International Journal of Heat and Mass Transfer 102 (2016) 980–990

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Visualized investigation of gas–liquid stratified flow boiling of water in a natural circulation thermosyphon loop with horizontal arranged evaporator

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ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form 25 June 2016
Accepted 25 June 2016
Available online 14 July 2016

Keywords:
Gas–liquid stratification
Flow boiling
Flow pattern
Thermosyphon
Heat transfer coefficient

ABSTRACT

The gas–liquid stratified flow boiling heat transfer of water in a natural circulation thermosyphon was investigated experimentally. The flow boiling test was carried out in a visual thermosyphon loop system with a 0.8-m-long, horizontally arranged, evaporator tube with an inner diameter of 15.0 mm and under a heat load of 1.0 kW. The development of the gas–liquid stratified flow in the evaporator and its effects on thermal performance of the thermosyphon loop were analyzed. The results show that flow pattern in the evaporator was gradually developed from the slug/stratified-wavy flow to the stratified-wavy/stratified-mist flow along the flow direction. Simultaneously, a periodic transition of the flow pattern was observed. A countercurrent flow at the exit of evaporator has emerged to prevent the development of the stratified-wavy flow to the mist flow which subsequently resulted in a drop in superheat. Moreover, two scales of dynamic instabilities were observed. The large scale was found to be the typical pressure drop type oscillation. The small scale, however, was found to be highly related to the flow pattern transition. Due to the countercurrent flow and backflow, a continuous density oscillation was observed. Finally, a modified correlation was developed for the local heat transfer coefficient that could account for the effect of the subcool and flow pattern transition.

1. Introduction

Thermosyphon and heat pipes have achieved a big success in the application to solar water system in the past decades, partly due to their high efficiency in heat transfer [1–4]. Recently, several successful attempts [5–11] have been made, with encouraging results, to use thermosyphon or heat pipes as the receiver in the concentrated solar thermal system for medium temperature steam generation. Hereinto, Fadar et al. [5,6] conceived a conceptual solar adsorptive refrigeration system by using heat pipe as the receiver in a parabolic trough solar concentrating system. Later on, Zhang et al. [9,10] set up a 50 kW parabolic trough natural circulation solar system for medium temperature saturated steam generation, which can generate saturated steam with a pressure as high as 0.75 MPa. A thermosyphon loop with a horizontally arranged U-type evaporators was applied as the solar receiver.

The choice of working fluid is limited by temperature range for thermosyphon systems. Water is a good candidate as working fluid in a solar steam generation system at medium temperature range (120–200 °C). Compared with other refrigerants [12,13], however, water has a much higher latent heat. Thus a distinct feature for a system using water is the gas–liquid stratification flow boiling phenomenon in evaporator when the heat flux is relatively low and the receiver is horizontally arranged, e.g., for the parabolic trough collector (PTC) system or compound parabolic concentrating (CPC) system.

In the previous studies, more attention has been given to the high heat and mass flux flow boiling phenomenon, and mostly they involve vertical tubes [14–17]. Few studies were focused on the gas–liquid stratified flow boiling phenomenon resulting from the low heat and mass flux, in not only horizontal tubes [17] but also the natural circulation thermosyphon system. The earliest model to predict the local gas–liquid stratified flow boiling was the Kattan–Thome–Favrat flow boiling heat transfer model [18–20],

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.089
0017-9310/

Nomenclature

A_l	cross-sectional area occupied by liquid phase, m^2
Bo	boiling number, $(q/(Gi_g))$
C_1–C_5	constant value
Co	convection number, $\left(\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\right)$
D	diameter, mm
e	error
Fr_l	Froude number of liquid $(G^2/\rho_l^2 g D_i)$
F_{fl}	fluid dependent parameter
FR	filling ratio, dimensionless
h	heat transfer coefficient, W/m^2 K
h_{cb}	convective boiling heat transfer coefficient, W/m^2 K
h_{nb}	nucleate boiling heat transfer coefficient, W/m^2 K
h_v	vapor convective heat transfer coefficient, W/m^2 K
h_{wet}	heat transfer coefficient for the wet perimeter, W/m^2 K
H_l	height of gas–liquid interface, m
I	current, A
k	thermal conductivity, W/(m·K)
L	heating length of evaporator, m
p	pressure, Pa
Pr	Prandtl number
Pr_v	Prandtl number in vapor phase $[c_{pv}\mu_v/k_v]$
Pr_l	Prandtl number in liquid phase $[c_{pl}\mu_l/k_l]$
q	net heat power, W/m^2
q_{el}	heat loss power of evaporator, W
R	radius, m
Re	Reynolds number
Re_v	Reynolds number of vapor phase $[GxD/\mu_v\varepsilon]$
Re_δ	Reynolds number of liquid film $[4G\delta(1-x)/\mu_l(1-\varepsilon)]$
t	time, s
T	temperature, K
$\overline{T}$	average temperature, K
ΔT	temperature difference, K
U	voltage, V
V	volume, ml
x	dryness fraction, dimensionless

