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Heat transfer enhancement in a vertical tube confining two immiscible falling co-flows

A.-R.A. Khaled*

Mechanical Engineering Department, King Abdulaziz University, P.O. Box 80204, Jeddah 21589, Saudi Arabia

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ABSTRACT

Heat transfer enhancement in falling two immiscible co-flows arranged concentrically inside a vertical tube is investigated in this work. The momentum and energy equations of both fluids are solved analytically and numerically. The numerical and the analytical results based on adiabatic and zero-shear-stress interfacial conditions are well matched. A parametric study including the influence of fluids relative densities, viscosities, thermal conductivities, specific heats and the flows relative radii is conducted for various reference Reynolds numbers. Different ranges of the fluids thermophysical properties that augment heat transfer are obtained and discussed. When the (inner, outer) fluids pair is given as (water, mercury), the maximum enhancement factor is found to be 1.029 fold relative to the case when the outer fluid filling the whole volume. Interchanging the fluids of that pair can increase the enhancement factor up to 4.58 fold due to flow rate amplification caused by the decrease in the friction force. The use of (air, mercury) pair can increase the enhancement ratio to above 2.82 fold if the flows are thermally fully developed due to significant reduction in effective viscosity. This work demonstrates that significant heat transfer enhancement is attainable when combining layering of immiscible fluids and flow rate amplification mechanisms.

1. Introduction

Recent heat transfer literature reviews [1–5] show that abundant researches have been made on heat transfer enhancement subject. According to many databases, the number of these researches increased significantly in the last five years to exceed five hundreds studies. Léal et al. [5]. indicated that heat transfer enhancement starts to become an important societal challenge as it results in saving energy and materials. Examples on heat transfer enhancement applications includes: electronic cooling [6], air-conditioning [7], and industrial processes [8]. Bergles et al. [9] divided the enhancement techniques into passive and active methods. Passive methods mainly consist of at least one of the following mechanisms: (a) increasing the heat transfer area [10,11], (b) disrupt the boundary layer to increase the convective coefficient [12,13], (c) use of liquid–vapor phase change [5], (d) use of surface coatings to increase velocity near boundaries [14], (e) use of additives to enhance thermophysical properties [4,15], (f) flow rate and velocity amplifications [16,17], and (g) layering of immiscible flows [18,19]. Of special importance to this work is the passive enhancement method obtained by combining layering of immiscible fluids and flow rate amplification mechanisms.

Enhancement of heat transfer by layering of immiscible fluids with direct and perfect contact at their interface has been recently identified and investigated by Khaled and Vafai [18] and Al Omari [19]. The perfect contact between the fluids is ensured when there is no intermediate region at the interface separating between the two immiscible fluids. The novel idea behind this method is to layer an immiscible fluid having favorable thermophysical properties in perfect contact with the coolant (the fluid facing the heated boundary), as shown in Fig. 1. For example, layering water in perfect contact with mercury (coolant) results in increasing the effective thermal capacity as $(\rho c_p)_w/(\rho c_p)_{\mathrm{Hg}} = 2.211$ and reducing the effective viscosity of the combined fluid since $\mu_w/\mu_{\mathrm{Hg}} = 0.56139$. Accordingly, enhancement of heat transfer can be achieved due to the increase in all of the following quantities: mean velocity, velocity near the hot boundary, mass flow rate, and the thermal fully developed length inside the channel. To the author best knowledge, there are few experimental evidences that support enhancing heat transfer by layering of two immiscible fluids [20–22]. However, none of these works have considered layering of these fluids concentrically along the tube length.

* Tel.: +966 12 6402000x68185; fax: +966 12 6952182.
E-mail addresses: akhaled@kau.edu.sa, akhaled4@yahoo.com.

