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学位論文の概要及び要旨

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題　　目　Study of Thermal Response in Highly Porous Heat Shield Materials Subjected to High Temperature Flows（高温気流下の高空隙熱防御材の熱応答に関する研究）

学位論文の概要及び要旨

The desire to expound knowledge about origin of the solar system has motivated steady growth of interest in planetary exploration missions. Fundamental objectives of these missions include: finding more information about the solar system as well as investigating possibility of pushing human existence to the moon and space beyond. The Apollo program made history in July 1969 and marked one of the greatest achievements by man when it landed on the lunar surface. Numerous missions such as the US Gemini, Mercury, Galileo, and Japan's Hayabusa, among others have been successfully conducted in the past.

When space vehicles return to earth's atmosphere from International Space Station (ISS), re-entry velocities are usually about 7.8 km/s. At these velocities, re-entry vehicle is subjected to strong shocks, equilibrium and non-equilibrium gas chemistry, huge amounts of heat fluxes and consequently extremely high temperatures. Most kinetic energy of the incoming flow is dissipated in form of heat at extremely high temperatures through dissociation or ionization of flow species in the radiative shock layer that forms around the vehicle. Efficient vehicle design requires desirable drag coefficient, aerodynamic stability together with the ability to survive extreme and severe conditions under all flow regimes. Heat fluxes at the surface of the vehicle can be quite severe in such re-entry environments. For instance, NASA's Pioneer-Venus experienced a high stagnation heating rate of about 55 MW/m^2 while JAXA's Hayabusa had a peak heating rate of 15 MW/m^2 during re-entry to earth's atmosphere. Critical challenge during space exploration missions is the assurance of safe and secure re-entry alongside successful touchdown. With such extreme heating rates, mandatory use of ablative thermal protection system (TPS) for the vehicle, crew and payload is paramount to ensure efficient rejection of aerothermal heat load. Therefore, mission's success will largely depend on the choice and reliability of performance prediction of its TPS.

However, use of TPS to protect the payload from extreme aerothermal heating rates has been posing severe challenges due to their mass constraints and infidelity in their performance prediction for some cases. For example, phenolic carbon ablators used for earth re-entry capsules like USERS REV and Hayabusa, or for planetary entry probes like NASA's Galileo, all had high density values in the range of 1.5 g/cm^3. Even though TPS community has greatly mitigated the challenge of TPS materials' mass to about a fifth of the above value, the problem of infidelity in numerical models for TPS performance analysis still exists today. Ablation phenomenon is another critical property of an ablative TPS that must be effectively accounted for to achieve an optimized design size of the TPS. Charring ablative TPS protects the vehicle by absorbing heat and ablates away as a result of chemical reactions at the surface, leaving behind receded material surface. It is hence important to accurately capture TPS surface recession during performance analysis to optimize its design and save on both mass and cost.

Sacrificial nature of the charring ablative TPS requires intensive performance analysis campaigns through actual in-flight tests, ground tests and numerical modeling. However, current budget constraints for actual in-flight tests as well as inability of ground tests to capture some intricate flow field details have singled out numerical analysis as the most viable option. Numerical models for ablative material performance and their coupling to fluid dynamic flow environment, on the other hand, have somehow stagnated at the level of empirical approximations, with many models assuming uniform radial distribution of flow variables over the test material. It is hence desirable to develop a high fidelity computer code that is capable of closely reproducing experimental data by accounting for the radial non uniformity within the flow.

For purposes of validating developed numerical models, ground tests are required. Ground test facilities are currently the only affordable possibility for material qualification and validation of material response codes. These facilitates are capable of simulating severe aerodynamic heating environment encountered during atmospheric re-entry. Because thermal response analysis of TPS material is an integration of several analysis processes right from the arc heater section all the way to the test chamber section, it is important to ensure that all numerical models involved perform within acceptable levels of accuracy. The ARCFLO3 computer code, developed to analyze arc heater freestream properties, can only analyze flow properties up to the physical nozzle throat. After which, flow distribution at the throat are imposed as input during flow analysis in the test chamber section. This approximation may justify questions about fidelity of computational fluid dynamics (CFD) flow codes developed based on this approach. Thus, there is dire need to simultaneously conduct numerical flow field analysis for the entire arc heated wind tunnel and further validate the models against measured data.

