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Two Phase Flow Boiling Pressure Drop in Small Channels

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Abstract

Two-phase pressure drop, flow instability and boiling regime identifications are an essential step in the design of a variety of plant in the power and process industries. Despite the wide spread applications, significant experimental data on flow boiling in small channel is not available. In the present work, experimental set-up was designed for studying boiling flows in 19 mm ID tube and identifies flow regimes at various mass and heat flux conditions by varying inlet fluid temperature. The steady-state pressure data was collected and flow regimes identified using pressure drop and pressure fluctuations inside the channel.

Keywords: flow boiling, pressure drop, flow instability, regime identification;

1. Introduction

Boiling in small channels is a topic of current interest with its application to steam tubes in boilers, compact evaporators, compact heat exchangers etc. Two-phase flow inside steam generators provides a very effective way of heat transfer and fluid movement. Design of steam generators is a challenging assignment in terms of degradation, rupture and leaking of steam generator tubes. In that case, heat transfer coefficient, flow regimes, pressure drop and also flow instabilities are playing a significant role. In present work, as an alternative of working directly on steam generator tubes, new approach is adopted of mimicking the steam generator tubes to laboratory scale tubes to study...
flow, heat transfer regimes and flow instabilities. In this approach, laboratory scale tube is reduced to 1m in length and diameter 19mm to develop and replicate an understanding in successive parts of the total tube that is used in steam generator. Study of two phase flow boiling pressure drop and flow instability and identification of flow regimes using pressure fluctuations is the main focus of present work.

Two phase pressure drop depends on a large number of independent parameters like 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, pressure drop mechanisms in micro and minichannels. Specifically, researchers have concentrated on the prediction of flow patterns, heat transfer characteristics and instability[1-5] in two phase flows in microchannels. The literature survey reveals that most of the work in the area of microchannels is concentrated in the range of 100 µm – 4mm using refrigerants and a relatively small number of studies have been performed with water as the working fluid. However, despite the large number of publications, it is rare to find detailed information regarding pressure drop, heat transfer and stability characteristics for small channels.

Thus, the aim of this work is to contribute to a better understanding of the underlying physical phenomena in two-phase flow boiling heat transfer of water in small channels. For this purpose, well characterized heat transfer experiments have been performed in uniformly heated, single, circular, vertical channel of diameter 19 mm and using water as working fluid. It observed that as flow regime changes continuously so the estimation of pressure drop becomes tedious task for the design engineer. Calculation of pressure drop across the full length of the heated channel is more complex due to the existence of several regimes along the channels. Experiments were performed to be run under adiabatic and diabatic conditions and to study flow instabilities occurring because of flow boiling. Also there was a need to obtain accurate two-phase pressure drop values over a wide range of experimental conditions and covering the different flow regimes and to evaluate the capabilities of the existing correlations for predicting the experimental data. Therefore, the flow boiling of water in the small channel (dh > 6mm) is investigated systematically in the present study.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Greek Letters</th>
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<tbody>
<tr>
<td>z Height</td>
<td>ε Void Fraction</td>
</tr>
<tr>
<td>x Vapor Quality</td>
<td>e Surface Roughness</td>
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<tr>
<td>G Mass Flux</td>
<td>Φ Two-Phase Multiplier</td>
</tr>
<tr>
<td>g Gravitational Acceleration</td>
<td>ρ Density, kg/m³</td>
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<tr>
<td>P Pressure</td>
<td>μ Dynamic Viscosity, kg/m.s</td>
</tr>
<tr>
<td>ΔP Pressure Drop</td>
<td>σ Surface Tension, N/m</td>
</tr>
<tr>
<td>T Temperature</td>
<td>Subscripts</td>
</tr>
<tr>
<td>d Diameter</td>
<td>m Mixture</td>
</tr>
<tr>
<td>Re Reynolds Number</td>
<td>L Liquid</td>
</tr>
<tr>
<td>C Chisholm parameter</td>
<td>g Gas</td>
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<tr>
<td>f Single Phase Frictional Factor</td>
<td>tp Two-phase</td>
</tr>
<tr>
<td>q Heat Flux</td>
<td>h Hydraulic</td>
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<tr>
<td>Γ Dimensionless physical property</td>
<td>i Inlet</td>
</tr>
<tr>
<td>FrH Froude Number</td>
<td>o Outlet</td>
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<td>WeH Weber Number</td>
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2. Experimental

