Experimental Thermal and Fluid Science 72 (2016) 18–30

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental study on metallic water nanofluids flow inside rectangular duct equipped with circular pins (pin channel)

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A R T I C L E I N F O

Article history:
Received 12 July 2015
Received in revised form 17 October 2015
Accepted 27 October 2015
Available online 30 October 2015

Keywords:
Heat transfer enhancement
Pin channel
Geometrical parameters
Nanofluid
Experimental

A B S T R A C T

An experimental investigation is performed to study the performance of three metallic nanofluids on fluid flow and heat transfer characteristics of a rectangular duct equipped with circular pins, i.e. pin channel. Tests are performed using 0.1 % weight concentration of Cu–water, Fe–water, and Ag–water nanofluids. Prior to the experiments, the required thermo-physical properties of nanofluids are measured. Effects of the flow rate (4–10 l/min), pins diameter (d = 1.0, 3.8, 4.8, and 6.0 mm), and longitudinal spacing of pins (p = 20, 40, and 60 mm) are investigated. Experimental results indicate that the use of pins inside the duct can noticeably improve the heat transfer performance. The maximum rise of 84.1% in the heat transfer coefficient is observed for the water flow inside the pin channel with d = 6.0 mm & p = 20 mm compared to the empty duct. Also, the results show that addition of small amounts of metallic nanoparticles to the base fluid augments the heat transfer coefficient of pin channels remarkably. It is found that based on the considered performance evaluation criterion, the Ag–water nanofluid yields best thermal–hydraulic performance (maximum value of 1.98). Correlations are also proposed for Nusselt number and friction factor which fit the experimental data within ±15%.

1. Introduction

Transport phenomena, i.e. fluid flow, heat, and mass transfer, problems across ducts are the traditional issue in many engineering applications including heat exchangers, operating units, chemical reactors, electronic systems, solar collectors, and power plants. Several surface modifications such as perforations, strips, louvers, curvatures, pins, winglets, and wings, as complex channels, are adopted and tested through the ducts to improve the performance. Generally, a complex channel has a higher heat transfer surface area to fluid volume ratio than the plain one and it complicates the fluid flow path. This intensifies the convective transport coefficients along with a certain pressure drop [1].

Also, nanoparticle colloids, i.e. nanofluids, have particular physical properties that make them useful for a wide range of applications including chemical, medicine, food, ceramic, and cooling [2]. Therefore, numerous studies have been carried out experimentally and theoretically to investigate the fluid flow, heat, and mass transfer performance of nanofluids in a number of fields in recent years [3]. However, most of the researches are for the nanofluid flow inside the plain or smooth channel, and there are very limited studies on the nanofluid flow inside the complex channels.

The effect of nanofluid flow on the forced convection in the sinusoidal-wall channel was investigated by Heidary and Kermani [4]. It was shown that the heat transfer in the channel can enhance by addition of nanoparticles in the base fluid by 50%. Thermal–hydraulic characteristics of nanofluid in the corrugated channels with triangular, sinusoidal, and trapezoidal waves were investigated by Ahmed et al. [5–7]. The application of nanofluid inside a counter flow corrugated channels was investigated by Pandey and Nema [8]. It was observed that heat transfer characteristics improve with increase in Reynolds number and Peclet number and with decrease in nanofluid concentration. Heat transfer characteristics of nanofluid in a wavy channel under pulsating inlet flow conditions were investigated by Akdag et al. [9]. Results indicate that there is a good potential in promoting the thermal performance enhancement by using the nanoparticles under the pulsating flow. A comparative study of nanofluid flow through different complex channels was carried out by Khoshvaght-Aliabadi et al. [10]. All the thermo-physical properties of the nanofluid were measured systematically. The appropriate thermal–hydraulic performance and maximum reduction of surface area were found for the vortex generator channel. The influences of seven effective geometrical parameters on the performance of vortex-generator channels with the nanofluid were investigated by Khoshvaght-Aliabadi et al. [11]. It was shown that the transverse pitch, attach angle, attack angle, and wing width have the greater effects on the considered performance evaluation criterion, respectively. The

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http://dx.doi.org/10.1016/j.expthermflusci.2015.10.029
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Nomenclature