The main objective of this study was to develop high fidelity computer code for analyzing thermal response of highly porous heat shield materials subjected to atmospheric re-entry heating conditions. The developed model was able to calculate material thermal response by coupling CFD flow and material response codes. Highly porous carbon materials of density 0.12, 0.15, and 0.27 g/cm^3 with respective porosities of 93%, 90% and 85% were analyzed. Both 0.12 and 0.15 g/cm^{3}materials were procured from Osaka Gas Chemicals Co. Ltd manufacturer whereas 0.27 g/cm^3 material was prepared through heat treatment of an in-house developed ablative material. A constant diameter of 50 mm was used across the test specimens. Test specimens were exposed to arc heated nitrogen freestream for 10, 15 and 25s for and 0.12, 0.15, and 0.27 g/cm^3 materials respectively. Radiative conductivity model for evaluating material thermal response was developed using individual material's extinction coefficient evaluated using its X-ray CT data. Material response was analyzed by solving two-dimensional axisymmetric governing equation of pure solid material energy conservation, conveniently leaving out governing conservation equations for flow within the test materials. Other objectives included: (1) validation of ARCFLO3 code and test chamber CFD flow calculation code and (2) investigation of effect of convective transfer to the overall thermal analysis within porous carbon materials.

Calculated operating conditions of the ARCFLO3 code were validated against the corresponding measured data. The measured conditions included: arc heater power 644 $\pm$ 7kW, arcjet freestream mass flow rate 18.6 g/s, arc voltage 1436 $\pm$ 5 V, electric current 449 $\pm$ 4 A, heater chamber wall pressure 510 $\pm$ 1 kPa, mass average enthalpy 14.7 MJ/kg and heater thermal efficiency of 42%. Our focus in the validation process was on the mass average enthalpy since earlier results had indicated enlarged disparity between measurement and calculation. In this case, we varied electric current and input arc heater power to achieve acceptable agreement, through trial and error though. Using electric current of 383 A and an input power of 450 kW, the code was able to record mass average enthalpy of 14.41 MJ/kg, effectively reducing error gap to within 2%. Calculated mass flow rate of 18.42 g/s was also achieved, effecting results agreement of about 1%.

Validation of CFD flow code for analyzing flow properties over a blunt body within the test chamber was done by comparing stagnation point calculation results for Pitot pressure and heat flux at various axial positions from the physical nozzle exit. Calculations were conducted for cases of blunt body placed 50, 60, 70 and 80 mm away from the nozzle exit. Extreme cases of non-catalytic and fully catalytic flow calculations were done for heat flux analysis at the stated axial positions. Results were able to satisfy the general expectation that the measured value should be within the limits of the extreme cases.

For the main objective of this study, coupling approach in the developed numerical model was able to effectively predict the final shape of test specimen after the heating process, implying that material surface recession was well modeled. After heating, material surface receded by about 0.3 mm at stagnation point. This was enhanced by the surface chemical reactions, especially nitridation, enabled in the developed model. The corresponding recession measurement was 0.3±0.16 mm. Coupling calculation also managed to qualitatively reproduce the concave nature of the material heated surface contours by efficiently accounting for radial non uniformity of arcjet freestream flow distribution. From the results of arcjet axial flow temperature and mole fractions of atomic and molecular nitrogen species, unsteady thermal diffusion within the test materials as well as comparison results of calculated and measured surface and in-depth (18 and 23 mm positions) time histories, an overall good agreement was noted. The unsteady thermal diffusion results indicated that radiative model developed was effective in the analysis. This could also assert that radiative conductivity values obtained from the micro-scale specimen information using the X-ray CT data could be sufficient to predict macroscopic energy transfer in TPS materials. However, an anomaly was observed with in-depth temperature distribution where a peculiar phenomenon of delay in onset of temperature ramping rate dominated calculations during heating. Preliminary examination suggested that omitting convective transfer in the calculations, as is the case with our coupling model, could be a likely cause.

Therefore, another set of material response calculations was done to investigate influence of convection in the entire heat transfer process. This time, calculations were done in an uncoupled manner by using normalized heat flux distribution to set heat flux values that were able to reproduce surface temperature time histories of the test material. The normalized heat flux distribution was numerically simulated from arcjet wind tunnel flows using an integrated numerical method. The main reason for using normalized heat flux distribution was to capture radial non-uniformity of flow variables for accurate analysis. Calculations were done by solving gas mass, momentum, and energy conservation equations alongside material solid energy conservation equation. Flow was initiated within the pores of the test material by setting different pressure values in front and at the rear surfaces of the test material. Calculation results registered reduction in the temperature rise delay that was experienced earlier with coupled calculations.