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Enhancement of phase-change evaporators with zeotropic refrigerant mixture using metal foams

Gholamreza Bamorovat Abadi, Kyung Chun Kim *

School of Mechanical Engineering, Pusan National University, San 30, Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea

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ABSTRACT

Almost all thermal systems use some kind of heat exchanger. In many cases, evaporators are needed for systems such as organic Rankine cycle (ORC) systems. Evaporators contribute to a big portion of the capital cost, and their price is directly related to their size or transfer area. Highly porous open-cell metal foams are being considered to improve performance while keeping the size of heat exchangers small. This study experimentally investigates the degradation of the heat transfer coefficient of zeotropic mixtures during phase change in a plate heat exchanger with metal-foam-filled channels. The working fluids were pure R245fa and a zeotropic mixture of R245fa/R134a (0.6/0.4 molar ratio). The results show that the metal foams significantly increase the recovered heat, overall heat transfer coefficient, and effectiveness of the heat exchanger for mass flux ranging from 90 to 290 kg/m^{2}s, but at the expense of increasing the pressure drop. The same improvement was observed for the mixture of refrigerants. The degraded heat transfer coefficient of the mixture compared to the pure refrigerants was recovered by the introduction of metal foams to the system. New correlations are proposed to predict the two-phase heat transfer coefficient of both pure R245fa and the refrigerant mixture in metal foam evaporators.

1. Introduction

The sizing of phase-change heat exchangers such as evaporators is one of the main design parameters of thermal systems that use these components. There have been extensive studies on the two-phase heat transfer mechanism in horizontal and vertical tubes, which represent the tube side of a shell-and-tube heat exchanger [1–3]. However, plate heat exchangers have not been investigated as much [4–6], and manufacturers have only published general performance data. Therefore, the available research on plate heat exchangers is not comprehensive [22]. The available data show that the performance of these heat exchangers could be improved by various means [11]. High-porosity open-cell metal foams have been proposed as a feasible solution to improve the thermal performance of evaporators while keeping their sizes compact [7–10].

Hsieh and Lin studied vertical plate heat exchangers [6]. They reported on the saturated flow boiling and associated frictional pressure drop for R410A as the working fluid. Corrugated sinusoidal shapes were used on the plates with a chevron angle of 60°. They examined mass flux ranging from 50 to 125 kg/m^{2}s, heat flux of 5 to 35 kW/m^2, and saturation pressure between about 10 and 14 bar. They showed that the heat transfer coefficient and pressure drop increase with the heat flux and mass flux. Hsieh et al. studied the subcooled flow boiling of the refrigerant R134a [4] in the same type of plate heat exchanger. For subcooled boiling, their data suggest that the mass flux has a greater effect on the heat transfer coefficient than the mass flux or the inlet subcooling degree.

Han et al. [5] performed experiments on the boiling of R410A and R22 refrigerants in brazed plate heat exchangers with chevron angles of 20, 35, and 45°. Their results show that for a given mass flux, an increase in the inlet vapor quality or a decrease in the saturation temperature increases the heat transfer coefficient. An increase in the mass flux or the vapor quality increases the pressure drop. They concluded that the R410A refrigerant has a higher heat transfer coefficient and a lower pressure drop than R22.

Longo and Gasparella [12] also performed experiments on the vaporization of R134a in brazed plate heat exchangers. Their plate heat exchanger had macro-scale herringbone corrugation with a chevron angle of 65°. The evaporative heat transfer coefficient of R134a increased with the heat flux or the outlet conditions. The pressure drop also increased with the mass flux. Longo and Gasparella also compared the data for vaporization of R134a to that of R410A and R236fa [13]. Their results indicate increases of

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* Corresponding author.
E-mail address: kckim@pusan.ac.kr (K.C. Kim).

