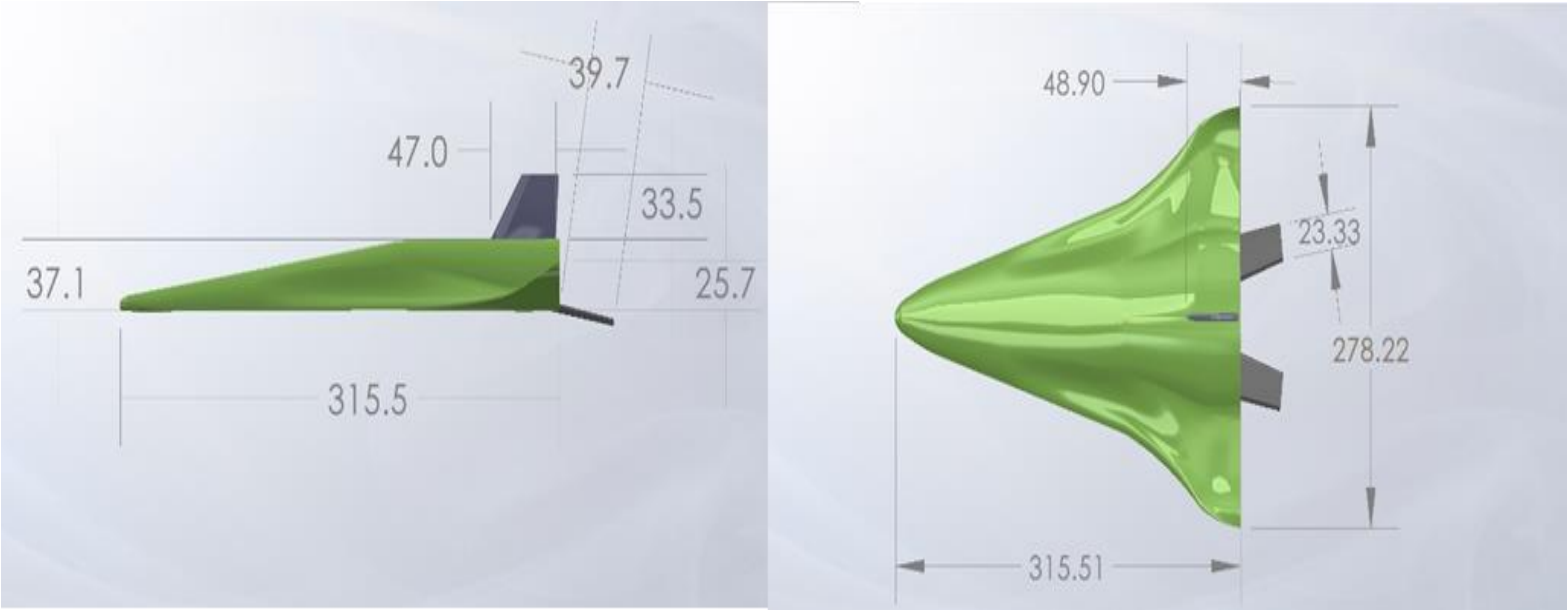
Design unique RLV inspired by HTV and X-33

Conduct numerical study to predict accuracy of its aerothermal behaviors.

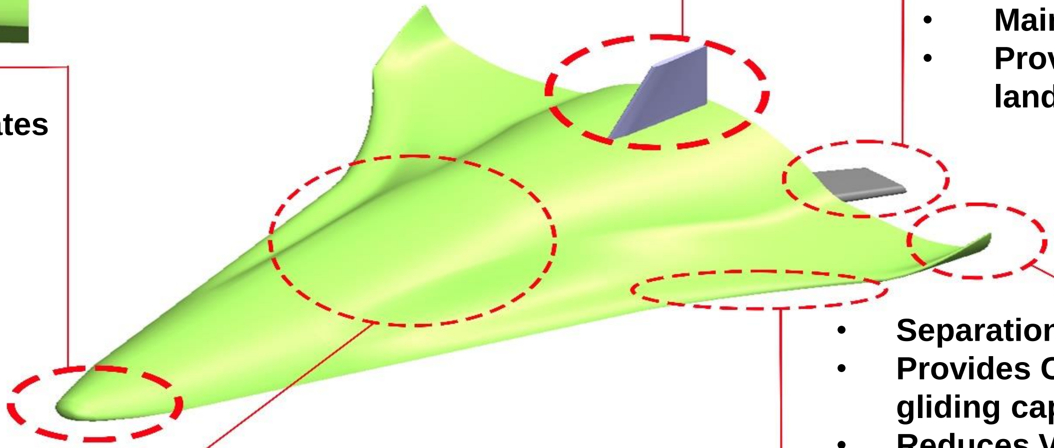
Perform mathematical anlaysis to examine the aerodynamic heating

Validating the model w.r.t the reference papers.

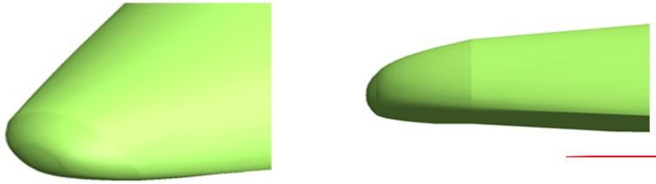
Geometry



Modified RLV Specifications

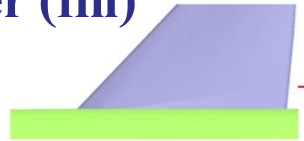


Blunt nose



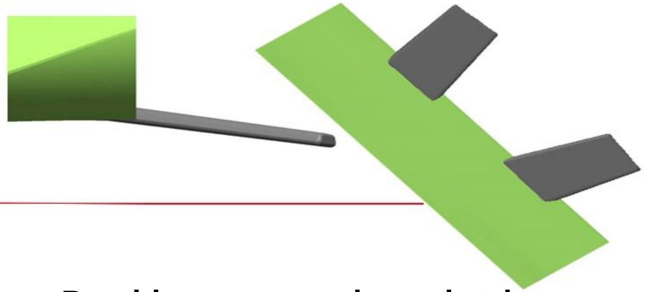
- Reducing heat transfer rates
- Mitigating kinetic heating

vertical stabilizer (fin)



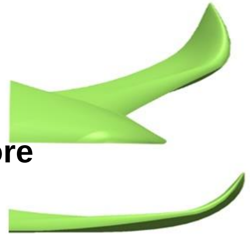
- Provide drag and Yaw controllability at hypersonic speed and also during landing.

