International Journal of Thermal Sciences 98 (2015) 395–408

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Forced convection through open cell foams based on homogenization approach: Transient analysis

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ARTICLE INFO

Article history:
Received 19 March 2015
Received in revised form
30 June 2015
Accepted 10 July 2015
Available online 15 August 2015

Keywords:
Convection
Porous media
Thermophysical properties
Heat transfer coefficient

ABSTRACT

Thermal transportation in case of open cell foams is a complex process that comprises of all the modes of heat transfer. In macroscopic numerical models the key parameters that govern these modes of heat transfer are stagnant effective thermal conductivity, k_e, dispersion conductivity, k_d, effective radiative conductivity, k_r and volumetric heat transfer coefficient, h_v. The purpose of this study is to determine these key parameters for the forced convection of air through open cell alumina foams. It is achieved by performing two different types of experiments on alumina foams having different PPI number (10, 20 and 30) and porosity (0.79–0.87). The first sets of experiments are based on the transient heat transfer and the aim of performing these experiments is to determine the volumetric heat transfer coefficient, h_v. The second sets of experiments are based on the steady state heat transfer and they are the outcome of our previous study. The aim of implementing steady state experiments is to determine dispersion conductivity, k_d by supplying the values of h_v as an input parameter from the transient analysis. Further, to supply effective thermal conductivity data to both transient and steady state analyses, the Kelvin cell model is implemented. The findings of this study exhibit that the convection heat transfer in case of transient analysis and the thermal dispersion in case of steady state analysis are the dominant modes of heat transfer. Further, this study reveals that by employing the proposed combined analysis, it is possible to predict the values of key parameters rather accurately. But still, the accuracy of the results predicted through the macroscopic models largely depends on the accuracy of the experiments.

1. Introduction

Open cell foams are defined as reticulated continuous structures. By virtue of their highly complex and tortuous shape they have excellent geometrical characteristics such as high specific surface area, low density and high porosity [1]. To acquire a variety of features based on the requirement of a particular application, they are produced through different base materials broadly classified as metal and ceramic foams. For instance metal foams in particular have high stiffness, high strength and light weight. They have enormous field of applications some of which are compact electronic panel cooling, heat exchangers, flow diffuser, cryogenic tanks and energy absorbers [2–6]. On the other side, ceramic foams have the ability to withstand high temperatures and they have excellent thermal shock characteristics. These features make ceramic foams suitable for applications such as filtration of molten metal alloys, substrates for catalysts, combustion incinerators, catalytic diffusion burners and convection to radiation converters [7–11]. Evidently the vast field of existing applications of open cell foams necessitates the need to maximize the efficiency of these applications by implementing better designs. Secondly, the possibility of potential use in the forthcoming technologies makes it important to investigate such characteristics of the open cell foams that can make these new applications more efficient. Therefore, from the application point of view, various researchers such as Carpenter et al. [12], Mancin et al. [13] and Guarino et al. [14] experimentally investigated the transport phenomena through open cell foams. Moreover, for new applications it is also important to conceptualize and optimize the designs based on mathematical models to simulate the actual testing conditions. The reason is reduction in time and cost incurred due to testing an actual prototype. Hence, it is important to develop these mathematical models based on the physical understanding of the fundamental fluid flow and heat transfer processes. Moreover, a physical process that can be a true representative for some of the above mentioned

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http://dx.doi.org/10.1016/j.ijthermalsci.2015.07.013
1290-0729/

applications is the forced convection of air through open cell foams. Further, in case of a homogenized numerical model, stagnant effective thermal conductivity, k_e, dispersion conductivity, k_d, effective radiative conductivity, k_r, volumetric heat transfer coefficient, h_v, permeability, K and inertial coefficient, F are the key parameters that can completely define a fluid flow and heat transfer process through open cell foam.

According to the current state of the art most of the investigations of thermal transportation through open cell foams are based on the macroscopic homogenization approach [1]. Because of the complex foam geometry, in this simplified approach the whole system is characterized by the effective properties of the two phases. Secondly, both the phases are considered as effective continuous media, whereas the thermal interaction between them is investigated at every grid point in the computational domain. This approach is further classified into one-equation model and two-equation model. The one-equation model having a single energy equation for the effective two-phase system is based on the assumption of local thermal equilibrium (LTE) and therefore thermal dispersion is the dominate mode of heat transfer in this case. On the other side, the two-equation model having separate energy equations for both the phases is based on the assumption of local thermal non-equilibrium (LTNE) and therefore interstitial convection is the dominant mode of heat transfer in this case. But in the previous work of Vijay et al. [15] at first it was demonstrated that the assumption of local thermal equilibrium (LTE) is not valid in case of high porosity open cell foam. Secondly, with a focus on steady state application setups, it was also demonstrated that the absence of thermal dispersion in case of two-equation model leads to incorrect results. And finally it was revealed that two-equation model with the consideration of thermal dispersion is not sufficient in itself to investigate the detailed transport phenomena through open cell foams due to numerical complications. As in such case there are two unknowns in terms of solid-phase and fluid-phase temperature to fit the numerically determined temperature curves with the experimental data, but to run every simulation it is initially required to guess the values of volumetric heat transfer coefficient, h_v and dispersion conductivity, k_d along with the values of effective thermal conductivity of the two phases known separately.

