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Flow boiling of R245fa in the brazed plate heat exchanger: Thermal and hydraulic performance assessment

Muhammad Imran [a,c], Muhammad Usman [b,d], Youngmin Yang [b,c], Byung-Sik Park [b,c,*]

[a] Energy Engineering Department, School of Engineering, University of Management & Technology, C-II Johar Town Lahore, Pakistan
[b] Energy System Engineering, Korea University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
[c] Energy Efficiency Research Division, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
[d] Department of Mechanical Engineering, University of Engineering & Technology, Lahore, G.T Rd, Lahore 54890, Pakistan

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ABSTRACT

Present study deals with the flow boiling of R245fa, a commercial working fluid used in organic Rankine cycle, in brazed plate heat exchanger with chevron angle of 45 degree and 60 degree. The effects of the heat flux, mass flux rate of refrigerant, saturation temperature on convective heat transfer coefficients are investigated. The operating conditions of the experiment are as mass flux: 30–40 kg m^{-2} s^{-1} quality at evaporator inlet: 0.1–0.8, heat flux: 2–15 kW m^{-2}. The heat transfer result suggests a nucleate boiling dominant process in the evaporator. The convective heat transfer coefficient showed a strong dependence on the heat flux and vapor quality at evaporator inlet. Moreover convective heat transfer coefficient show a linear relationship with mass flux of the refrigerant. It is worth mentioning that heat transfer coefficient is higher at higher saturation temperature and chevron angle. Based on the experimental data, empirical correlations were developed for the prediction of heat transfer coefficients and frictional pressure drop of refrigerant R245fa in brazed plate heat exchanger.

1. Introduction

From last few decades, the increasing environmental concerns have accelerated research work in the field of efficient utilization of the energy resources. The low grade and waste heat recovery can considerably mitigate the greenhouse gas emissions. Low grade and waste heat is available in different forms, ranging from the waste heat of industrial processes, heavy duty vehicles and to the renewable sources of biomass, geothermal, and solar energy. The organic Rankine cycle (ORC) is considered a viable technology for efficient recovery of low grade heat and [1]. The ORC unit is similar to conventional steam Rankine cycle, but uses an organic fluid such as refrigerants and hydrocarbons instead of water. Although the ORC technology has been successfully adopted in industry but the need of efficiency improvement and cost reduction still persists [2]. The economic feasibility of a plant depends not only on the cycle efficiency, but also on the capital investment which is strongly correlated with the heat exchanger size [3]. The evaporator and condenser size depends on the heat transfer and pressure drop characteristics of the working fluids of the ORC, estimated using the empirical correlations. These correlations are sensitive to the geometry of heat exchanger, operating conditions and working fluid. Plate heat exchanger (PHE) provide a large heat transfer surface area per unit volume, which makes them particularly suited for installation in confined spaces, particularly for small-scale ORC plants. However, the heat transfer characteristics of ORC working fluids in such PHEs have been studied very little as compared to conventional refrigerants used in air conditioning and refrigeration systems. This calls for urgent research in this area in order to provide engineers with tools to design efficient and economically viable cycles.

Danilova et al. [4] investigated the flow boiling of R12, R22, R113 and NH_3 in PHE. Convective heat transfer coefficient show linear variation with vapor quality and refrigerant mass flux. Engelhorn et al. [5] conducted flow boiling experiments of R22 in PHE. It was observed that the convective heat transfer coefficient decreases with increase in evaporation temperature. Later, it was also reported that heat transfer coefficient of R142b in PHE is 30% compared to PHE without distributor [6]. Kumar et al. [7] suggested that the heat transfer coefficient of R22 and NH_3 decreases with increase in vapor quality up to 0.7 and then decreases. Comprehensive review of flow boiling in PHE was presented [8]. In order to distinguish between the pool boiling and nucleate boiling, they have introduced the multiplication of the Lockhart-Martinelli

* Corresponding author at: Energy System Engineering, Korea University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea.
E-mail address: bspark@kier.re.kr (B.-S. Park).