Body Flaps



- Provide more aerodynamic trim
- Maintaining Lift/Drag Ratio
- Provide more control (steering, descent, and landing)

Winglet

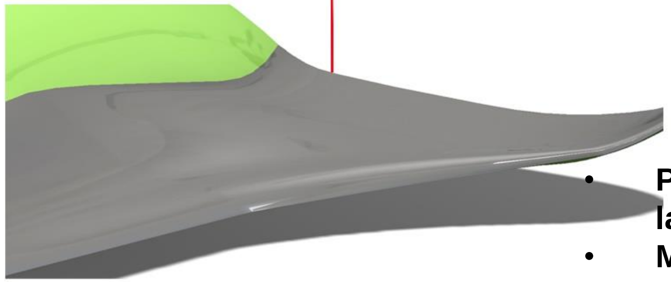


- Separation of Heat and Air Flow
- Provides Controllability with more gliding capability
- Reduces Vortex at the tip

Slender Fuselage

- Provides a more rigid body to accommodate devices and lower heat transfer rate.
- Overall aerodynamic control
- Lower drag, higher lift, and Reduction of weight
- Reduction of fluid density over vehicle surface wall.

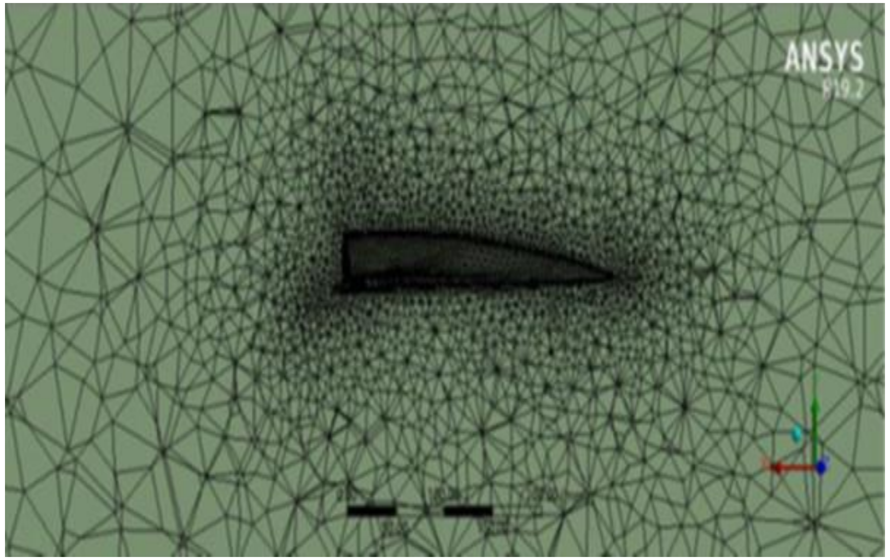
High Cambered airfoil



- Provide more lift during landing
- More stability
- Higher lift/Drag ratio reduces speed while re-entering the atmosphere

Meshing

Names	Description
Grid size	90mm
Face sizing	80 mm
Inflation	first layer
Elements	671492
Nodes	195040
Mesh method	Tetrahedron
Orthogonal quality	0.051
First layer thickness	2.26E-05
Reynold number	7.89E+06
Kinematic viscosity m^4/s	8.012E-04
Y+	1



Numerical Study Procedures

3D design of RLV

Grid Independence Test

Turbulence Model Validation Check

- Aerodynamic heating analysis calculating Fay-Riddle stagnation point heat transfer coefficient

Names	Description
Solver	Steady-state, density based, energy equation
Air density	Ideal Gas
Air viscosity	Sutherland three coefficients
Turbulence model	K–ω SST
Scheme	AUSMD implicit
Courant	0.35
Convergence criteria	10^-05
Iterations	5000

Numerical Equations

Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (1)$$

x momentum equation

$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial(u)}{\partial x}+\rho v\frac{\partial(u)}{\partial y}+\rho w\frac{\partial(u)}{\partial z}=-\frac{\partial p}{\partial x} \quad (2)$$

y momentum equation

$$\rho\frac{\partial v}{\partial t}+\rho u\frac{\partial(v)}{\partial x}+\rho v\frac{\partial(v)}{\partial y}+\rho w\frac{\partial(v)}{\partial z}=-\frac{\partial p}{\partial y} \quad (3)$$

z momentum equation

$$\rho\frac{\partial w}{\partial t}+\rho u\frac{\partial(w)}{\partial x}+\rho v\frac{\partial(w)}{\partial y}+\rho w\frac{\partial(w)}{\partial z}=-\frac{\partial p}{\partial z} \quad (4)$$

Energy

$$\frac{\partial s}{\partial t}+u\frac{\partial(s)}{\partial x}+v\frac{\partial(s)}{\partial y}+w\frac{\partial(s)}{\partial z}=0 \quad (5)$$

For a calorically perfect gas can be replaced by the following equation-

$$\frac{\partial}{\partial t}\left(\frac{p}{\rho^{\gamma}}\right)+u\frac{\partial}{\partial x}\left(\frac{p}{\rho^{\gamma}}\right)+v\frac{\partial}{\partial y}\left(\frac{p}{\rho^{\gamma}}\right)+w\frac{\partial}{\partial z}\left(\frac{p}{\rho^{\gamma}}\right)=0 \quad (6)$$

$$\rho\left[\frac{\partial V}{\partial t}+(V.\nabla)V\right] = -\nabla P+\nabla.[\lambda(\nabla.V)\bar{I}]+\nabla.[\mu(\nabla V+\nabla V^{tr})] \quad (7)$$

$$\frac{\partial \rho}{\partial t}+\nabla.(\rho V)=0 \quad (8)$$

$$\rho C_p\left[\frac{\partial T}{\partial t}+(V.\nabla)T\right]=\nabla.(k\nabla_T)+\frac{\partial \rho}{\partial t}+(V.\nabla)P+\Phi \quad (9)$$