Subsequently, in the context of above mentioned problem as we know that convective heat transfer coefficient of a system depends on the boundary layers formed over the heat transferring interface, which further depends on the geometrical and flow characteristics [16]. Hence, irrespective of the different methods implemented for determining h_v, its value needs to be same. So it is reasonable to determine h_v separately by implementing some other technique and use its value in the steady state application setup for the accurate determination of k_d. One such technique to determine h_v is single-blow transient method. It is a transient process during which the stream of gas (that is gradually raised to higher temperatures) is passed through a system (that is initially at lower temperature). Younis et al. [17] have implemented the same technique for determining h_v for ceramic foams. They concluded that h_v has a strong dependence on the mean pore diameter. Fu et al. [18] further extended the work of Younis et al. [17] by developing heat transfer correlations for different characteristic lengths such as mean pore diameter, the reciprocal of the specific surface area, the ratio of the inertial to viscous friction coefficients and hydraulic diameter. They concluded that the choice of characteristic length affects the results of empirical correlation between Nusselt and Reynolds number as well as the applicable range of Reynolds number. Further, Yee et al. [19] also determined h_v by passing preheated air through ceramic foams and concluded that for a given Reynolds number h_v increases with increased PPI number (PPI – pores per inch). Hwang et al. [20] also used single-blow transient technique for determining h_v. They studied the effect of porosity and concluded that for a fixed Reynolds number h_v increases with decreased porosity. Finally, based on all the above mentioned works, one important aspect that can be noticed is that all of them implemented two-equation model without the consideration of radiative heat transfer by performing experiments at relatively lower temperatures. Further, Yee et al. [19] and Hwang et al. [20] have also implemented the models of dispersion conductivity in the two-equation model for implementing the effects of thermal dispersion, but without reporting the actual amount of heat transferred due to thermal dispersion. On the other side, Younis et al. [17] and Fu et al. [18] have assumed thermal dispersion to be negligible and therefore it was not considered in the two-equation model. Hence, it is important to further investigate the role of thermal dispersion in case of transient analysis to answer the question of considering or dropping dispersion conductivity models from the analysis.

Nevertheless, based on the available literature [17–20] it can still be concluded regarding the transient experiments that the time span of these processes (until the system reaches the thermal equilibrium) depends on the fluid velocity and on the specific heat capacity of the solid-phase. Secondly, unlike in case of a steady state application setup, where a constant heat flux is applied to both the phases of the two-phase system, in case of a transient process heat is supplied only to the fluid-phase which further transmits it to the solid-phase through convection. It means that for a constant value of convective heat transfer coefficient the temperature difference between the two phases is relatively larger during the short time span of a transient process in comparison with the temperature difference between them in a steady state process. It further augments the possibility of convective heat transfer (over the solid–fluid interface) as the dominant mode of heat transfer during a transient process. Consequently, it can be assumed to some extent that thermal dispersion through the fluid-phase in the longitudinal direction of flow has negligible contribution towards the overall heat transfer. But still it is important to quantify this negligible contribution before making such assumptions and to further drop it from the analysis. Nevertheless, if it can be proved that heat transfer due to thermal dispersion is negligible then the value of k_d can be dropped form the analysis which will make it possible to determine h_v (then the only unknown in the two-equation model for transient analysis) by curve fitting the transient homogenized numerical models with transient experimental data along with the values of effective thermal conductivities known separately. Furthermore, using the values of h_v from the transient analysis, it will be possible to determine k_d (then the only unknown in the two-equation model for steady state analysis) for more practical steady state applications, where the fluid-phase thermal dispersion effects are more significant and cannot not be dropped form the analysis [15]. Therefore, the main objective of this study is to conduct separate transient experiments and implement the results of steady state experiments performed on the same samples in the previous work [15] to determine all the key parameters necessary to design a steady state application setup. Moreover, the objectives of this study are outlined as follows:

- To demonstrate that interstitial convection is the dominate mode of heat transfer in case of a transient analysis.
- To reveal that the combined consideration of LTNE and thermal dispersion that is important for a steady state application setup can be relaxed for a transient analysis.
- To investigate the effects of radiative heat transfer (if any) on the overall thermal transportation for the temperature ranges considered in the present study.