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Pool boiling of iso-butane and quasi azeotropic refrigerant mixture on coated surfaces

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ABSTRACT

An experimental study was carried out to investigate saturated pool boiling of iso-butane and quasi-azeotropic mixture (R-600a and R-410A) for four horizontal copper surfaces fabricated by flame spraying technique. The copper powder was used as a coating material applied to the outer surface of copper tube. Boiling experiments were performed on 25.4 mm diameter copper tubes with the active length of 116 mm. Data were taken over a heat flux range of 5–50 kW m^{-2} and saturation temperature of 10 °C. The effects of heat flux and coating parameters (coating thickness, pore diameter and porosity) on nucleate boiling heat transfer coefficient of both refrigerants are thoroughly compared. The boiling heat transfer coefficient of copper coated surface was enhanced approximately 1.1–2 times that of plain surface. The experimental heat transfer coefficients were also compared with some existing correlations and the results of other authors published data. An empirical correlation was also developed to predict the heat transfer coefficient of both refrigerants during pool boiling over coated surfaces.

1. Introduction

Since 1930s, chlorofluorocarbons (CFCs) were widely used in refrigeration and air-conditioning equipment. CFCs molecules have a very long life when exposed to the atmosphere due to their stable chemical structure. However, they react with ozone molecules and were found to be responsible for the destruction of the ozone layer. Therefore in 1987, the Montreal protocol [1] was proposed to phase out the ozone depleting substances (UNEP, 1987). The most of the developed countries have prohibited the production and use of ozone depleting substances, thus CFCs has been phased out and hydrochlorofluorocarbons (HCFCs) are going to be before 2020. The halocarbons and CFCs, the foremost anthropogenic depleting agents, are now controlled under the Montreal protocol [2] and Kyoto protocol [3]. In order to fill the gap caused by the phase out of CFCs, researches have been carried out extensively to find alternative refrigerants whose ozone depletion potential (ODP) is zero. Hydrocarbons (HCs) have low global warming potential (GWP) as well as zero ODP, but the only concern is its flammability. Nowadays, design engineers have put remarkable efforts in designing efficient and compact systems thus reducing the risk of flammability. Therefore, HC (R-600a) can be better alternative refrigerant for CFCs and HCFCs because of its good thermodynamic properties as well as eco-friendly features. The refrigerant blend R-410A is also a long-term alternative refrigerant with zero ODP for time being in developing countries. For refrigeration and air conditioning applications R-410A was preferred because it has better low temperature efficiency, and lower discharge temperatures, favorable physical and transport properties. However, due to high global warming potential (GWP), this refrigerant may be phase out in the near future. Even though iso-butane (R-600a) and quasi-azeotropic refrigerant mixture (R-410A) were proposed as alternative refrigerants in the present study. In this area very few literatures are available and lot of work is still remaining.

In recent years, enhanced boiling heat transfer has emerged as a potential research area to meet the challenges of technological developments in refrigeration and air-conditioning, power generation, chemical and other allied industries. Various enhancement methods developed over the last few decades and were described by Thome [4], Webb [5] and Bergles [6]. These methods were categorized into active, passive and compound techniques. Out of them, passive methods seem to be of great promise over active methods due to ease of fabrication and non-employment of any external energy supply. Metallic powder coating on the substrate surface is one of the most attractive passive methods for enhancing the boiling heat transfer coefficient. Few investigators [7–20] have studied boiling of alternative refrigerants on metallic coated heating surfaces and observed significant enhancement of boiling heat transfer coefficient. However, the information available in

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Nomenclature

A	surface area of tube [m^2]
C_{pl}	specific heat of liquid [$J\ kg^{-1}\ K^{-1}$]
D	tube diameter [mm]
$F(p)$	pressure function
d	diameter [μm]
Gr	Grashof number, $Re^2 P_r^{1/3}$ [-]
h	boiling heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
h_{lv}	latent heat of vaporization
I	current [A]
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
k_{eff}	effective thermal conductivity, $\varepsilon k_l + (1-\varepsilon)k_c$ [$W\ m^{-1}$ - K^{-1}]
M	molecular weight [$g\ mol^{-1}$]
Nu	Nusselt number, ht/k_{eff} [-]
p	pressure [MPa]
p_r	reduced pressure, p_{sat}/p_{cr} [-]
Pr	Prandtl number [-]
Q	heat transfer rate, W
Ncq	constant heat flux number, $\mu_l^2/\rho_l \sigma d_p$ [-]
q	heat flux [$W\ m^{-2}$]
Ra	Rayleigh number, $GrPr$ [-]
Re	Reynolds number, $qd_p/\varepsilon\mu_l h_{lv}$ [-]
R_s	surface roughness [μm]
t	coating thickness [μm]
T	temperature [K]
ΔT	temperature difference [K]
V	voltage [volt]