$$P=\rho RT \quad (10)$$

$$\Phi=\lambda(\nabla.V)^2+\frac{\mu}{2}(\nabla V+\nabla V^{tr})^2 \quad (11)$$

$$C_l=\frac{L}{0.5\,\rho v^2\,S_{ref}} \quad (12)$$

$$C_d=\frac{D}{0.5\,\rho v^2\,S_{ref}} \quad (13)$$

$$C_m=\frac{M}{0.5\,\rho v^2\,l_{ref}S_{ref}} \quad (14)$$

Aerodynamic Heating Calculation Equations

- Calculating the Fay-Riddell equations is essential for analyzing aerodynamic heating at the stagnation point during hypersonic re-entry.
- These equations offer a way to estimate the heat transfer rate at the stagnation point of a reentry vehicle traveling at hypersonic speeds.
- The Fay-Riddell equation is commonly used to validate contemporary computational fluid dynamics (CFD) solutions, serving as a reliable benchmark due to its accuracy in predicting heat flux.
- The modified versions of the equations provided by Fay and Riddell [26] are as follows—

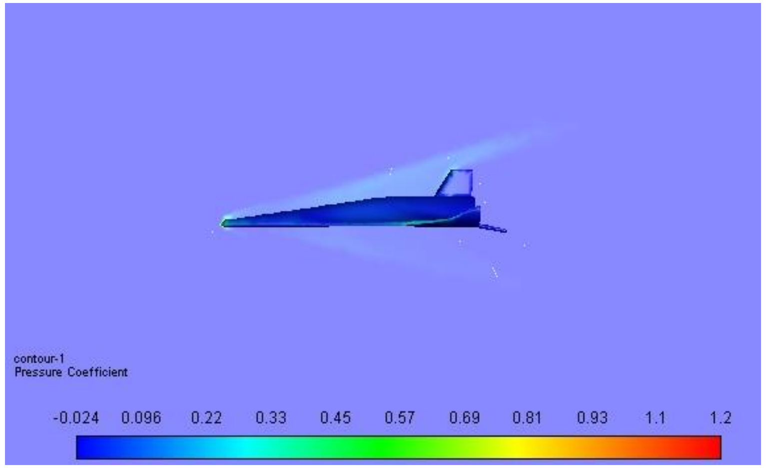
$$h = 0.94K_1(\rho_s\mu_s)^{0.4}(\rho_w\mu_w)^{0.1}\sqrt{(\frac{dU}{dx})_{x=0}} \quad (15)$$

$$(\frac{du_e}{dx})_s = \frac{1}{R_{eff}}\sqrt{\frac{2(p_s - p_\infty)}{\rho_s}}$$

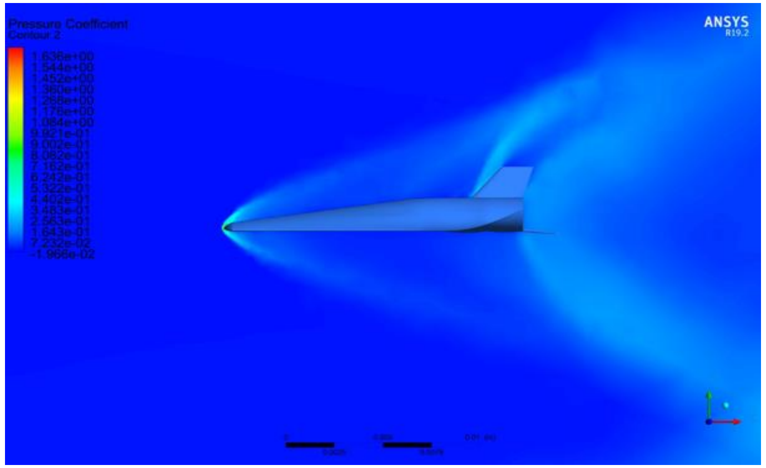
$K_1 = 1$ for the axisymmetric body,
ρ_s is static density,
ρ_w is wall density,
μ_s is the viscosity at the static condition and
μ_w is the viscosity of the wall.

Grid Sensitivity Analysis

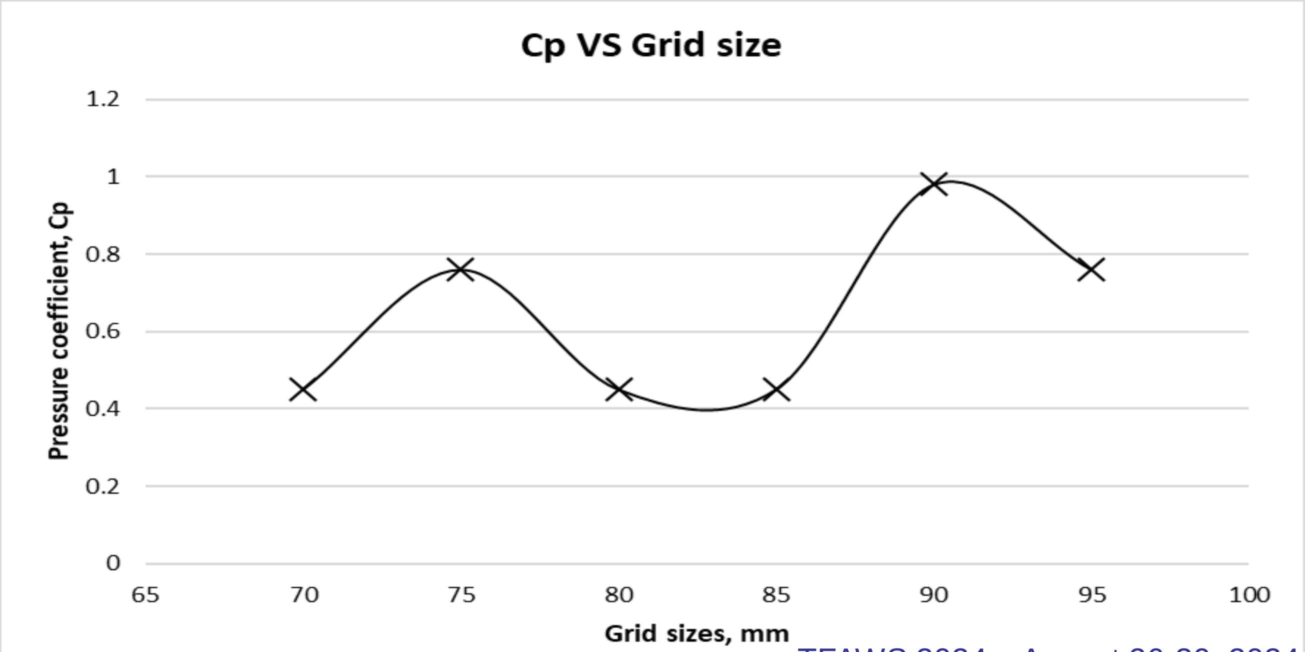
Edge Sizing Element Size mm	Face Sizing 2 Element Size mm	Mesh Elements
65	65	314270
70	70	421512
75	75	314270
75	75	314270
80	80	320738
85	85	421512

