Indian Journal of Pure & Applied Physics
Vol. 44, October 2006, pp. 719-723

Evaluation of thermal conductivity of ablative material

N K Sundaresan, A Ambirajan, A Ramasamy, P P Gupta & D R Bhandari
Thermal Systems Group, ISRO Satellite Centre, Bangalore 560 017

Received 4 October 2005; accepted 12 July 2006

Ablatives are very often used in the Thermal Protection System of re-entry spacecraft. Their thermal conductivity will play an important role in determining the temperatures of components and payloads during the on-orbit and re-entry phases on the mission. A series of calorimetric tests were conducted on these materials to ascertain their thermal conductivity. A description of the experiments and the results of analyses of the experimental temperature data from the ablatives are presented in this paper. Three-dimensional mathematical model of the experiment was developed and analysed. The thermal conductivity of two ablative samples is determined by manually minimising the root sum of squares error (RSSE) between experimental and numerical data. The results obtained using this technique are compared with the results of a one-dimensional analysis.

Keywords: Thermal conductivity, Ablative material, Re-entry spacecraft

IPC Code: G01N25/18

1 Introduction

Ablatives are very often used in the thermal protection system of re-entry spacecraft. Their thermal conductivity will play an important role in determining the temperatures of components and payloads during the on-orbit and re-entry phases of the mission. Steady state calorimetric experiments were used to evaluate thermal conductivity of the ablative samples. A mathematical model of the experiment was developed using the IDEAS-TMG software. The thermal conductivities of two ablative samples (Phk25 and Phk80-30) were determined from the experimental data in two ways: (1) by direct application of the one dimensional Fourier law; (2) manually minimising the root sum of squares error (RSSE) between experimental and numerical data from a 3-dimensional mathematical model. These two methods are compared in this paper.

2 Experiment Details

A steady state calorimetric method is used for estimating the thermal conductivity of the ablative. The ablative samples are of square geometry with thickness ranging from 19.59 to 22.6 mm. The salient features of these ablatives are presented in Table 1.

A schematic of the experimental set-up is shown in Fig. 1. Two square ablative samples of the same type (e.g. Phk25A and Phk25C) are bonded to 4 mm thick aluminium plates (Fig. 1). The 4 mm thick aluminium heater plates sandwich a thermo-foil heater. All elements of this sandwich have the same cross-sectional dimensions of 150 mm × 150 mm. Black painted aluminium plates of thickness 0.28 mm are adhesively bonded on both the ablative outer faces. These black painted surfaces are the sink plates that reject heat to the surroundings either radiatively or convectively. To minimise side heat losses, the lateral surfaces are with covered with low emittance tape (ε = 0.06). Thermocouple sensors are fixed on the grooved insides of the two square heater plates. To determine the temperature uniformity and gradient, a number of T type thermocouples are fixed on the heater plate and sink plate. The thermocouple and the

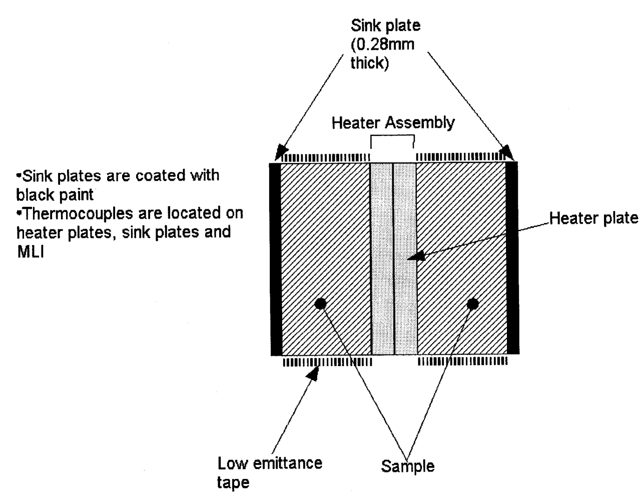

Fig. 1—Schematic of experiment

Table 1—Details on samples used in the experiments

Sample material (Ablative)	1 Phk25A and Phk25C: 0.23g/cc 2 Phk80-30A and Phk80-30B: 0.43g/cc
Sample dimensions	1 Phk25A and Phk25C: 150 mm × 150 mm × 19.59 mm 2 Phk80-30A and Phk80-30B: 150 mm × 150 mm × 22.6 mm