The test section fabricated and designed with SS-110 was used for study of two-phase flow boiling pressure drop. The schematic of test section is as shown in Figure 1a. Vertical concentric double pipe heat exchanger with inner diameter as 18.8mm and heated length 1.05 meters was used as two phase flow channel for the present study. Water as a working fluid was circulated from bottom to top along the inner pipe and hot oil used as heating medium flowing co-currently along the annulus. Pressure sensors “WIKA-S10” having a pressure range of 0-0.16 bar was used for absolute pressure measurement. Four such pressure sensors were mounted on this channel horizontally at locations P1, P2, P3, P4 (i.e. along the axial length of channel) with distance between them to measure fluid pressure as shown in Figure 1b. Special care was taken for pressure sensors to be leak proof. Heating medium was stored and circulated using hot oil bath (Julabo SL-6) with heat fluxes varying in range of 9-28 kW/m². Water flow rate was regulated by peristaltic pump (RS232; MXI Technologies) with three various mass flux conditions (2.9, 3.9, 5.9 kg/m² s). Initially single phase flow experiments (adiabatic) and then two phase experiments (diabatic) were carried out by varying inlet fluid temperature i.e. 30, 60, 95°C. Accordingly, absolute pressure fluctuations data was recorded during each experiment at every 1 sec at points P1, P2, P3, P4 against time. Pressure data was recorded into the data recorder where average pressure fluctuations data for last 10 minutes 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.

2.1 Single phase study
Pressure drop in single-phase (adiabatic process) in vertical channels is attributed to gravitational head and frictional head. Acceleration pressure drop ($\Delta P_a$) is zero in single phase since density variation is negligible. Sample plots of single phase pressure fluctuations at P1, P2, P3, P4 locations are shown in Figure 2. Comparison of experimental and calculated pressure at these locations were steady at fixed pressure range and are well in agreement with each other in ± 0.05 % range.

2.2 Two phase diabatic flow
The pressure drop in two phase diabatic flow consists of three components i.e. gravitation, acceleration, frictional. Pressure drop was calculated using various pressure drop models and co-relation studied earlier. Sample plots of
pressure fluctuations at 30, 60 and 95°C inlet fluid conditions are given in Figure 3 and 4. Schematic of overall data reduction for the entire pressure drop component is as shown in Figure 5. From Figure 5, it was observed that various models have developed for void fraction and corresponding pressure drop. Void fraction ($\varepsilon$) is the fraction of channel volume occupied by the gas phase. Importance of void fraction in pressure is very evident when two-phase flow boiling characteristics like flow patterns, heat transfer and pressure drop are discussed especially when vertical channels are taken into consideration. The value of void fraction governs many important parameters such as two-phase mixture density and viscosity. The fact that pressure due to gravity dominates the total pressure in vertical channels and in turn depends upon two phase mixture density makes void fraction a very crucial aspect of most of the study. Therefore, judicious selection of void fraction correlation is the key to quantify pressure drop along the channel. For stable flow conditions (at 30°C as inlet), no significant differences in pressure oscillations were observed. Whereas when inlet fluid temperature changed to 60 and 95°C, pressure fluctuations were observed in fluid profiles.

![Figure 2: Single phase pressure study at four axial locations](image2)

![Figure 3: Comparison of two phase pressure fluctuations at four axial locations at 2.9kg/m²s and 14.8 kW/m² and 60°C as inlet](image3)
2.3 Regime identification using pressure fluctuations

The pressure fluctuation data recorded during each experiment by the pressure sensors for 1hr whereas for analysis purpose this data was averaged for last 10 minutes and further processed as steady-state data. Pressure fluctuations were due to the acceleration of liquid slugs by the formation and growth of individual confined bubbles. The fluctuations may cause flow reversal if there is some compressibility in the incoming flow. The high-frequency pressure fluctuations cause local fluctuations in saturation temperature and the consequent variations in wall superheat may be of similar magnitude to the mean superheat driving heat transfer, modifying the processes of bubble nucleation and growth that drive the fluctuations. At such situations various flow regimes like bubbly flow, slug flow and annular flow could be identified. It was however difficult to differentiate between slug flow and annular flow. Measured fluctuations in pressure were therefore analyzed to explore whether any clues for identification of flow regimes may be obtained.

