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Boiling pressure drop and local heat transfer distribution of water in horizontal straight tubes at low pressure

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ABSTRACT

The objective of the present work is to investigate the heat transfer and pressure drop in flow boiling at low pressure with water as the working medium. The effect of pipe diameter, heat flux and mass flux on boiling pressure drop and local heat transfer coefficient is studied. In the present work, the available correlations are revisited for low pressure flow boiling. Comparison of local heat transfer coefficient with the existing correlation is carried out to identify an appropriate correlation which performs well in complete flow boiling range (subcooled regions and saturated regions) for water at low system pressure.

Experiments are performed with eight test sections made of thin walled stainless steel (SS 304) tubes having inner diameters from 5.5 mm to 12 mm and length varying from 550 mm to 1000 mm. The system pressure is varying form 1 bar to 3 bar. No change in slope of heat transfer curve is found for subcooled regions. Heat transfer in all the three regions of subcooled boiling namely partial subcooled boiling, fully developed subcooled and net vapour generation are predicted by a single correlation. Tube diameter has no effect on boiling heat transfer distribution. However, tube diameter affects two phase pressure drop. Increase in mass flux increases the convective heat transfer coefficient. However, mass flux has no influence on subcooled and nucleate boiling heat transfer coefficient. Heat flux increases the boiling heat transfer coefficient. Increase in tube diameter and mass flux decreases the two-phase pressure drop. Most of all the correlations in the subcooled region predict heat transfer coefficient with reasonable accuracy. Kandlikar and Shah correlations perform well in the low pressure saturated boiling i.e. nucleate and convective. None of the available two-phase pressure drop correlations are able to predict the pressure drop in a low pressure system. A correlation is developed to predict two-phase pressure drop in low pressure flow boiling system with a reasonably good accuracy.

1. Introduction

Heat transfer enhancement is one of the major issues in modern thermal technologies. The economic aspects of heat transfer enhancement are mainly related to the pressure drops. In particular, in situations where very high heat fluxes are expected, flow boiling is commonly encountered. Designers of equipment of heat transfer used in chemical and power-generating processes *i.e.,* Boilers, heat exchangers, steam generators, nuclear reactors etc. are always exploring various heat transfer enhancement methods. Different heat transfer regimes are associated in the heat transfer process. Single-phase liquid enters into the heat transfer system at a temperature below the saturation point. Liquid comes in contact with a sufficiently high surface heat flux. The heat-transfer regime changes from a single-phase forced convection to subcooled nucleate boiling, saturated nucleate boiling, saturated convective boiling and finally to superheated vapour.

The maximum heat transfer performance with an optimal use of two-phase pressure drop is one of the primary design goals of the designer of heat transfer equipments. Heat transfer coefficient and rate of pressure drop in different regimes of flow are different. Measurement of the local heat-transfer coefficient along the tube is difficult as the local conditions (quality, pressure) are continuously varying. Prediction of the heat transfer coefficient in different regimes of flow depends on the point of transition from one regime to another. The point of transition in a given flow boiling system depends upon the system pressure at that point. Hence, in order to accurately predict the heat transfer coefficient, it is necessary to

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Nomenclature

Symbol

Cp	Specific heat at constant pressure J/kg K
d, D	Diameter of tube m
f	Friction factor
G	Mass flux kg/m^{2}s
g	Gravitational constant m/s^2
h	Heat transfer coefficient W/m^{2}K
i	Enthalpy J/kg
k	Thermal conductivity W/m K
L	Length m
M	Molecular Weight g/mol
$\dot{m}$	Mass flow rate kg/s
P	Pressure N/m^2
Q	Heat supply W
q''	Heat flux W/m^2
T	Temperature °C
x	Quality of steam
X, X_{LM}	Lockhart Martinelli parameter $X = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}$

Greek

$\varnothing$	Two phase flow multiplier $\varnothing^2 = \frac{\Delta P_{TP,fric}}{\Delta P_{1P}}$
μ	Dynamic viscosity N·s/m^2
ρ	Density kg/m^3
σ	Surface tension N/m