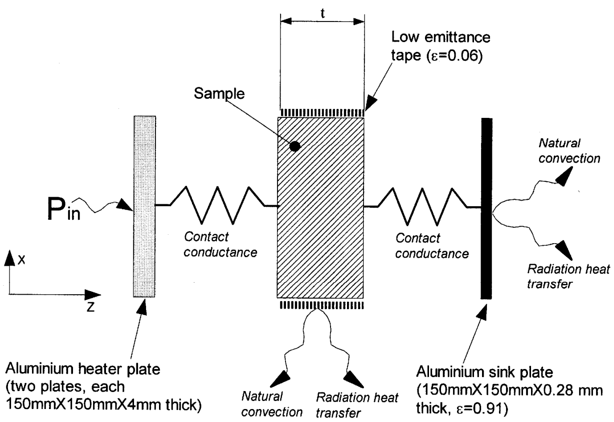

Fig. 2—Schematic of mathematical model

heater wires are bundled into a neat harness and insulated with multilayer insulation.

Heat, supplied to the heater plate through the foil heaters, diffuses through the heater plate, sample and sink plate to the surroundings via natural convection and radiation heat transfer. The following two configurations are considered in this paper:

(1) *Tile in evacuated vacuum chamber*: Conduction through tile followed by radiation heat exchange with shroud. Shroud may be either liquid nitrogen (T_{shroud} ~ -185°C) or water cooled; (2) *Tile in still ambient*: Conduction through ablative followed by radiation heat exchange with ambient and natural convection.

For a given ablative, the experiment is conducted for various heater powers for each configuration mentioned in Table 1. The temperature of the heater plates varied from 0 to 150°C. Knowing the heater power and temperatures on each ablative, the thermal conductivity of the ablative can be estimated.

3 Estimation of Thermal Conductivity

A schematic of the 3-dimensional mathematical model used in the present analysis is shown in Fig. 2. When the test package is placed in the vacuum chamber, the mathematical model assumes the surroundings to be black at the mean temperature of the shroud. When the test package is suspended in still air, there are both radiative and free convective interactions with the surroundings. For radiation calculations, the surroundings are assumed to be black at the temperature of air. Free convection correlations used in the 3-dimensional mathematical model,[1] are presented in Table 2 . The characteristic length (L) of the plate, as used in the free convection correlations listed in Table 3, is taken to be 150 mm in this study. The thermal contact conductance for the interfaces (heater plate to sample and sample to sink plate) is taken to be 300 $Wm^{-2}K^{-1}$. Assuming that the ablative has a thermal conductivity of the order of 0.1 $Wm^{-2}K^{-1}$ and thickness of the order of 20 mm, its conductance is of the order of 0.1/0.02 = 5 $Wm^{-2}K^{-1}$ which is much less than the contact conductance (300 $Wm^{-2}K^{-1}$) used in the analysis. Hence, the estimated thermal conductivity of the sample is relatively insensitive to the interface contact conductance.

Table 2—Free convection correlations for air* (Ref. 1)

Geometry	Correlation	Regime
Vertical plate	$h_m = 1.42\ (\Delta T/L)^{1/4}$	Laminar
Horizontal plate (upper surface hot or lower surface cold)	$h_m = 1.32\ (\Delta T/L)^{1/4}$	Laminar
Horizontal plate (Lower surface hot or upper surface cold)	$h_m = 0.59\ (\Delta T/L)^{1/4}$	Laminar

*L is the characteristic length

Table 3—Experimental cases analysed in this report

Ablative	Vacuum chamber		Ambient
	Water	*LN2*	
Phk25	Yes	Yes	Yes
Phk80-30	No	Yes	Yes

Note: Water and LN2 (liquid nitrogen) refer to the cooling medium of the vacuum chamber shroud. Ambient refers to the case where the tile is placed in still ambient air

The finite volume mathematical model was formulated using the IDEAS-TMG (produced by Maya Heat Transfer Technologies Ltd.) software. The heater and sink plates each have 225 elements and are one element thick, respectively (i.e. each element on the heater plate is 10 mm × 10 mm × 4 mm, and each element on the sink plate is 10 mm × 10 mm × 0.28 mm). The sample has 2250 elements (i.e. there are 225 elements in the XY plane and 10 elements in the Z direction). Numerous surface coat elements in the model are presented for the conductive and radiative couplings. The lateral surfaces of the sample are surface coated with null elements of emissivity 0.06. The thermal conductivity of the ablative in the mathematical model is assumed to be constant.

