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Single-phase flow and heat transfer characteristics of ethanol/polyalphaolefin nanoemulsion fluids in circular minichannels

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ABSTRACT

This work experimentally studied the single-phase flow and heat transfer characteristics of a novel nanostructured heat transfer fluid**:** "Ethanol/Polyalphaolefin nanoemulsion fluid" flowing through twelve circular minichannels of 1 mm diameter each. In this study, ethanol and "polyalphaolefin (PAO)" fluids were used to prepare Ethanol/PAO nanoemulsion fluid: it is a thermodynamically stable system formed by dispersing ethanol into a mixture of PAO and surfactants, in which ethanol forms self-assembled micelles of tens of nanometers in diameter. The formed Ethanol/PAO nanoemulsion fluids were used as the working fluids to study the effect of ethanol nanodroplets on its single-phase flow and heat transfer characteristics. In addition, the effect of flow regime on its heat transfer characteristics was examined as well. In this experiment, the Reynolds number was varied between 140 and 3400 to cover the range of flow regime from laminar to transitional. The friction factor and convective heat transfer coefficients were measured for nanoemulsion fluids of two different mass concentrations, and then compared with those of the base fluid. It is found that using Ethanol/PAO nanoemulsion fluids can improve single-phase convective heat transfer compared to that of pure PAO: under laminar flow, there is no significant difference in Nusselt number between Ethanol/PAO nanoemulsion fluids and pure PAO; however, Ethanol/PAO nanoemulsion fluids showed a substantial increase in Nusselt number when entering into transitional flow. Meanwhile, there is an increase in pressure drop and early onset of transition to turbulence for Ethanol/PAO nanoemulsion fluids compared to pure PAO. The results from this work suggest that as a single-phase heat transfer fluid, nanoemulsion fluids should be used in either transitional or fully developed turbulent flow in order to yield enhanced heat transfer performance. While the mechanisms behind are not clear yet, the stronger interaction and interfacial thermal transport between nanodroplets and base fluid at transitional flow regime is believed to be the contributing factor.

1. Introduction

The thermal management challenges faced in various industries have urged the heat transfer community to develop novel thermal management solutions including more efficient heat exchangers, and new heat transfer fluids with significantly improved thermal properties, etc. [1–5]. To date, although more advanced works have been performed to develop high performance heat exchangers with varieties of shape, size and tube surface augmentation, the development of heat transfer fluids with significantly improved thermal properties over those currently available remains one of the most challenging tasks. Nevertheless, there are several heat transfer fluid candidates reported such as nanofluid [6–28], dilute emulsion [29,30], and emulsion [31–35]: Nanofluid was proposed in 1995 by Choi [36], and since then it has been intensively studied for its preparation, phase stability and its potential applications in high heat flux cooling such as nuclear power system, solar collector and compact high power density electronics system etc. An emulsion fluid is a mixture of two immiscible liquids in which one liquid (the dispersed or droplet component) forms a suspension of many small droplets in the other liquid phase (the continuous component). Using emulsion to enhance heat transfer can be dated back to 1959 by Moore [37]. Later on, the emulsion of the dispersed

Abbreviations: NIST, National Institute of Standards and Technology; NCNR, NIST Center for Neutron Research; PAO, polyalphaolefin; SANS, small angle neutron scattering; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number; HTC, heat transfer coefficient; CHF, critical heat flux.

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Nomenclature

Acronyms and abbreviations
PAO polyalphaolefin fluid

Symbols
A area, m^2
D inner diameter of the minichannel, m
f friction factor
h heat transfer coefficient, $W/(m^2 \cdot K)$
L length, m
n number of channels inside the heat exchanger
P pressure, Pa
Q power, W
q heat flux, W/m^2
T temperature, K
V velocity, m/s

Greek letters
k thermal conductivity ratio, $W/(m \cdot K)$
ρ density, kg/m^3
μ dynamic viscosity, $Pa \cdot s$

