



Modified Flash Method for Thermal Diffusivity Measurement of Porous Materials

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Abstract

In this research, a new technique for measuring thermal diffusivity of porous material using thermography is presented. This technique has at least two advantages than the traditional flash method. First, there is no temperature sensor installed on a specimen, so there is no heat accumulation in the sensor. Moreover, it is not necessary to have a good sensor installation skill to make a good contact between the specimen and the temperature sensor. Therefore, the measured temperature distribution should have more accuracy. Second, the initial condition used for calculating the thermal diffusivity is obtained immediately after flash heating the specimen. The special algorithm was developed for treating data in order to obtain the temperature initial condition function in an appropriate form. The specimen was installed in an apparatus that has insulated walls and contains stationary air to reduce heat losses by forced convection for better results. The specimen was heated using laser beam or hot spot wire and the evolution of temperature distribution was recorded by thermographic camera. The measured data in conjunction with present numerical method are used to calculate thermal diffusivity of the tested specimen. Stainless steel AISI 304 which represented a homogenous material and a series of Alumina ceramic, which represented porous material, were used for validation the present method. The measuring results were well agreement with the value found in material properties standard books.

Keywords: thermal diffusivity, thermography, porous material, infrared camera

1. Introduction

In this work the method for measuring thermal diffusivity of porous materials using thermography is introduced. To measure thermal diffusivity, there are many methods available for measuring thermal diffusivity of solid substances, but one that dominates all methods is the Flash Method [1]. This method requires a small and simple-geometry specimen and can measure

thermal diffusivity, specific heat, and thermal conductivity of solids in a single short period of time causing a very little heat losses. However, this method cannot be applied to a porous material as stated by Katsunori [2]. There are many methods for measuring thermal diffusivity of porous materials; some uses the modification of the initial condition [2], some uses specimen thickness correction [3,4], and some uses the

sandwich structure to measure effective thermal diffusivity [3]. Moreover, there is a prediction method for determining thermal properties using a numerical and an analytical approach [5].

Due to the energy penetration into the specimen the initial condition of the original flash method cannot be applied to porous materials. Therefore, instead of using assumed initial condition as in the original flash method causing a considerable error in thermal diffusivity measurement of porous materials, the actual temperature distribution is measured and used as the initial condition in this work.

2. Measurement Method Development

From the our previous work [6] the method for measuring thermal diffusivity using thermography was developed and it is now refined by using regression method to reduce some white noise from measured data. The mathematical model used in this work is the solution of one-dimensional heat diffusion problem in a solid without any heat losses as follows

$$T(x, t) = \frac{1}{L} \int_0^L T(\zeta, 0) d\zeta + \frac{2}{L} \sum_{n=1}^{\infty} \int_0^L T(\zeta, 0) \times \cos \frac{n\pi\zeta}{L} d\zeta \cos \frac{n\pi x}{L} e^{-\alpha \left(\frac{n\pi}{L}\right)^2 t} \quad (1)$$

where T is the temperature distribution, L is the specimen length, α is thermal diffusivity, and $T(x, 0)$ is the initial condition. Due to the fact that if the specimen has pores, the input energy will penetrate into the specimen and the assumed initial condition of the original flash which assumes that the input energy is accumulated at the tip of the specimen is no longer valid. Therefore, the actual temperature

distribution at the initial state is used to construct an initial condition having the form of

$$T(x, 0) = T_{\infty} + \Delta T_{i, \max} e^{-ax^b} \quad (2)$$

Substitute the initial condition into the Eq. (1) to obtain

$$T(x, t) = T_{\infty} + \frac{\Delta T_{i, \max}}{L} \int_0^L e^{-a\zeta^b} d\zeta + 2 \frac{\Delta T_{i, \max}}{L} \sum_{n=1}^{\infty} \int_0^L e^{-a\zeta^b} \cos \left(\frac{n\pi\zeta}{L} \right) d\zeta \times \cos \left(\frac{n\pi x}{L} \right) e^{-\alpha \left(\frac{n\pi}{L} \right)^2 t} \quad (3)$$

Two dimensionless variables are defined as in the flash method as

$$V(x, t) = \frac{T(x, t) - T_{\infty}}{\Delta T_{i, \max}} \quad (4)$$

$$\omega = \frac{\pi^2 \alpha t}{L^2} \quad (5)$$

After rearranging the Eq. (3) according to the two variables defined in the Eqs. (4) – (5), one obtain

$$V(x, \omega) = \frac{1}{L} \int_0^L e^{-a\zeta^b} d\zeta + \frac{2}{L} \sum_{n=1}^{\infty} \int_0^L e^{-a\zeta^b} \times \cos \left(\frac{n\pi\zeta}{L} \right) d\zeta \cos \left(\frac{n\pi x}{L} \right) e^{-\omega n^2} \quad (6)$$

The Eq. (6) is used to determine thermal diffusivity with the measured data. From the measurement the measured data is in the form of a series of images which represents the temperature distribution in the specimen at each time. The reference image is chosen and used to determine the coefficients in the Eq. (2) to construct the initial condition $T(x, 0)$, and then the temperature distributions at the time greater than zero in the later images are used to determine the ω corresponding to each time by curve fitting.