In the following analysis, T_{mhp} and T_{msp} are the average measured temperatures of the heater and sink plate, respectively. The expression for estimating the thermal conductivity of the ablative based on the one-dimensional Fourier law is:

$$\lambda = \frac{Q_{sp} t}{(T_{mhp} - T_{msp})A} \quad \ldots \quad (1)$$

The heat rejected by the sink plate in vacuum is estimated by:

$$Q_{sp} = \varepsilon_{sp} \sigma A(T_{sp}^4 - T_s^4) \quad \ldots \quad (2)$$

and the heat rejected by the sink plate in still ambient air is estimated by:

$$Q_{sp} = \varepsilon_{sp} \sigma A(T_{sp}^4 - T_s^4) + h_m A(T_{sp} - T_s) \quad \ldots \quad (3)$$

In the one-dimensional analysis, h_m is taken to be 5 $Wm^{-2}K^{-1}$.

Let T_{chp} and T_{csp} be the mean temperatures of the hot plate and sink plate, respectively predicted using the 3-dimensional mathematical model, then the RSSE is defined as:

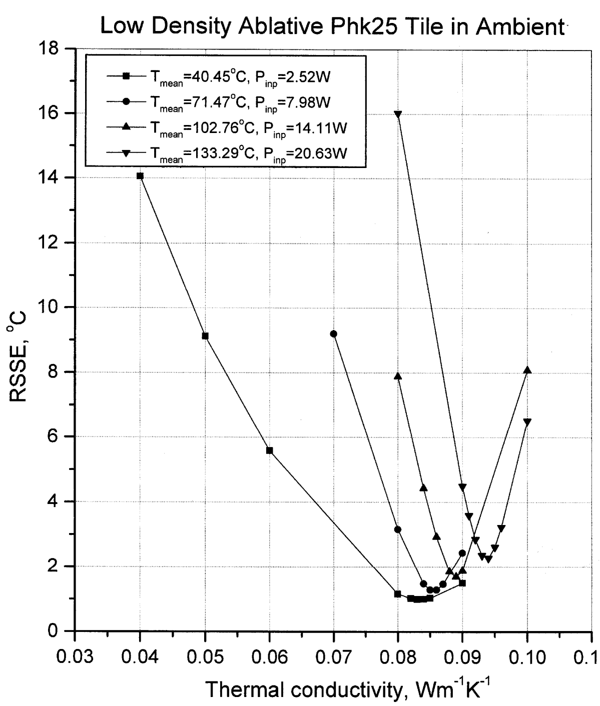

Fig. 3—Variation of RSSE with thermal conductivity

$$\text{RSSE} = [(T_{mhp} - T_{chp})^2 + (T_{msp} - T_{csp})^2]^{1/2} = (e_{hp}^2 + e_{sp}^2)^{1/2} \quad \ldots \quad (4)$$

The thermal conductivity of the sample is estimated by minimising the RSSE between experimental and numerically predicted temperatures at the heater and sink plates respectively, using the exhaustive search approach[2]. This involves solving the mathematical model for various thermal conductivities and choosing the value corresponding to the smallest RSSE. The present approach involved manually solving the mathematical model for a variety of thermal conductivities in contrast to the more sophisticated schemes[2]. As an example of the application of this technique, the RSSE versus thermal conductivity for various heater powers is plotted in Fig. 3 for Phk25. For each heater power level, the estimated thermal conductivity corresponds to the minima in the RSSE curve (Fig. 3). The approach is used for all the cases presented in Table 3.

4 Results

The results of the analyses on the Phk25 and Phk80-30 ablative test samples are presented. The experimental configurations shown in Table 1, are analysed in this paper. Figures 4 and 5 show the plots of the thermal conductivities. The estimated thermal conductivity of both ablatives (Phk25 and Phk80-30) increases with temperature for both the one-dimensional and 3-dimensional cases. When the sample is in vacuum the thermal conductivity estimates using the one-dimensional analysis are consistently lower than the corresponding multi-dimensional result. This is partly due to the fact that Eq. (1) assumes that the heat flow through the sample is Q_{sp}. Since the heat input to the sample is P_{in} and the rejected heat is Q_{sp}, Eq. (1) underestimates the thermal conductivity. Further, for the case of the sample in still air, the calculations show that the fraction of heat rejected from the sink plate is about 60%. Thus, Eq. (1) significantly underestimates the thermal conductivity when the sample is placed in still air.

