Chapter

Experimental Approaches to Measurement of Vapor Quality of Two-Phase Flow Boiling

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Abstract

Vapor quality is one of the crucial parameters substantially affecting the flow boiling heat transfer coefficient. Hence, the reliability and accuracy of vapor quality measurements is of a great significance to accurately investigating the effect of vapor quality on the local flow boiling heat transfer coefficients. In the present study, various experimental approaches are represented to measure and control local vapor quality for flow boiling tests. Experimental approaches are classified based on the type of thermal boundary conditions imposed on the tube wall, that is, known constant wall heat flux and constant wall temperature (unknown variable wall heat flux). In addition, in-situ techniques are also investigated to measure local vapor quality regardless of the governing thermal boundary conditions within two-phase flow experiments. Finally, the experimental methodologies are compared based on their level of reliability and accuracy in measurement, costliness and affordability, and simplicity in execution to address their potential merits and demerits.

Keywords: vapor quality measurement, experimental methodologies, two-phase flow boiling, thermal boundary conditions

1. Introduction

Vapor quality is a crucial parameter which affects the flow boiling heat transfer behavior [1, 2]. **Figure 1** shows flow development inside a vertical tube under a constant wall heat flux, where the fluid moves in the upward direction. The figure also depicts various two-phase flow regimes in a vertical tube on the left and typical variations in local boiling heat transfer coefficient versus vapor quality on the right. From **Figure 1**, it can be inferred that flow boiling heat transfer coefficient is typically maximized in the range of vapor quality between 50% and 85%, while the smallest heat transfer coefficients tend to appear in the vapor forced convection region due to the low thermal conductivity of vapor as compared to that of the liquid. Accordingly, the accuracy of vapor quality measurements plays a significant role in properly investigating the impact of vapor quality on the local flow boiling heat transfer coefficient. On the other hand, in order to develop more efficient two-phase flow heat transfer systems, a specific range of vapor qualities should be targeted in design of thermal systems to achieve a higher range of boiling heat transfer coefficients. This also clearly highlights the significance of accurate vapor quality measurements at both the inlet and outlet of a test section.

