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Boiling pressure drop, local heat transfer distribution and critical heat flux in horizontal straight tubes

B.K. Hardik, Gajendra Kumar, S.V. Prabhu *

Department of Mechanical Engineering, Indian Institute of Technology, Bombay, India

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ABSTRACT

The objective of the present work is to measure the heat transfer and pressure drop in flow boiling with refrigerant R123 as the working medium. Local heat transfer coefficient along the axial length of tube and overall averaged heat transfer coefficient are compared with available correlations. In the present study, spatial variation in heat transfer coefficient along the axial length of tube is analysed with the increase of quality. Variation in heat transfer coefficient in different flow boiling region *i.e.* subcooled, nucleate and convective is studied. The experiments are conducted with seven test sections made of SS304 having four different tube diameters 5.5 mm, 7.5 mm, 9.5 mm and 12.0 mm with two different heated lengths 500 mm and 1000 mm. The system pressure is varying from 1.3 bar to 3.2 bar. The experimental data of two-phase pressure drop and critical heat flux are compared with available correlations. Correlations are suggested to measure the local heat transfer coefficient during boiling process, two-phase pressure drop and critical heat flux. Data of critical heat flux are published to contribute in the data bank for horizontal straight tubes.

1. Introduction

The use of horizontal straight tubes in heat transfer devices is important in heat exchangers, evaporators, boilers and nuclear reactor. World's energy demand, fast depletion of fossil fuel resources and climate changes leads the investment in nuclear power and clean energy. Pressurise heavy water reactor (PHWR) has horizontal fuel channel alignment in nuclear reactor. Solar thermal energy is an attractive option as a renewable source of energy for power generation. Concentrating solar thermal power uses horizontal straight tube configuration for heat transfer. In the practical applications, flow boiling is the heat-transfer mode, where the highest heat transfer coefficient is achieved. Hence, it is essential to have well established correlation for boiling heat transfer coefficient. Most of the correlations available in the literature are developed for overall averaged heat transfer coefficient. To design a heat transfer device, it is important to measure different parameters at any local point. Rate of heat transfer at a given location is dependent on the spatial heat transfer coefficient at that location. In a flow boiling process, different heat transfer regimes are associated which changes with local quality. Heat transfer coefficient in different regimes of boiling like subcooled boiling, nucleate boiling and convective boiling are different. Hence, to improve the design of heat transfer devices, it is necessary to develop a correlation that predicts local heat transfer coefficient accurately. In the present work, local heat transfer coefficient is measured along the axial length of a straight tube with the increase in quality. Experimental local heat transfer coefficient is compared with the available correlations. A correlation is suggested to predict not only overall averaged heat transfer coefficient but also local heat transfer coefficient in different flow boiling regions.

Critical heat flux (CHF) sets the limit to exchange the heat in different industrial applications. With excessive heat supplied, boiling creates burnout of the tube either because of departure from nucleate boiling or dryout of liquid film. Hence, the ability to predict CHF during boiling process is of great practical importance. Numerous studies on CHF in straight vertical tubes are reported in literature. There are well developed look-up tables available to measure CHF and many methods to predict the CHF in vertical tubes. However, literature on CHF in horizontal tube is very less compared to that on vertical tubes. Number of CHF data on horizontal tube is very less compared to that of vertical tubes. Hence, there is no data bank or general correlation is available for horizontal tubes unlike vertical tubes. Literature survey is carried out on CHF in straight horizontal tubes. Details of each work along with the fluid used and corresponding operating and geometric

* Corresponding author at: Department of Mechanical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai 400 076, India.

E-mail addresses: h.kothadia@gmail.com (B.K. Hardik), gkviitb@gmail.com (G. Kumar), svprabhu@iitb.ac.in (S.V. Prabhu).