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Nomenclature

A	area of heat exchanger, m^2
b	plate spacing, m
Bo	boiling number
D	port diameter, m
D_h	hydraulic diameter, m
f	friction factor
G	mass velocity, kg m^{-1} s^{-1}
$HPCD$	horizontal port center distance, m
i_{fg}	enthalpy of vaporization, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	length of plate, m
$LMTD$	log mean temperature difference, °C
$\dot{m}$	mass flow rate, kg s^{-1}
Nc	no. of channels
U	overall heat transfer coefficient, W m^{-2} K^{-1}
$VPCD$	vertical port center distance, m
n	no. of thermal plates
Nu	Nusselt number
P	pressure, Pa
$PPTD$	Pinch point temperature difference
Pr	Prandtl number
q'	average heat flux, W m^{-2}
Q	heat transfer rate, kW
Re	Reynolds number
T	temperature, °C
t	plate thickness, m
W	width of plate m
x	vapor quality

Subscripts

c	cold side
h	hot side
eq	equivalent
p	plate
e	effective
r	refrigerant side
w	water side
sp	single phase
f	liquid phase
g	vapor phase
eV	evaporation
tp	two phase
i	inlet
o	outlet

Greek letters

β	chevron angel, degree
ρ	density, kg m^{-3}
μ	viscosity, kg s^{-1} m^{-1}
η_p	isentropic efficiency of pump
Φ	enlargement factor, the ratio of the developed length to the projected length

parameter. Later, the same authors [9] studied flow boiling of R134a in PHE. It was observed that the heat flux does not affect the convective heat transfer coefficient; however, vapor quality strongly affects the convective heat transfer coefficient. The research group of Lin [10–12] conducted number of flow boiling studies of R134a and R410a in PHE and proposed empirical correlations based on boiling number and an equivalent Reynolds number. Hsieh et al. [13] conducted the subcooled flow boiling study of R134a in PHE and investigated the effect of mass flux, heat flux and evaporation pressure on the convective heat transfer coefficient. Donowski et al. [14] performed experiments to investigate the flow boiling of R134a in PHE and they noticed large discrepancy in experimental data of [12] while comparing their own experimental data with empirical correlations of [12]. They proposed modified correlations for single and two phase heat transfer coefficients. The research group of Longo et al. [15–20] performed comprehensive experiments to investigate the flow boiling of R134a, R410A, R236fa, R600a, R290, R1270 and R1234yf in PHE for complete evaporation. In contrast to [9], Longo et al. [17] suggested that heat transfer coefficient strongly depends on heat flux and vapor quality while it is less sensitive to saturation pressure. Palm et al. [21] modified the Cooper [22] nucleate pool boiling correlation by a multiplication factor of 1.5 to account the heat transfer enhancement of PHE. Han et al. [23] studied flow boiling of R410a and R22 in PHE with different geometrical parameters and proposed empirical correlation based on equivalent Reynolds, Boiling numbers and non-dimensional geometrical parameters of the PHE. The Appendices A and B provide a comprehensive list of empirical correlations equations for flow boiling heat transfer and two phase pressure drop of refrigerants in plate heat exchangers. Despite of these studies, there are still open questions regarding the application of these empirical correlations for heat transfer and pressure drop assessment of ORC working fluids in PHE. Although, a number of correlations are presented in open literature (Appendices A and B) but they are limited to conventional refrigerants for HVAC applications and when they are applied for working fluids of ORC, results in an error for the prediction of heat transfer and pressure drop due to variation of thermophysical properties of the working fluids. A comparison of the most common thermophysical properties of two working fluids, R134a (conventional refrigerants), and R245fa (ORC working fluid) is presented in Fig. 1.

The thermal conductivity and density ratios (vapor density/liquid density) of the R245fa along saturation temperature show entirely different trends compared to R134a, these variations in thermophysical properties of working fluids will have significant impact on the estimation of heat transfer and pressure drop characteristics.

The proposed study aims to provide the insight to flow boiling of R245fa in PHE and develop empirical heat transfer and pressure drop correlations. The research outcomes of the project will present significant benefits to both academia and industry. Moreover, by contributing to the design of more efficient organic Rankine cycle units and by enabling the utilization of new renewable energy sources, this project will provide an essential contribution toward building a sustainable future with no carbon dioxide emissions.

2. Experimental infrastructure

For the heat transfer and pressure drop analysis of R245fa in brazed plate heat exchanger, an initial layout and schematic of the experimental testbed is developed. The design and selection of the components is based on the required operating rage of experiments (mass flux, heat flux, evaporation pressure). For present study, operating conditions are as mass flux: 30–40 kg/m^2 s, inlet quality: 0.1–0.8, evaporation pressure: 5–6 bar, heat flux: 2–15 kW/m^2. Schematic and PID diagram of the test facility is shown in Fig. 2.

Experimental setup has two heat source each 7.5 kW, pre_evaporator, evaporator and measuring instruments. The main