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HEAT TRANSFER PARAMETERS FOR SPHERICAL PARTICLES SUBJECT TO IMMERSION HEATING

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ABSTRACT

In this study, simple models are provided to determine the heat transfer parameters in terms of the thermal diffusivities and heat transfer coefficients during heating of spherically shaped particles. A center temperature distribution of a spherical brick particle was measured and employed. The lag factor and heating coefficient are obtained and incorporated into the present models. The dimensionless theoretical center temperature distribution was computed using the obtained heat transfer parameters and compared with the experimental measurements. In the comparison, a very good agreement was found. As a result, we presented an approach and hence developed simple and accurate models. In this respect, we believe that these models will be beneficial to people and industry involved in practical heating applications.

Introduction

Transient heat transfer takes place in many engineering applications ranging from hot processing of metals to food-cooling. An exact analysis of transient heat transfer during cooling or heating of solid objects is required to improve the processing conditions, and to save the energy, leading to high quality products. In this regard, the ultimate objective is to develop simple and accurate, as well as practical heat transfer parameter models and techniques over the complex techniques and methods.

In the analysis of the transient heat transfer, three important criteria are considered, namely, $Bi<0.1$, $0.1<Bi<100$, and $Bi>100$. Within these criteria, the case of $0.1<Bi<100$ is the most realistic and practical.

The main purpose of this paper is to obtain simple and accurate models for the heat transfer parameters during heating of spherical metals, and to estimate the theoretical center temperature distribution by using the heat transfer parameters determined here.

Modelling

Consider that a spherical particle is heated by the air stream. Heat is transferred by convection and radiation from the surroundings to its surface and by conduction within the metal object from the surface to the interior of the object. Under the following assumptions, for example, constant thermal and physical properties of the homogeneous and isotropic object and the heating medium, no internal heat generation, and constant object initial temperature and medium temperature, the governing time-dependent heat conduction for a spherical particle in terms of the excess temperature (i.e., $\phi = T - T_i$) can be written as

$$[(\partial^2\phi/\partial r^2) + (2/r)(\partial\phi/\partial r)] = (1/a)(\partial\phi/\partial t) \qquad (1)$$

and the boundary conditions can be taken, respectively, as

$\phi(r,0) = \phi_i = (T_a - T_i)$; $\phi(0,t)$ = finite or $(\partial\phi(0,t)/\partial r) = 0$; and $k[\partial\phi(R,t)/\partial r] + h\phi(R,t) = 0$.

The general solution to this problem by the laplace transform technique or the separation of variables is available [1-3]. Therefore, the center transient temperature distribution in the dimensionless form results as follows:

$$\theta = \sum_{n=1}^{\infty} A_n B_n \qquad (2)$$

where

$A_n = [(-1)^{n+1}(2Bi)((Bi - 1)^2 + \mu_n^2)^{1/2}]/[\mu_n^2 + Bi^2 - Bi]$ and $B_n = \exp(-\mu_n^2 Fo)$.

It is possible to simplify Eq.(2), we can consider that the values of the Fourier number higher than 0.2 reflect the entire heating process, (i.e., other remaining terms are negligible) and take n=1. Eq.(2) then becomes

$$\theta = A_1 B_1 \qquad (3)$$

where

$A_1 = [(2Bi)((Bi - 1)^2 + \mu_1^2)^{1/2}]/[\mu_1^2 + Bi^2 - Bi]$ and $B_1 = \exp(-\mu_1^2 Fo)$.

The following dimensionless quantities are introduced:

$$Bi = (hR/k) \qquad (4)$$

$$Fo = (at/R^2) \qquad (5)$$

$$\theta = (T - T_a)/(T_i - T_a) \tag{6}$$

The dimensionless center temperature distribution of a spherical object subject to heating, as being in a cooling process, in terms of the lag factor and heating coefficient (in the heating case), is written as follows [4]:

$$\theta = L\exp(-Ht) \tag{7}$$

The value of A_1 is simplified to [5]:

$$A_1 = L = \exp[(0.7599Bi)/(2.1 + Bi)] \tag{8}$$

The characteristic equation for Eq.(2) is $\mu_n \mathrm{Cotg}\mu_n = (1 - Bi)$, this equation is simplified to the following correlations developed earlier [6]:

$$\mu_1 = [(1.12)\ln(4.9Bi + 1)]^{1/1.4} \quad \text{for } 0.1<Bi<10 \tag{9}$$

$$\mu_1 = [(1.66)\ln(2.2Bi + 152.4)]^{1/1.2} \quad \text{for } 10<Bi<100 \tag{10}$$

