Aerothermal design, qualification and flight performance

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Reusable Launch Vehicle-Technology Demonstrator (RLV-TD) experiences severe thermal environment during its ascent as well as re-entry into the atmospheric regime. Structures should be designed to withstand this thermal load. Thermal environments were estimated for RLV-TD and depending on the peak heat flux and heat load, hot structure design for nose cap, wing, vertical tail and control surfaces was developed. Thermal protection system (TPS) using silica tile and flexible insulation was designed to protect the windward and leeward regions respectively. It is essential to verify and establish the design and also physically corroborate the actual thermal performance. Besides the design, the hot structures and TPS functionality as a system has to be qualified and thereby yield full confidence on the total performance during flight. To qualify the hot structures and TPS, various qualification tests were undertaken. The demonstration of their fly-ability and qualification under the combined effect of structural and thermal load was carried out successfully for all structures. This article provides details of aerothermal design of RLV-TD and various qualification tests carried out. Comparison of the estimated structure temperatures with measured temperatures in flight shows the robustness of the design methodologies adopted.

Keywords: Heat flux, reusable launch vehicle, temperature, thermal protection system.

Introduction

DURING atmospheric flight of Reusable Launch Vehicle-Technology Demonstrator (RLV-TD), which includes ascent as well as re-entry into the atmosphere, the vehicle experiences severe thermal environment. The kinetic energy of air is converted into thermal energy and part of this energy is transferred to the body by viscous diffusion. Structures should able to withstand this thermal load. Hence thermal environments need to estimated for RLV-TD and structures designed. A design code has been developed and validated for computation of heat transfer rates over a re-entry winged body and its thermal response analysis for a given trajectory.

Various tests like thermo-structural test, infrared (IR) heating test, shear flow testing and, plasma wind tunnel test were carried out for qualifying the hot structures and Thermal Protection System (TPS) for worst-case thermal environments. All the tests yielded full confidence on the total performance during flight and structures were cleared for flight.

Various temperature measurements were provided on RLV-TD to verify the design. Post-flight analysis was carried out and the measured temperatures compared with those predicted.

Heat flux estimation

Heat fluxes at various locations were estimated using engineering correlations. These computations are fast when compared to estimation of heat flux by Computational Fluid Dynamics (CFD) methods. For RLV-TD, heating rates at the stagnation point of nose cap for ascent and descent phases of the flight were estimated using Fay and Riddell correlation[1]. For locations other than the stagnation point, heat flux was computed based on Van Driest theory for laminar and turbulent flow[2,3]. Beckwith and Gallagher[4] correlation was used for the wing and vertical tail stagnation by assuming an infinite swept cylinder for the flows with an angle of incidence.

Figure 1 shows the structure details of RLV-TD. Estimated coldwall heat flux histories at various locations of RLV-TD for the worst-case trajectory are also shown in Figure 2. Temperature of the structure was evaluated by solving one-dimensional conduction equation with insulated boundary condition. Depending on peak heat flux and heat load, various materials and their thicknesses were arrived at various regions for meeting the specified temperature constraints. After arriving at optimum thickness, three-dimensional model of each component was developed and thermal response was determined using commercial software ANSYS. Spatial as well as transient variations in heat flux were considered for thermal response analysis. Three-dimensional thermal response analysis was carried out simulating all the interfaces, and design of the hot structures was finalized. Nose cap, wing leading edge, elevon, vertical tail and rudder were designed as hot structures, i.e. these structures could withstand structural load at higher temperatures as well.

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For windward and leeward regions, TPS like silica tile and flexible insulation used in space recovery experiment (SRE) was provided to protect the structures.

Qualification test programme

It is essential to verify and establish the design and also physically corroborate the actual thermal performance. As mentioned earlier, various tests were carried out for qualifying the hot structures and TPS for worst-case thermal environments.

Thermo-structural test

Hot structures are mechanically stressed by aerodynamic loads, inertial loads, control loads and vibration loads.