A_c	frontal surface area (m^2)
A_t	total surface area (m^2)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
d	pin diameter (m)
D_h	hydraulic diameter (m)
G	mass velocity ($kg\,m^{-2}\,s^{-1}$)
H	channel height (m)
h	heat transfer coefficient $W\,m^{-2}\,K^{-1}$)
L	channel length (m)
M	number of the independent variables
Q_{conv}	convective heat transfer rate (W)
P	pressure (Pa)
p	pin pitch (m)
ΔP	pressure drop (Pa)
R	dependent variable
T	temperature (K)
ΔT	temperature difference (K)
V	volumetric flow rate ($m^3\,s^{-1}$)
W	channel width (m)
X	independent variables
Greek symbols	
ρ	density ($kg\,m^{-3}$)
μ	dynamic viscosity (Pa s)
κ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
η	performance evaluation criterion
Dimensionless groups	
f	Fanning friction factor
Nu	Nusselt number
Re	Reynolds number
Subscripts	
b	bulk fluid
bf	base fluid
b, in	fluid inlet
b, out	fluid outlet
j	specific parameter counter
$LMTD$	logarithmic mean temperature difference
nf	nanofluid
w	wall
Acronyms	
EEW	electro-exploded wire
PEC	performance evaluation criterion

effect of nanoparticle shapes on the forced convection flow of SiO_2/ethylene glycol nanofluids on the performance of wavy channels was investigated by Vanaki et al. [12]. It was found that the nanofluid with the platelets nanoparticle shape gives the highest heat transfer enhancement. An experimental study on the forced convective flow of different nanofluids through a corrugated channel was performed by Khoshvaght-Aliabadi et al. [13]. The effects of different factors including nanoparticles weight fraction, type of nanoparticles, and base fluid material were examined. It was found that SiO_2/water–ethylene glycol mixture of 75:25 nanofluid has the greatest thermal–hydraulic performance factor. The laminar forced convection flow of nanofluid in the sinusoidal-wavy channel with different phase shifts was studied by Ahmed et al. [14]. Results indicate that the optimal performance is achieved by 0° phase shift channel over the ranges of Reynolds number and nanoparticles volume fractions. Finally, Khoshvaght-Aliabadi [15] analyzed the heat transfer and flow characteristics of the sinusoidal-corrugated channel with the nanofluid. The effects of different geometrical parameters were evaluated. It was found that the channel height and wave amplitude have the highest influences on Nusselt number and friction factor values.

Details about the mentioned literature such as the studied method, channel shape, nanofluid, parameters, and ranges are presented in Table 1. As depicted in the table, most of the studies were conducted numerically, and experimental studies on the nanofluid flow inside the complex channels are very scarce. Furthermore, the flow and heat transfer characteristics of the different metallic water nanofluids across other complex channels have been not investigated in the past. The scope of the current work is to investigate heat transfer and pressure drop characteristics as a result of utilizing two passive heat transfer enhancement techniques namely pin channels and metallic water nanofluids. Experiments are performed in very dilute weight concentrations of copper, iron, and silver nanoparticles, 0.1 wt%. It involves probably no penalty of the nanoparticles deposition on the experimental apparatus. Prior to the experiments, all the thermo-physical properties of the prepared nanofluids are systematically measured. Then, effects of the geometrical parameters and nanofluids flow rate are studied.

2. Working fluid and test section

2.1. Metallic water nanofluids and properties

An one-step technique, namely electro-exploded wire (EEW), is applied to prepare dilute and stable suspensions of copper (Cu), iron (Fe), and silver (Ag) nanoparticles in the deionized water as ‘Cu–water, Fe–water, and Ag–water nanofluids’, respectively. The deionized water is used as a traditional host liquid due to its high thermal conductivity, abundance, low cost, and friendliness to the environment [16]. The EEW is performed in R&D division of Payamavaran Nanotechnology Fardanegar Company (PNF Co.), Iran [17] using a manufactured device namely PNC1k system. Details of this technique have been presented in [18,19]. The produced metallic nanoparticles have almost spherical shape with the average diameter of 30–50 nm. A proper dispersion of the nanoparticles into the base fluid is conducted using a certain surfactant at a very low concentration (0.005%) and subsequent sonication. The weight concentration less than 0.5% shows good stability and thermal conductivity [20]. Also, it was shown that 0.1% of nanofluid is more stable concentration [21]. So in this work, 0.1% of concentration is selected as the suitable concentration. The stability of nanofluids is evidenced using a photographic method. The nanofluid samples are monitored for equal time intervals. The stability period for the Cu–water, Fe–water, and Ag–water nanofluids is found to be 5, 2, and 7 days, respectively. For instance, the procedure of Fe–water nanofluid sedimentation is presented in Fig. 1. Finally it must be note that during experiments, no sedimentation is observed even at the lowest flow rate.

Thermo-physical properties of the nanofluids are also systematically measured and evaluated in the laboratories of Materials and Energy Research Center (MERC). The thermal conductivity (κ) is measure using a transient hot-wire apparatus (KD2 Thermal Properties Analyzer, Decagon Devices). Measurement of the dynamic viscosity (μ) is performed using an accurate rheometer (Physica MCR 301 Anton Paar) with a computer controlled temperature bath to set the nanofluid temperature. The specific heat (C_p) is calculated by measuring the difference in the heat required to raise