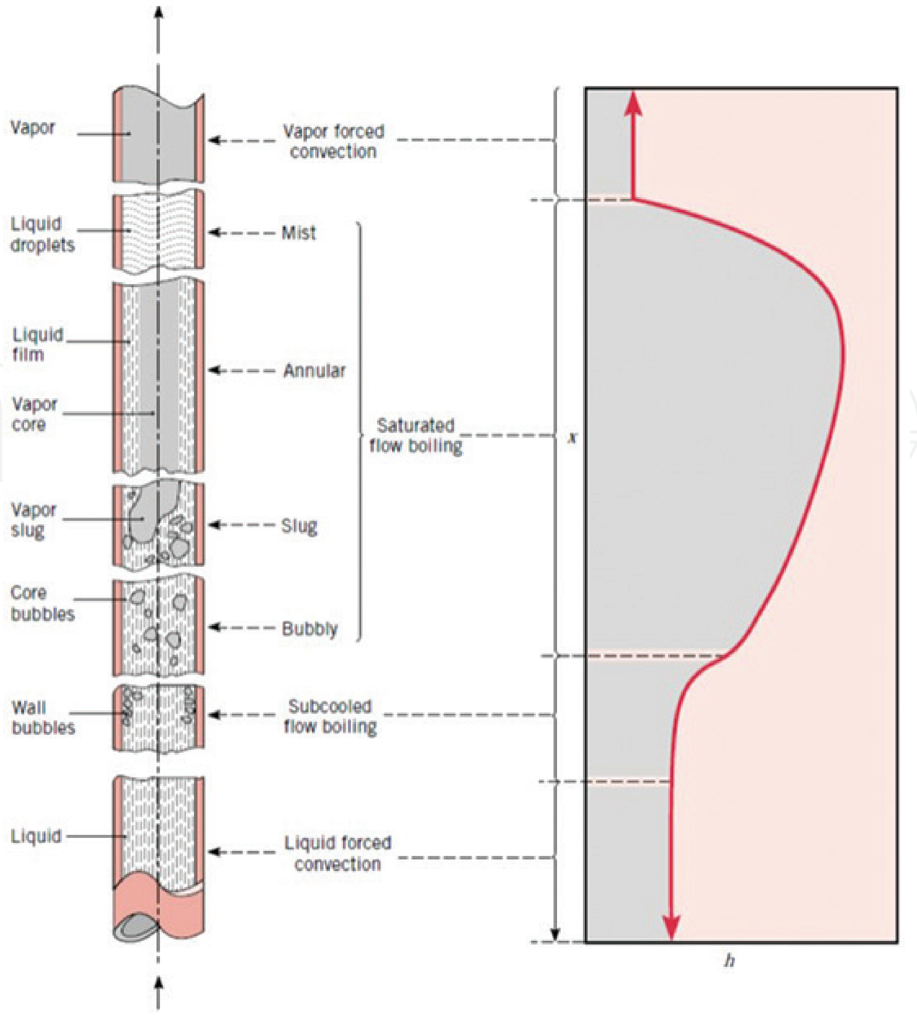

Figure 1.
Typical variations in heat transfer coefficient with vapor quality for forced-convection flow boiling in a tube [1].

Hardik and Prabhu [3] performed experiments to investigate the heat transfer and pressure drop of a diabatic two-phase water flow boiling in horizontal thin walled stainless steel tubes with different inner diameters under uniform wall heat flux conditions. To investigate the impact of vapor quality on the local boiling heat transfer coefficient, they measured vapor quality at the outlet of test section using a known range of uniform wall heat fluxes directly supplied by electrical heating tapes wrapped around the test sections. The effect of inlet vapor quality was not investigated in their study since a saturated liquid flow was provided at the inlet of test sections. In their study, the heat losses from the heating tapes were estimated using theoretical calculations of convective and radiative heat losses from the surface of test sections to the surroundings, and no single-phase experiments were conducted to empirically estimate heat losses at the same mass flux range of flow boiling tests.

A similar approach to measurement of outlet vapor quality was adopted by Yan *et al*. in two different studies [4, 5] to investigate the influence of crucial parameters, consisting of heat flux, mass flux, and vapor quality on the heat transfer performance of water flow boiling in a uniformly heated vertical nickel alloy tube as well as in a vertical 304 stainless steel (SS304) tube with twisted tape inserted under high heat flux conditions.

Although many experimental studies have been conducted to date to investigate the impact of local vapor quality on boiling heat transfer performance, majority of these studies have taken the similar approach to measure local vapor quality only at the outlet of test section mainly under uniform wall heat flux boundary conditions using electrical heating [6–12]. There are limited studies investigating the effect of local vapor quality for other thermal boundary conditions [13, 14], while their techniques to measure local vapor quality are not reported clearly. Hence, there is a considerable gap in the literature concerning vapor quality measurement under other thermal boundary conditions (e.g. uniform wall temperature and unknown boundary conditions) than the uniform wall heat flux using electrical heating.

The measurement and control of local vapor quality for uniform wall heat flux conditions using heating tapes wrapped around the test section is simpler than that for uniform wall temperature or variable wall heat flux conditions where the latent heat for two-phase flow boiling is supplied by a hot-side fluid at test section. In the latter case, there is no opportunity for a direct control of vapor quality at test section unless using in-situ measurements of local density through the existing instruments with a currently low accuracy.

Concerning the existing gaps in the literature addressed above, the present study aims to investigate various experimental approaches to measure and control vapor qualities at both the inlet and outlet of a typical test section under different thermal boundary conditions imposed on a test section during two-phase flow boiling heat transfer process, including uniform wall temperature, uniform wall heat flux, and unknown boundary conditions. The experimental techniques are then compared based on their level of accuracy and overall uncertainty, costliness, as well as simplicity in implementation.

2. Heat loss considerations

Measurements of local vapor quality of a saturated boiling flow can strongly be affected by accuracy in estimating the heat losses and calibrating the latent heat supplies. This is due to the existence of latent heat during a boiling process with a constant saturation temperature of fluid while enthalpy increases with the increase of local vapor quality as a result of heat acquisition [1, 2]. This is therefore evident that inaccurate estimation of heat losses and imprecise calibration of latent heat supplies would pose unreliability in collected heat transfer data and large errors in results as well.

Although different theoretical and experimental approaches have been engaged to date to estimate heat loss during flow boiling, majority of these methods are based on the estimation of heat loss from single-phase flow [6, 9–15]. Indeed, single-phase experiments were conducted to estimate heat loss percentages for a range of mass fluxes and heat fluxes. Then, the same heat loss percentages derived from the single-phase flow were directly used for two-phase flow at the same mass fluxes [6, 9–11]. Alternatively, the heat losses extracted from single-phase flow for a range of mass and heat fluxes were developed for flow boiling over another range of mass and heat fluxes using either interpolation or extrapolation [12, 13, 15].

