International Journal of Heat and Fluid Flow 71 (2018) 210–219

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Experimental study of R134a flow boiling in a horizontal tube for evaporator design under typical Organic Rankine Cycle pressures

Zhang Yue[a], Tian Ran[a], Dai Xiaoye[b], Wang Dabiao[a], Ma Yuezheng[a], Li Hui[a], Shi Lin[a,*]

[a] *Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China*

[b] *Department of Chemical Engineering, Tsinghua University, Beijing 100084, China*

ARTICLE INFO

Keyword:
Organic Rankine Cycle
Flow boiling
Dryout
Stratified flow

ABSTRACT

The heat transfer characteristics of organic fluids at high pressures for Organic Rankine Cycle (ORC) application has not been well studied and relevant experimental results are scarce. R134a flow boiling was investigated experimentally in a 10.3 mm horizontal tube at high pressures of 2.5–3.3 MPa (0.62–0.81P_c) with mass fluxes of 300–600 kg/m^{2}s, heat fluxes of 20–50 kW/m^2. The results showed that dryout more easily occurred at the top surface at higher pressures indicating the predominant flow pattern was stratified flow with partial dryout. With the expansion of dryout, the heat transfer coefficient decreased with increasing vapor quality. The heat flux and pressure affected the heat transfer coefficient at vapor qualities less than around 0.3, while higher mass fluxes improved the heat transfer for the whole range of vapor qualities. An improved correlation was developed for stratified flow conditions by combining the Gungor and Winterton correlation and the Wojtan correlation to overcome their respective defects in predicting cases in this study. The combined correlation has a better prediction accuracy with a mean absolute prediction error of 12.5% for 270 data points for various experimental stratified conditions and the prediction accuracy is less sensitive to the experimental parameters.

1. Introduction

The utilization of low-grade heat sources including geothermal heat, biomass heat, solar power and industrial waste heat will greatly reduce the effects of the energy crisis. Among the various systems developed to use these low-temperature heat sources, the Organic Rankine Cycle (ORC) has been shown to be a promising solution for generating power from several hundred kilowatts to several megawatts (Angelino et al., 1994). Considering thermodynamic performance, safety, reliability and prevalence, R134a is an important and suitable working fluid for ORC application as well as for study purpose (Bertrand et al., 2009). The evaporator is one of the most important parts of an ORC system with a more efficient evaporator not only improving the turbine inlet conditions, which increases the overall system efficiency, but also reducing the heat transfer area, which makes the apparatus more compact.

R134a horizontal flow boiling in evaporators has been widely studied for air conditioning, heat pump and refrigeration systems, and R134a flow boiling experiments in the past 30 years have been mostly conducted for low pressures near or below 1 MPa. Fang summarized nineteen R134a two-phase flow boiling experiments in the past 10 years and compiled a database of 2286 data points (Fang, 2013). The maximum saturation pressure among these many experiments was only 1.3 MPa. Del Col (2010) and Padovan et al. (2011) noticed this issue and increased the reduced pressures to 0.53P_c in their experiments for R134a, which is still low for ORC applications. ORC heat source temperatures are mainly 100–250 °C which leads to evaporating temperatures of 50–150 °C (Bao and Zhao, 2013; Quoilin et al., 2013). Thermodynamic optimization studies have shown that the optimal evaporating pressure range for R134a in ORC systems is 2.33–3.5 MPa (0.58 to 0.86P_c) (Bertrand et al., 2009; Zhai et al., 2014; Zhang et al., 2011; Roy et al., 2010). Therefore, additional heat transfer experiments are needed for these higher pressures and comparisons between existing flow boiling correlations and these experimental results are necessary for validating applicability of such correlations for R134a flow boiling under high saturation pressures.

Existing experiments at low pressures with flow boiling of R134a in tubes have shown that different working conditions lead to different heat transfer phenomena. Bertsch and Groll (2008) studied the variation of the heat transfer coefficient with vapor quality and found a peak in the heat transfer coefficient at vapor qualities around 0.2. However, Kundu et al. (2014) reported a peak at high vapor qualities around 0.7. Lee and Mudawar (2005) found that the heat transfer coefficient

* Corresponding author.
E-mail address: rnxsl@mail.tsinghua.edu.cn (L. Shi).

https://doi.org/10.1016/j.ijheatfluidflow.2018.04.008
Received 29 January 2018; Received in revised form 7 April 2018; Accepted 11 April 2018
0142-727X/

Nomenclature

a	Empirical correction coefficient
Bd	Bond number, $= \frac{gL^2\left(\rho_L-\rho_g\right)}{\sigma}$
Bo	Boiling number, $= \frac{Q}{GH_{LV}}$
d	Diameter, m
e_{AB}	Mean abs. deviation, $= (1/N)\sum[\lvert h_{exp}-h_{cal}\rvert/h_{exp}]\times 100$
e_R	Average deviation, $= (1/\mathrm{N})\sum[(h_{exp}-h_{cal})/h_{exp}]\times 100$
E	Enhancement factor
g	Gravitational acceleration, m/s^2
G	Mass flux, kg/(m^{2}s)
H	Enthalpy, kJ/kg
H_b	Calculated local enthalpy, kJ/kg
H_{LV}	Latent heat, kJ/kg
h	Heat transfer coefficient, W/(m^{2}K)
k	Thermal conductivity, W/(mK)
L	Length, m
P_r	Reduced pressure
P_c	Critical Pressure, MPa
q	Heat transfer rate, W
Q	Heat flux, kW/m^2
Re	Reynolds number, $= \frac{GD}{\mu_l}(1-x)$
S	Suppression factor
x	Vapor quality

