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# Thermal Design and Testing of External Protuberance of Hypersonic Carrier Vehicle Airframe

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Hypersonic carrier vehicle airframe experiences high rate of heat transfer caused by aerodynamic heating due to very high-speed flow during flight. A wire tunnel over the carrier vehicle is used to accommodate the communication and electric cables routed along the external surface of rocket motor casing from electronics packages section to rear part of the carrier vehicle. The wire tunnel leading edge forms an external protuberance. The protuberances are subjected to severe heating during the flight especially at hypersonic speed. Thermal design of the protuberance structure is imperative to ensure safe operation in the severe thermal environment experienced during flight. This paper describes thermal design of the protuberance of wire tunnel assembly. Further, the design of wire tunnel assembly is ascertained by thermal test conducted in infra-red heating facility for aerodynamic heating condition corresponding to the flight trajectory.

***Keywords*:** Hypersonic Vehicle, Wire Tunnel, Aerodynamic Heating and Thermal Design

## 1. Introduction

A flying vehicle like missile airframe experiences aerodynamic heating caused by very high-speed flow during launch phase especially at hypersonic speed [1, 2]. This effect is dominant at protuberances due to effect of wedge compression. The wire tunnel assembly on missile forms the external protuberance that must survive in sever aerodynamic heating environment. The leading edge attached to the front segment of the wire tunnel experiences severe rate of heat transfer due to three-dimensional wedge compression flow and flow disturbances on the flat region due to protrusion wedge angle.

This paper depicts the thermal design of wire tunnel assembly. The thermal design involves the estimation of heat flux distribution over wire tunnel leading edge protrusion and selection of suitable material of construction alongwith wall thickness by considering thermal response analysis of wire tunnel assembly. Aerodynamic heating analysis is used for the prediction of augmented heat flux distribution of the protuberance. Wall temperature prediction by transient three-dimensional heat transfer analysis is required to check whether proper selection of material of construction so that it retains its strength at elevated temperatures. Parametric study has been carried out considering various parameters such as protrusion leading edge angle, geometry, wall thickness and materials of construction. Based on the thermal design and analysis, the front segment of the wire tunnel leading edge configuration with variable thickness has been finalized. The methodology for evaluation of heat flux distribution, prediction of wall temperature distribution and selection of wall thickness based on parametric study is discussed.

## 2. System Description

Typical hypersonic carrier vehicle configuration and location of the wire tunnel is shown in Fig. 1. The missile is considered to fly in lower atmosphere at a Mach number of the order of as high as 6 to 8. The missile experiences severe aerodynamic heating due to high acceleration during propulsion system operation.

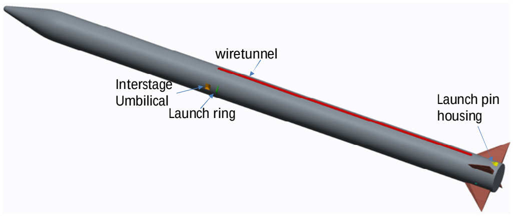



Fig. 1. Typical hypersonic carrier vehicle configuration

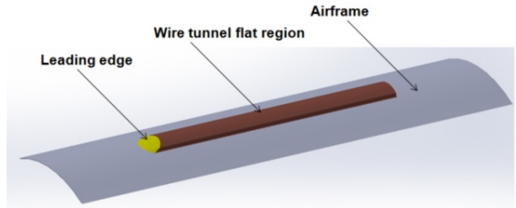



Fig. 2. Front segment of the wire tunnel assembly mounted on airframe

The enlarged view of front segment of the wire tunnel assembly mounted on the airframe is shown in Fig. 2. Communication and electric cables routed along the external surface of rocket motor casing from electronics packages section to rear part of the launch vehicle. The cables are housed inside the wire tunnel. The wire tunnels are provided to protect the cables from high speed flow and aerodynamic heating during the flight. The wire tunnel protuberance is 3-D compression corner with deflection angle of $30^o$. Material of construction is mild steel. The design criteria of the wire tunnel are based on the strength and stiffness requirements, with the objective of minimum weight.