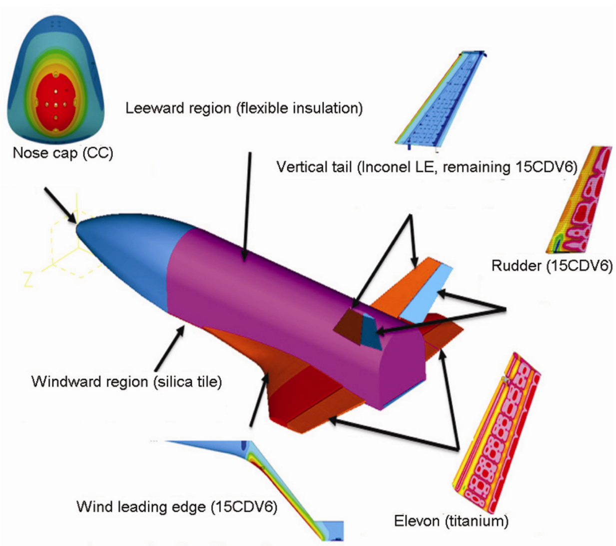

Figure 1. Various structures of RLV-TD.

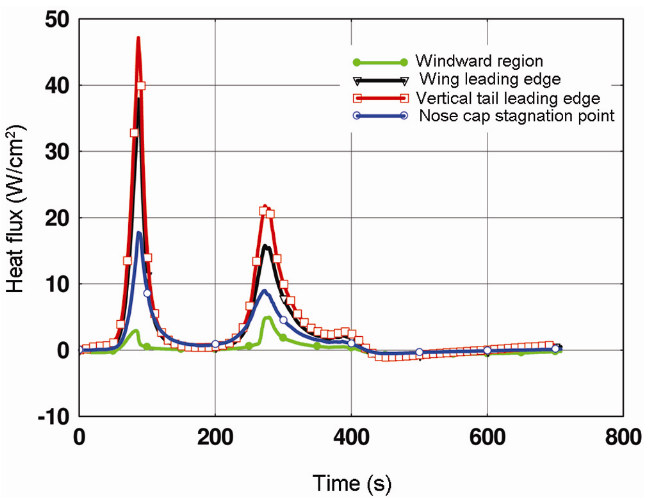

Figure 2. Cold wall heat flux estimated at various locations of RLV-TD.

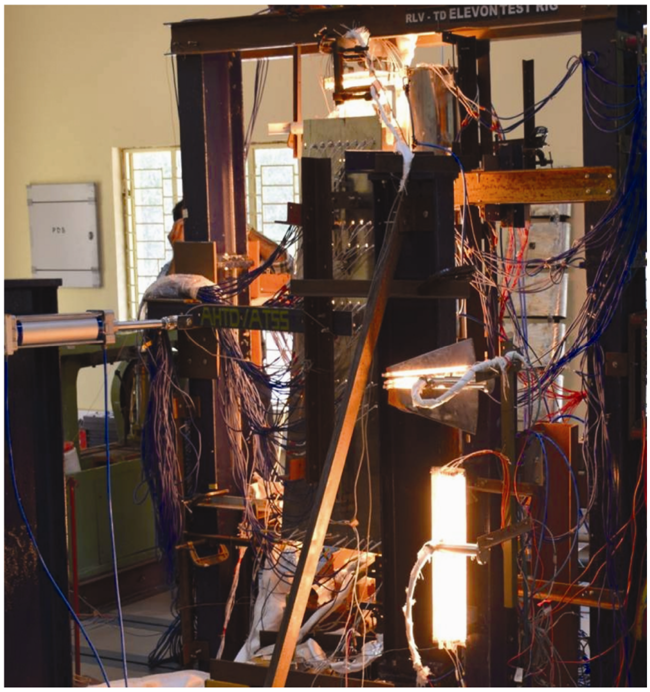

Figure 3. Elevon thermo-structural test.

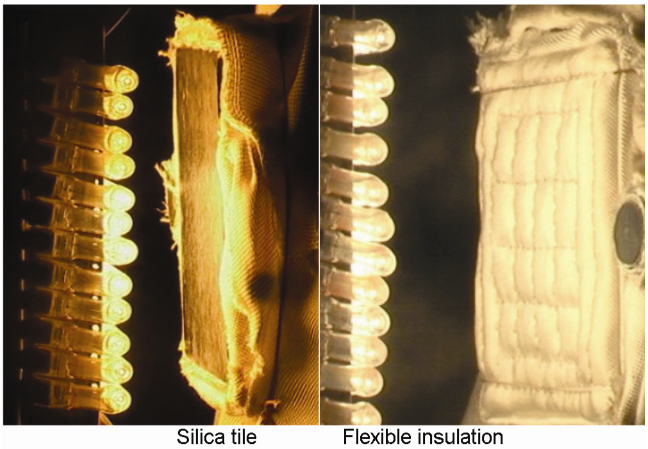

Figure 4. Infrared heating test.

