International Journal of Thermal Sciences 88 (2015) 33–39

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Experimental study of convective heat transfer of a nanofluid through a pipe filled with metal foam

Mohsen Nazari [a], Mojtaba Ashouri [a], Mohammad Hasan Kayhani [a], Ali Tamayol [b,*]

[a] Department of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran
[b] Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

ARTICLE INFO

Article history:
Received 1 January 2014
Received in revised form
26 June 2014
Accepted 15 August 2014
Available online

Keywords:
Metal foam
Nanofluids
Heat transfer
Pressure drop
Experimental study

ABSTRACT

The interaction of nanofluids with extended surfaces in the form of porous structures and its effect on the thermal performance of the heat exchanger is not well documented. In this study, the forced convective heat transfer due to flow of Al_2O_3/Water nanofluid through a circular tube filled with a metal foam is investigated experimentally. An isothermal boundary condition is created and the pressure drop and the heat transfer rate are measured over a range of flow rates. The results are compared with values for water flowing through a similar tube without the metal foam insert. The experimental data indicate a significant improvement in the heat transfer rate at the cost of a pressure drop increase. Our experimental data also show a direct relationship between the Nusselt number and the volume fraction of Al_2O_3.

1. Introduction

Two parameters that can play key roles in convective heat transfer augmentation are the surface area and the thermal conductivity of the working fluid. The surface area can be enhanced by attaching fins or porous structures to the heat transferring surfaces and the thermal conductivity can be adjusted by mixing highly conductive nanoparticles with the working fluid to create nanofluids. Open cell porous structures with high thermal conductivity such as metal foam has emerged as a substitute to conventional fins due to their high surface area to volume ratio, mechanical stability, low flow resistance, and their ability in mixing the passing fluid [1,28]. In the last decade, cellular structured materials have been extensively studied experimentally and theoretically for design novel thermal solutions and compact heat exchangers [2,29].

One of the important parameters in heat exchangers design is the flow pressure drop through tubes, which has drawn the attention of many researchers [30]. For example, Pavel and Mohamad [3] used experimental and numerical methods to investigate the effects of metallic porous materials, inserted in a pipe, on the rate of heat transfer. The results were compared with the case of empty channel. The obtained results led to the conclusion that higher heat transfer rates could be achieved using porous inserts at the expense of a reasonable pressure drop rise. Also, the authors showed that for an accurate simulation of heat transfer when a porous insert is employed its effective thermal conductivity should be carefully evaluated. Hutter et al. [4] characterized the heat transfer in tubular reactors filled with commercial metal foams, over a wide range of Reynolds numbers. They developed a novel continuous heat exchanger reactor and a strongly increased heat exchange due to direct integration of the foam with the wall was observed by authors. In another study, Hsieh et al. [5] experimentally studied the effects of porosity, pore density (PPI) and air velocity on the heat-transfer characteristics of aluminum-foam heat sinks in a pipe. Results showed that the Nusselt number increases with the increase pore density due to the fact that the metal foam with a larger pore density has a larger heat-transfer area. Kurtbas et al. [6] experimentally studied the mixed convection in a hot rectangular horizontal channel filled with the aluminum foam. The result showed that the average Nusselt number increased very rapidly with respect to a critic value of Reynolds number.

Another strategy for reducing the size of thermal solutions is the utilization of nanofluids in which the working fluid is mixed highly conductive metallic and non-metallic nanoparticles [13–17]. Although previous researchers have shown an enhancement in the heat transfer rate by the utilization of nanofluids instead of plain fluids, an increase in the pressure drop and the pumping power has been reported. Thus, the variation in the overall thermal performance depends on the salient parameters such as geometry, flow rate, and

* Corresponding author.
E-mail addresses: atamayol@mit.edu, ali.tamayol@mail.mcgill.ca (A. Tamayol).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.08.013
1290-0729/

nanoparticle concentration. The convective heat transfer of nanofluids through channels filled with porous materials holds a great promise for designing compact thermal solutions. However, there are only a few experimental and theoretical studies devoted to this topic.

Hajipour and Molaei Dehkordi [7] studied the mixed-convective heat transfer of nanofluids in a vertical channel partially filled with highly porous medium both numerically and experimentally. The results clearly indicated an enhancement in the heat transfer rate due to the presence of nanoparticles in the working fluid. Matin and Pop [8] numerically investigated the fully developed forced convection of a nanofluid through a horizontal porous channel filled. Closed form analytical solutions were presented for the governing dimensionless momentum, energy and concentration equations and the effects of nanoparticle volume fraction, Darcy, Brinkman, and Soret numbers were investigated on the Nusselt number, velocity as well as the temperature and concentration fields. In another study, Maghrebi et al. [9] investigated the force convective heat transfer of nanofluids in a porous channel and the effects of flow and migration of nanoparticles on heat transfer in a channel occupied with a porous medium. It was also assumed that the nanoparticles are distributed non-uniformly inside the channel. The effects of Lewis number, Schmidt number, and modified diffusivity ratio on the volume fraction distribution were also studied and discussed. Nield and Kuznetsov [21] studied analytically the fully-developed laminar forced convection in a parallel-plate channel occupied by a nanofluid or by a porous medium saturated by a nanofluid, subject to uniform-flux boundary conditions. A model incorporating the effects of Brownian motion and thermophoresis was adopted by authors. In another study, Ghaziani and Hassanipour [22] reported the heat transfer of nanofluid slurry through metal foam by suspending Aluminum Oxide nanoparticles in the base fluid to increase the heat transfer rate.