Subscripts
f fluid
x location
m mean
f,in fluid flow into the minichannels
f,out fluid flow out of the minichannels
wall top surface of the minichannel heat exchanger

component occupies ~5% or less of the emulsion by volume is called "dilute emulsion", and it has attracted interests from several research groups [29–35,38,39]. However, the understanding of phase change heat transfer inside emulsion is limited. One of the most detailed descriptions of how emulsions boil is the work of Bulanov and Gasanov [32–35,38,39], in which they proposed chain-reaction boiling of the droplets as an explanation for the observed superheated droplets and bubble dynamics on the heat surface. Their recent study has shown that the concentration and size of droplets formed inside the emulsion has a significant impact on its boiling heat transfer [40,41]. To further understand the boiling mechanism of dilute emulsions, Rosele [42] et al. carried out an experimental study of boiling heat transfer of water-based dilute emulsions from a horizontal heated wire. Their study has shown that the heat transfer coefficient was enhanced in dilute emulsions compared to that of water. Aside from all the efforts mentioned above, recently, the author has proposed a radically new design for heat transfer fluids called "nanoemulsion fluids". Nanoemulsion fluids completely eliminate solid particles, which usually cause abrasion and erosion problems issues even with extremely fine particles such as nanoparticles [43–47], and instead, uses liquid nanostructures [48–57]. Nanoemulsion fluid is a suspension of liquid nanodroplets in another immiscible fluid as part of a broad class of multiphase colloidal dispersions [58]. The nanodroplets formed inside the nanoemulsion fluids typically have a length scale less or equal to 50 nm, which makes the nanoemulsion fluids thermodynamically stable and transparent to natural light. A comparison of nanoemulsion with emulsion (dilute emulsion) is shown in Table 1 below [58].

When the fluid added inside to form nanodroplets has a superior thermophysical properties (i.e., higher thermal conductivity) compared to the base fluid, it can be used to improve the thermophysical properties (i.e., thermal conductivity) of the based fluids. For example, the thermal conductivity of water/FC72 nanoemulsion fluid containing 12% water nanodroplets by volume increased by 52%, and its effective specific heat was enhanced approximately by 126% when these water nanodroplets added inside undergo phase change [48,49]. Furthermore, when these nanodroplets undergo phase change, the overall heat transfer coefficient of the system can be significantly enhanced. For example, pool boiling heat transfer studies of nanoemulsion fluids have also shown a significant increase in heat transfer coefficient (HTC) and critical heat flux (CHF) compared to constitutive fluid [51,55,56]: up to 300% enhancement for HTC and 200% for CHF of Ethanol/PAO nanoemulsion compared to pure ethanol.

Despite the significant enhancement observed in pool boiling heat transfer of nanoemulsion fluids compared to that of base fluids, it remains inconclusive whether the same optimistic outlook can be expected in the convective heat transfer of nanoemulsion fluids. Meanwhile, convective heat transfer of conventional heat transfer fluids inside micro/minichannel heat exchanger has been intensively studied due to its capability to remove high heat flux [27,59,30,60–67]. So far, no previous study has been carried out to investigate the convective heat transfer of nanoemulsion fluids inside micro/minichannel heat exchangers yet.

In this study, the single-phase flow and heat transfer characteristics of Ethanol/PAO nanoemulsion fluids from laminar to transitional flow were investigated experimentally. This paper presents a thorough study of the single-phase flow and heat transfer of nanoemulsion fluids in circular minichannels for the first time. Through this study, it is expected to obtain a better understanding of: (1) the effect of the flow and heat transfer behaviors of nanoemulsion fluids with respect to their constituent base fluid; (2) the applicability of established physical correlations in predicting the flow and heat transfer of nanoemulsion fluids; and (3) to explore the fundamental mechanisms underlying the single-phase convective heat transfer in nanoemulsion fluids.

Table 1
Comparison of nanoemulsion and emulsion (dilute emulsion).

Property	Nanoemulsion	Emulsion (Dilute emulsion)
Appearance	Transparent	Turbid
Interfacial tension	Ultra low (usually ≪1 mN/m)	Low
Droplet size	<50 nm	>500 nm
Phase stability	Thermodynamically stable, long shelf-life	Thermodynamically unstable
Preparation method	Self-assembly	Need of external shear
Viscosity	Newtonian	Non-Newtonian

2. Material and methods

2.1. Nanoemulsion fluids preparation and thermophysical properties

To minimize the impact of the differences in thermophysical properties of the two constitutive fluids on the convective heat transfer experiments, ethanol and PAO fluids were used to prepare