



Enhancement of forced and free convection heat transfer rates by inducing liquid–liquid phase separation of a partially-miscible equal-density binary liquid system



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ABSTRACT

In attempt to enhance single-phase convective heat transfer in small diameter pipes, the possibility of using phase transition of liquid–liquid systems was tested. The liquid system used is a partially miscible solvent system, with a Critical Solution Temperature (CST). A two-component system with almost identical densities was chosen in the present work in order to confirm the findings that convective heat transfer rates in pipe flow are enhanced by the phase separation also under micro gravity conditions. The heat transfer augmentation is attributed mainly to the self-propulsion of droplets and the resulting mixing, which are driven by Korteweg capillary forces during the non-equilibrium stages of phase separation. It was found that phase separation can enhance significantly the forced convection heat transfer in small diameter pipes (up to 150%) even in the equal density two-phase system. The experimental correlation developed for the heat transfer enhancement indicates that the main influential parameters are the quenching depth and quenching rate.

The equal density solvent system is also used to explore the free convection heat transfer phenomena from a vertical plate during phase separation. Unexpectedly, here too, enhanced heat transfer rates (up to 100%) are found compared to single phase free convection for the same temperature difference. Visualization of the flow field during the phase separation enables to associate the heat transfer augmentation to the observed flow phenomena. A film model was developed to represent the experimental heat transfer rates.

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1. Introduction

One of the emerging technologies for removal of a large amount of heat from a small area is sub-cooled forced convection boiling in small (mini and micro) channels (e.g. [1]). The high heat transfer rates during boiling are commonly attributed to the pumping mechanism due to the bubble detachment from the heated surface [2,3]. Bubble detachment results in inflow of fresh, cold liquid into the thermal boundary layer, thus increases the rate of heat removal from the surface.

The most important parameter in using convective boiling for heat removal is the critical heat flux (CHF). At CHF the surface is covered by vapour (dry-out), leading to a very large increase in the surface temperature that results in overheated and damaged equipment. Controlling the system to operate close, yet below the CHF, is one of the main concerns in employing convective

boiling for cooling, in particular under variable heat loads. This problem is more severe in micro channels as the detaching bubble size is of the order of the channel diameter. In this case earlier dry-out occurs and when operating in parallel channels, instabilities are encountered. To overcome the above limitations, single phase flow in parallel small diameter channels is employed.

The possibility of using phase transition in liquid–liquid systems to enhance the single phase heat transfer rates was examined [4–8]. The liquid–liquid systems used are partially miscible solvent systems with a Critical Solution Temperature (CST). Such systems can alter from a state of a single liquid phase, to a state of two separated liquid phases, by a small change of temperature. In solvent systems that are characterized by an Upper Critical Solution Temperature (UCST), the transition from a single phase to two phases is brought about by reducing the temperature. In other solvent systems, which are characterized by a Lower CST, the phase separation occurs with increasing the temperature. Detailed lists of binary and multi-component systems possessing a critical temperature were collected by Francis [9] and Sorensen and Arlt [10].

When a partially miscible liquid–liquid mixture is quenched (or heated) from its single-phase region to a temperature below

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Nomenclature

A	surface area (m^2)
AF	augmentation factor (-)
C	empirical constant Nu_{fc} (-)
C_p	specific heat ($\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$)
D	tube inner diameter (m)
g	gravity acceleration (m s^{-2})
h	enthalpy [kJ kg^{-1}]
h^{ex}	excess enthalpy (J kg^{-1})
h_{mix}	heat of mixing (J kg^{-1})
h	heat transfer coefficient ($\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$)
Ja	Jacobs number (-)
k	thermal conductivity ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$)
K	defined in Eq. (31) (-)
L	length of the test section (m)
\dot{m}	mass flow rate (kg s^{-1})
\dot{m}	local mass flux ($\text{kg m}^{-2} \text{ s}^{-1}$)
m	mass fraction of a phase (-)
Nu	Nusselt number (-)
Pe	Peclet number, UD/α (-)
Pr	Prandtl number (-)
Q	heat transfer rate (W)
Ra	Rayleigh number (-)
Re	Reynolds number (-)
T	temperature ($^\circ\text{C}$, K)
u	axial velocity in the film (m s^{-1})
U	average axial velocity (m s^{-1})
x	mole fraction (-)
\dot{V}	volumetric flow rate ($\text{m}^3 \text{ s}^{-1}$)

