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Forced convective heat transfer and flow characteristics of ionic liquid as a new heat transfer fluid inside smooth and microfin tubes

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ABSTRACT

Ionic liquids (ILs) have thermophysical and chemical properties that may be suitable for use as heat transfer fluids from the low to high temperatures. This paper presents the experimental results of forced convection heat transfer for 1-hexyl-3-methylimidazolium tetrafluoroborate ([HMIM]BF_4) IL, in microfin and smooth tubes. The horizontal test section is a counter flow double tube heat exchanger with IL flowing in the inner tube and cooling water flowing in the annulus. In addition to evaluating the forced convection heat transfer, thermophysical properties of [HMIM]BF_4 such as thermal conductivity, density, heat capacity, and viscosity were also experimentally measured over the temperature range of 303–453 K. The correlations of thermophysical properties were fitted with measured data. The experimental results show that the frictional coefficient and Nusselt number inside the smooth tube agree with those predicted by the Hagen–Poiseuille and Sieder–Tate correlations. In the Reynolds number range of 57–538, the frictional coefficient and Nusselt Number of the microfin tube are 5.6% and 5.4–11.3% higher than those of the smooth tube, respectively. Based on the experimental data, the empirical correlations were developed to calculate the frictional coefficient and convective heat transfer coefficient for the microfin tube under laminar flow condition.

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1. Introduction

Ionic liquids (ILs) are a group of salts that are composed of organic cations combined with organic or inorganic anions, and that are liquid at or near ambient temperature. The main advantages include the wide liquid temperature range, high heat capacity, high density, high thermal and chemical stability, low vapor pressure, and non-harmfulness. The possible use of ILs as heat transfer fluids (HTFs), for heat exchange in chemical plants and solar thermal power generation, from refrigeration systems at the low temperature up to solar energy collection and storage at high temperatures has been discussed [1–2].

Accurate knowledge of thermophysical properties is valuable as it is necessary for assessing the feasibility of using ILs as HTFs. The number of published thermophysical and thermochemical studies for ILs has increased remarkably in the past few years with a large number of research groups doing measurements around the world. Valkenburg et al. [3] have measured the thermal and chemical properties of three ILs including melting point, boiling point, liquidus range, heat capacity, heat of fusion, vapor pressure, thermal conductivity, density and viscosity. The results show that they are suited for use as HTFs. In many ways they are superior to present commercial HTFs such as the silicone oil based SYLTHERM®, and the Therminol® diphenyloxide/biphenyl fluids at mid- to high-temperature range. Because their applications are limited by some intrinsic disadvantages such as low decomposition temperature, low density, inflammability, high vapor pressure, harmfulness, and low chemical stability [2]. Tenney et al. [4] have carried out a computational and experimental study of the heat transfer properties including the thermal conductivity, density, viscosity, glass transition temperature, and heat capacity values of nine different ILs. Classical molecular mechanics force fields were developed and used to calculate thermodynamic and transport properties for these ILs using molecular dynamics. They concluded that for all the ILs, the convective effects would dominate in heat transfer applications due to the large Prandtl number. Franc et al. [5] have analyzed the effect of the uncertainty of thermophysical data of ILs (density, heat capacity, thermal conductivity, and viscosity) used as HTFs in the design of a heat exchanger. They found that the influence of actual errors in the thermophysical properties of ILs can render any future design as not working or excessively costing.

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Nomenclature

a	constant
A	area (m^2)
b	constant
C_p	heat specific (J/kg K)
d	diameter (m)
de	equivalent diameter (m)
f	friction factor
h	fin height (m)
K	total heat transfer coefficient (W/m^2 K)
L	length (m)
LMTD	log mean temperature different (K)
m	mass flow rate (kg/s)
Nu	Nusselt number
p	fin pitch (m)
P	Pressure (Pa)
Pr	Prandtl number
Q	heat transfer rate (W)
R	thermal resistance m^2 K/W
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
Greek symbols	
α	heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/m K)
ρ	mass density (kg/m^3)
μ	viscosity (kg/m s)
β	helix angle (°)
θ	vertex angle (°)
δ	tube wall thickness (m)
Δ	difference
Subscripts	
ave	average
b	bulk
i	inside or inlet
il	ionic liquid
o	outside or outlet
w	water

