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Research Paper

Experimental investigation of flow and heat transfer characteristics in double-laminated sintered woven wire mesh

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HIGHLIGHTS

- The double-laminated porous media have a strong potential for engineering application.
- Average porosity of wire mesh has a great influence on flow and heat transfer behaviors.
- Air-injected direction affects heat transfer behaviors but not flow behaviors.

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ABSTRACT

Porosity is one of the major parameters of the porous media. Flow and heat transfer characteristics of double-laminated sintered woven mesh with inhomogeneous porosity were investigated experimentally. Each test piece was made up of two parts which have same wire diameter and thickness but different porosities. All experiments were performed with compressed air and the defined inlet Reynolds numbers changed approximately from 10 to 65. The specimens were heated electrically and the surface temperatures of test pieces were measured with an infrared camera. The mass flow rates and pressure drop between inlet and outlet were measured to analyze the flow behavior. The Nusselt numbers were obtained with the average wall temperature to analyze the heat transfer characteristics. The experimental results showed that different porosity combinations affect the above parameters clearly. The permeability increases with the increase in average porosity, while the inertia coefficient had an opposite tendency. Friction factors decrease with the increase in Reynolds number and Nusselt numbers increase with the increase in Reynolds number. In addition, the Nusselt numbers were different under different air flow directions.

1. Introduction

The porous media have been applied rapidly in many engineering fields such as solar energy heaters, electronic cooling equipment, chamber and turbine blade cooling and many others [1–5] in decades. The porous material refers to the composite body of solid phase and gas/fluid phase; generally there are a large amount of pores in solid phase. The sintered stainless steel fibers, wire mesh screen, porous ceramic material, porous metal particles and some composite materials are known as commonly used porous media. As porous media have complex structures, so heat conduction and convection heat transfer are also complicated. Parameters including matrix material property, porosity, pore size range, pore size distribution, sintered or non-sintered, etc., have great influence on the overall effective thermal conduction and convection heat transfer behaviors in the porous media. Forced convection heat transfer and heat conduction occur frequently in porous medium applications that the flow behavior, convection heat transfer characteristic [6–24] and thermal conductivity [25–32] have been studied for a long history.

Kays and London [6] presented the curves of frictional factors of four different woven-screen types in 1964. They pointed out that an effective way to improve the performance of a heat exchanger is to increase its surface area to volume ratio and that metal woven mesh is suitable in this context. Richards and Robinson [7] studied the friction factor of different wire mesh structures and found that it is a function of porosity and construction. The concept of effective porosity was proposed for general mesh structures. Huang and Chao [8] studied the enhancement of heat transfer in two sintered bronze beads: a medium inserted in a rectangular channel and a porous heat sink with geometric dimensions of $5 \times 5 \times 1$ cm. Sodre and Parise [9] and Armour and Cannon [10] investigated the flow behaviors of different woven metal screens and proposed different empirical equations of fluid flow parameters. Park and Wirtz [11,12] found that the thermal performance of heat exchanger matrices with a screen was better than that with a particle bed at the

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same mass per volume since the effective thermal conductivities of wire mesh were at least twice as large as those achieved in other comparable porous medium configurations. Wu et al. [13] developed an empirical equation of friction characteristic of plain-square-type woven metal screens based on the measured pressure drops of four woven metal screens and found that the developing region is very short, less than the thickness of a single layer of the metal screen. Jiang et al. [14–17,23] have worked on porous medium for a long time. Forced convection heat transfer of water and air in bronze porous and glass particles was studied through numerical or experimental methods [14–16]. The influence of porosity, wall effect, sintered or not and boundary conditions on heat transfer or fluid flow behaviors were discussed. Also, they found that the convection heat transfer in the sintered porous channel was more intense than that in the non-sintered porous channel [17]. Liu et al. [18] studied the flow behavior and heat transfer characteristics of sintered woven wire mesh with different porosities. A new empirical equation of friction factors for the sintered woven wire mesh structures was obtained and the heat transfer ability was studied.

At the same time, the internal mechanism and flow and heat transfer in the porous media were widely investigated with numerical methods. More representative research such as that of Green et al. [19], Miguel et al. [20], Teitel [21,22], Jiang and Lu [23] and Xu et al. [24] numerically investigated flow and heat transfer in the porous media, especially wire mesh screens, and presented empirical equations. As for the thermal conductivity, Pia et al. [25–28] and Huai et al. [29–32] built different models with a different math theory to evaluate the thermal conductivity of the porous media. Pia and Sanna [25–28] proposed fractal models to calculate the thermal conductivity and porosity of the porous media and discuss the relations between thermal conductivity and pore size distribution and geometric; they also proved that the IFU (intermingled fractal units) is a valuable tool to understand the correlation between microstructures and properties. Li and Peterson [32] studied the effect of porosity and experimentally investigated the thermal conductivity of wire screens. Their results indicated that the most important factors in the determination of the effective thermal conductivity were the conductivity of the base material and the contact conditions between the individual wires as well as the individual layers. In parallel with the experimental investigation, an analytical model was established and accurately predicted the above factors' influence on the effective thermal conductivity of sintered wire screens.