While the numerical simulation of nanofluids flow and heat transfer in the porous media were previously investigated by researchers, to the best knowledge of authors, there are very limited experimental studies on convective heat transfer of nanofluids through porous pipes; therefore, the focus this study is on experimental measurement of Al_2O_3 nanofluid with various concentrations through a tube field with a metal foam. The temperature of the tube wall is kept constant during the experiments. The pressure drop and heat transfer rate are measured over a range of flow rates and nanoparticle concentrations and are compared with values for water flowing through a similar tube without the metal foam insert.

2. Experiments and methods

2.1. Preparation and specification of the nanofluid

Al_2O_3 nanoparticles with the average size of 40 nm were purchased from Nanostructured & Amorphous Materials Inc. (Houston, TX). There are two methods applicable in producing nanofluids: one step method and two step method. In one step method nanoparticle are formed and dispersed in fluid in a single process [10]. In the one step method, drying, storage, and dispersion of nanoparticles is eliminated and thus the chance of particle agglomeration is reduced [11]. In the two step method, nanopowder is prepared in the nano-scale size and is then mixed and stabilized in the base fluid. Estman et al. [12], Lee et al. [13], Wang et al. [14] and Murshed et al. [15] were among the researchers who used the two step method in producing Alumina nanofluid. Other nanofluids which have been distributed by this method are: gold, silver, carbon nanotubes and silica. Lee et al. [16] synthesized the nanofluid water-copper of 1–100 nm using the two step method. Results showed that Zeta potential and absorption are two major parameters of choosing distribution conditions of nanoparticles in the fluid. Sedimentation pictures and size distribution of particles showed that by adding the appropriate distributor, a better distribution of nanoparticles in the fluid can be achieved.

To prepare nanofluids, we mixed the nanoparticles with water at the desired concentration and then sonicated the mixture at 40 kHz at 40% of full power of the ultrasonic mixer (700 W) for 2hr to obtain a homogeneous solution. It is noteworthy that no other additive substance such as surfactant or dispersant was used. We prepared Al_2O_3/water nanofluid in five different volume fractions of 0.1, 0.25, 0.5, 1 and 1.5 (%w/w). We have also characterized the properties (viscosity and thermal conductivity) of Al_2O_3/water nanofluid for various concentrations and temperatures in a previous study [17]. We used the values from Figs. 1 and 2 of Ref. [17]. Ensuring the stability of the prepared nanofluid is a key factor in adaptation of these materials as working fluid in thermal solutions. Each sample was stored for at least 48 h to ensure of the stability of the suspension. The results of samples in which any visible sign of settling of nanoparticles was observed in less than 48 h, were not considered in the analysis.

2.2. Experimental setup

The test section is an aluminum tube with the length of 30 cm and diameter of 2 cm and less than 1 mm thickness, filled with aluminum open-cell porous media with porosity of 50%. Casting around space holder materials method [18] was used for fabricating the metal foam. For this reason, the NaCl particles (as space holder) with an average size of 3–5 mm diameter were placed in an empty aluminum tube and then molten aluminum directly injected in the tube and filled around the salts. After aluminum injection, the salt was leached out using water at 60 °C, leaving behind a hollow foam-like structure. An image of the test section and the metal foam are shown in Fig. 1. An empty circular tube with the same property has been also used as the control.

The schematic of the experimental setup is shown in Fig. 2, which is comprised of porous pipe (test section), pump, heat exchanger, flow meter and data acquisition system. In order to maintain the constant wall temperature the test section was placed in a water/ice chamber (Fig. 2). The temperature of the working fluid in the tank was kept constant during the experiments. The water with constant temperature is used as a coolant fluid of heat exchanger. The working fluid was pumped from the tank and was passed through the test section and then was returned. The pump used in this system was a 'Pentax PM45'with maximum flow rate of 550 ml/s and maximum head of 35 m. The flow measuring system was installed at the outlet of the porous tube with precision of ±1 ml/s. A bypass line of the pump (section 3 in Fig. 2) was also to control the flow rates of the system. The flow rates were measured by collecting the fluid in a reservoir tank for a period of time with the help of a precise measuring jar and a stop watch.

Two PT100 temperature sensors (JUMO GmbH & Co., Germany) with the sensitivity of 0.1 °C were inserted at the inlet/outlet of the tube. To monitor the wall temperatures, several temperature sensors were also inserted inside the water/ice chamber to control the temperature of the mixture. The temperature of the mixture was kept constant at 2 °C (±0.1 °C). The thickness of the tube was also small (about 1 mm), therefore, the outer wall temperature (that measured by the temperature sensors) has been used in the calculations. Another sensor was located inside the reservoir of heat exchanger. The PT100 sensors were connected to ADAM4015 data logger machine which was capable of sensing multiple sensors. The data logger was connected to ADAM4561data convertor which paired with a PC to record data. Also, an LD301 (HART) Intelligent Differential Pressure Transmitter device with 1 mbar accuracy was used to measure the pressure drop across the test section. Three independent experiments were carried out for each condition and