Greek letters

ρ	density [$kg\ m^{-3}$]
ν	kinematic viscosity [$m^2\ s^{-1}$]
σ	surface tension [$N\ m^{-1}$]
η	enhancement ratio $\left[\frac{h_c}{h_u}\right]$
ε	porosity [%]

Subscripts

c	coating
cr	critical
exp	experimental
i	inner
l	liquid
o	outer
mp	mean pore
$pred$	predicted
sat	saturation
V	vapor
w	wall

the literature are quite extensively, there is still considerable confusion about the impact of these coatings on the boiling heat transfer. Metallic coating surface provides more distributed active nucleation sites for heat transfer in boiling liquids. This nucleation site density is one of the important factors in nucleate boiling, depends on the surface structure as well as the thermo-physical properties of refrigerants. The influences of these factors on nucleate boiling heat transfer were well described by Benjamin and Balakrishnan [21].

The motivation of the present paper is to provide experimental data of pool boiling of isobutane and quasi-azeotropic refrigerant mixture on metallic coated surfaces so that it may be helpful to the design of highly efficient evaporators for refrigeration and air-conditioning industry. This study also investigates the effect of imposed heat flux, coating thickness, porosity and pore diameter on the pool boiling characteristics. The empirical correlation was developed to predict nucleate boiling heat transfer coefficients for these alternative refrigerants on coated surfaces.

2. Experimental facility and procedures

2.1. Experimental setup and test section

Fig. 1 shows the schematic diagram of experimental facility to provide the pool boiling heat transfer characteristics of both refrigerants. The test arrangement was composed of a boiling vessel, test sections, condensing loop, and power supply arrangements. The sealed boiling vessel was fabricated with a 490 mm long stainless steel pipe of 150 mm internal diameter and flanges at both ends. Two vision windows on the opposite sides were installed in the boiling vessel for visual observation. A Flame spraying method having copper powder used as coating material was applied on outer surface of the copper tubes to prepare the test sections. The copper tubes of 25.4 mm outer diameter, 16.65 mm inner diameter and a length of 201 mm, fitted with a stainless steel flange at one end of the boiling vessel. The test section has been shown schematically in Fig. 2. It is made by drilling a central hole of 16.65 mm diameter in a copper rod up to a distance of 186 mm from one end. A portion of 15 mm is left undrilled at the other end of the tube. The undrilled portion of the tube outer covered with a thick sheet of polytetrafluoroethylene (PTFE) and drilled end was covered with a PTFE sleeve. This insulation was required to minimize possibility of any heat flow in longitudinal direction. The test sections were heated by cartridge heaters. Each cartridge heater was 16.54 mm diameter with an actual heated length of 116 mm, and was inserted into the copper tube. Before insertion, the heater was coated with a thermal epoxy to provide tight contact with the copper tube for improving thermal performance. Thermal contact was also enhanced by applying MgO (magnesium oxide) and stainless steel wall structure on the heating coil of heater. The maximum power supplied was 900 W, which produced a uniform heat flux on the surface of the heat transfer tube. By regulating power supply with variable voltage AC heat source, heat input to test section has been controlled. The voltage and current were measure by a digital panel meter (voltmeter and ammeter) to determine applied heat input. The cartridge heater is made of nichrome wire heating coils, pure magnesium oxide (MgO) filler and stainless steel sleeve. Heater is coated by magnesium oxide and is covered by a stainless steel. To confirm heat loss in the heater assembly, two thermocouples were embedded close to the heating coils at the inner surface of magnesium oxide and another two thermocouples at the surface of the stainless steel. The thickness of magnesium oxide and stainless steel are 1 mm and 1.5 mm respectively in cartridge heater used in this study.

The temperatures at the inner (close to the heating coil) and stainless steel surfaces were measured for varying power inputs. The values of heat transfer from the cartridge heater were calculated by applying the one-dimensional heat conduction equation. Then the values of heat transfer was compared with the supplied heat input and heat losses were found. Heat loss in the heater assembly was estimated to be less than 1.86 W which can be ignored. A series of tests were conducted by changing the