In many application fields of the porous media, a new idea about porous media applied in transpiration cooling was proposed by some researchers that double-laminated porous media combined with different porous materials could be used as a transpiration cooling matrix. Von Wolfersdorf [33] studied a simplified double-laminated model's cooling performance influenced by volumetric heat transfer and the thermal conductivity of the top layer: the base layer was a metallic porous medium with good mechanical properties and the second layer was a ceramic porous material with a higher melting point. Shi and Wang [34] optimized a porous structure which consisted of two layered media subjected to transpiration cooling with a genetic algorithm based on an analytical solution of a simplified local thermal non-equilibrium model. The optimal composition, porosity and thickness of the two layers were assessed under different conditions. Liu et al. [35] numerically researched the influence of the thermal conductivity and porosity of the porous wall based on models manufactured from one or two layers. They found that both the thermal conductivity and the porosity variations of the top layer which contact the mainstream strongly affect the specimen surface temperature.

The sintered woven wire mesh structure is a typical porous medium with many outstanding properties such as high permeability and mechanical strength, good solder ability, corrosion resistance and excellent machinability. Despite that previous investigations have been widely done, models of composite (or double-laminated) porosity of sintered mesh screens lack both experimental and numerical investigation. Therefore, the effect of porosity change along the flow direction on the flow behavior and heat transfer characteristics of sintered wire woven mesh was studied experimentally in this article.

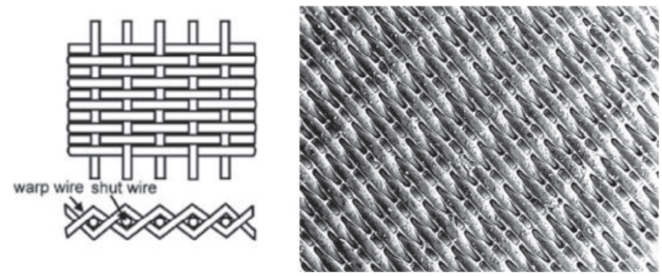

Fig. 1. Weaving pattern and structure amplification of Dutch weave.

2. Experimental description

2.1. Woven wire mesh structures and specimen

Sintered metal wire mesh is one of the traditional porous media which is widely used. The general classification of metal wire mesh is based on the weaving structure of a single layer and the classification rules were presented clearly by Armour and Cannon [10] and Wu et al. [13]. The Dutch weave structure was investigated in this paper. The test pieces are sintered with the same stainless steel wire of which the average diameter is 0.14 mm. The stainless steel wires, which are twined and then arranged suitably, comprise the single-layer structure. The single-layer structures are compressed, rolled and sintered in vacuum sequentially to form multi-layer wire mesh structures. The warp wires remain straight and the weft wires pass alternately under each warp wire but lie as close as possible against each other. The weaving pattern and structure amplification image of Dutch weave are shown in Fig. 1.

Table 1 lists the relevant parameters of specimens supplied by wire mesh manufacturer. The porosity ranges from 25.6% to 55.1%. The porosity of the wire mesh is determined by the number of layers in the unit thickness. The porosity is calculated by the following equation:

$$\varepsilon = 1 - \frac{\rho_0}{\rho_s} = 1 - \frac{M/V}{\rho_s} \tag{1}$$

As shown in Fig. 2, the width and height of the cross-section of the test pieces are 12 mm and 5 mm respectively and have a total thickness of 6 mm. The double-laminated specimens were sintered with the two pieces of wire mesh (A and B in Fig. 2). Each part has a homogeneous porosity and a thickness of 3 mm. The porosity combination is listed in Table 2. In Table 2, the formula 55.1% + 46.9% means that part A in Fig. 2 has a porosity of 55.1% and part B has a porosity of 46.9% which means the air is injected into part A and then flows from part B.

Table 1
Relevant parameters of the specimen.

Test no.	Number of layers (in 3 mm thickness)	Average pore size (μm)	Porosity
1	20	93.7	55.1%
2	24	90.9	46.9%
3	28	66.9	37.1%
4	33	43.6	25.6%