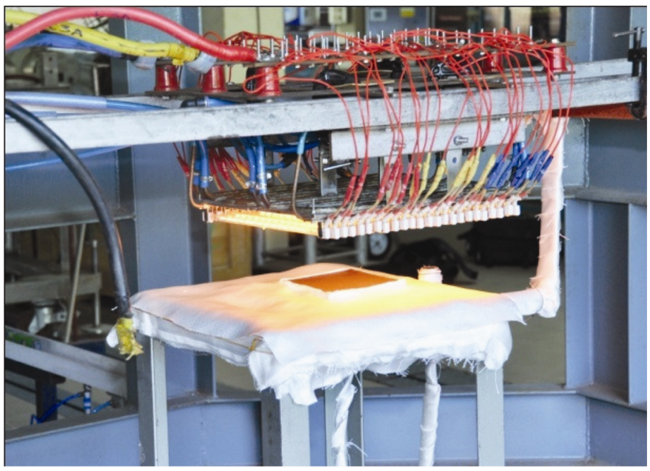

Figure 5. Testing radio frequency performance at high temperature.

Simultaneously, extreme aerodynamic heating causes high temperature gradients and associated thermal stresses. The thermo-structural design of these complex structures, interface brackets, bolt attachments, weld joints, sliding joints and clearances needs to be verified in ground facilities prior to flight. The distribution of transient history of heat flux and mechanical loads needs to be simulated simultaneously to assess the temperature limits, strain, deformation and margins available for the structure. For RLV hot structures, demonstration of their fly-ability and qualification under the severe environment of thermal and structural loads acting simultaneously was undertaken for all hot structures. Figure 3 shows a typical thermo-structural testing of elevon. Thermo-structural testing of hot structures confirmed the integrity under thermal and structural loads experienced in flight.

IR heating test

This test was carried out for design verification of silica tile on the windward region and flexible insulation on the leeward side of RLV-TD. Panel-level qualification test was carried out (Figure 4). Simulation of actual real-time heat flux history was done using IR heating to establish the adequacy of TPS design. Acceptance criteria for the test were such that structure temperature measured during the test should be within the design/material limit of 120°C and that there should not be any damage on the TPS due to the test.

High-temperature effects on radio frequency (RF) performance of telemetry antenna placed under silica tile and flexible insulation were also evaluated using IR heating as shown (Figure 5). Functional performances of telemetry under flight thermal environments were qualified.

Shear flow test

During atmospheric flight of RLV-TD, in addition to thermal load it experiences aerodynamic shear of the order of 150 Pa. In shear flow tests, the total heat load and peak aerodynamic shear corresponding to Mach number (M) = 3, and total temperature (T_0) = 723 K were simulated in heat transfer facility. All the specimens withstood the flow and thus TPS was qualified. Figure 6 shows the flexible insulation before and after the shear flow test.

Plasma wind tunnel

Carbon–carbon nose cap was attached with aluminium alloy ring through molybdenum bracket, molybdenum bolt and molybdenum nut. It is essential to study the joint behaviour of C–C nose cap with molybdenum bracket, wherein dissimilar materials having different coefficients

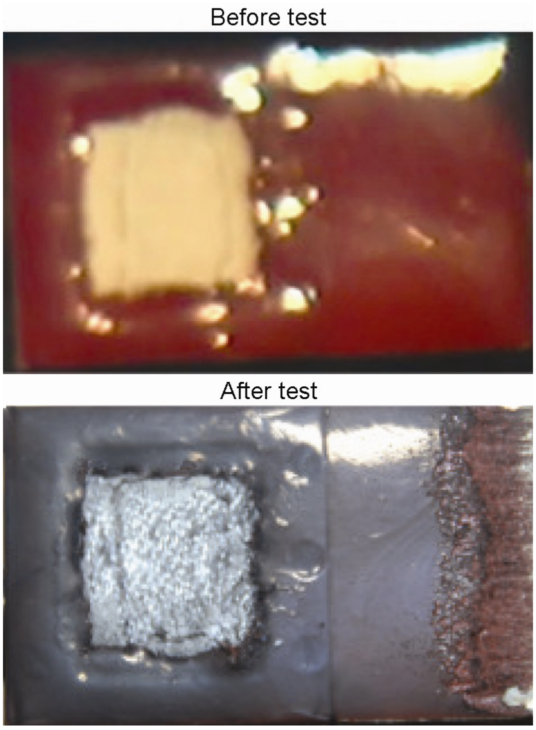

Figure 6. Shear flow test.

