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Numerical and Experimental Studies of Heat Transfer in Porous Media

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Abstract— **The subject of heat transfer through porous media is an area of rapid growth in contemporary research. Porous media consists of solid matrix and fluid matrix. The void matrix in the porous media is filled with fluids or gases. Heat transfer through porous media includes conduction, convection and radiation. The objective of this study is to determine the thermal response of a porous media under varying heating conditions. In the present study only one mode of heat transfer, heat conduction, is used to determine the thermal response of a porous media. For this analysis effective properties of porous media are used and the effective properties are determined using correlations. An explicit finite difference scheme is used for numerical formulation of the problem. The numerical model can be augmented by experimental results, which is also included in the scope of this work. Porous materials are used to protect the reentry space shuttle from failure due to aerodynamic heating. Silica tiles, which are essentially a porous material, made from pure silica fibre are used to protect the space shuttle. The experiments were carried out on silica tiles in a facility having capability to simulate time varying heating conditions and studied the thermal response of the material. The experiments were repeated for different specimens with variation in thickness at varying heating conditions. Experimental results are found to be in good match with the numerical results.**

Index Terms—**Heat Transfer, Porous Media, Correlations.**

I. INTRODUCTION

The general subject of heat transfer through a porous media is an area of rapid growth in contemporary research. Examination of heat transfer in porous media relies on the knowledge we have gained in studying heat transfer in plane media. The presence of permissible solid influences these phenomena. Porous media consists of solid phase and void phase. The voids in the porous material may or may not be interconnected. In ground condition the void matrix is filled with fluids or gases. The mode of heat transfer in porous material includes conduction, convection and radiation. The topic of pure heat transfer by conduction through porous media, which has received so much attention during the past three decades, is only a special limit of heat transfer phenomena reviewed in this paper.

The analysis of heat transfer in porous media is required in a large number of applications. One of the important applications of porous media is the thermal protection of reentry space vehicle from failure due to aerodynamic heating. Thermal protection system (TPS) is used to maintain a launch vehicles structural temperature within acceptable limits during reentry flight. Silica tile is one of the major TPS material used for thermal protection of reentry vehicles and it is essentially a porous material. Heat transfer through these tiles during atmospheric reentry involves combined modes of heat transfer: solid conduction through fibres, convection through gases in space between fibres, radiation exchange through participating media.

The objective of this study is to find out the thermal response silica tile which is essentially a porous material at different thermal loads with a numerical model validated by experimental tests. The tests were carried out in a facility which is having a capability to provide the rapid transient heating required for simulating the transient reentry heating profile.

The thermal response of silica tiles were modeled by considering only conduction heat transfer. For the analysis of thermal response of silica tiles, correlations for effective properties such as effective thermal conductivity were used. The effective thermal conductivity depends upon the thermal conductivity of each phase.

II. LITERATURE REVIEW

Heat transfer in porous media has been the subject of numerous investigators because it is required in a large number of applications. This increased use of porous media has made it essential to have better understanding of the associated transport process. Han and Cosner [1] studied the effective thermal conductivity of fibrous composites. They investigated a class of heat conduction problems for which the proximity effects of the embedded fibres are significant. Based on a lumped parameter model, Hsu, et al. [2] obtained expressions for effective thermal conductivity for a porous media. Stark and Frickle [3] developed an improved heat transfer model to porous insulations. Nimic and Leith [4] investigated the heat transfer through a granular porous media. This paper describes an improved modelfor estimating conductivity of granular porous media, in which radiations and convection heat transfer effects were considered negligible. Modified Zehner-Shlunder [5] models are proposed for calculations of the stagnant thermal conductivity of porous material. Calunidi and Mahajan [6] studied the effective thermal conductivity of high porosity fibrous metal foams. Heat transfer in high temperature fibrous insulation was analyzed by Kamran Daryabeigy [7]. A generalized model for the effective thermal conductivity of porous media

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Table 1: Test Specimen Details

Sl. No	Specimen Designation	Size (mm)	Thickness (mm)	Density (Kg/m^3)	Absorptivity and emissivity
1	Specimen-A	150 x 150	23.5	329	0.8
2	Specimen-B	150 x 150	22.0	329	0.8

was develop by Yougin Feng,Mingging Zou and Daunuing [8].