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Nomenclature

A	area, m^2
A_{total}	total surface area of the metal-foam-filled channel, m^2
A_{empty}	surface area of the empty channel, m^2
Bo	boiling number
c_p	specific heat, J/kg·K
D_h	hydraulic diameter, m
d_p	pore diameter, m^2
f	friction factor
G	mass flux, kg/m^2s
g	gravitational acceleration, m/s^2
h	enthalpy, kJ/kg
h_{fg}	latent heat of evaporation, J/kg
k	thermal conductivity, W/mK
L	distance, m
M	molecular mass, kg/kmol
$\dot{m}$	mass flow, kg/s
P	pressure, bar
Pr	Prandtl number
P_r	reduced pressure
$\dot{q}$	Heat flux, kW/m^2
Q	heat, W
Re	Reynolds number
t	thickness, m^2
T	temperature, K
U	overall heat transfer coefficient, W/m^2 K
x	vapor quality
X_{tt}	martinelli number
X	liquid mole fraction
Y	vapor mole fraction

Greek symbols

α	heat transfer coefficient, W/m^2 K
ε	effectiveness
ε_0	porosity
μ	viscosity, Pa·s
ρ	Density, kg/m^3
σ	surface tension, N/m

Subscript

c	cold side
cb	convective boiling
h	hot side
i	inlet
id	ideal
int	intermediate
l	liquid
nb	nucleate boiling
o	outlet
p	port, pore
r	refrigerant
sh	superheat
tp	two phase
v	vapor
w	water

40–60% in the heat transfer coefficient and a decrease in the pressure drop for R410A compared to R134a and R236fa.

Zeotropic mixtures are also used in plate evaporators. Taboas et al. [14] experimented with the saturated flow boiling heat transfer of zeotropic mixtures of ammonia and water in a plate heat exchanger. The heat transfer coefficient was influenced far more by the mass flux than the heat flux or saturation pressure. The increase in mass flux and quality greatly increased the frictional pressure drop. No relation between the heat flux and the frictional pressure drop was reported. A mixture of R134a and ammonia was also investigated. Djordjevic and Kabelac [15] studied the evaporation of this mixture in plate heat exchangers with chevron-pattern corrugation. Parallel flow yielded a higher overall heat transfer coefficient than counter-flow. Lower chevron angles of the corrugations also resulted in a lower heat transfer coefficient. Lee and Lee [16] proposed a correlation for predicting the two-phase evaporative heat transfer coefficient in small rectangular channels similar to those found in plate heat exchangers. The heat transfer coefficient of R113 is directly related to the mass flux and the vapor quality, but the heat flux had only a small influence.

When experiments are not an option, models can be used to predict the performance of evaporators with good accuracy. Some models use a moving boundary method, while others use a discretized method. Discretized models are less cumbersome and easier to implement [20,21], but the moving boundary method is probably the most accurate. This method directly uses the Navier–Stokes equations of mass, momentum, and energy conservation [17–19]. By dividing the evaporator into three subsections for the liquid phase, two-phase, and vapor phase, the heat transfer coefficient and the pressure drop of the evaporator can be obtained using the Navier–Stokes partial differential equations for each part, especially the two-phase section. However, the right-hand side of these equations need assumptions for simplification.

Most if not all of commercialized plate heat exchangers use a method of surface enhancement (most commonly chevron corrugation). However, inserting metallic foam in plain rectangular channels could be even more beneficial in terms of thermal enhancement. Although metal foam has been around for a while, its application in heat transfer enhancement has gained attraction recently. Kim et al. [23] investigated the pressure drop and heat transfer of plate-fin heat exchangers with aluminum metal foams. They reported that the friction factor and heat transfer coefficient are significantly affected by the permeability and porosity of the metal foams. They concluded that metal foams are preferable for compactness of the heat exchanger. They also provided correlations for both the friction factor and j-factor, which were verified in experiments by other researchers. Calmidi and Mahajan [24] studied the convective heat transfer in aluminum metal foams with air as the fluid medium. They correlated their Nusselt number data with the Reynolds number of the pores. Mancin et al. [25,26] and Hamadouche et al. [27] did similar experiments for the air flow in aluminum metal foams.

Two-phase flow in metal foam channels has not been investigated as much. Diani et al. [28] and Mancin et al. [29] studied the boiling of R134a, R1234yf, and R1234ze(E) in a 5-PPI (pores per inch) copper foam. Mancin et al. [29] reported the effects of the mass flow, heat flux, and vapor quality on the heat transfer coefficient, and they visualized the boiling phenomena using a high-speed camera. In their experiments, the ratio of the two-phase heat transfer in a metal foam tube to that in a smooth, empty tube varied between 1.8 and 4.8. The best improvement was achieved at low mass velocity and heat flux.

Zhu et al. [30,31] visualized the boiling of R410A refrigerant in a 7.9-mm tube filled with 5-PPI metal foams and provided a correlation for the two-phase heat transfer data. They provided flow maps for the two-phase flow of the refrigerant in the copper foam and

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