Greek letters

δ	liquid film thickness, m
ε	cross-sectional vapor void fraction
μ	dynamic viscosity, kg/(m·s)
θ_{dry}	dry angle of tube perimeter, rad
θ_{strat}	stratified angle of tube perimeter, rad

Subscripts

A–E	cross section A–E of receiver
cond-in	inlet of condenser
cond-out	outlet of condenser
circ	circulate water in the jacket tube of condenser
circ-in	inlet of the jacket tube of condenser
circ-out	outlet of the jacket tube of condenser
cycle	cycle of flow pattern transition
D	diameter
evap	evaporator
evap-in	inlet of evaporator
evap-out	outlet of evaporator
f	working fluid
faller	falling tube
faller-1(2)	position 1(2) of the faller
h	heat transfer coefficient
i	inner tube diameter
I	current
l	liquid phase
L	length
o	outer tube diameter
q	net heat power
q_{el}	heat loss power of evaporator
riser-1(2)	position 1(2) of the riser
sat	saturated vapor temperature in receiver
thermo	thermosiphon or thermosiphon loop
strat	stratified flow
TP	two phase
T	temperature
ΔT	superheat
TP-nonstrat	two phase of non-stratified flow
U	voltage
v	vapor phase

which was based on the flow patterns features identified by the experimental data of R134a, R123, R502, R402A, and R404A in horizontal smooth tubes. Later on, Wojtan et al. [21] improved the accuracy of the Kattan–Thome–Favrat flow pattern map. For the gas–liquid stratification flow, the stratified-wavy region was divided into three sub-regimes (i.e., slug, stratified-wavy and slug, and stratified-wavy flows) based on the dynamic void fraction measurements for R22 and R410A [22]. Subsequently, an improved heat transfer model for stratified-wavy, dryout and mist flow [23] was also proposed by modifying the dry angle in the heat transfer model of the Kattan–Thome–Favrat model. Furthermore, Cheng et al. [24–26] and da Silva Lima et al. [27,28] verified the applicability of the model developed by Wojtan et al. [21,23] for CO$_2$ and R134a in the round horizontal tube, respectively. Recently, Quibén et al. [29,30] attributed the unsatisfactory performance of the modified model by Wojtan et al. [21,23] in some flow regimes to the identification error of flow regimes resulted from the physical parameters of the flattened tube. And a modification should be made to improve the accuracy of the model based on real flow visualization in the flattened tubes.

As mentioned above, the structure details of the flow pattern are very important in understanding the complex gas–liquid two phase flow boiling phenomena, especially the gas–liquid stratified flow boiling phenomena. In addition to the refrigerants used in the development of the models by Kattan et al. [18–20] and Wojtan et al. [21,23], further work should be encouraged to verify the applicability of these models to other working fluids, especially water. Presently, there is hardly any publication which concerns to the gas–liquid stratified flow boiling of water based on the local visualized flow pattern after a literature review, let alone the stratified natural flow boiling. So far, only a small number of experimental investigations [31–36] related to the flow boiling in horizontal tubes using water as working fluid were reported. Nevertheless, none of them were devoted to the gas–liquid stratified flow boiling characteristics. Recently, a series of researches regarding the thermal performance of the thermosyphon system under a gas–liquid stratified flow regime in the evaporator have been investigated by Zhang et al. [9,37,38] and Hua et al. [39]. The present work of Zhang et al. [9,37,38]and Hua et al. [39], however, had neither figured out the characteristics of the local flow patterns nor clarified the relationship between the local heat transfer characteristics and the flow patterns.

Therefore, in the present study, an extended work is devoted to investigate the gas–liquid stratified flow pattern characteristics in thermosyphon systems with horizontal evaporator and its