International Journal of Heat and Mass Transfer 79 (2014) 507–517

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A fast numerical method for the analysis of the heat transfer performance of graded metallic honeycomb materials

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ARTICLE INFO

Article history:
Received 8 December 2012
Received in revised form 25 June 2014
Accepted 13 August 2014
Available online 7 September 2014

Keywords:
Graded metallic honeycomb
Heat transfer
Two-dimensional lattice
Finite element analysis and finite difference method

ABSTRACT

A fast numerical method that combines the finite element and finite difference methods (FE–FDM) is proposed to analyze the forced convection heat transfer performance of graded honeycomb heat exchangers. The temperature distribution in the cross-section of the graded honeycomb perpendicular to the direction of flow is described using discrete finite elements that include the convective heat transfer of the two side surfaces. The temperature distribution in the flow direction is obtained by the finite different method. The most important difference with previous methods is the assumption of Constant Cross-sectional Fluid Temperature (CCFT) is relaxed. The fluid temperature of every individual channel is assumed constant and the different channels may have different temperatures in the same cross-section. Comparison with the results by the CFD model shows that FE–FDM has high precision and efficiency. The results of examples illustrate that its precision is similar to CFD model, but its calculation efficiency is increased 10^2–10^4 times as compared to CFD simulation. The assumption of CCFT is only suitable for heat transfer analysis of uniform honeycombs.

1. Introduction

Metallic honeycomb material (also named as 2-D cellular material or prismatic cellular material) is an ultra-light multifunctional material developed more than 10 years [1–3]. The most distinctive feature is that they can be functionally tailored for specific single- or multi-functional applications. The honeycomb materials in most of the applications are uniform, and the typical design of honeycomb materials are for multifunctional applications by selecting a cellular topology from a small library of standard cellular topologies (e.g., square, triangular, hexagonal, cf. [3–4]) and modifying cell wall thicknesses to adjust structural and thermal properties [5–11]. Numerous natural and engineering examples [12–19] show that materials with a graded distribution in mesostructure exhibit better performance. To design a graded honeycomb with high multifunctional performance, it is very important to develop the effective and fast analysis methods since the performance should be analyzed repeatedly during the whole optimization process.

Metallic honeycomb structures with a single "easy flow" direction appear particularly interesting for and heat exchanger applications. This paper will focus on the methods of heat transfer performance analysis of graded honeycomb material under forced convection. Presently, there are primarily two kinds of fast analytical methods for heat transfer of honeycomb structures. One kind is the equivalent continuous medium model based method [6,20–23] and the other is the fin model based method [5–8,24–28], in which the details of the microscopic structure of honeycomb is described. These two models are established based on the following two assumptions.

I: The temperature variation of cooling fluid in the cross-section is neglected, the mean temperature of the fluid is used and it is only regarded as a function of position coordinates of the fluid in the flow direction.

For the convenience of discussion later, this assumption is called "Constant Cross-sectional Fluid Temperature (CCFT)". According to the assumption, the temperature distribution of the entire cooling fluid inside the exchanger or heat sink can be determined through the finite difference method based on the known fluid temperature at the entrance. The key problem is how to find the heat transfer on the solid wall at any cross-section perpendicular to the flow direction.

II: For the solid wall of a metallic honeycomb structure, the temperature gradient perpendicular to the flow direction of the fluid is much greater than that along the flow direction of the fluid. Therefore, the second assumption is that the heat flux inside the wall is only conducted perpendicular to the direction of the fluid flow.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.036
0017-9310/

Under such an assumption, the solution to the three-dimensional temperature distribution of the solid wall is changed into the solution of the two-dimensional temperature distribution of the cross-section perpendicular to the fluid flow. Different solving schemes are used in the two types of analytical methods.

The equivalent continuous medium model transforms the problem of porous medium heat transfer with internal heat convection to the problem of continuous medium heat conduction with an internal heat source, where the equivalent coefficient of heat conduction and the coefficient of the internal heat source are represented as functions of the microstructure parameters. Using this method, the equation of equivalent continuous medium heat conduction can be mathematically extended to the honeycomb material with a gradient distribution easily and the equivalent equation with constant coefficient changes to an equivalent equation with variable coefficients. Based on this, a two-dimensional finite element heat analysis was proposed by Kumar and McDowell [22] to predict the heat transfer performance of gradient honeycomb depending upon the different distributions of honeycomb types that were discussed. Similarly, the distribution of the hexagonal honeycomb pore was discussed by Wang and Cheng [23] using design variables that included porosity and pore diameter. This is commonly used for the conceptual design of honeycomb microstructures. Unfortunately, these methods may lead to large errors in the calculation of the gradient honeycomb because the present equivalent methods are usually based on the periodic distribution assumptions of the microstructure.