Since each image corresponds to the exact time t , the temperature distribution in

each image is a function of space only and is fitted into the Eq. (6) to determine ω which acts as a curve fitting coefficient. The series of ω obtained from fitting each image into the mathematical model in the Eq. (6) is a function of time and used to determine thermal diffusivity by fitting the series of ω into the Eq. (5) where thermal diffusivity α acts as a curve fitting coefficient. The regression method used in this work was a non-linear iterative curve fitting which can be accomplished by FMINSEARCH, the standard MATLAB function.

3. Thermal Diffusivity Measurement and Results



Fig. 1 The specimen holder and the thermographic camera were installed in the environmental controlling box.

Since it is assumed that the heat diffusion in the specimen is one-dimensional which is true for high thermal diffusivity materials having axial heat flux much greater than circumferential convective heat flux, the measurements were made in an apparatus controlling the measurement environment to prevent heat losses from the specimen by heat convection to ensure this assumption. A specimen holder and a thermographic camera were installed in the apparatus under environment control, as shown in the Fig. 1.

The specimen used in this work was an alumina rod having a porosity of 0.38%, a diameter of 6 mm., and a length of 50.1 mm. Its surface was coated with flat black spray paint to increase the infrared emissivity, as shown in the Fig. 2.



Fig. 2 Alumina rod coated with flat black spray paint is used as a specimen.

To induce a temperature gradient, the specimen was heated by a soldering iron whose temperature was controlled by a dimmer to protect excess temperature damaging thermographic camera, as shown below.



Fig. 3 A soldering iron and a dimmer are used to heat a specimen up.

The thermographic camera used in this work was the FLIR ThermoVision A40V having thermal sensitivity of 0.08°C at 30°C, as shown in the Fig. 4. This camera was controlled by its official software, ThermaCAM Researcher Pro, which is also used to monitor the recorded data.

The measurement process was started from heating the specimen by a soldering iron having temperature of 51°C, as shown in the Fig. 5. The measurement was separated into two cases according to the heating duration; 20

seconds for the first case and 30 seconds for the second case.



Fig. 4 FLIR ThermoVision A40V.

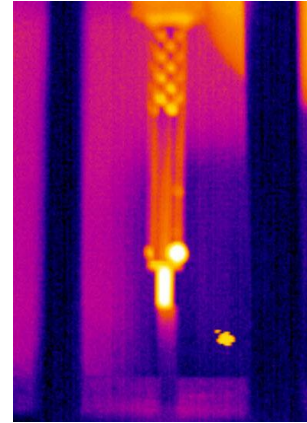


Fig. 5 Soldering iron was used to heat the specimen.

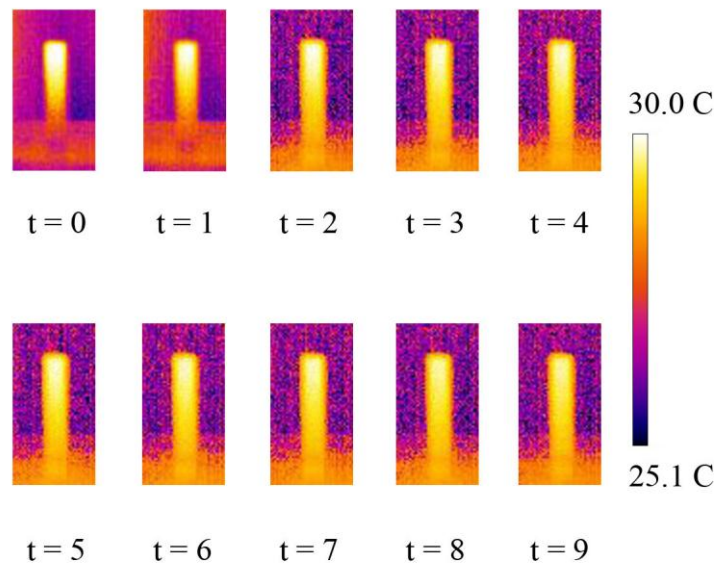


Fig. 6 Temperature distribution after being heated for 20 seconds.