III. EXPERIMENTAL PROCEDURES

Tests were carried out in Kinetic Heating Simulation (KHS) facility of VSSC/ISRO. The tests were conducted to simulate the reentry aerodynamic conditions. The various components of KHS facility were used to simulate the thermal load on the test specimen. The required heating condition or heat flux history was simulated by exposing the test specimen to infrared radiation from an array of quartz enveloped tungsten filament infrared lamps in modular form. The facility uses a closed loop control system to irradiate the test specimen. The system is a closed loop real time test set up using Proportional Integral Derivative (PID) controllers and Silicon Controlled Rectifier Controllers for regulating the power to lamp module. A heat flux gauge is placed near the test specimen for sensing the heat flux incident on the specimen mounted in front of the lamp. The heat flux gauge provides the real time feed back signal to the PID controller. The PID controller works on an automatic mode. During the test, at every second the heat flux data is fed to the PID controller. The PID controller compares the predicted data and simulated data and check the error between them. The error signal is used for controlling the power input to the lamps, thus creating a closed loop control system. Cooled Gordon type heat flux gauges are used to measure the heat flux incident on the front wall of the specimen. The temperature of the back wall was measured with the help of K type thermocouples cemented at specified locations. The data acquisition system of the facility uses a personal computer for collection of data from thermocouple and heat flux gauges. Infrared pyrometers were used to measure the front wall temperature of the specimen during the test.

Test Specimen and Instrumentation

Tests were carried out on 150 x 150 mm silica tiles made from pure silica fibre. For thermal response evaluation test, specimens were instrumented with thermocouples for measuring the back wall temperature. Table.1 gives the details of the test specimen and Fig.1 shows the test specimen configuration with instrumentation.

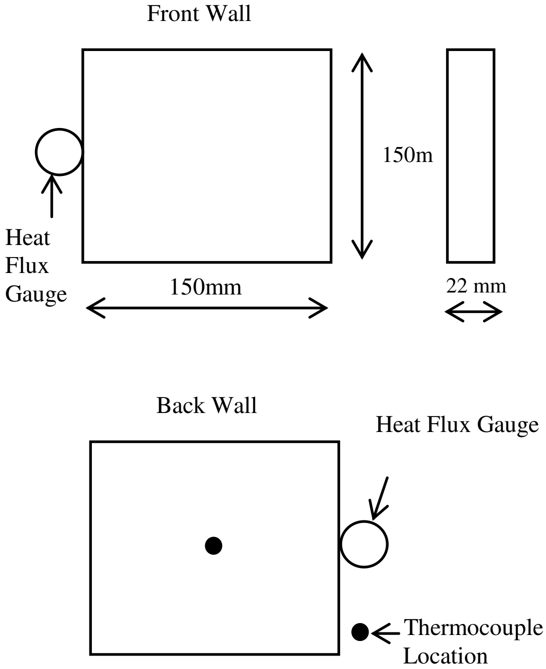

Fig. 1 Specimen Configuration with Instrumentation

Test Procedure

The objectives of the test were realized by carrying out the thermal simulation tests on the test specimens. For that fix the heat flux gauge near the test specimen for measuring the heat flux. Thermocouples are fixed on the back wall of the specimen for measuring the temperature. The test specimens with the thermocouples and positioned heat flux gauge are fixed in panel test set up for a certain distance. Thermocouples and heat flux gauges are then coupled to respective channels which are connected to the data acquisition system. The required or predetermined heat flux data is then fed to the computer and using the closed loop control system, subject the specimen to the required heat flux using IR lamps. The parameters like initial temperature, absorptivity, gauge constants are also given. Using the data acquisition system, acquire the data from the thermocouples and heat flux gauges.

Fig. 2 Test Process

IV. NUMERICAL FORMULATION

One dimensional transient conduction was considered for studying the thermal behavior of silica tiles. Fig.3 shows the computational domain. The governing equations, initial and boundary conditions are given below.