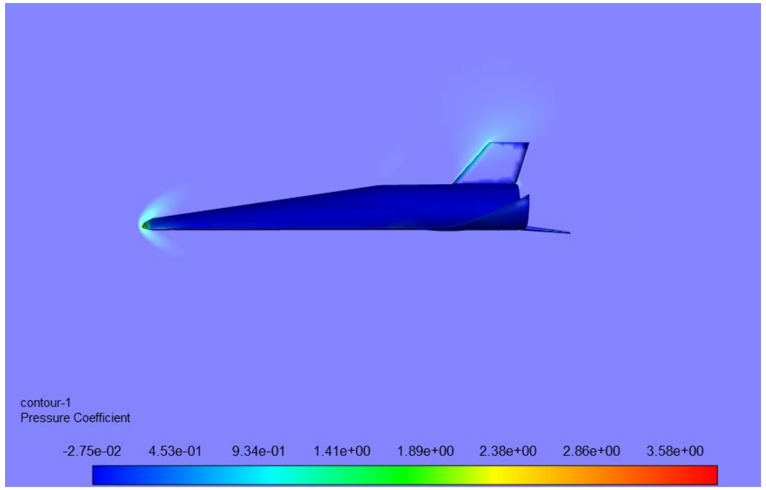


(a) Grid Quantity 0.31M



(b) Grid Quantity 0.32M



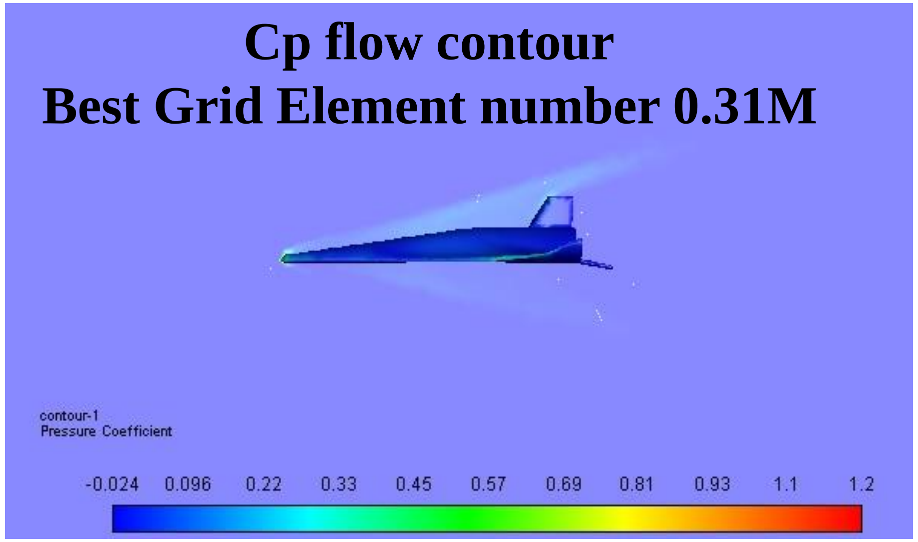


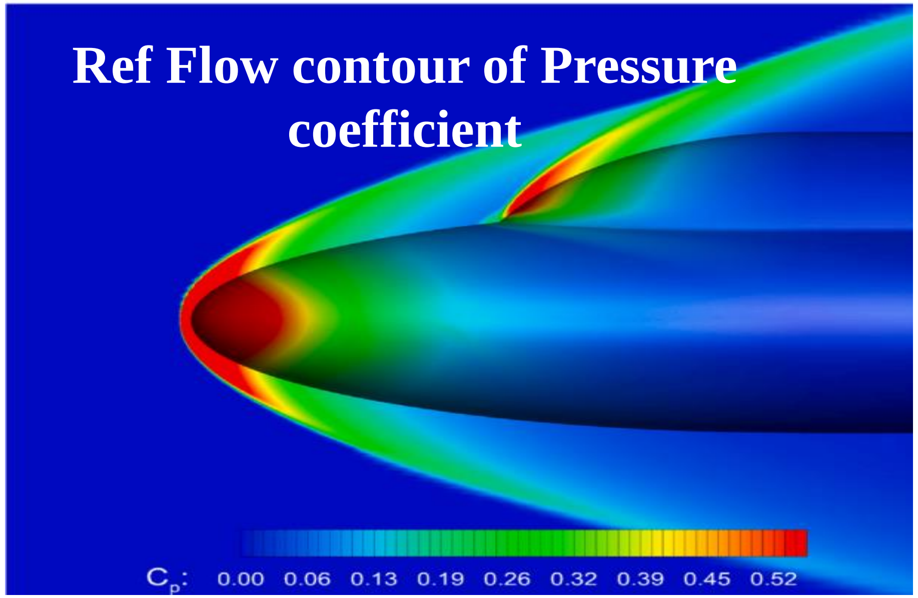
(c) Grid Quantity 0.42M

Variations in Cp with different grid quantities

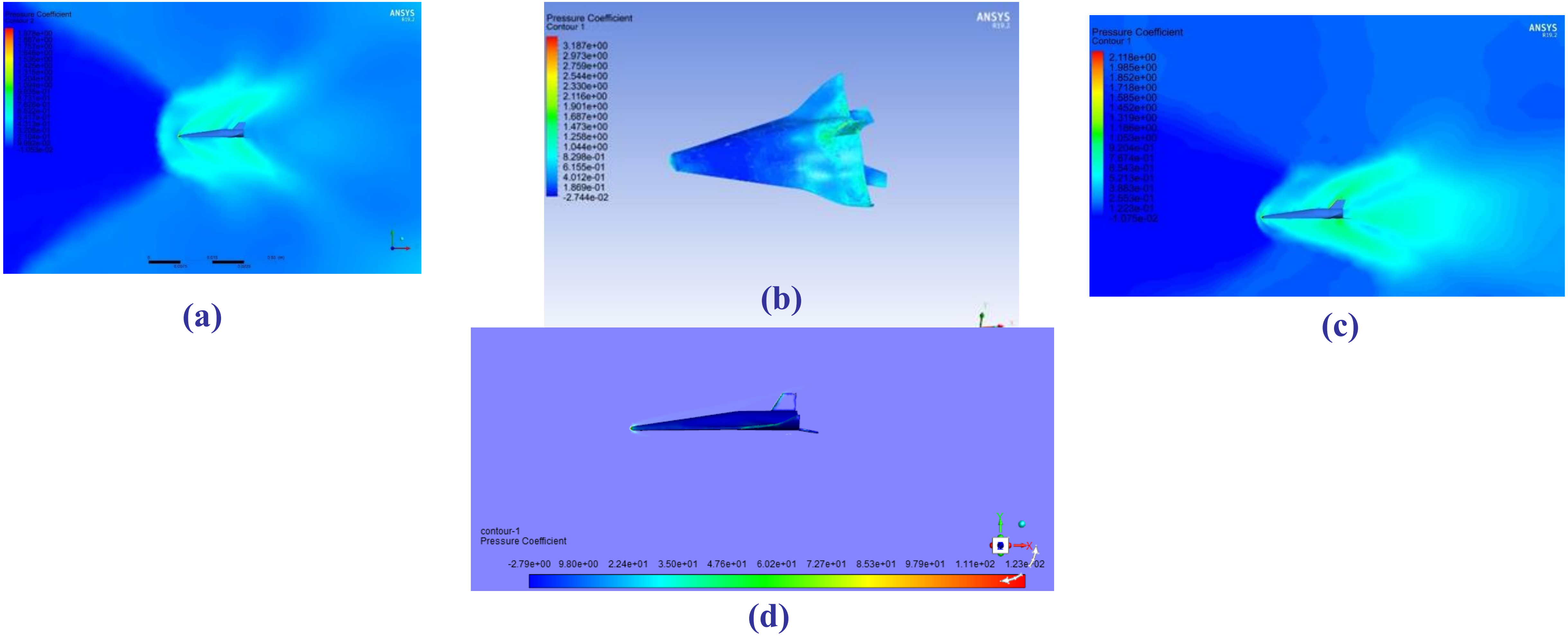
Grid Sensitivity Analysis

Obtained data		Ref Data	
Mesh Elements	Cp	Cp	Error%
0.31 M	0.49	0.52	6.122449
0.42 M	0.76	0.52	-31.5789
0.32 M	0.98	0.52	-46.9388