3.1 Heating for 20 seconds

The temperature distributions as shown in the Fig. 6 were used to determine thermal diffusivity. First, the temperature distribution at time $t = 0$ was fitted into the Eq. (2), as shown in the Fig. 7, and the resulting initial condition was

$$T(x, 0) = 26.05 + 4.14e^{-321.233x^{1.384}} \quad (7)$$

After obtaining all the necessary parameters, the temperature distributions at time $t = 1$, $t = 2$, $t = 3$, and $t = 4$ were fitted into the Eq. (6) to determine corresponding

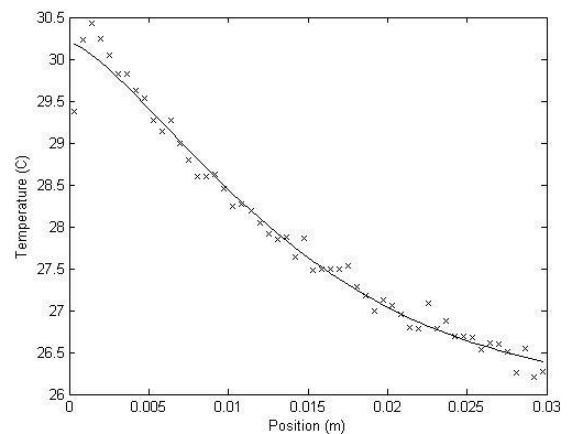


Fig. 7 The resulting curve fitting for constructing the initial condition in the Eq. (7). dimensionless variables ω for each time t , as shown in the Table. 1.

Table. 1 The resulting ω used to determine thermal diffusivity of alumina in the first case.

Time (s)	ω
1	0.06337
2	0.11341
3	0.15775
4	0.20205

The series of ω at the time $t=1$, $t=2$, $t=3$, and $t=4$ in the Table. 1 were fitted into the Eq. (5), as shown in the Fig. 8, to determine thermal diffusivity. The resulting value was $13.3 \times 10^{-6} \text{ m}^2/\text{s}$ which differs from the already published values of $11.9 \times 10^{-6} \text{ m}^2/\text{s}$ [7]

and $12 \times 10^{-6} \text{ m}^2/\text{s}$ [8] by 11.76 % and 10.83 %, respectively.

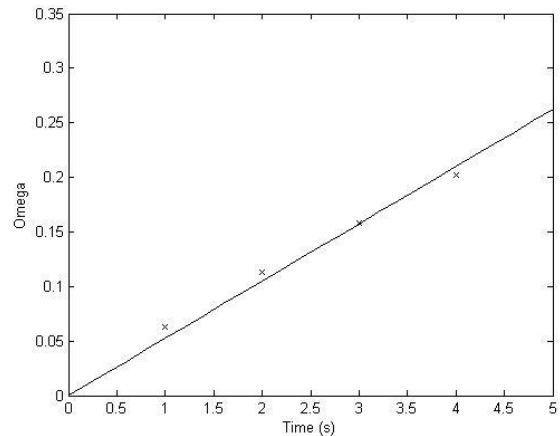


Fig. 8 The resulting curve fitting for determining thermal diffusivity in the first case.

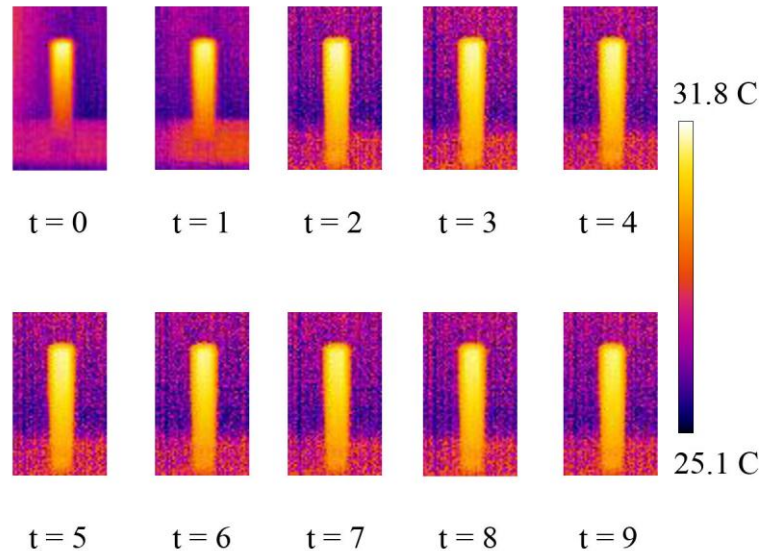


Fig. 9 Temperature distribution after being heated for 30 seconds.