Under the consideration of A_1=L, after equating Eqs.(3) and (7), $(\mu_1^2 Fo)=(Ht)$ is found. After substituting the Fourier number into this equation, the following thermal diffusivity model in terms of the heating coefficient is obtained:

$$a = (HR^2/\mu_1^2) \tag{11}$$

After inserting the Biot number equation into Eq.(8), the following heat transfer coefficient model in terms of the lag factor is obtained:

$$h = (k/R)[(2.1\ln L)/(0.7599 - \ln L) \tag{12}$$

Experimental

The experimental apparatus and procedure used for the present investigation is similar to that explained earlier by Kilic et al. [7]. But for this investigation, five spherically shaped brick particles at an average diameter of 0.03 m were formed by grinding from larger pieces of the fire brick, and used as test samples. The particles, fixed on a handle, had a tiny hole of 0.5 mm diameter into which the thermocouples of 0.1 mm diameter were well-inserted at the centers of the samples and heated up to 860°C in a fluidized bed combustor at the medium temperature of 860°C. During the heating process, their center temperatures were measured and recorded, and then averaged for data analysis. This center temperature distribution was used to verify the present heat transfer parameter models.

Results and Discussion

The temperature measurements during heating of the spherical brick particles (D=0.03±

0.0005 m) in a fluidized bed combustor at T_a=860±5°C and u_a=0.85 m/s were carried out. The measured temperature distribution at the center of an individual particle was non-dimensionalized using Eq.(6). Then, this dimensionless center temperature distribution was regressed in the form of Eq.(7) by means of the least squares method (Fig.1). The lag factor and heating coefficient were determined as: L=1.44 and H=0.061 1/s with a high correlation coefficient of 0.958. The thermal conductivity of the particle was measured to be 1.1 W/mK. After extracting the Biot number from Eq.(8), the Biot number was calculated to be 1.92. The characteristic value was calculated from Eq.(9), due to the value of the Biot number between 0.1 and 10, i.e., μ_1=1.99. Then, the thermal diffusivity and heat transfer coefficient were determined by using the present models, i.e., Eqs.(11) and (12), as $a=3.47\times10^{-6}$ m^2/s, and h=140.8 W/m^2K. As evident, the Biot number is 1.92 and this shows that there are the minor internal and major external resistances to the heat transfer from the air-flow to the particle. This also supports the criterion considered in the modelling. We introduce an application of the models. The dimensionless theoretical center temperature distribution is computed from Eq.(13). This is the same as Eq.(3), but only here $\theta=1 - (T - T_a)/(T_i - T_a)$ due to the common use, and the dimensionless experimental temperatures were obtained from this equation using the center temperature measurements. In the form of Eq.(3), the temperature profile decreases with the Fourier number, in the form of Eq.(13), and this profile increases with the Fo.

$$\theta = 1 - A_1 B_1 \tag{13}$$

The measured and computed dimensionless center temperature profiles are shown in Fig.2. As can be seen, in this case, the measured and computed temperature curves increase with an increment in the Fourier number. The computed temperature values were not accurate for the Fourier numbers between 0 and 0.1, due to the negligence made in the modelling by taking the Fourier number values higher than 0.2. But in this problem, 0.1 is enough to make the first term approximation. In light of this result, we can say this period (Fo=0-0.1) took 6.4 seconds and is 5.8% of the total heating period. After Fo=0.3, the maximum difference between the measured and computed temperature values is within the error line of ±2.0%. This shows a remarkably good agreement for this comparison. The results indicated that the present models are the simple tools to determine the thermal diffusivities and heat transfer coefficients for the spherical particles subject to heating in any medium. On the other hand, it is possible to extend this method for regular and irregular shaped particles. But there is a need to calculate some geometric indexes.