Although some thermophysical properties of ILs have been measured, the convective heat transfer of ILs is rarely studied. This is needed for industrial take-up of the technology particularly process development and scale-up. Paul et al. [6] presented the experimental results of natural convection heat transfer for $[C_4mim][NTf_2]$ IL in rectangular cavity with different aspect ratios. They found that the convective heat transfer coefficient of IL is lower than De-Ionized (DI) water for the same heat input due to the higher viscous force of IL than DI water and lower thermal conductivity. A new correlation for Nusselt Number as a function of Rayleigh Number was proposed. Chen et al. [7] have carried out the experiments on the thermal and rheological behavior of the ionic liquid, $[C_4mim][NTf_2]$, and the forced convective heat transfer of the ionic liquid under the laminar flow conditions over the temperature range of 20–90 °C. Their study showed that the convective heat transfer coefficient inside smooth tube is much lower than that of distilled water under the same conditions, and fitted well to the conventional Shah's equation under the experimental conditions.

The previous researches showed that heat transfer coefficients were obviously lower for ILs than those of water due to the low thermal conductivity of ILs. Therefore, it is very important to enhance the heat transfer for ILs used as HTFs. The microfin tube was first developed by Fujie et al. of Hitachi Cable [8]. Since then, many experimental and theoretical investigations had been extensively performed for convective condensation and boiling heat transfer in microfin tubes [9–14], and the phase change heat transfer enhancement mechanisms were presented. Compared to phase change heat transfer, experimental investigations of single phase heat transfer characteristics in microfin tubes are less reported. Chiou et al. [15] and Wang et al. [16] presented single phase heat transfer as well as pressure drop characteristics for commercially available microfin tubes with water as the working medium. The heat transfer coefficients were obtained using the Wilson plot technique. It was found that the microfin tube exhibits a rough tube's characteristics. The Dittus–Boelter-type Wilson plot function cannot correlate the heat transfer data well in the experimental range. Their study showed that critical Reynolds number is an important parameter for enhanced heat transfer. They suggested that heat transfer data can be correlated by using heat momentum transfer analogy instead of Dittus–Boelter type equation. Copetti et al. [17] compared experimentally heat transfer and friction characteristics of smooth and microfin tubes at different flow rates from a laminar to a turbulent flow using water as test fluid. They developed an empirical correlation for prediction of microfin tube heat transfer data and compared them with experimental results. Li et al. [18] presented an experimental study in order to determine single phase heat transfer and pressure drop in microfin tubes by using water and oil as working fluids. Their study showed that critical Reynolds number is an important parameter for heat transfer enhancement. For Reynolds numbers higher than critical Reynolds number, the heat transfer enhancement can be observed. The friction factors in the microfin tube are almost the same as for a smooth tube for Reynolds numbers below 10,000. For Reynolds numbers higher than 30,000, the friction factor is about 40–50% higher than for a smooth tube. Celen et al. [19] investigated experimentally the single phase pressure drop characteristics of smooth and microfin tubes using water as test fluid. Their research showed that the friction factor and pressure drop values for the microfin tube were higher than those for the smooth tube. They developed a new correlation by using experimental data and graphical program to predict the friction factor for investigated microfin tube. Wang and Rose [20] compiled an experimental database, covering a wide range of tube and fin geometric dimensions, Reynolds number and including data for water, R11, and ethylene glycol for friction factor for single-phase flow in spirally grooved, horizontal microfin tubes. The results showed that the Jensen and Vlakancic correlation was found to be the best and represents the database within ±21%. Eiamsa-ard and Wongcharee [21] investigated the combined effects of nanofluids, dual twisted-tapes and a microfin tube on the heat transfer rate, friction factor and thermal performance factor characteristics. Nanofluids consisting of CuO and water at CuO concentrations between 0.3% and 1.0% by volume, were used as working fluids in the microfin tube equipped with dual twisted-tapes, for Reynolds number between 5650 and 17,000. The results show that the microfin tube equipped with dual twisted-tapes consistently gave superior thermal performance factor to the one equipped with a single twisted-tape as well as the microfin tube alone at similar operating conditions. Akhavan-Behabadi et al. [22] carried out an experimental investigation on the heat transfer oil-copper oxide nanofluid flow in horizontal smooth and microfin tubes. Oil and nanofluid with the

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