The nonlinear analysis tool was used on the time series to characterize the oscillations at varied inlet fluid conditions. Raw pressure data of all pressure sensors (i.e. for fluid) was used in order to study variation in flow boiling regimes. MATLAB software was used for analyzing the acquired transient pressure data. The collected time-pressure data were analyzed using the fast Fourier transform (FFT) technique. FFT analysis was performed on pressure fluid data to obtain the frequency distribution for different fluid temperatures at different axial locations at 2.9 kg/m²s mass flux and 14.8 kW/m² heat flux. Results discussed in following section.

3. Results and Discussions

The heat transfer experiments were conducted for the above mentioned design and operating conditions. The pressure drop was analyzed with respect to the vapor quality along the axial length of experimental test rig. Vapor quality was estimated via energy balance. Typical experimental data of pressure drop at different heat and mass flux were analyzed and are discussed in the following section.

3.1 Effect of heat and mass flux

As per the overall methodology and data reduction mentioned earlier, pressure drop was estimated. Where void fraction and frictional pressure drop were calculated using Lokhart-Martinelli and homogeneous correlation. Figure 6a and Figure 6b showed the variations of pressure drop with vapor quality and heat flux at constant mass flux i.e. 2.9 kg/m²s condition respectively at 30, 60 and 95°C inlet fluid conditions.
Total Pressure Drop
\[ \Delta P_{tpt} = \Delta P_{tpg} + \Delta P_{tpf} + \Delta P_{tpa} \]

Gravitational Pressure Drop
\[ \Delta P_{tpg} = (\rho_m g z) \frac{1}{(\rho_m)_{in}} - \frac{1}{(\rho_m)_{out}} \]

Acceleration Pressure Drop
\[ \Delta P_a = \frac{G^2}{\varepsilon} \left( \frac{\rho_L}{\rho_g} \right) \frac{1}{(1-x)^2} \left( \frac{1}{2} - \frac{1}{1-\varepsilon} \right) \]

Frictional Pressure Drop
Homogenous Flow
\[ \Delta P_{tpf} = \frac{2 f_{tp} g^2 z_t}{d_h \rho_f} \left[ 1 + \frac{x_l}{2} \left( \frac{\rho_L}{\rho_f} \right) \right] \]
Where \( f_{tp} = 0.003 \)
Separated Flow Approach
\[ \Delta P_{tpf} = \Delta P_{f} \Phi_t^2 \]

Mixture Density
\[ \rho_m = (1-\varepsilon) \rho_L + \varepsilon \rho_g \]

Homogeneous
\[ \varepsilon = [1 + (1-x)\left( \frac{\rho_L}{\rho_g} \right) \left( \frac{\rho_L}{\rho_L} \right)]^{-1} \]

Lockhart-Martinelli
\[ \varepsilon = [1 + 0.28(\frac{1-x}{x})^{0.64}\frac{\rho_L}{\rho_L}^{0.36} \left( \frac{\rho_L}{\rho_g} \right)^{0.07}]^{-1} \]

Fauske
\[ \varepsilon = [1 + (1-x)^{0.5} - \frac{1}{0.5}]^{-1} \]

Chisholm
\[ \varepsilon = [1 + \sqrt{1 - x} \left( \frac{\rho_L}{\rho_g} \right)^{0.65}]^{-1} \]

Spedding and Chen
\[ \varepsilon = [1 + 2.22(\frac{1-x}{x})^{0.65} \left( \frac{\rho_L}{\rho_L} \right)]^{-1} \]

Graham et. al.
\[ \varepsilon = [1 + \left( \frac{1}{f_{tr}} \right) + \left( \frac{1}{f_{tr}} \right)^{0.321}] \]

where \( F_t = \left( \frac{G^2}{(1-x)^2} \right) \frac{2}{\rho_L} \)

and \( X_t = \left( \mu_L \right)^{0.1} \left( \frac{1-x}{x} \right)^{0.9} \left( \frac{\rho_L}{\rho_L} \right)^{0.5} \)

Single Phase Frictional Pressure Drop
\[ \Delta P_f(f_o) = \frac{2 f_{L} g^2 (1-x)^2 \Delta z_t}{d_h \rho_f} \]

\[ f = 64/Re ; \text{ for } Re < 2000 \]
\[ \frac{1}{\sqrt{f}} = 0.86 \ln \left( \frac{e}{3.75} + \frac{2.51}{Re \sqrt{f}} \right) \text{ for } Re > 3000 \]
\[ f = 0.079/Re^{0.25} \text{ (Diabatic study by LM) } \]