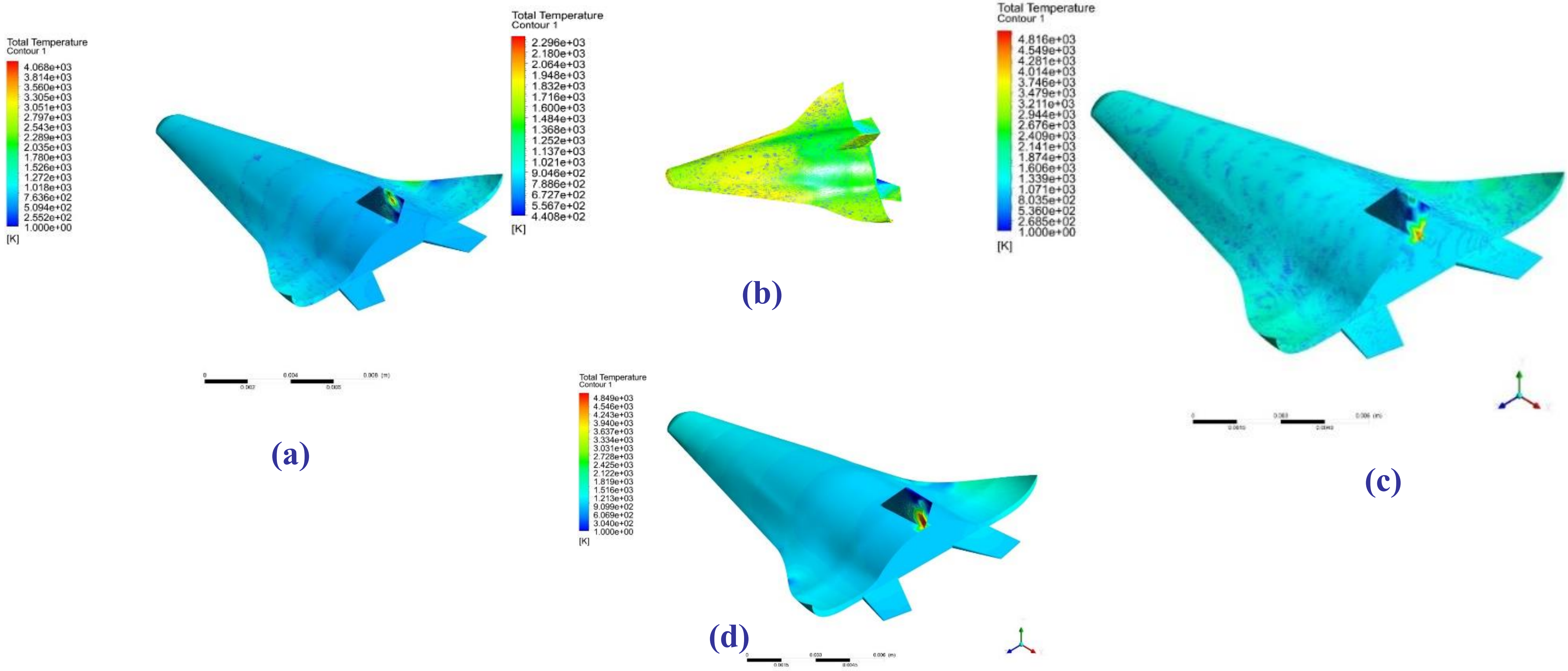


Turbulence Model Validation



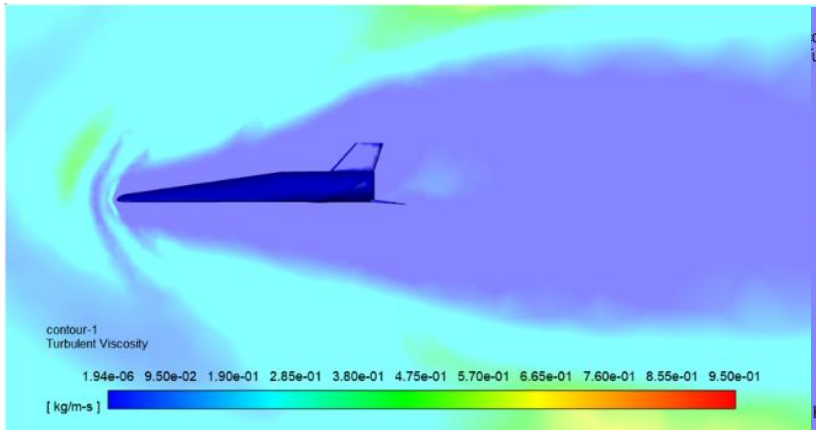
Variation of Pressure Coefficient for Turbulence Models (a) K-w SST, (b) K-e Realizable, (c) K-e Standard, and (d) LES

Turbulence Model Validation