The quantity RSSE/ΔT_c is a measure of the relative error in the calculated temperature difference across the ablative using the 3-dimensional mathematical model and is used here as a measure of the uncertainty in the estimated thermal conductivity (λ). The ratio RSSE/ΔT_c is always less than 15% for all

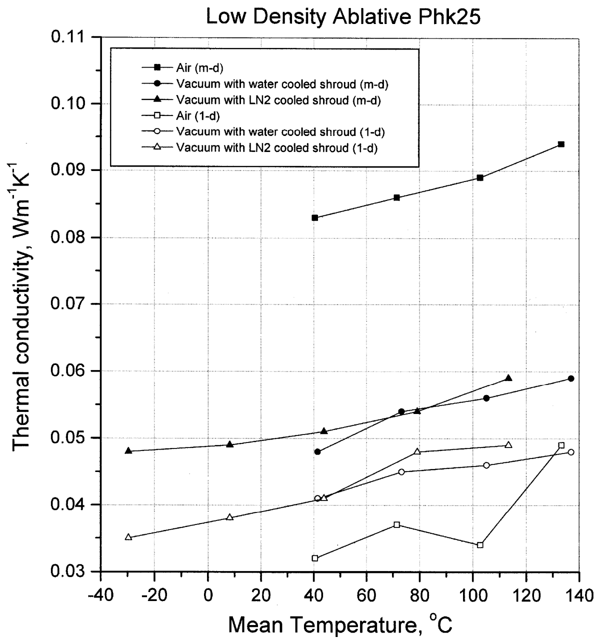

Fig. 4—Variation of thermal conductivity of Phk25

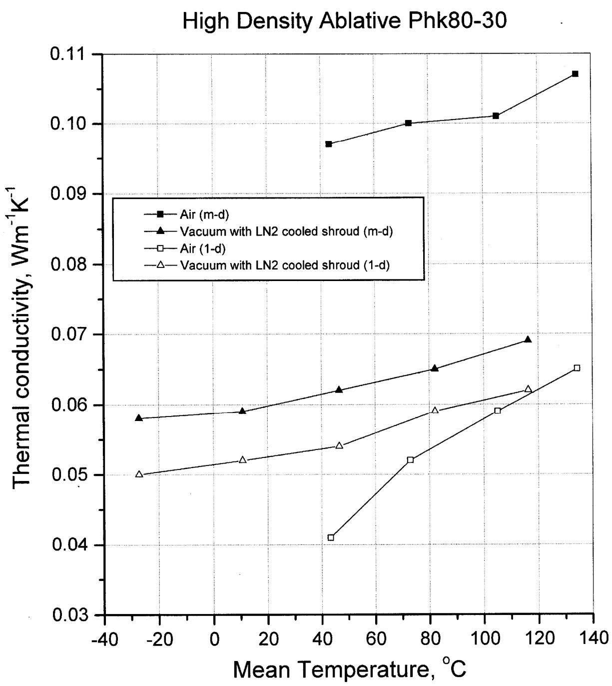

Fig. 5—Variation of thermal conductivity for Phk80-30

cases. This can be taken as an upper bound on the error in these estimates for ablative thermal conductivity.

The thermal conductivity of a given in sample in air, λ_{amb}, is always greater than the thermal conductivity of the sample in vacuum (λ_{vacuum}) at a specified mean temperature of the sample. It is also