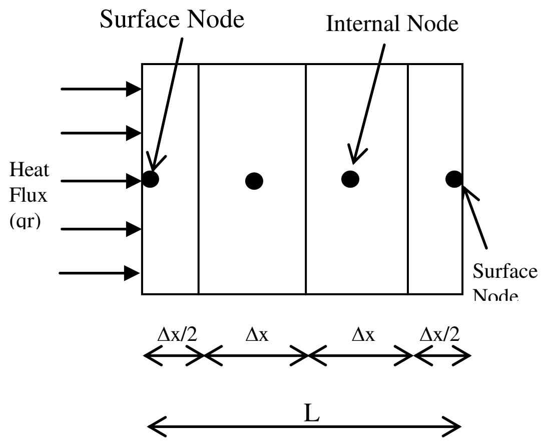

Fig. 3 Computational Domain

The numerical solution of heat transfer can begin when the laws governing these processes have been expressed in terms of differential equations. The governing equations for one dimensional transient conduction problem are given by

Fourier's equation

$$Q = -k A \frac{dT}{dx} \quad (1)$$

Newton's law of cooling

$$Q = h A \Delta T \quad (2)$$

Stefan-Boltzmann equation

$$Q = \sigma \varepsilon A F T^4 \quad (3)$$

Initial condition is

$$T_i = T_f \qquad \text{At } t = 0 \ (i = 1, 2, 3\ldots)$$

and other boundaries were considered to be insulated.

Energy balance method is applied to find the change in energy or increase in energy of each node. Explicit finite difference method is used to find the solution to the problem.

Effective conductivity values of each node were used for finite difference formulation of the problem and it can be calculated using the correlation

$$\frac{k_e}{k_f} = \left(\frac{k_s}{k_f}\right)^{0.280 - 0.757 \log\phi - 0.057 \log\left(k_s/k_f\right)} \quad (4)$$

Finite difference formulation for the front wall surface node is given by

$$T_i^{\tau+1} = [1 - 2F_o - 2F_oB_i - 2F_ok_1k_2]T_i^{\tau}$$

$$+2F_o\left[\frac{q_r\Delta x}{k} + B_iT_f + k_1k_2T_f + T_{i+1}^{\tau}\right] \quad (5)$$

The equation shown below gives the finite difference formulation for an internal node.

$$T_i^{\tau+1} = [1 - F_{o1} - F_{o2}]\, T_i^{\tau} + F_{o1}\, T_{i-1}^{\tau} + F_{o2}\, T_{i+1}^{\tau} \quad (6)$$

The finite difference formulation for a node on back wall surface is given by

$$T_i^{\tau+1} = [1 - 2F_o - 2F_oB_i - 2F_ok_1k_2]\, T_i^{\tau}$$

$$+ 2F_o[T_{i-1}^{\tau} + B_iT_f + T_fk_1k_2] \quad (7)$$

Where

$$k_1 = \frac{\sigma \Delta x\, \varepsilon F}{k}$$

$$k_2 = [T_i^{\tau} + T_f][(T_i^{\tau})^2 + (T_f)^2]$$

T_f is ambient temperature, σ is Stefan-Boltzmann constant, Δx is the distance between nodes, F is radiation shape factor. F_o, F_{o1}, F_{o2} are finite difference form of Fourier number, B_i is the finite difference form of Biot number. k is the effective conductivity between nodes and q_r is the heat flux incident on the specimen. T_i, T_{i-1}, T_{i+1} are temperatures of nodes. ε is the emissivity of the material. k_s and k_f are thermal conductivity of solid and fluid respectively. k_e is the effective conductivity of a node. ϕ is the porosity of the material.

V. RESULTS AND DISCUSSION

Tests were carried out in specimens having different thickness. Fig.4 shows the heat flux history recorded during the test for the specimen-A. The maximum surface temperature measured was 1296°C. For the specimen-A, the maximum back wall temperature was 131°C. Fig.5 shows the comparison of the temperature history for specimen-A. Fig.6 shows the heat flux simulated for the specimen-B. The maximum surface temperature measured was 1306°C. For the specimen-B, the maximum back wall temperature measured was 163°C. Fig.7 shows the comparison of temperature history for specimen-B.

Surface temperatures were read manually at intervals of 10s. For both the specimens, no change in emissivity was found after testing. Temperature history was computed at the surface as well as at the back wall of the specimens. The predicted temperature history is compared with that measured during the test.

