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Experimental analysis of thermal–hydraulic performance of copper–water nanofluid flow in different plate-fin channels

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ABSTRACT

An experimental assessment of the copper–water nanofluid flow through different plate-fin channels is the main purpose of this study. Seven plate-fin channels, including plain, perforated, offset strip, louvered, wavy, vortex generator, and pin, were fabricated and tested. The copper–water nanofluids were produced by a one-step method, namely electro-exploded wire technique, with five nanoparticles weight fractions (i.e., 0%, 0.1%, 0.2%, 0.3%, and 0.4%). The required properties of the nanofluids were systematically measured, and empirical correlations were proposed. To obtain accurate results, a highly precise test loop with the ability to produce a constant wall temperature was designed and fabricated. The results depicted that both the convective heat transfer coefficient and the pressure drop values of all the channels enhance with increasing the nanoparticles weight fraction. The appropriate thermal–hydraulic performance and maximum reduction of surface area were found for the vortex generator channel. Finally, correlations were proposed to predict the Nusselt number and Fanning friction factor of the base fluid and nanofluids flows in the studied plate-fin channels.

1. Introduction

A plate-fin heat exchanger (PFHE) consists of a block with alternating layers of extended surfaces as plate-fin channels. Parting sheets as cover plates separate the plate-fin channels, and side bars restrain the cover plates. Large heat transfer area, light weight per unit volume, high thermal performance, possibility of heat exchange among several streams, and close temperature on channels are the advantages which make the PFHE one of the popular type of heat exchangers.

The PFHEs have been used in the aircraft industry more than five decades and in the cryogenics, railway, and automobiles engines about 30 years. Applications of these heat exchangers have been expanded in the air conditioning, electronic cooling, waste and process heat recovery, and recently in the chemical process. Based on different applications, various types of the plate-fin channels such as plain, perforated, offset strip, louvered, wavy, vortex generator, and pin are used in these heat exchangers.

The great advantages and different applications of the PFHEs are the factors that motivate many investigators to study the performance of these heat exchangers. Therefore, numerous experimental and numerical studies have been conducted on characteristics of each plate-fin channel. The experimental and numerical thermal–hydraulic data of the PFHEs with different channels are given for perforated [1,2], offset strip [3–9], louvered [10–15], wavy [16–26], vortex generator [27–33], and pin [33–38].

Because of differences in geometrical parameters, working fluids, and data reduction methods which have been adopted in different literature, a comprehensive assessment of the plate-fin channels is not possible. Also, in most previous studies, common fluids such as air and water were considered as working media, and there are very limited studies of advanced working fluids such as nanofluid inside the PFHEs. Pantzali et al. [39,40] investigated efficacy of nanofluids as coolants inside both the industrial and the miniature scale of PFHEs. They concluded, while the use of nanofluids is an effective way to improve the performance of miniature PFHEs, it seems inauspicious in industrial PFHEs. The thermal performances of two types of commercial nanofluids (oxides of alumina dispersed in water and aqueous suspensions of nanotubes of carbons) inside two identic PFHEs were experimentally investigated by Maré et al. [41]. Recently, Javadi et al. [42] and Tiwari et al. [43] exhibited that the use of nanofluids in the PFHEs can enhance their thermal performance, whereas Kabeel et al. [44] depicted that the application of nanofluids in PFHEs is doubtful. Therefore, a further research work for the same field is required to remove the inauspicious between different researchers.

To the best of our knowledge, no study has compared the thermal–hydraulic performance of different plate-fin channels when a