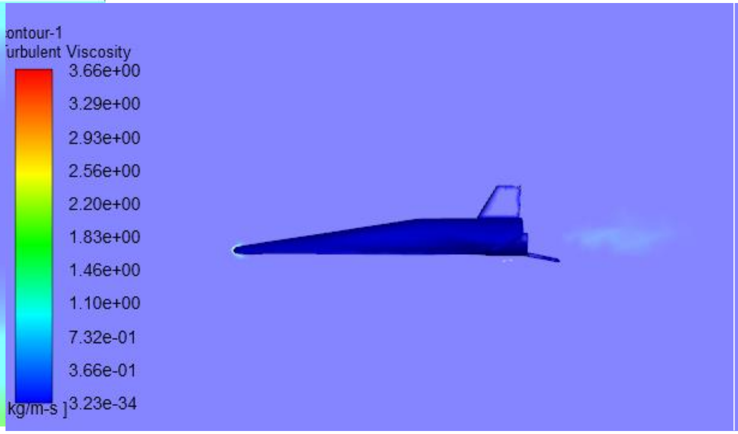


Changes in Total Temperature for Turbulence Models (a) K-w SST, (b) K-e Realizable, (c) K-e Standard, and (d) LES

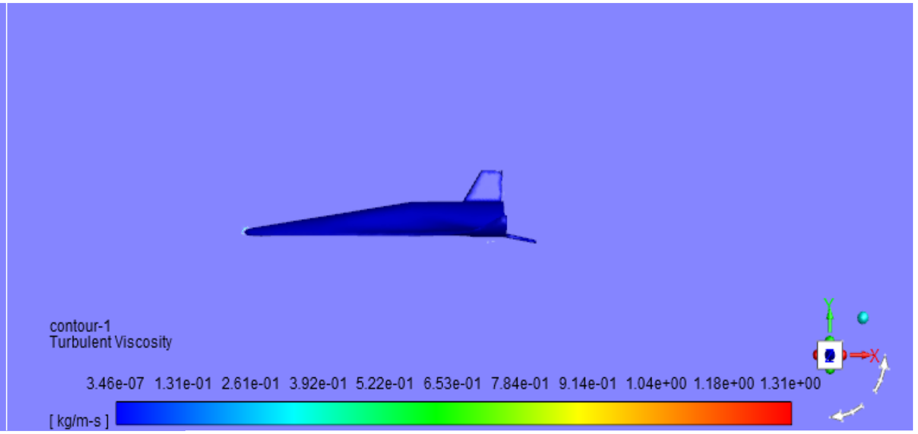
Turbulence Model Validation



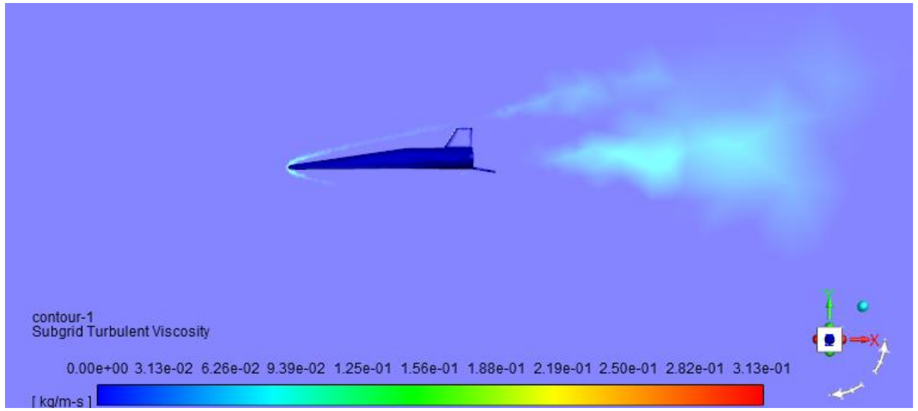
(a)



(b)



(c)



