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Two-phase flow boiling pressure drop in small channels

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ABSTRACT

Two-phase flow boiling in small channels finds a variety of applications in power and process industries. Heat transfer, boiling flow regimes, flow instabilities, pressure drop and dry out are some of the key issues related to two-phase flow boiling in channels. In this work, the focus is on pressure drop in two-phase flow boiling in tubes of 19 mm diameter. These tubes are typically used in steam generators. Relatively limited experimental database is available on 19 mm ID tube. Therefore, in the present work, the experimental set-up is designed for studying flow boiling in 19 mm ID tube in such a way that any of the different flow regimes occurring in a steam generator tube (from pre-heating of sub-cooled water to dry-out) can be investigated by varying inlet conditions. The reported results cover a reasonable range of heat and mass flux conditions such as 9–27 kW/m^2 and 2.9–5.9 kg/m^2 s respectively. In this paper, various existing correlations are assessed against experimental data for the pressure drop in a single, vertical channel during flow boiling of water at near-atmospheric pressure. A special feature of these experiments is that time-dependent pressures are measured at four locations along the channel. The steady-state pressure drop is estimated and the identification of boiling flow regimes is done with transient characteristics using time series analysis. Experimental data and corresponding results are compared with the reported correlations. The results will be useful for understanding key aspects of flow boiling in small channels.
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1. Introduction

Boiling in small channels finds applications in a variety of areas including steam tubes in boilers, compact evaporators, compact heat exchangers etc. Two-phase flow inside tubes provides a very effective way of heat transfer and fluid movement. The design of such steam generator tubes involves an understanding of heat transfer coefficient, flow regimes, pressure drop and the flow instabilities. In the present work, an approach is developed for mimicking the flow, heat transfer regimes and flow instabilities occurring in long steam generator tubes in laboratory scale tubes. In this approach, laboratory scale steam generator tube of 1 m length and diameter 19 mm is used. Inlet and boundary conditions are varied to simulate different flow regimes occurring in long steam generator tubes. Study of two-phase flow boiling pressure drop, flow instability and identification of flow regimes using pressure fluctuations is the main focus of the present work.

Two-phase pressure drop depends on various parameters like the geometric configuration of the channel, mass and volume fractions of the individual phases, pressure, fluid properties, mass flux, orientation of the channel (i.e. horizontal, vertical or inclined) and flow patterns. Further, in many engineering applications, two-phase flow systems can be adiabatic or diabatic. To cater to the needs of these diverse applications, a large amount of work has been devoted to the study of fluid flow and heat transfer along with pressure drop mechanisms in micro and mini channels. Specifically, researchers have concentrated on the prediction of flow patterns (Lee et al., 2003; Qu and Mudawar, 2003), heat transfer characteristics (Zhang et al., 2002; Wu and Cheng, 2004) and instability (Hetsroni et al., 2005; Lee and Yao, 2010) (in two-phase flows in micro channels). Kandlikar (2002) has highlighted the effect of small diameter on the boiling phenomena, the nature of heat transfer and pressure drop and the difference between single and multiple channels. The literature survey reveals that most of the work in the area of micro-channels is focused in the range of 100 μm–4 mm using refrigerants and relatively limited studies have been performed with water as the working fluid. In recent years, a notable research growth was observed on two-phase flow and evaporation heat transfer in the micro-scale channels. However, despite a large number of publications (see Table 1), it is rare to find detailed information regarding pressure drop, heat transfer and stability characteristics for the small channels. These flow boiling characteristics are extremely important to evaluate the current status of the research in the mentioned areas.

Predicting the two-phase distribution in the system for given operating conditions is a formidable task for most of the industrial

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Nomenclature

z	Height
x	Vapor quality
v	Velocity
P	Pressure
ΔP	Pressure drop
T	Temperature
d	Diameter
Re	Reynolds number
C	Chisholm parameter
f	Single phase frictional factor
q	Heat flux
A	Flow area
A_r	Flow area ratio
A_0	Smaller flow area
Γ	Dimensionless physical property
Fr_H	Froude number
We_H	Weber number

Subscripts

a	Acceleration
g	Gravitational
f	frictional
f	frictional factor
m	Mixture
L	Liquid
G	Gas
G	Flow rate
g	Gravitational constant
tp	Two-phase
h	Hydraulic
i	Inlet
o	Outlet