In this commonly applied methodology, the amounts of heat experimentally supplied for the test section (Q_{suppl}) to increase the temperature of single-phase flow from a known value of Tsp, in at the inlet to another known value of Tsp, out at the outlet are monitored and recorded for a range of flow rates. On the other hand, the actual amounts of heat transferred to the fluid $\left(Q_{transf}\right)$ can be calculated by the following energy balance for a range of flow rates:

$$Q_{transf} = \dot{m}\, Cp\left(T_{sp,out} - T_{sp,in}\right) \tag{1}$$

The difference between Q_{suppl} and Q_{transf} reveals the heat losses $\left(Q_{loss} = Q_{suppl} - Q_{transf}\right)$. A correlation is then developed by plotting the variations of heat transferred to the fluid $\left(Q_{transf}\right)$ versus heat supplied $\left(Q_{suppl}\right)$, which can be used for calibrating the heat supplies as an imperative step to further measure vapor qualities within the flow boiling tests.

3. Experimental approach for known uniform wall heat flux boundary conditions

After estimating heat losses and calibrating heat supplies for any of electrical heater units in a test setup, local vapor qualities at the inlet and outlet of a test section can be measured by energy balance on the enthalpy change of vaporization. **Figure 2** depicts the schematics of a typical setup to conduct measurements of vapor qualities under known constant wall heat flux boundary conditions using the electrical heating either through the direct resistance heating of the test tube or with the heating tapes wrapped around the tube.

As shown in **Figure 2**, while inlet vapor quality can be controlled using the heat-supplying unit located right before the test section (called Pre-Heater), local vapor quality at the outlet of test section may be controlled from the heat-supplying unit at the test section (called TS-Heater). The subcooled liquid at a certain pressure of P_{sat} with a bulk temperature of T_{sp} is warmed up by a heat-supplying unit (i.e. SP-Heater) in order to reach the state of saturated liquid (x = 0%) at the saturation temperature of T_{sat} corresponding to the system pressure of P_{sat}. Using the Pre-Heater located right before the test section, the saturated liquid therefore reaches a certain vapor quality at the inlet of the test section (x_{in}) and is afterwards exposed to a known constant wall heat flux supplied by the TS-Heater at the test section to reach a two-phase flow of higher vapor quality at the outlet (x_{out}), and then keeps recirculated.

To ensure the state of saturated liquid, the subcooled liquid is warmed up by the SP-Heater to reach a temperature infinitesimally lower than the saturation temperature of T_{sat} targeted for the flow boiling experiments. Using the sight glass shown in **Figure 2**, the state of saturated liquid is also directly observed in order to check whether or not there is any vapor bubble in the saturated liquid flow.

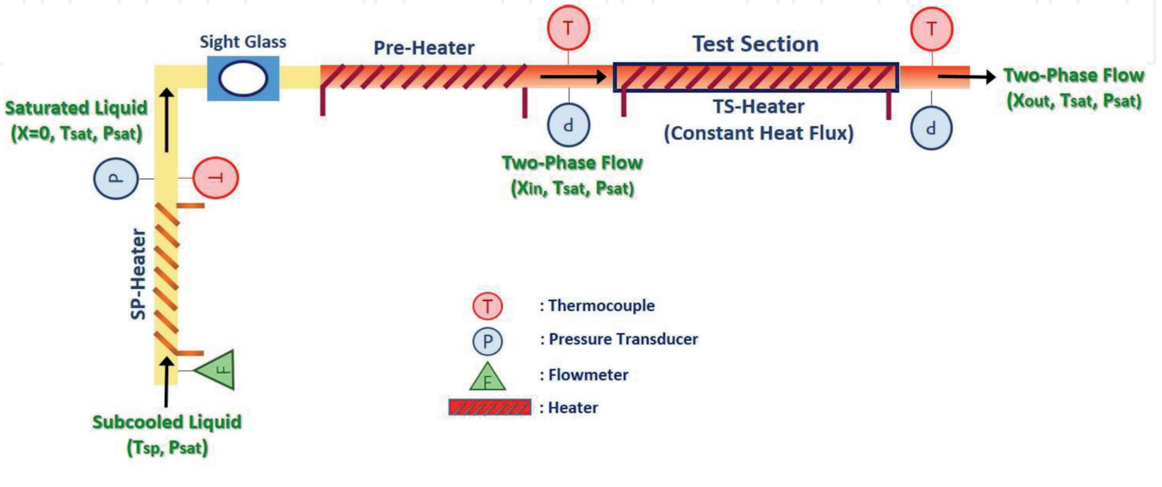

Figure 2.
The experimental approach to measuring vapor qualities for uniform wall heat flux boundary conditions.