## 3. Methodology of Heat Transfer Analysis

A code [3, 4] developed in-house has been used for the estimation of heat flux distribution due to aerodynamic heating over the wire tunnel assembly. It is a versatile code based on classical engineering methods using well established correlations. The code estimates the distribution of local flow properties over the airframe surface including protrusion. The primary advantage of the code is its capability for quick analysis as compared to computational tools. The effect of wedge angle and angle of attack is simulated through modified Newtonian theory [1].

### 3.1. Local Flow Propertie

The aerodynamic heating on the leading edge is considered as a flow over inclined plate and it depends on the leading-edge wedge angle. At hypersonic speeds, thermal boundary layer over the protrusion becomes thin which gives rise to higher pressures that result in higher rate of heating [2]. During flight, the carrier vehicle experiences various combinations of flight parameters, viz., altitude, velocity and angle of attack. It results in time variable distribution of local flow parameters over the airframe during the flight. The static pressure distribution corresponding to missile attitude has been computed using modified Newtonian theory. The local pressure ($P_L$) at protrusion ramp angle is calculated from pressure coefficient $C_p$ using the following Eqs. (1),

$$C_P = \frac{P_L - P_\infty}{P_{dyn}} = C_{p\max} \cos^2(90 - (\alpha + \theta_w)) \tag{1}$$

The $P_\infty$, $\alpha$ and $\theta_w$ are free-stream static pressure, angle of attack and wedge angle respectively. $C_{Pmax}$ is the maximum pressure coefficient corresponding to the stagnation pressure behind the normal shock. $P_{dyn}$ is the dynamic pressure. From the estimated local pressure distribution, the other local parameters viz., static temperature and Mach number are calculated using isentropic relations.

### 3.2. Heat Flux Estimation

Heat flux distribution over the protrusion is calculated using Eckert-reference enthalpy method [5] for high speed flow over a flat plate considering estimated local flow parameters as edge of the boundary layer condition. Heat flux is estimated using Eckert's relation:

$$\dot{q}_w = St^* \rho^* V_e \left(h_{aw} - h_w\right) \tag{2}$$

Reference Stanton number $St^*$ has been calculated using relations corresponding to the turbulent flow conditions. The $h_e$ and $h_w$ are specific enthalpy corresponds to local static temperature and updated wall temperature respectively. $V_e$ is velocity at edge of the boundary layer and air density $\rho*$ is calculated from perfect gas law. The air properties used in the calculation of heat flux have been considered as function of temperature and pressure, taking into account real gas effect as well [5]. Indian Standard Atmosphere data is used in the calculation of heat flux.

### 3.3. Heat Conduction Analysis

Transient three-dimensional heat conduction analysis based on finite element method (FEM) has been carried out using tabular boundary condition option of the solver, ANSYS Thermal [6]. Temperature dependent thermo-physical properties of the materials are used in the present analysis. The finite element mesh of the wire tunnel front segment including leading edge is shown in Fig. 3.