Greek letters

α	thermal diffusivity ($\text{m}^2 \text{ s}^{-1}$)
β	thermal expansion coefficient (K^{-1})
γ	Global film mass flow rate per unit width ($\text{kg m}^{-1} \text{ s}^{-1}$)
δ	film thickness (m)
μ	viscosity (Pa s)
ν	kinematic viscosity ($\text{m}^2 \text{ s}^{-1}$)
ρ	density (kg m^{-3})
ω	component mass fraction in the phase

Subscripts

b	bulk
cp	cloud point
D	diameter as characteristic length
f	film
fc	free convection
h	heavy phase
in	in
id	ideal
l	light phase
L	surface length as characteristic length
out	out
PT	phase transition
sp	single phase
$vert$	vertical
w	wall

Superscript

\sim	dimensionless
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(above) the composition-dependent spinodal curve, it phase separates via the so-called spinodal decomposition, characterized by the spontaneous formation of single-phase domains, which then proceed to grow and coalesce. Unlike nucleation, which starts from a metastable state, where activation energy is required to initiate the separation, spinodal decomposition starts from an unstable state and involves the growth of any fluctuations whose wavelength exceeds a critical value. Experimental and theoretical studies indicate that the typical size of the domains formed during spinodal decomposition grows with time according to a power-law, t^n , with an exponent $n = 1/3$ when diffusion is the dominant mechanism of material transport, while $n = 1$ when hydrodynamics become important (e.g., [11–13]).

Most experimental studies show that right after it is quenched below the miscibility curve, the mixture starts to separate by diffusion and coalescence, leading to the formation of patches with bulk concentrations that approach one of the two mutual equilibrium values. The morphology of these patches depends on the initial composition: for critical mixtures, it is dendritic, while for off-critical mixtures, it is spherical drops.

The self-propulsion of droplets/domains and their enhanced coalescence result from the Korteweg capillary forces during the intermediate, non-equilibrium stages of spinodal phase separation. These forces produce self-induced agitation and, therefore, effective fluctuations of the velocity, temperature and composition fields. Eventually, the domains of the separating phases become large enough (the size of the capillary length), where buoyancy may dominate surface tension and the mixture further separates by gravity (sedimentation).

The potential for exploiting the self-propulsion and the resulting mixing effects for heat transfer applications has been recognized and demonstrated. In a preliminary study conducted in a small closed cell Poesio et al. [6] found an up to 10-fold reduction in cooling time as compared to a pure conduction cooling in the

absence of convective effects. Gat et al. [4,5] reported an increase by a factor of 2 of the average Nu number during phase separation of a three-component (water–ethanol–ethyl acetate) system flowing in a mini tube (2 mm i.d.). The free convection from the outer surface of the tube (4 mm i.d.) was also studied [5] and found to be enhanced (approximately by a factor of 2). The augmentation in this case was attributed mainly to the larger density difference of the separating phases, as compared to single phase free convection for the same temperature difference. Those experimental results are encouraging and show the potential for significant improvements in cooling efficiency.

This paper presents results of a study in which a two-component system with almost identical densities was used, in order to confirm that convective heat transfer rates in pipe flow are enhanced also in practically zero gravity systems. The equal density solvent system was also used to explore the free convection heat transfer phenomena from a vertical plate during phase separation.

2. Experimental Setup and Procedure

2.1. Solvent System-

An ‘upper CST’ two-component solvent system is used in the tests. It is composed of acetone and hexadecane. This solvent system was selected because its components can be used relatively safely in large volumes. In addition, as these compounds have low density difference, gravitational effects on the studied phenomena are minimized.

The co-existence curve (see Fig. 1) of the acetone–hexadecane system was obtained experimentally using the cloud point procedure [14] according to the following steps (for USCT system):

- Preparing a mixture with a known composition.

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