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Nomenclature

a_i, a_o	(inner, outer) flow aspect ratio ($a_i = r_i/L$, $a_o = r_o/L$)
C_i, C_o, C^*	(inner, outer, reference) flow thermal capacity [W K^{-1}]
C_R	dimensionless combined flow thermal capacity, Eq. (25)
$c_{p,i}$, $c_{p,o}$	(inner, outer) fluid specific heat [J kg^{-1} K^{-1}]
d_i, d_o	(inner, outer) flow diameter [m]
g	gravitational acceleration [m s^{-2}]
h	convection heat transfer coefficient [W m^{-2} K^{-1}]
k_i, k_o	(inner, outer) fluid thermal conductivity [W m^{-1} K^{-1}]
L	tube length [m]
M_i, M_o	(inner, outer) fluid dimensionless mass flow rate, Eqs. 20 and 21
$\dot{m}_i$, $\dot{m}_o$	(inner, outer) fluid mass flow rate [kg s^{-1}]
Nu	Nusselt number ($Nu = h[d_o - d_i]/k_o$)
Nu^*	Nusselt number defined for the reference case ($Nu^* = hd_o/k_o$)
Nu_S	Nusselt number defined for the limiting case ($Nu_S = hd_o/k_o$)
Pr_i, Pr_o	(inner, outer) fluid Prandtl number($Pr_{i,o} = \mu_{i,o}(c_p)_{i,o}/k_{i,o}$)
q_s''	heat flux at the tube inner boundary [W m^{-2}]
R	dimensionless radial coordinate of the outer fluid ($R = [r - r_i]/[r_o - r_i]$)
Re_i, Re_o	(inner, outer) flow Reynolds number, Eq. (8)(a, b)
$Re_{i,r}$, $Re_{o,r}$	(inner, outer) flow reference Reynolds number, Eq. (8)(c, d)
r	radial coordinate [m]
r_i,r_o	(inner, outer) flow radius [m]
$\bar{r}$, r^*	dimensionless (inner, reference) flow radius ($\bar{r} = r/r_i$, $r^* = r/r_o$)
$\bar{r}_o$	dimensionless outer flow radius ($\bar{r}_o = r_o/r_i$)
T_i, T_o	(inner, outer) fluid temperature [K]
U_i, U_o	(inner, outer) fluid dimensionless average axial velocity [m s^{-1}]
u_i, u_o	(inner, outer) fluid axial velocity [m s^{-1}]
$\bar{u}_i$, $\bar{u}_o$	(inner, outer) fluid dimensionless velocity ($\bar{u}_{1,2} = u_{1,2}/u_{(1,2)avg}$)
x, $\bar{x}$	(inner, outer) axial distance ([m], $\bar{x} = x/L$)

Greek symbols

ε	effectiveness, Eq. (51)
λ	heat transfer enhancement indicator, Eq. (50)
μ_i, μ_o	(inner, outer) fluid dynamic viscosity [kg m^{-1} s^{-2}]
ν_i, ν_o	(inner, outer) fluid kinematic viscosity [m^2 s^{-1}]
θ_i, θ_o	dimensionless (inner, outer) fluid temperature, Eq. (9)(a, b)
ρ_i, ρ_o	(inner, outer) fluid density [kg m^{-1}]

Subscripts

1, L	value at (inlet, exit)
avg	average value
eff	effective value
i, o	(inner, outer) fluid or flow
m	mean bulk value
max	maximum value
r	reference quantity
s	limiting case
W	value at boundary

In addition to the methods proposed by Khaled and Vafai [16,17,23,24], denser fluids can be used to magnify the flow rate and the velocity inside vertical tubes if the flow is driven by the gravitational force [25,26]. This type of flow does not require cost for pumping down the fluids that can be in form of either falling film or falling flow completely filling the tube cross-section [27]. Also, the power needed to pump back up the two fluids can be minimized by having a large hydraulic diameter return system that is isolated from the main cooling system. Both falling flow types are seen in the cooling of nuclear reactors applications [25,26]. Heat transfer enhancement due to combining both layering of immiscible fluids and flow rate amplification by gravitational force mechanisms has received almost no attention in heat transfer literature [1–4,8,9,15]. Accordingly, this topic is considered as the main motivation behind the present work.

In the next sections, heat transfer inside a vertical tube filled with two layers of immiscible co-flows is analyzed. Both flows are driven by gravitational force and distributed concentrically through

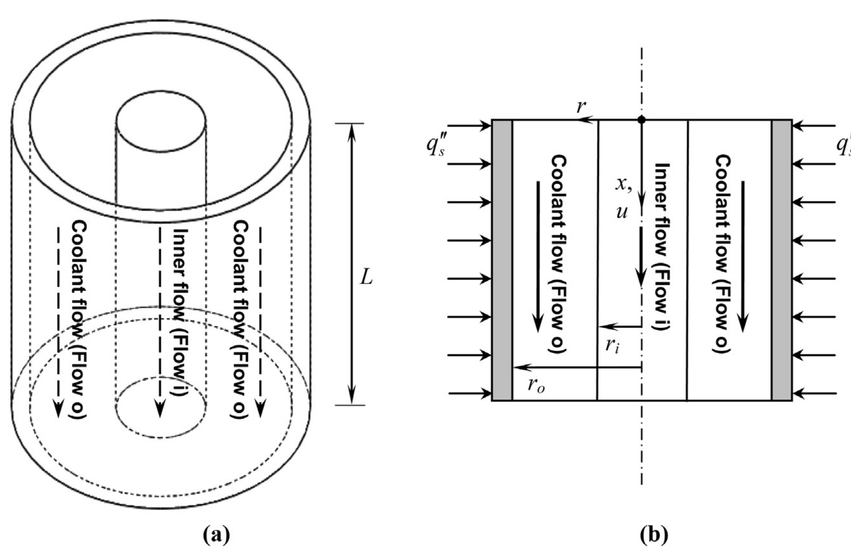

Fig. 1. Two immiscible falling fluid flows inside a vertical tube: (a) 3D view, and (b) schematic profile with the coordinates system.