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Nomenclature

Symbol	Definition [Unit]
Cp	specific heat at constant pressure [J/kg K]
d	tube diameter [m]
G	mass flux [kg/m^2 s]
g	acceleration due to gravity [9.81 m^2/s]
h	heat transfer coefficient [W/m^2 K]
i	enthalpy [J/kg]
I	current [A]
k	thermal conductivity [W/m K]
L, l	length [m]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [N/m^2]
p	periphery [m]
P_r	reduced Pressure (P_{sys}/P_{cr})
Q	heat supply [W]
q''	heat flux [W/m^2]
T	temperature [°C]
V	voltage [V]
x	quality of steam

Greek

μ	dynamic viscosity [Ns/m^2]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscript

acc	acceleration
b	bulk
cr	critical
d	dryout
e	exit
fg	liquid to vapour
$fric$	friction
g	vapour
H	horizontal position
h	heated
i, in	inlet
l	liquid
o	outer
sat	saturated
sc	sub-cooled
sys	system
TP	two-phase
V	vertical position
w	wall
W	wetted

Abbreviation

CHF	critical heat flux [W/m^2]
HTC	heat transfer coefficient [W/m^2 K]

Dimensionless number

Bo	Boiling number, $Bo = q''/Gi_{fg}$
Ja	Jacob number, $Ja = Cp(T_{sat} - T_{in})/i_{fg}$
Pr	Prandtl number, $Pr = \mu Cp/k$
Re	Reynolds number, $Re = Gd/\mu$

parameters used to derive correlation of each work are presented in Table 1.

Comprehensive literature review on boiling heat transfer coefficient and two-phase pressure drop is presented in Hardik and Prabhu [14]. Hardik and Prabhu [14] collected the correlations available in literature on boiling heat transfer coefficient and two-phase pressure drop. Kandlikar [17] presented quantitative flow boiling curve which represents heat transfer coefficient with increase of quality. The heat transfer coefficient varies with increase of quality. The curve changes it slope in different regions of flow boiling *i.e.* subcooled flow boiling, nucleate flow boiling and convective flow boiling. The boiling curve describes the boiling process for different liquid to vapour density ratio fluids. Kandlikar [17] shows that the boiling process varies with variation in liquid to vapour density ratio. Almost all the available literature derived the correlations using different number of data points. Till now there is no work is reported to compare the correlation with complete flow boiling profile.

The experiments are conducted with seven test sections made of SS304 having four different tube diameters 5.5 mm, 7.5 mm, 9.5 mm and 12.0 mm with two different heated lengths 500 mm and 1000 mm. The wall thickness of all the test section is 0.25 mm. The system pressure is varying from 1.3 bar to 3.2 bar. Spatial variation in heat transfer coefficient along the axial length of tube is analysed with increase of quality. Variation in heat transfer coefficient in different flow boiling regions *i.e.* subcooled, nucleate and convective is studied. The correlations available in literature for boiling heat transfer coefficient, pressure drop and critical heat flux are used for refrigerant R123 fluid to check the effectiveness of the correlations. Correlations are suggested to predict the local heat transfer coefficient during boiling process, two-phase pressure drop and critical heat flux. Data of critical heat flux would serve in a data bank for horizontal straight tubes.

2. Description of the experimental rig

A schematic diagram of the experimental facility is shown in Fig. 1. It is a closed loop well insulated flow system with refrigerant R123 serving as a working fluid. The test facility consists of an insulated fluid reservoir, magnetically coupled sealless gear pump, pre-heater, condenser, ball valves and straight horizontal tube test section. Refrigerant R-123 has high boiling point temperature. Due to its high boiling point, water is used as secondary fluid to condense vapor in condenser and repeat the cycle. Secondary water circuit is open loop cycle. This makes system less complex, more stable and required less time to reach steady state. The gear pump with a mass flow rate range from 0 to 360 g/s is driven by a D. C. motor. The speed of the D. C. motor is varied between 0 and 3500 rpm by a motor controller. The temperature, pressure and flow rate measuring devices are instrumented with system to measure the pressure drop and heat transfer coefficient in the test sections. Coriolis mass flow meter (Make: Emerson, Sensor model: CMF025, Transmitter model: 1700R) is used to measure the mass flow rate of fluid. Coriolis mass flow meter has facilities to measure density of fluid and bulk fluid temperature. The inlet and outlet bulk fluid temperatures are measured with K-type thermocouples fixed on the surface of copper tubes. Infra-Red thermal camera (Make: Themoteknix, Model: VisIR640) is used to measure the wall temperature of the test section without disturbing test sections. The test section is painted with a thin coat of high temperature black board paint to have a uniform emissivity of 0.85. The differential pressure transmitters are used to measure the pressure drop across test sections and the pressure transmitters to measure the system pressure at the inlet and exit of the test section. Pressure transmitters and differential pressure transmitters are connected with the common pressure taps at inlet and exit of test section. Inlet tap is drilled 100 mm before the test section and exit tap is