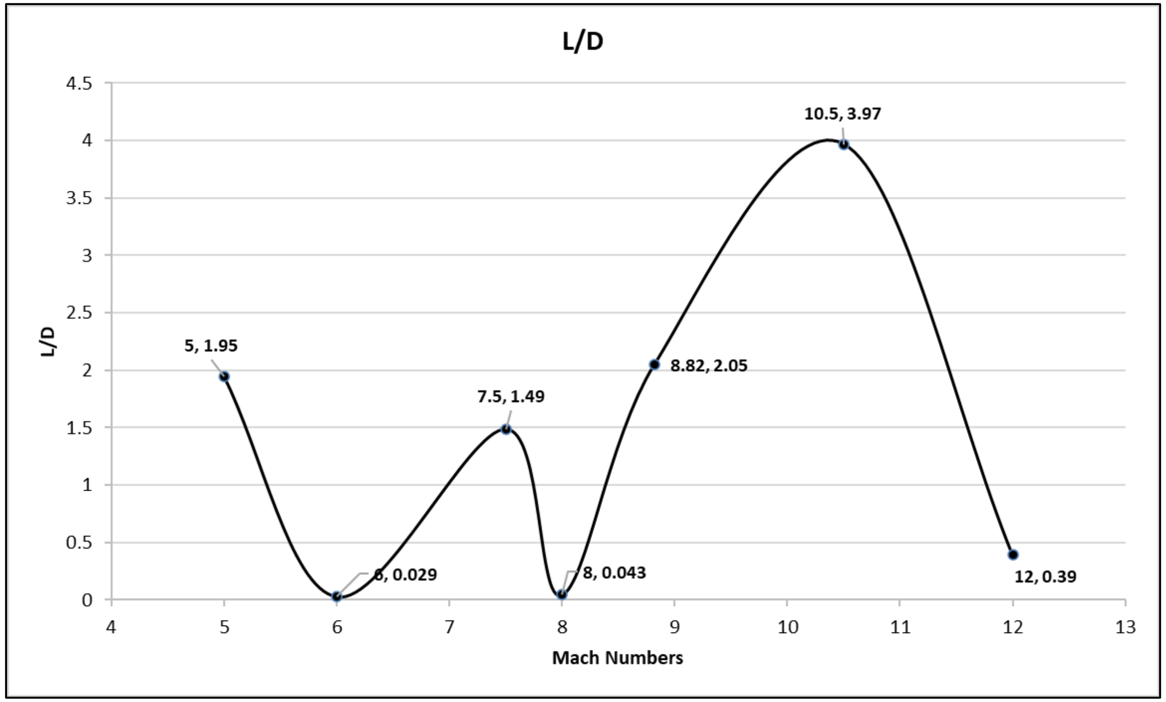
(d)

Changes in Turbulence Viscosity for Turbulence Models (a) K-w SST, (b) K-e Realizable, (c) K-e Standard, and (d) LES

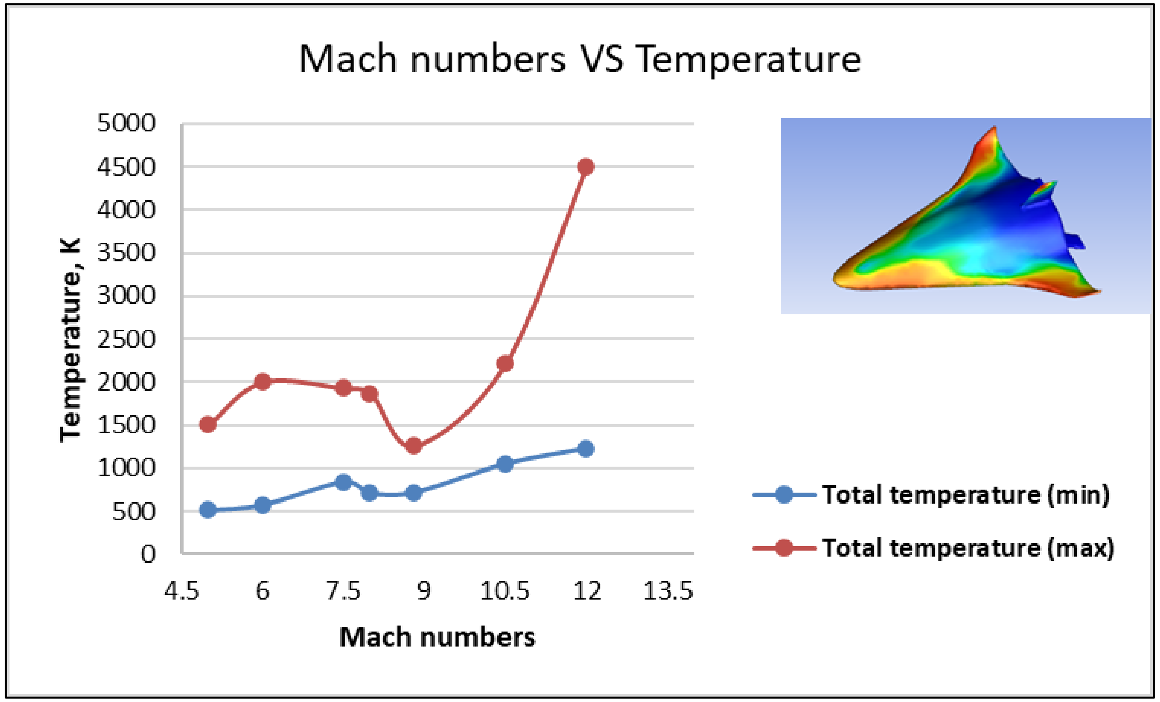
Aerodynamic Heating Analysis for Different Mach Cases

Mach M	Pressure P Pa	Density, kg/m^3 ρ_e	Viscosity μ_e	Velocity, m/s V_∞	Temperature, K T_∞
5	1196.22	1.84E-02	1.47E-05	1.70E+03	2.26E+02
6	5529.1	1.23E+00	1.42E-05	2040	216.65
7.5	5529.1	0.0081	1.47E-05	2550	216.65
8	1127.6	0.0081	1.42E-05	2720	252.1
8.82	98635.61	7.07E-04	1.42E-05	2887.3	267
10.5	121000	1.99E-05	1.10E-05	3570	227
12	1.0365	1.99E-05	1.10E-05	4080	180.65