Greek letters

ε	Void fraction
e	Surface roughness
Φ	Two-phase multiplier
ρ	Density , kg/m^3
μ	Dynamic viscosity, kg/m s
σ	Surface tension, N/m

applications. One of the critical unknown parameter involved in predicting the pressure drop/loss and heat transfer in any gas–liquid system is the void fraction (ε) which is the volume of space occupied by the vapors. The accurate prediction of void fraction in vertical channels is of immense importance in determining the two-phase pressure drop. For many practical situations, designers and analysts often require some guidance to choose appropriate correlations. Most of these correlations are flow pattern–specific and are limited in their application in terms of the range of flow variables. In order to choose the right correlation for the desired application from a pool of available correlations in the literature (Godbole et al., 2011), it is utmost importance to sort out and identify the correlations applicable to a range of flow variables and channel orientations.

Therefore, in the present work, an attempt has been made to systematically investigate the two-phase flow with phase change in a 19 mm channel size. Heat transfer experiments were performed in uniformly heated, single, annular, vertical channel using water as a working fluid. The experiments were performed under adiabatic and diabatic conditions to study flow instabilities occurring because of flow boiling. Efforts were taken to acquire two-phase pressure fluctuations at different axial locations and the results were compared with the experimentally calculated pressure drop over a range of experimental conditions using existing empirical correlations. An attempt has been made to classify different flow regimes based on the analysis of pressure fluctuations. The results will be useful for understanding the key aspects of the flow boiling in small channels.

2. Experimental facility

Vertical concentric double pipe heat exchanger with an inner diameter of 19 mm and the heated length of 1.05 m was used for the present study. This experimental test section was fabricated and designed with SS-110. The schematic of the test section is as shown in Fig. 1a.

The main components of the system include the feed vessel, pump, rotameter, heating oil bath, pre-heater and a condenser. As indicated in Fig. 1a, water was pumped by the peristaltic pump to the test section through regulated rotameter (calibrated over the range of 1–5 l/h flow rate of water). Before starting the two-phase flow experiments; calibration of heating oil bath (manufactured by JULABO: SL_6) was carried out to establish actual mass flow rate at different temperature set points of the oil bath. Data acquisition system was connected to the computer for online measurement via HMI (Human Machine Interface). The test section was designed like a co-current flow tube-in-tube heat exchanger as shown in Fig. 1b where water was flowing from inside tube and hot oil was circulated from the outer tube. Water, as a working fluid, was circulated from bottom to top along the inner pipe and hot oil, used as a heating medium, was made to flow co-currently along the annulus. Pressure sensors “WIKA-S10” having a pressure range of 0–0.16 bar, sampling rate of 1 Hz and response time $<$ 1msec were used for absolute pressure measurement. Four such pressure sensors were mounted horizontally along the axial length of the channel at locations Z1, Z2, Z3, Z4 to measure corresponding fluid pressure P1, P2, P3, P4 respectively inside the annulus as shown in Fig. 1b. Special care was taken for pressure sensors to be leak proof. Heating medium was stored and circulated using hot oil bath with varying heat flux. Water flow rate was regulated by a peristaltic pump (RS232; MXI Technologies). Before taking heat transfer measurements, initial system testing was performed and the power as well as water to the facility was activated after ensuring proper functioning of all the components. The variable speed peristaltic pump was then turned on to establish steady water flow. The flow oscillations were dampened using damper and continuous steady flow was sent to test section. Initially single phase flow experiments (adiabatic) and then two-phase experiments (diabatic) were carried out; continuous cold water supply was maintained externally to the condenser to cool the outlet steam from channel and also to avoid over-heating of feed tank.

Two-phase flow experiments were performed at four different heat flux conditions (9.8, 14.8, 21.4, 27.8 kW/m^2) for each of the three mass flux conditions (2.9, 3.9, 5.9 kg/m^2 s). Each of these experiments were carried out with three different conditions of inlet water temperature (30 °C, 60 °C, 95 °C). Accordingly, absolute pressure fluctuations data was recorded via HMI (Human Machine Interface) during each experiment at every 1 s up to 60 min at points P1, P2, P3, P4 where average pressure fluctuations data for last 10 min of each run was taken for detailed steady-state analysis. Fully developed conditions were analyzed for different operating conditions and observed pressure fluctuations pattern was saved on personal computer. Temperature fluctuations and corresponding energy balance has been broadly discussed by Sardeshpande et al. (2015).

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