Subscript

acc	Acceleration
b	Bulk
f	Film
fg	Fluid to gas
fric	Friction
g	Gas
h	Heated
l	Liquid
lo	Liquid only
P	Phase
sat	Saturated
SC	Subcooled
sys	System
T	Total
TP	Two phase
tt	Turbulent liquid and Turbulent vapour
lt	Laminar liquid and Turbulent vapour
w	Wall

Abbreviation

RMS	Root Mean Square

Dimensionless number

Bo	Boiling number $Bo = q''/G\ i_{fg}$
Ja	Jakob number $Ja = Cp \cdot \Delta T_{sc}/i_{fg}$
Nu	Nusselt number $Nu = h \cdot d/K$
Pr	Prandtl Number $Pr = \mu \cdot Cp/K$
Re	Reynolds number $Re = 4\dot{m}/\pi d\mu$

predict the pressure drop in the system.

1.1. Review on the boiling heat transfer coefficient in a straight tube

In almost all the practical heat exchanger application systems, the fluid enters in a system as single phase liquid and exits as a two phase fluid with some fraction of liquid and vapour. Hence, from the design point of view, it is better to conduct and analyse the experimental results with all regimes together as in actual applications. Most of the literature, experimental results are generated separately for single phase or subcooled or saturated flow. Collier [1] presented flow boiling map giving relation between heat transfer coefficient and quality for different heat fluxes. This curve represents the heat transfer coefficient in different regimes of fluid flow *i.e.*, single phase, subcooled, nucleate and convective boiling. Kandlikar [2] compared experimental results of different fluids with this map and concluded that this map represents only for water at low pressure. This map is just qualitative representation of heat transfer coefficient as it does not show different regions of subcooled boiling. Further, it shows a linear increment of heat transfer coefficient in the subcooled boiling. Kandlikar [2] gave a new quantitative flow boiling map that represents heat transfer coefficient of different fluids and shows changes in slope in different regions of subcooled boiling. Kandlikar [2] divided subcooled region into three sub regions namely partial subcooled, fully developed subcooled and net vapour generation. Kandlikar [2] validated different sections of flow boiling map with the experimental results separately and gave a correlation for heat transfer coefficient for each region. Hence, it is difficult to conclude that their correlations (boiling map) are valid for all sections when fluid enters as a single phase liquid and exits as a saturated two phase fluid with a certain exit quality. The boiling map is not experimentally validated with all the flow regions in a single test experiment by Kandlikar [2]. Kandlikar [2] gave different correlations for different regions of subcooled flow boiling and saturated boiling. Literature other than Kandlikar [2] gave a single correlation for complete range of subcooled boiling. Shah [3], Liu and Winterton [4], Gungor and Winterton [5], Baburajan et al. [6], Yan et al. [7] and many others suggested only one correlation that predicts complete range of subcooled boiling. Baburajan et al. [6] derived a correlation for low pressure low flow rate (LPLF) condition while Yan et al. [7] derived a correlation for high heat flux and high mass flux (HHHM) application. Similar to subcooled flow, many researchers suggested a single correlation for complete range of saturated boiling. Liu and Winterton [4], Gungor and Winterton [5] and Chen [8] suggested a single correlation for saturated boiling that is valid for both nucleate and convective boiling. Shah [9] and Kandlikar [10] suggested separate correlations for nucleate and convective boiling. To validate these correlations and to differentiate the actual application range of each of these correlations, it is necessary to compare all these correlations with the measured local heat transfer coefficient where the fluid enters as a single phase liquid and exits as a saturated two phase fluid just as given in the boiling map.

1.2. Review on the two-phase pressure drop in a straight tube

In the flow boiling application, when fluid enters as a single phase liquid and exits as a liquid vapour mixture, to calculate the length of subcooled region and saturated region it is essential to know the pressure at that point. Substantial research work is carried out on two-phase pressure drop. Most of the correlations are developed for adiabatic high pressure flow. Idsinga et al. [11]