Aerodynamic Heating Analysis for Different Mach Cases



Lift-to-Drag Ration VS Mach numbers



Mach numbers VS Total Temperature at different positions (a) Nose and (b) Body

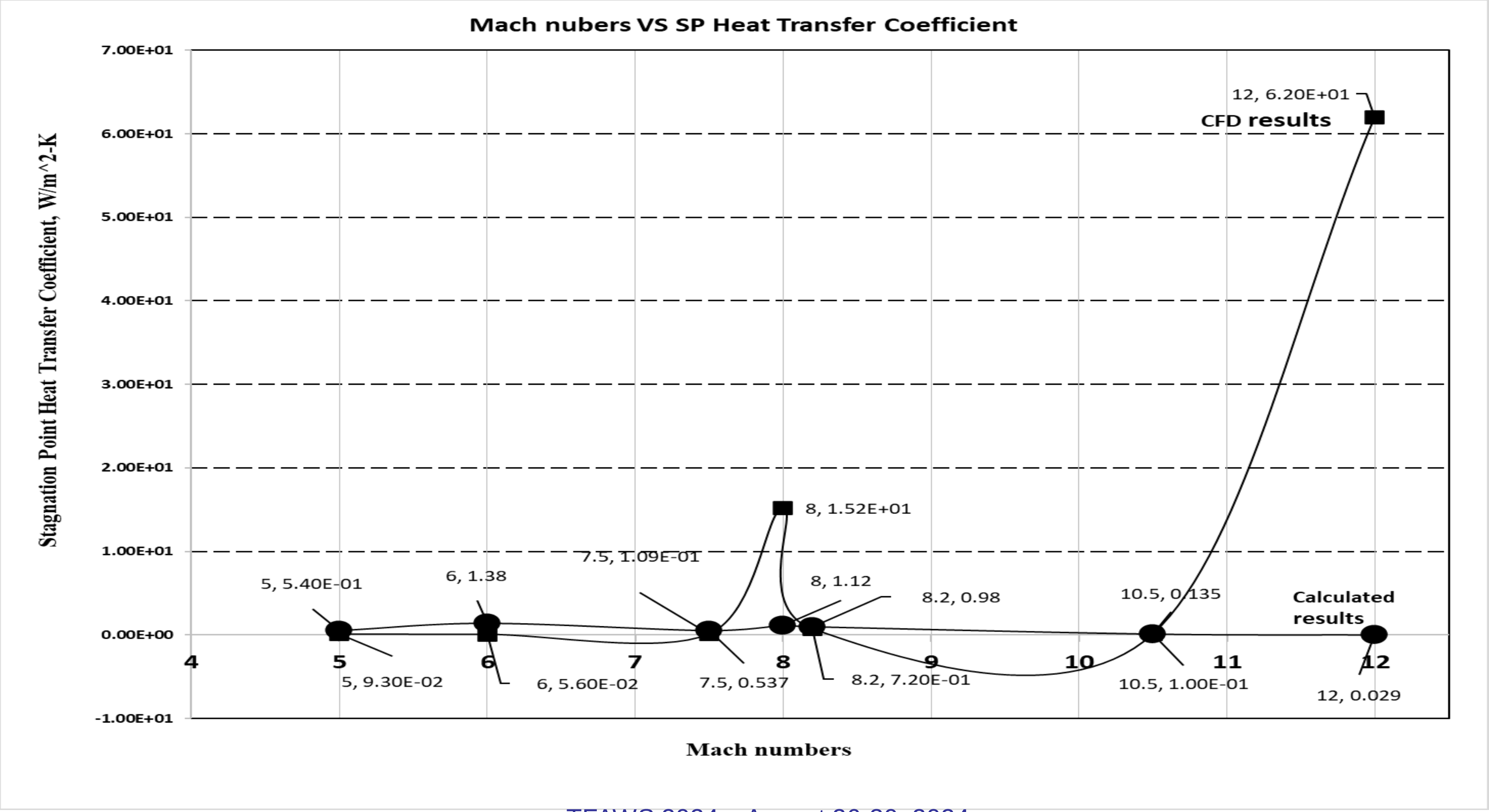
Aerodynamic Heating Analysis for Different Mach Cases

List of Variables used to calculate stagnation point heat transfer coefficient

Mach	Density ρ_e	Density (wall) ρ_w	Viscosity μ_e	Viscosity wall μ_w	Velocity, m/s V_∞	Enthalpy h_s	R-eff (ref nose radius, m)	Temperature T_∞	Velocity gradient DV/Dx	SP Heat Transfer Coefficient
5	1.84E-02	2719(default)	1.47E-05	1.78E-05	1.70E+03	1.82E+06	2.70E-03	2.26E+02	1.34E+05	0.54
6	1.23E+00	2719(default)	1.42E-05	1.78e-05(default)	2040	1822323	0.0027	216.65	3.13E+04	1.38
7.5	0.0081	2719(default)	1.47E-05	1.78e-05(default)	2550	1822323	0.0027	216.65	2.56E+05	0.537
8	0.0081	2719(default)	1.42E-05	1.78e-05(default)	2720	1822323	0.0027	252.1	1.15E+06	1.12
8.82	7.07E-04	2719(default)	1.42E-05	1.78e-05(default)	2887.3	1822323	0.0027	267	6.13E+06	0.98
10.5	1.99E-05	2719(default)	1.10E-05	1.78e-05(default)	3570	1822323	0.0027	227	2.50E+06	0.135
12	1.99E-05	2719(default)	1.10E-05	1.78e-05(default)	4080	1822323	0.0027	180.65	118944.7	0.029

Aerodynamic Heating Analysis for Different Mach Cases

Comparison between obtained stagnation point heat transfer from CFD and Calculated Stagnation point heat transfer coefficient at different Mach cases



Conclusion

The blunt nose effectively reduced peak temperatures by generating a detached shock wave and turbulent wake, leading to lower heat transfer intensity.

The K-ω SST turbulence model, used with an optimal grid size of 0.31 million elements, provided the most accurate predictions for both aerodynamic behaviours and thermal management

At Mach 10.5, the model achieved higher lift-to-drag ratios, enhancing altitude sustenance and reducing thermal stress on the Thermal Protection System (TPS)

The model demonstrated better thermal management with reduced heat transfer coefficients and peak temperatures compared to traditional designs.

The overall design improvements validated the model's superior performance in high-speed flight conditions, showcasing its effectiveness in both aerodynamic and thermal evaluations.

Acknowledgement

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Any Questions?

Thank You