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Flow boiling heat transfer and pressure drop characteristics of R134a, R1234yf and R1234ze in a plate heat exchanger for organic Rankine cycle units

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ABSTRACT

The optimal design of the evaporator is one of the key issues to improve the efficiency and economics of organic Rankine cycle units. The first step in studying the evaporator design is to understand the thermal-hydraulic performance of the working fluid in the evaporator of organic Rankine cycles. This paper is aimed at obtaining flow boiling heat transfer and pressure drop characteristics in a plate heat exchanger under the working conditions prevailing in the evaporator of organic Rankine cycle units. Two hydrofluoroolefins R1234yf and R1234ze, and one hydrofluorocarbon R134a, were selected as the working fluids. The heat transfer coefficients and pressure drops of the three working fluids were measured with varying saturation temperatures, mass fluxes, heat fluxes and outlet vapour qualities, which range from 60 °C to 80 °C, 86 kg/m^2 s to 137 kg/m^2 s, 9.8 kW/m^2 to 36.8 kW/m^2 and 0.5 to 1, respectively. The working conditions covered relatively high saturation temperatures (corresponding reduced pressures of 0.35–0.74), which are prevailing in organic Rankine cycles yet absent in the open literature. The experimental data were compared with existing correlations, and new correlations were developed that are more suitable for evaporation in organic Rankine cycles. The experimental results indicate that heat transfer coefficients are strongly dependent upon the heat flux and saturation temperature. Moreover, the results suggest better thermal-hydraulic performance for R1234yf than the other two working fluids at the same saturation temperatures. With the new heat transfer and pressure drop correlations, agreements within ±25% were obtained for experimental data in similar experiments with high saturation temperatures.

1. Introduction

With rising fuel prices and concerns for the environment, utilizing the available energy sources in the most efficient manner and increasing the use of renewable energy sources have become necessities. Low-grade heat is available in different forms, ranging from waste heat including marine diesel engines, industrial processes and refrigeration plants to renewable sources such as biomass combustion, and geothermal and solar heat sources. The organic Rankine cycle (ORC) technology has gained worldwide acceptance as an efficient way to utilise low-grade heat [1] and the ORC market has seen a near exponential growth in the last decade [2]. Due to the large heat transfer area per volume, the plate heat exchanger (PHE) has some great features including compactness, effectiveness, design flexibility and low cost. Plate heat exchangers are the most common type of heat exchangers used in small-scale ORC plants, while shell and tube heat exchangers are commonly used in large-scale ORC systems [2]. Plate heat exchangers can be brazed, gasketed or of shell and plate type. Compared with gasketed and shell and plate heat exchangers, brazed PHEs have better sealing performance, higher resistant to corrosion and pressure load [3]. Brazed PHEs are commonly applied for evaporators in small-scale ORC units [e.g. 4–7], and is therefore the heat exchanger type that is considered in this work. The heat transfer and pressure drop characteristics of organic working fluids in PHEs have significant effects on the ORC design. In this case, the research on the heat transfer and pressure drop performance in PHEs is of crucial importance in order to design heat exchangers for more efficient and economically feasible ORC units.

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Nomenclature

Symbols

A	heat transfer area, m^2
b	amplitude of corrugation, m
Bd	Bond number
Bo	Boiling number
c_p	specific heat capacity, J/kg K
D	diameter, m
f	friction factor
G	mass flux, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
h_{fg}	enthalpy of evaporation, J/kg
k	thermal conductivity, W/m K
L	length, m
LMTD	log mean temperature difference, °C
M	molecular weight
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Q	heat transfer rate, W
q	heat flux, W/m^2
Re	Reynolds number
T	temperature, °C
U	overall heat transfer coefficient, W/m^2 K
W	width, m
We	Weber number
x	vapour quality

Greek symbols

γ	dimensionless corrugation parameter
β	chevron angle, °
φ	enlargement factor of corrugation surface
μ	dynamic viscosity, Pa s
ρ	mass density, kg/m^3
λ	corrugation pitch, m
Δ	difference
δ	thickness of plate, m
σ	surface tension, N/m

Subscripts

acc	acceleration
cri	critical
eq	equivalent
eva	evaporator
exp	experimental
fri	frictional
g	gravitational
gra	gradient
h	hydraulic
in	inlet
l	liquid
lo	liquid only
m	mean
oil	oil
out	outlet
p	port
pre	pre-heater
pred	predicted
r	reduced
sat	saturation
tf	two-phase
v	vapour
vo	vapour only
w	water
wall	wall
wf	working fluid

Abbreviations

HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
MAE	mean absolute error
ODP	Ozone Depletion Potential
ORC	organic Rankine cycle
PHE	plate heat exchanger
GWP	Global Warming Potential

The accurate evaluation of heat transfer mechanisms during the flow boiling in PHEs is imperative for prediction of the heat transfer coefficient, and thus for the designing of the heat exchanger. In the flow boiling process, two main heat transfer mechanisms exist, which are named nucleate and convective boiling. A common phenomenon has been presented in some research [8–12], that is, nucleate boiling and convective boiling are predominant at low and high vapour qualities, respectively. With the further increase of vapour quality, the flow enters into the dryout regime. Unlike the experimental results in Refs. [8–12], a nucleate boiling-dominant process was found by Huang et al. [13] when outlet vapour quality $x_{out} = 0.4–1$. The authors performed an experimental investigation of the heat transfer and pressure drop of R134a and R507A with three industrial PHEs. From the test results, it was concluded that nucleate boiling is dominant in their study, for which the heat transfer coefficient showed a strong dependence on the heat flux, and a weak dependence on the refrigerant mass flux, vapour quality, and the chevron angle. Moreover, Lee et al. [14] carried out an experimental investigation of water flow boiling in the PHE. The results showed that water flow boiling was in the convective boiling region even though the vapour quality and mass flux were relatively low. This phenomenon is different from those reported in Refs. [8–12], and it is attributed to the fact that water has very different thermophysical properties than those of refrigerants. Overall, the issues surrounding which mechanism is predominant for the flow boiling in PHEs and what the proven transition criteria are, remain open.

Furthermore, flow boiling in PHEs is a complex heat transfer process, which is affected by many factors including mass flux, heat flux, vapour quality, saturation temperature (pressure), the properties of the working fluids and the structures of the PHEs. However, experimental results regarding the effects of the above factors on the heat transfer and pressure drop are inconsistent from the open literature. Taking the effects of saturation temperature on heat transfer as an example, the present results from different research are inconsistent. Khan et al. [11] carried out an experimental investigation of heat transfer and pressure drop of ammonia in a commercial PHE with different saturation temperatures ranging from −25 °C to −2 °C. Experimental results showed a strong influence of saturation temperature and other operational conditions on the heat transfer and pressure drop in the PHE. Both the heat transfer coefficient and pressure drop were found to increase with an increase in saturation temperature. Han et al. [15] conducted the experiments on the evaporative heat transfer and pressure drop in a brazed PHE using refrigerants R410A and R22 and varying the evaporating temperature 5 °C, 10 °C and 15 °C. From the test results, it can be found that both the evaporation heat transfer coefficient and the pressure drop increase with