Fig. 3. Finite element mesh of wire tunnel segment-1

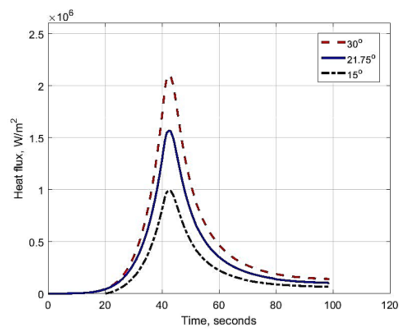



Fig. 4. Comparison of heat flux vs time for various ramp angles

### 4. Thermal Design and Analysis

Thermal design of wire tunnel is carried out in following steps. The heat transfer analysis of aerodynamic configuration of wire tunnel front segment is carried out as a design check considering specified wall thickness of 0.039h. In order to reduce the heat flux as well as wall temperature, a parametric study on protrusion ramp angle is carried out considering 30$^o$, 21.75$^o$ and 15$^o$. The comparison of heat flux profiles, correspond to isothermal wall condition of 300K, for specified ramp angles of the wire tunnel is shown in Fig. 4. The heat flux at the leading-edge protuberance for the ramp angles of 30$^o$, 21.75$^o$ and 15$^o$ is of the order of 2.09MW/m$^2$, 1.56MW/m$^2$ and 1.07MW/m$^2$ respectively. Aerodynamic configuration of the wire tunnel leading edge with 30$^o$ protrusion angle is shown in Fig. 5(a). As the heat flux decreases with decrease in ramp angle, minimum possible ramp angle of 21.75$^o$ has been arrived out based on the constraint of wire tunnel height, space available ahead of ramp region and mounting scheme. Further, additional block of material is provided at the leading-edge region of the wire tunnel to increase the heat capacity as well as to form a minimum possible protrusion ramp angle as shown in Fig. 5(b).

Further, transient heat transfer analysis of modified wire tunnel assembly is carried out by applying heat flux boundary condition for the flight duration of 101seconds. Heat flux distribution over flat portion of the wire tunnel assembly for various isothermal wall conditions is obtained from N-S CFD analysis. The stiffeners inside the wire tunnel have also been considered in the analysis. Based on the analysis, wall thickness varies from 0.039h to 0.23h is chosen over a length of 2.88h for the flat region of the wire tunnel. The final configuration of wire tunnel assembly and materials of construction is shown in Fig. 6. The wall temperature distribution and wall temperature time history at various location of the wire tunnel assembly is shown in Fig. 7 and Fig. 8 respectively. The maximum predicted linear deformation due to thermal expansion is 0.002mm and is shown in Fig. 9.

## 5. Thermal Test Setup

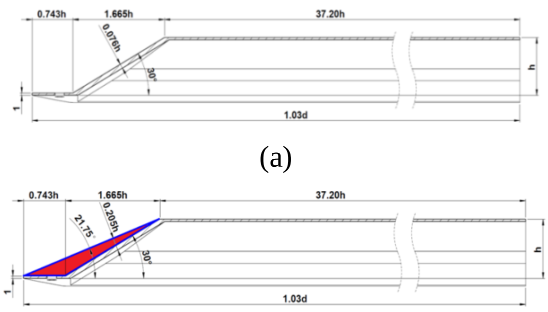
The kinetic heating test on wire tunnel is carried out using closed-loop temperature control. The controller embedded in the control system is based on the industrial form of the three-term (PID) controller. Two thermocouples bonded on leading edge portion and three thermocouples bonded on the surface of the wire tunnel, are used for the purpose of temperature control. By using the thermocouple sensor output as the feedback for the IR controller, the heat intensity of the IR lamp is controlled as per given temperature profile.

The wire tunnel assembly is placed in horizontal position during the test. The IR heaters are placed in front of the wire tunnel assembly at a distance of 0.0307h. Two sets of cable are routed through the wire tunnel assembly as in the flight hardware assembly. The cables are connected to the data acquisition system and are protected by thermal insulation as per flight configuration. The additional length of the cable came out from the wire tunnel assembly is also thermally protected. The end of the wire tunnel opening is covered with silica cloth to avoid direct heating of inner surfaces. The functionality of the cable has also been ensured during the thermal test.

The wire tunnel assembly is withstood the thermal loads without any visual observations. The controlled temperature profile on the wire tunnel surface is shown in Fig. 10. The controlled temperature profile is in very good agreement with desired one. The maximum temperature measured on the thermal insulation cloth of cables is 748K at the end of 100seconds. All the measured temperatures are within the specified limits with respect to the input temperature profiles. The deformation measured at the end of the wire tunnel is plotted in Fig. 11. The maximum deformation measured is 2.639 mm at the end of 100seconds and is in good agreement with the prediction. The snapshot of wire tunnel assembly after thermal test is shown in Fig. 12. The structural integrity of the wire tunnel assembly is ensured from thermal load point of view and is cleared for intended application.

## 6. Conclusions

The thermal design of first segment of the wire tunnel assembly has been presented considering the rate of heat transfer arising out of carrier vehicle flying at hypersonic speed. The wall temperature of leading-edge region is brought down to the acceptable strength limit by the design of variable wall thicknesses along the length. An extensive parametric study carried out has made it possible to finalize the configuration of wire tunnel leading edge region. The design has been validated through thermal testing in IR test facility.