3.2 Heating for 30 seconds

The resulting temperature distributions were shown in the Fig. 9 and the temperature distribution at time $t=0$ was fitted into the Eq. (2), as shown in the Fig. 10, and the resulting initial condition was

$$T(x,0) = 26.55 + 3.81e^{-2959.877x^{1.959}} \quad (8)$$

As in the first case, the series of ω were obtained from fitting temperature

distributions at the time $t=1$, $t=2$, $t=3$, and $t=4$ to the Eq. (6) and were shown in the Table. 2.

To determine thermal diffusivity, the series of ω were fitted into the Eq. (5), as shown in the Fig. 11.

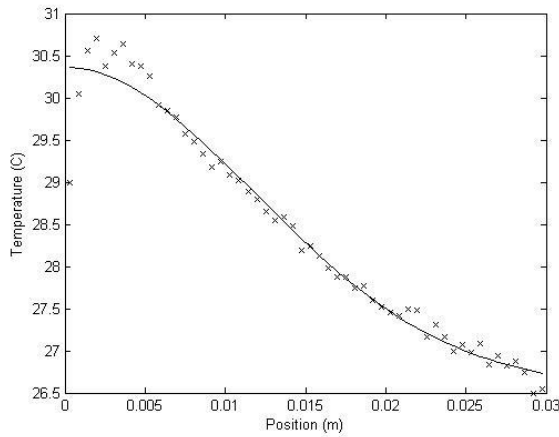


Fig. 10 The resulting curve fitting for constructing the initial condition in the Eq. (8).

Table. 2 The resulting ω used to determine thermal diffusivity of alumina in the second case.

Time (s)	ω
1	0.05492
2	0.10469
3	0.15445
4	0.20530

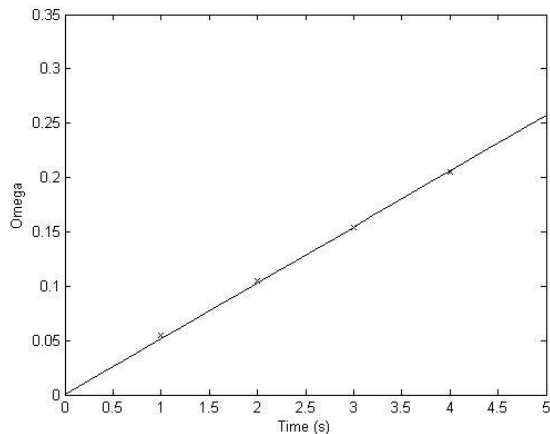


Fig. 11 The resulting curve fitting for determining thermal diffusivity in the second case.

The resulting thermal diffusivity was $13.1 \times 10^{-6} \text{ m}^2/\text{s}$ which differs from the already published values of $11.9 \times 10^{-6} \text{ m}^2/\text{s}$ [7] and $12 \times 10^{-6} \text{ m}^2/\text{s}$ [8] by 10.08 % and 9.17 %, respectively.

The measurements were repeated for reliability analysis and all results were summarized in the Table. 3. For the measurement consistency, the test-retest method, which is suitable for measurements performed by a single person or instrument on the same item and under the same condition, is used to estimate reliability.

Table. 3 The resulting thermal diffusivity of alumina

Heating Duration (s)	First Measurement (m^2/s)	Second Measurement (m^2/s)
20	13.3×10^{-6}	13.2×10^{-6}
30	13.1×10^{-6}	12.8×10^{-6}
PMCC	0.9998	

The results in the Table. 3 were used to determine Pearson product-moment correlation coefficient (PMCC) [9] which corresponds to 0.9998 showing high test-retest reliability.

4. Discussion and Conclusion

Thermal diffusivity of alumina obtained from the 2 cases of study showed high reliability and the relative differences between the measured value and the reference value which are only about 10 % have no significance. The differences occurred are caused by the transfer of heat in the specimen which is not one-dimensional perfectly as assumed in the mathematical model. Due to the fact that the heating area of the soldering iron is smaller than the specimen cross-sectional area and that the heat losses may take place. Nevertheless, it is reasonable to assume that the few heat losses can take place since the maximum temperature rise was quite low compared with the ambient temperature and the short period of time was



used in the measurement process. The other important factor causing error in the measurement is the initial condition, which should represent the initial temperature distribution correctly. The developed initial condition in the Eq. (2) can be used to represent the temperature distribution after heating, as shown in Fig. 7 and Fig. 10, and can be applied to porous materials as well as homogeneous materials.

5. References

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