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Nomenclature

A	wavy fin amplitude, m
A_c	minimum free flow area, m^2
$A_{ch.f}$	total surface area in contact with working fluid, m^2
C_p	specific heat, J kg^{-1} K^{-1}
D_h	hydraulic diameter, m
d_h	radius of perforations, m
d_p	radius of pins, m
F_h	fin height, m
F_p	fin pitch, m
G	mass velocity, kg m^{-2} s^{-1}
$\bar{h}$	effective heat transfer coefficient, W m^{-2} K^{-1}
L	fin length, m
L_a	louver angle, °
L_h	louver height, m
L_o	lance length, m
L_p	louver pitch, m
L_w	wave length, m
L_z	wavy fin passage length, m
M	number of the independent variables
$\dot{m}$	mass flow rate, kg s^{-1}
n_h	number of perforations
n_l	number of louvers
n_p	number of pins
n_t	number of tabs
$\dot{Q}_{conv.}$	convective heat transfer rate, W
S	distance between two perforations, m
S_l	longitudinal pin spacing, m
S_t	transverse pin spacing, m
T	temperature, K
t	fin thickness, m
V_h	vortex height, m
V_l	longitudinal vortex spacing, m
V_t	transverse vortex spacing, m
ΔP	pressure drop, Pa
R	dependent variable
ΔT	temperature difference, K
X	independent variables

Greek symbols

ρ	density, kg m^{-3}
μ	dynamic viscosity, kg m^{-1} s^{-1}
κ	thermal conductivity, W m^{-1} K^{-1}
φ	nanoparticle weight fraction

Superscript

.	rate
-	effective

Subscripts

BF	base fluid
conv.	convective
f	fluid
f,in	fluid inlet
f,out	fluid outlet
i	a plate-fin channel type
j	specific parameter counter
LMTD	Logarithmic Mean Temperature Difference
NF	nanofluid
plain	plain plate-fin channel
w	wall

Dimensionless groups

A_i/A_{plain}	VG-I criterion = $(j_{plain}/j_i)^{3/2}/(f_i/f_{plain})^{1/2}$
j	Colburn factor = $Nu/RePr^{1/3}$
JF	Thermal–hydraulic performance factor = $(j_i/j_{plain})/(f_i/f_{plain})^{1/3}$
f	Fanning friction factor = $\rho D_h \Delta P/2LG^2$
Nu	Nusselt number = hD_h/κ
Pr	Prandtl number = $\mu C_p/\kappa$
Re	Reynolds number = GD_h/μ
St	Stanton number = h/GC_p

Acronyms

AD	Average Deviation
MD	Maximum Deviation
PFHE	Plate-Fin Heat Exchanger

nanofluid has been used as working media. In this regard, this motivates us to evaluate the performance of different plate-fin channels along with a nanofluid. Seven common channel shapes, including plain, perforated, offset strip, louvered, wavy, vortex generator, and pin, were fabricated and tested by using a proper experimental procedure at the constant temperature boundary condition. The thermal–hydraulic specifications in these channels were obtained and presented in the dimensional and non-dimensional forms.

2. Nanofluid preparation and their properties

Preparation of a uniform nanofluid without rapid agglomeration and sedimentation phenomena along with accurate measurements of its thermo-physical properties are the primary steps in the studies associated with nanofluids. In the present study, a one-step method, namely electro-exploded wire (EEW) technique, was employed to produce the dilute suspensions of the copper-deionized water nanofluids. The nanofluids in different weight fractions of copper nanoparticles (i.e., 0%, 0.1%, 0.2%, 0.3%, and 0.4%) were prepared with 30–50 nm average diameters. The prepared nanofluids stayed stable for a period of a week without any visible settlement.

The thermo-physical properties of the prepared nanofluids were experimentally measured as function of the nanoparticles weight fraction under the range of the operating temperature (i.e., 298.15–313.15 K). Then, based on the measured properties, empirical correlations were developed based on the following format,

$$\frac{\Gamma_{NF} - \Gamma_{BF}}{\Gamma_{BF}} = (a \times T + b)\varphi^n \quad (1)$$

where the general variable Γ represents κ, μ, or ρ; φ symbolizes the weight fractions of the copper nanoparticles; T is the operating temperature; and a, b, and n are the correlation constants.

The transient hot-wire method (THW), also called transient line heat source method, was utilized to measure the thermal conductivity by using a thermal properties analyzer, KD2 Pro system (Decagon Devices). The thermal conductivity variations of the working fluids with the temperature and nanoparticle weight fraction are shown in Fig. 1. As depicted in the figure, the thermal conductivity of all the fluids increases and shows a strong sensitivity