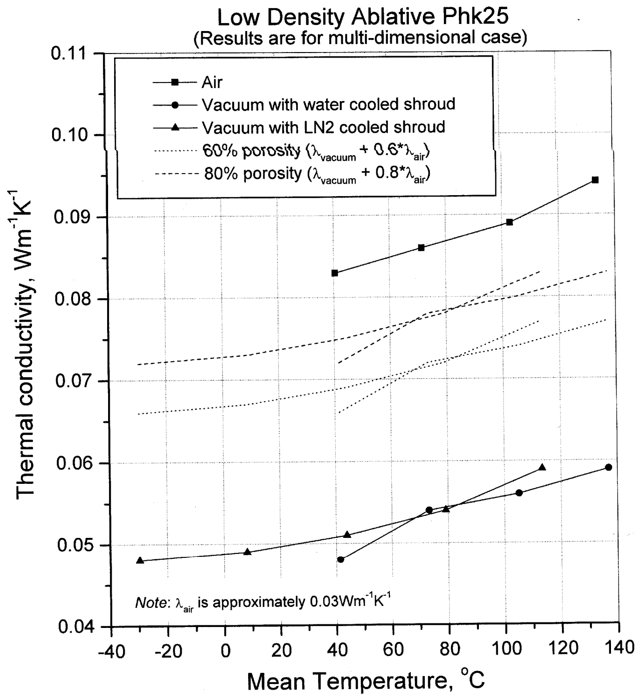

Fig. 6—Effect of porosity on the thermal conductivity of Phk25

interesting that the difference between λ_{amb} and λ_{vacuum} is of the order of 0.03 $Wm^{-1}K^{-1}$ ($\lambda_{air} \sim 0.03$ $Wm^{-1}K^{-1}$) for both Phk25 and Phk80-30. Since ablatives are porous, the following relation can be used to evaluate the thermal conductivity of an ablative in air:

$$\lambda_{amb} = \lambda_{vacuum} + \varphi\lambda_{air} \qquad \ldots (5)$$

Figure 6 shows the effect of porosity on the thermal conductivity of Phk25. Increasing the porosity brings the expected thermal conductivity of the ablative in still air closer to those actually obtained by experiment. In fact with a presumed porosity of 80%, the expected thermal in air is within 0.01 $Wm^{-1}K^{-1}$ of the experimental value. The discrepancy is probably due to natural convection within the porous medium (resulting in a higher apparent thermal conductivity).

5 Conclusions

The calorimetric experiments were performed to determine the thermal conductivity of two ablatives namely Phk25 and Phk80-30. The thermal conductivity of these ablatives is estimated in two ways namely the one-dimensional Fourier conduction equation by minimizing the RSSE. The two methods yielded results that are reasonably in agreement when the samples are in vacuum. The small discrepancies are partly due to the use of Q_{sp} in the one-dimensional calculations. The one-dimensional method yielded significantly lower thermal conductivities than the multi-dimensional method when the samples were in still air. This is because only about 60% of the heater input power is actually rejected to air.

The 3-dimensional method yielded estimates for conductivity that has a likely error of less than 15%. The estimated thermal conductivities in air and vacuum have shown a constant difference. This is because the specimens are porous.

Acknowledgement

We acknowledge the help given by Mr A N Krishnamurthy and Mr M Vishnumurthy for developing the instruments and conducting the extensive set of experiments referred to in this report.

References

1 Ozisik M N, *Heat Transfer: A Basic Approach,* (McGraw-Hill Book Co., New York), 1985.

2 Beck J V & Arnold K J, *Parametric estimation in engineering and science*, (John Wiley, New York), 1977.

Nomenclature

.

A = Area of plates and ablatives (m^2)

e_{hp} = T_{mhp} - T_{chp} (°C)

e_{sp} = T_{msp} - T_{csp} (°C)

h_m = Convective heat transfer coefficient ($Wm^{-2}K^{-1}$)

P_{in} = Input heater power to a single ablative sample (Watts)

Q_{sp} = Heat loss through sink plate (convective or radiative) (Watts)

RSSE = Root sum of squares error (°C)

t = Thickness of ablative (m)

T_M = Mean measured temperature of ablative (°C)

T_{csp} = Numerically predicted temperature of sink plate (°C)

T_{chp} = Numerically predicted temperature of heater plate (°C)

T_{msp} = Measured temperature of sink plate (°C)

T_{mhp} = Measured temperature of heater plate (°C)

T_s = Temperature of the surrounding (shroud or ambient) (°C)

ΔT_c = T_{chp} - T_{csp} (°C)

ΔT_m = T_{mhp} - T_{msp} (°C)

ε_{let} = Emissivity of low emissivity tape

ε_{sp} = Emissivity of sink plate

λ = Thermal conductivity ($Wm^{-1}K^{-1}$)

λ_{air} = Thermal conductivity of air ($Wm^{-1}K^{-1}$)

λ_{amb} = Thermal conductivity of ablative in still air ($Wm^{-1}K^{-1}$)

λ_{vacuum} = Thermal conductivity of ablative in vacuum ($Wm^{-1}K^{-1}$)

ϕ = Porosity

ψ = Calculated fraction of heater input power rejected though sink plate