Lockhart Martinelli (liquid–laminar, vapour–laminar)
\[ \Phi_L^2 = 1 + \frac{5}{x_{ev}} + \frac{1}{x_{ev}} \]

Lockhart Martinelli (liquid–laminar, vapour-turbulent) \[ \Phi_L^2 = 1 + \frac{12}{x_{ev}} + \frac{1}{x_{ev}} \]

Friedel\[ \Phi_L^2 = A_1 + \frac{3.34 A_2 A_3}{Fr_{th} 0.03 W_e^{0.5}} \text{ where } \]
\[ Fr_{th} = \frac{g^2}{h_{ph}^2} \text{ and } W_e = \frac{g^2 d_h}{\sigma_{ph}} \]

Chisholm B coefficient model
\[ \Phi_L^2 = 1 + (f^2 - 1) \left( B x 0.0075 (1 - x 0.0075) + x 1.75 \right) \]
Where \( f^2 = \frac{\mu_L}{\rho_g} \left( \frac{\rho_L}{\rho_g} \right) \]
\[ B = 55/G^{0.5} \text{ for } 0 < G < 9.5; \]
\[ B = 520 / G^{0.5} \text{ for } 9.5 < G < 28; \]
\[ B = 15000 / G^{0.5} \text{ for } G < 28 \]

Figure 5: Schematic of overall two phase flow boiling pressure drop
It was observed that significant effect on local pressure drop and vapor quality. It was observed that with increasing heat flux, vapor quality increased and the total pressure drop decreased. The fraction of the wall surface subject to nucleate boiling increases, until bubble formation occupies the entire heated surface. Bubble density increases rapidly with increasing wall superheat. Heat transfer is dominated by local conditions in the vicinity of the wall generated by bubble growth and departure. These bubbles transport large amounts of latent heat from the surface at the fluid saturation temperature and greatly increase fluid turbulence and mixing in the vicinity of the wall. Following Collier and Thome\cite{12} and overall analysis of observed trends of various key parameters, an attempt was made to classify flow regimes: when estimated vapor quality is less than zero, flow regime is sub cooled boiling regime. If vapor quality is between 0 < x < 0.2 bubbly flow may be assumed. When vapor quality is between 0.2 and 0.6, slug or annular flow regimes may exist. For vapor quality values above 0.6 and less than 0.8, dry out or partial dry out regime may occur. Beyond the value of 0.8, flow regime may be considered as mist flow. Obviously, this classification is indicative rather than definitive.

3.2 Time series analysis for regime identifications

For stable flow conditions (at 30\degree C as inlet), no significant differences in pressure oscillations were observed. Whereas when inlet fluid temperature changed to 60 and 95\degree C, dominant frequencies were observed in fluid pressure profiles. The frequency oscillations in the signals of both were characteristic of cycles as seen in Figure 7 (a-b). Pressure signals and their corresponding amplitude spectra derived from Fourier-transform were analyzed. Although there are still arguments on the classification of the flow patterns, most researchers agreed to categorize their observations into four main flow patterns: bubbly, slug, annular and mist. Once the evaporation process begins; the fluid gains latent heat which results in constant fluid temperature with phase change. At the very low qualities, the encountered flow regime is called bubbly flow which can be distinguished by small discrete bubbles of vapor which are dispersed in the liquid. As the fluid gains more heat, a transition from bubbly flow to slug flow occurs. Depending upon the flow conditions, there may be a transition from bubbly flow to slug and annular flow. Therefore, dominant peaks and their harmonics were observed for slug flow in the range of 5–7 Hz and 10–12 Hz at 60\degree C inlet condition. For annular and mist flow there was only one significant peak with lower and lower amplitude along the axial locations (i.e. P3 and P4) as shown in Figure 7.
4. Conclusions

The flow boiling characteristics of water-steam in small channel with the diameter of 18.8mm ID are investigated systematically. This part focuses on the two-phase flow instability and two-phase flow pressure drop. Main conclusions are drawn as follows:

a) Flow boiling regimes in vertical channel such as bubbly, slug, annular and mist regimes well analyzed from two phase flow boiling pressure drop and vapor quality variation along the length and with inlet fluid temperatures

b) Pressure drop data well in agreement with predicted pressure drop using Lokhart-Martinelli and homogeneous model when 60°C as inlet condition where slug and annular regimes were more dominant

c) Identification of regimes well determined from pressure fluctuations data using FFT plots.

References