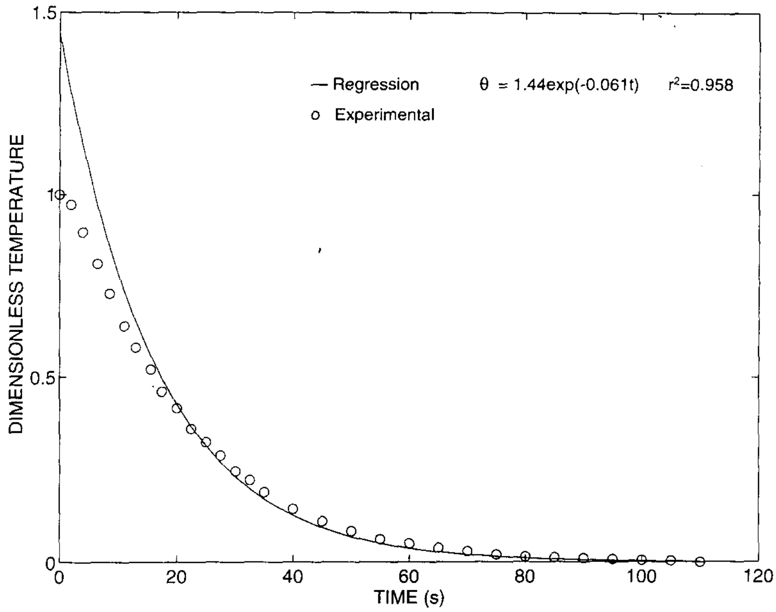

FIG. 1
Measured and regressed dimensionless center temperature distributions for a spherical brick particle being heated

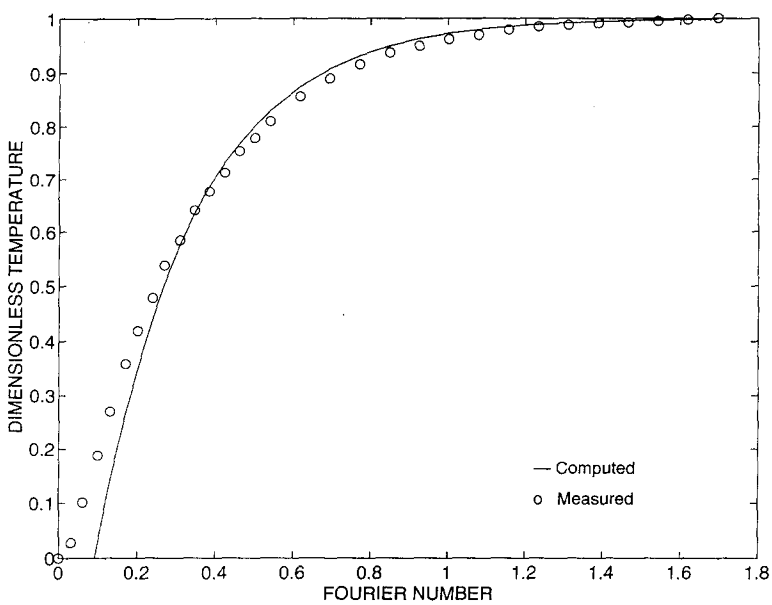

FIG. 2
Measured and computed dimensionless center temperature distributions for a spherical brick particle being heated

Conclusions

An analysis of transient heat transfer during heating of an individual spherical particle was carried out. An experimental investigation was conducted to measure the center temperature distribution of the individual spherical brick particles exposed to heating in the fluidized bed in the air flow at the temperature of 860°C and the flow velocity of 0.85 m/s. The models were developed to determine the heat transfer parameters in terms of the thermal diffusivity and heat transfer coefficient for the spherical solid particles subject to heating. The theoretical center temperature distribution was computed by using the present results ($a=3.47x10^{-6}$ m^2/s, and $h=140.8$ W/m^2K) and compared with the experimental measurements. A great majority of these data were within ±2%. This shows that a remarkably good agreement was found. We can conclude that the present models are capable of determining the heat transfer parameters in a simple and accurate manner for practical applications.

Nomenclature

a = thermal diffusivity, m^2/s
A,B = constants
Bi = Biot number
D = diameter, m
Fo = Fourier number
h = heat transfer coefficient, W/m^2K
H = heating coefficient, 1/s
k = thermal conductivity, W/mK
L = lag factor
r = radial coordinate
R = radius, m
t = time, s
T = temperature, °C or K
u = average air-flow velocity, m/s

Greek Letters

ϕ = temperature difference, °C or K
θ = dimensionless temperature
μ = root of transcendental equation

Subscripts

a = medium
i = initial
n = nth number
1 = 1st number

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