(a)

(b)

Fig. 5. (a) Aerodynamic configuration and (b) Modified configuration of the wire tunnel

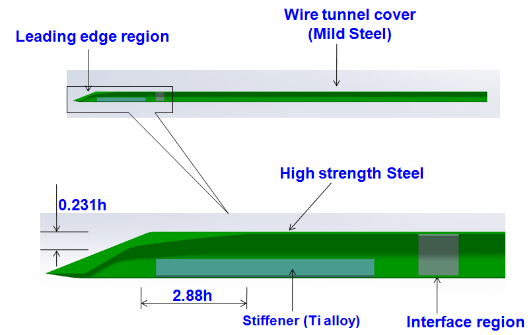


Fig. 6. Final configuration of wire tunnel and its materials of construction

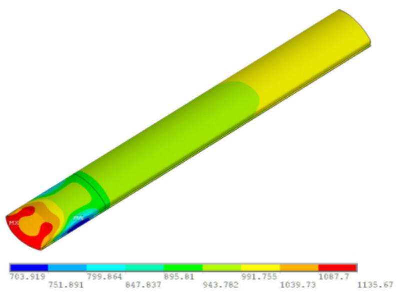


Fig. 7. Wall temperature distribution of wire tunnel assembly at 101seconds

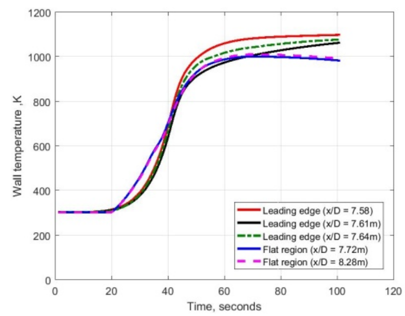


Fig. 8. Wall temperature vs time profile at various locations of the wire tunnel

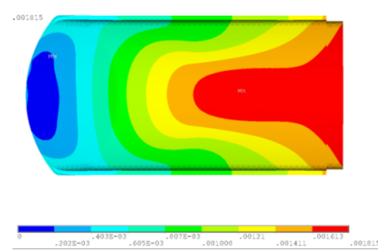


Fig. 9. Linear expansion distribution over leading edge of the wire tunnel

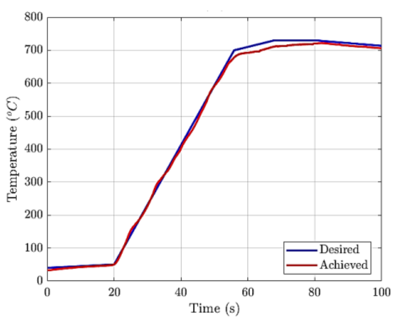


Fig.10. Controlled temperature profile at external surface of leading edge portion

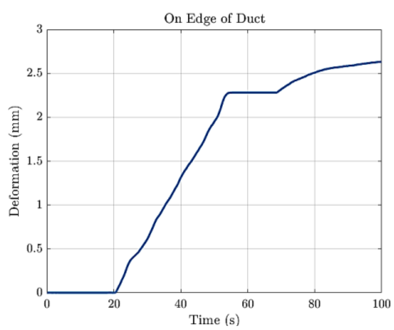


Fig. 11. Measured deformation during wire tunnel thermal test


Fig. 12. The wire tunnel assembly after thermal test

## References


[1] Anderson, J. D.: *Hypersonic and High temperature Gas Dynamics*, McGraw-Hill Inc, New York, 1989.

[2] John J. Bertin: *Hypersonic Aerothermodynamics*, AIAA Education Series, Washington DC,1994.

[3] Heiser William H. Heiser and David T.Pratt: *Hypersonic Airbreathing Propulsion*,AIAA Education Series, Washington DC, 1994.

[4] G. Vijayakumar: *A Report on Methodology for Kinetic Heating Analysis*, Internal Technical Report, DRDL/DOP/HTD/2007-190, February 2007.

[5] J.P.Holman, *Heat Transfer*, 8th Ed., McGraw-Hill Book Co., 1997.

[6] ANSYS User's Manual, *Thermal analysis guide*, ANSYS (2017), USA.