Greek symbols

σ	Surface tension, N/m
ρ	Density, kg/m^3
θ	Angle

Subscripts

dry	Unwetted wall section
cb	Convective boiling
in	Inlet
l	Liquid
nb	Nucleate boiling
sat	Saturation
tp	Two-phase
v	Vapor
wet	Wetted wall section
wo	Outside wall

decreased with vapor quality over the whole vapor quality range. Saitoh et al. (2005) found that the heat transfer coefficient was flat or slightly increasing at low vapor qualities but significantly increased at higher vapor qualities. Shiferaw et al. (2009) reported the opposite results that the heat transfer coefficient decreased with increasing vapor quality at high vapor qualities.

Various studies have also reported different variations of the heat transfer coefficient with other experimental parameters. Saisorn et al. (2010) found that the heat transfer coefficient increased with increasing heat flux and decreasing pressure, while the mass flux had little effect. da Silva Lima et al. (2009) found that the influence of the saturation pressure on the heat transfer coefficient was dependent on the vapor quality range. Ribatski and Thome (2006) reported the effect of saturation pressure on heat transfer coefficient was almost negligible. Shiferaw et al. (2009) reported that the heat transfer coefficient was independent of the heat flux at high vapor qualities and heat fluxes and that the mass flux had only a limited impact. Del Col (2010) reported that the pressure had an obvious impact only at low qualities while the heat flux influenced the heat transfer over the whole range of qualities.

Researchers usually explain the phenomena by analyzing the boiling mechanisms. Saitoh et al. (2005) added an intermediate region between nucleate boiling and convective boiling where neither nucleate boiling nor convective boiling was dominant. Lin et al. (2001) reported that nucleate boiling was dominant at low vapor qualities while convective boiling was dominant at high vapor qualities. Kenning and Cooper (1989) showed that nucleate boiling was usually suppressed at vapor qualities higher than 0.2; thus, the heat transfer in single channels was mostly due to convective boiling. Callizo (2010) pointed out that numerous macroscale investigations have shown that when the flow boiling was dominated by nucleate boiling, the heat transfer coefficient increased with increasing heat flux and saturation pressure and was independent of the mass flux and vapor quality, while when convective boiling was the major driving mechanism, the heat transfer coefficient increased with increasing mass flux and vapor quality while the heat flux had little impact.

Previous studies have shown a wide range of results. Higher saturation pressures result in higher vapor densities, lower surface tensions, higher vapor viscosities and lower liquid viscosities, so the variations in the two-phase heat transfer are very complex. Therefore, further experimental study of R134a flow boiling at higher pressures is necessary.

The objective of this study is to provide experimental data for R134a flow boiling in horizontal tubes at high saturation pressures for ORC application, including the variation of heat transfer coefficients with vapor quality. The heat transfer characteristics were studied by analyzing the differences between the flow patterns at high and low pressures as well as the effects of the heat flux, mass flux and saturation pressure on the heat transfer coefficient. The experimental data was also compared against existing flow boiling correlations to identify the causes of errors and to develop an improved flow boiling correlation. This study aims to provide guidance for evaporator designs in ORC applications.

2. Experimental method

2.1. Experimental apparatus

Fig. 1 shows a schematic of the major components in the experiment rig for two-phase flow boiling of organic fluids at the various conditions listed in Table 1. The system included the main loop, cooling system and pressure control system. A pre-heater was installed before the test section to regulate the fluid subcooling entering the test section. The heat input into the pre-heater and the test section was by electrical resistance heating from a DC power which was controlled by adjusting the voltage and current. A cooling system was installed after the test section with the R134a cooled in a plate heat exchanger that was cooled by water from a cooling tower. A circulating pump designed for organic fluids and a Coriolis flow meter were installed to give the desired mass flux, which was regulated manually by a valve. Some of the fluid after the circulating pump was sent through a bypass back to the test section exit to cool the fluid exiting the test section, which was sometimes superheated vapor. This design greatly reduced the load on the plate heat exchanger and increased the safety as the fluid entering the pump and flow meter had to be subcooled liquid to avoid cavitation damage in the pump and ensure the accuracy of the flow meter. The system pressure was regulated by a pressurizer connected to a nitrogen cylinder and nitrogen and R134a were separated by a membrane in the pressurizer.

The test section was a smooth stainless steel tube with an inner diameter of 10.3 mm and an outside diameter of 12.7 mm. The test section was 2.5 m long with a 0.5 m entrance length to make sure that