Based on the above assumptions, in the fin models (also called corrugated wall models [6]) where the microscopic honeycomb structure can be described in detail, the change of temperature along the wall thickness is neglected because the dimension of the unit cell is far greater than wall thickness. The problem of two-dimensional temperature distribution in the wall surface is simplified into a problem of one-dimensional heat conduction. The total amount of heat exchanged between the walls and fluids in the cross-section is calculated using two steps according to the fin model [5]. First, the influence of the fins are not considered, only the temperature field of the corrugated walls are calculated to obtain the total amount of heat dissipated from the corrugated wall surfaces. Second, according to the energy balance, the heat transfer contribution of the fin surfaces is calculated to determine the overall heat transfer of the entire wall surface. However, since the influence of the fin surface is neglected in the calculation of the temperature field of the corrugated wall surface, so the heat transfer efficiency is overestimated in the energy balance. The transfer matrix method was proposed by Liu et al. [28] which corrected the defect of the fin model. Fin and corrugated surfaces are both considered in the calculation of the temperature field in the wall surfaces of the honeycomb, where the result tends to agree with the measured value. According to research results, the transfer matrix method has good computational accuracy for uniform honeycomb structures. Obviously, the fast numerical analytical method of a graded honeycomb structure based on the fin model should be expected to achieve greater computational accuracy.

In this paper, a hybrid finite element/finite difference method, called the FE–FDM is proposed for the heat transfer analysis of graded honeycomb heat exchangers, in which the effects of the mesostructures of the honeycomb materials and the temperature distribution of the fluid in the cross-section are considered. The structure of this paper is as follows: first the problem description and then the FE–FDM is proposed in the second section, in which a new one-dimensional heat conduction element with heat convection on the side surfaces is proposed to determine the temperature distribution of the solid walls, and the finite difference procedure for determining the fluid temperature distribution along the channel is presented. Numerical examples and discussion are given in Section 3 to verify the effectiveness and accuracy of the method. The conclusions are given in the final section.

2. Problem description and FE–FDM

As shown in Fig. 1, a compact exchanger with general cross-section shape is filled with prismatic cellular material (honeycomb material), where the prismatic holes are fluid channels through which cooling fluid flows. On the side surfaces of the honeycomb exchanger, the surface is either isothermal or a constant heat flux is imposed. Heat dissipation occurs through forced convection between the fluid and honeycomb walls.

The cooling fluid enters the heat exchanger at the inlet and exits at the outlet. The pressure of the fluid is assumed uniform over the entire cross-section including the inlet and outlet, and the fluid temperature at the inlet is assumed constant. In addition, the usual assumptions are made for steady state laminar flow, and constant thermal/physical properties of both the fluid and solid.

The purpose of the heat transfer analysis is to determine the temperature distribution in the honeycomb mesostructure and the rate of steady state heat transfer from the honeycomb heat exchanger surfaces to the fluid flowing through the channels. Although detailed CFD models can provide the same information, a fast, accurate and easily reconfigurable method is needed, especially for facilitating rapid exploration of a broad design space. Next, we will present a fast method, a hybrid finite element/finite difference method, called the FE–FDM for the heat transfer analysis of honeycomb heat exchangers or any exchanger that has similar configurations.

In the z direction in Fig. 1, the honeycomb is divided into sections at regular intervals of Δz. If the length of the heat exchanger is L and the total number of sections is n_{slc} then Δz is equal to L/n_{slc}. The graded square honeycomb structure is used as an example to demonstrate the discretization of FE–FDM as shown in Fig. 2. The fluid channel numbering is shown in Fig. 2a and the section numbering is shown in Fig. 2b. Within each section, each solid cell wall is modeled as a finite element, and each fluid channel is modeled as a fluid cell. The fluid cell numbering can be expressed by the section numbering and channel numbering, and the ith fluid cell of the kth channel is shown in Fig. 2c.

By modeling the solid walls of the honeycomb as elements, we assume that the temperature across the thickness of a wall is unchanged because the walls are thin and the heat conduction in the direction of fluid flow is negligible. This assumption is often used in previous methods.

The fluid temperature of a cell in the cross section is assumed constant, unlike the assumption of CCFT used by the conventional methods, we do not set the temperatures of the fluid cells on the cross section being considered to be equal. In order to discuss the difference between the two assumptions, the formula of FE–FDM with CCFT is also given in this section.

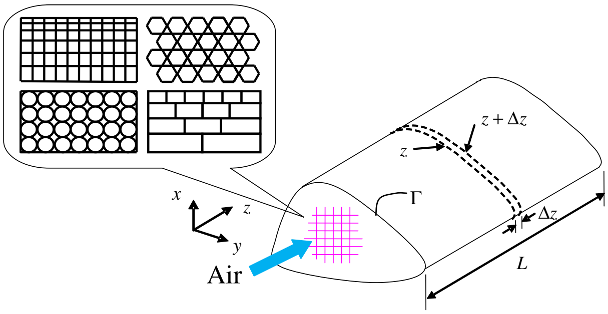

Fig. 1. The geometric model of a heat exchanger with a honeycomb core.