Figure 7. Plasma wind tunnel.

of thermal expansion are attached. Accordingly, a test was carried out to qualify the interface configuration in 6 MW plasma wind tunnel facility (Figure 7). Total heat load was simulated and it was found that the joints withstood the load. The specimen qualified for 9 W/cm^2 heat flux for 30 s duration. These above-mentioned tests simulated near-flight conditions and the structures were cleared for flight.

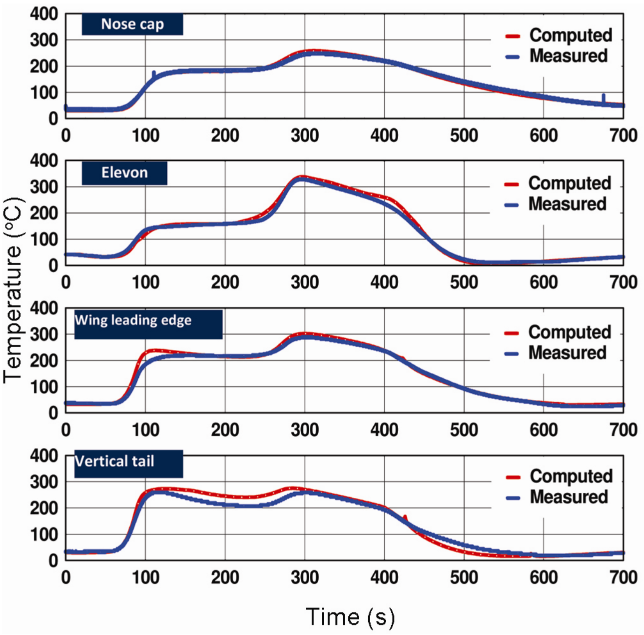

Figure 8. Comparison of computed and measured temperature histories.

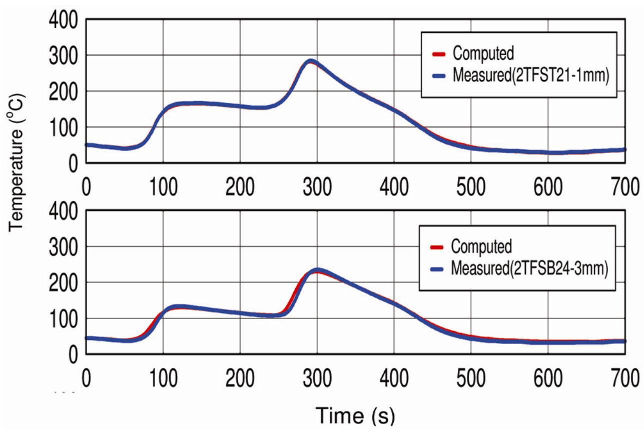

Figure 9. Comparison of computed and measured temperature histories on silica tile.

Post-flight analysis and discussions

Various temperature measurements were provided on RLV-TD to verify the design. Post-flight analysis was carried out and measured temperatures compared those predicted. Figure 8 shows a typical comparison of temperatures at nose cap, wing leading edge, elevon and vertical tail. Fairly good comparison between estimated and measured values shows that thermal behaviour is according to expectation and design is adequate.

Figure 9 shows a comparison of computed and measured temperatures on silica tile. The thermal performances of silica tile were in line with the predictions. Temperature measurements in the leeward region also indicated that flexible insulation withstood the thermal load during flight.

Conclusion

Aerodynamic heating rates for a re-entry mission have been computed using engineering methods. RLV-TD hot structure and TPS design was developed to take care of thermal load. Various qualification tests were carried out and all the structures withstood structural and thermal loads. Temperature measurements from flight indicated that design of the hot structures was adequate. Measurements on the silica tile and flexible insulation in the windward and leeward regions also validated the design methodology and proved its adequacy.

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ACKNOWLEDGEMENTS. We thank Shri B. Sundar (VSSC, Thiruvananthapuram) for support and guidance; Dr B. Deependran, Shri. John Geo, Shri B. Chiranjeevi Phanindra, Shri R. Manoj and Smt. K. Vanitha (ATSD, AERO) for help with thermo structural testing; and Shri Sreenivas, APLD and Shri Aravindakashan Pillai (APRG) for plasma wind tunnel testing.

doi: 10.18520/cs/v114/i01/64-67