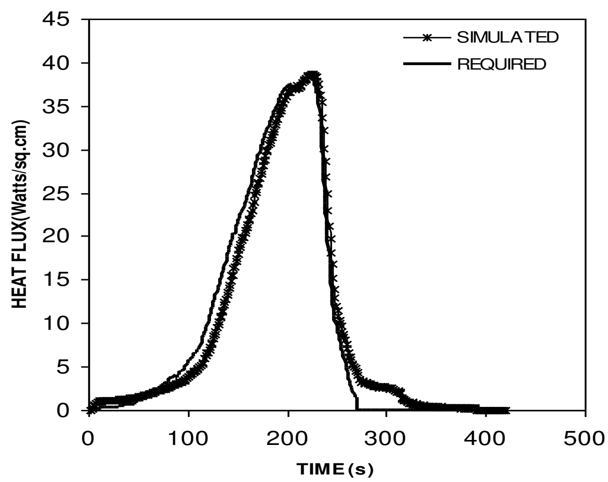

Fig.4 Heat flux history for specimen-A

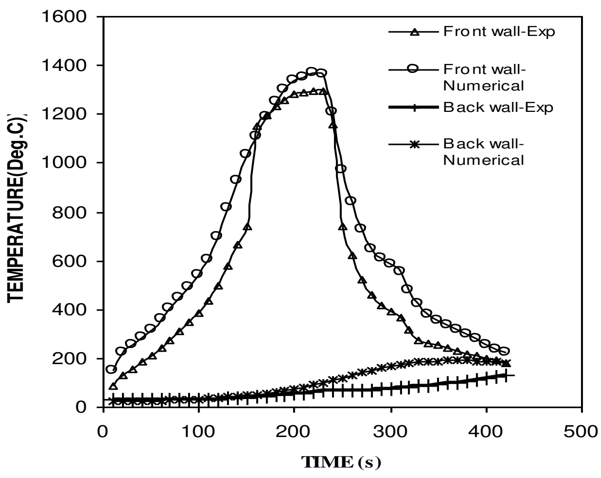

Fig.5 Temperature profile for specimen-A

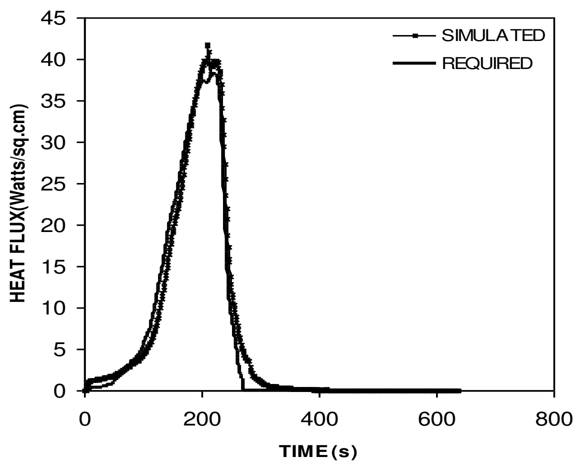

Fig.6 Heat flux history for specimen-B

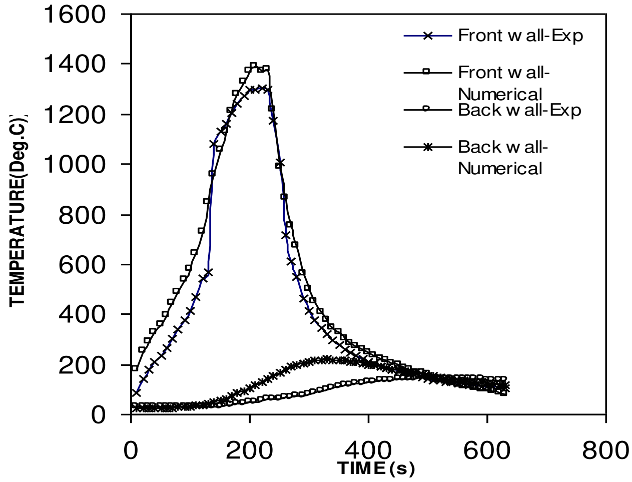

Fig.7 Temperature profile for specimen-B

VI. CONCLUSIONS

Transient tests simulating reentry aerodynamic conditions were carried out on silica tile insulation. No physical damage to any part of the tile was observed after the test. A numerical model was developed for modeling heat transfer in silica tile insulation. The numerical model was validated by transient thermal tests simulating reentry aerodynamic heating condition. Slight variations are due to assumptions made.

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