As represented in **Figure 2**, the inlet vapor quality is measured and controlled by adjusting the calibrated heat supplied by the Pre-Heater to take the saturated liquid (x = 0) to the two-phase flow with a desired inlet quality of x_{in} as follows:

$$Q_{calib-pre} = \left(Q_{suppl-pre} - Q_{loss-pre}\right) = \dot{m}\left(h_{x[in]} - h_{f(x=0)}\right) \quad (2)$$

where h_{x} accounts for the enthalpy at vapor quality of x, Q_{suppl_pre} is the heat experimentally supplied by the Pre-Heater, $Q_{loss-pre}$ is the corresponding heat loss from this heat-supplying unit, and $Q_{calib-pre}$ stands for the calibrated heat which is actually transferred to the boiling flow. Having the enthalpy of saturated liquid ($hf_{(\text{x=0})}$) known, the only unknown parameter in Eq. (2) is the enthalpy at the inlet of the test section from which the inlet vapor quality can simply be derived at the operating saturation temperature and pressure.

After having the inlet vapor quality known, the outlet vapor quality can be measured from the calibrated heat at the test section (TS-Heater) as follows:

$$Q_{calib-ts} = \left(Q_{suppl-ts} - Q_{loss-ts}\right) = \dot{m}\left(h_{x[out]} - h_{x[in]}\right) \quad (3)$$

where $Q_{suppl-ts}$ is the heat experimentally supplied by the heating unit at the test section, $Q_{loss-ts}$ is the corresponding heat loss from this heat-supplying unit, and $Q_{calib-ts}$ stands for the calibrated heat which is actually transferred to the boiling flow. Having the inlet quality already measured, the only unknown parameter in Eq. (3) is the enthalpy at the outlet of the test section ($h_{x[out]}$) from which the outlet vapor quality can be extracted at the operating saturation temperature and pressure.

This is important to point out that the outlet vapor quality derived from the test section contains an accumulated error arisen from earlier measurement of the inlet vapor quality. As clearly shown in Eq. (2), the inlet vapor quality can be measured and controlled by obtaining the enthalpy at the inlet of test section ($h_{x[in]}$), which contains the uncertainties in measurement of mass flow rate ($\dot{m}$), bulk fluid temperature (T_{sat}), and calibrated heat supplies by the Pre-Heater ($Q_{calib-pre}$). This measured value of inlet vapor quality ($h_{x[in]}$) is used as a known parameter in Eq. (3) to obtain the vapor quality at the outlet of test section ($h_{x[out]}$). The measured value of outlet vapor quality, in turn, contains uncertainties in measurement of bulk fluid temperature and calibrated heat supplies by the test section heater ($Q_{suppl-ts}$) in addition to the earlier measurement error imposed by the value of inlet vapor quality, which eventually leads to the accumulation of more errors in measurement of outlet vapor quality through Eq. (3) as compared to that of inlet vapor quality.

4. Experimental approaches for unknown variable heat flux or constant wall temperature boundary conditions

In the case of constant wall temperature boundary conditions for the test section, the wall heat flux is subject to change. The measurement and control of local vapor quality at the outlet of a test section under uniform wall temperature boundary conditions is more challenging than that of uniform wall heat flux boundary conditions. In a single loop of internal flow boiling, the outlet vapor quality is typically measured and controlled by directly monitoring the constant amounts of surface heat flux provided by heating tapes wrapped around the test section. However, the use of hot fluid heating rather than electrical heating to generate constant wall temperature conditions does not allow the direct control of outlet vapor quality due to the unknown variable surface heat flux exchanged between the hot-side fluid (e.g. external condensation of steam or single-phase hot liquid) and the cold-side fluid (i.e. internal flow boiling).

4.1 Approach I: auxiliary after-heater

Figure 3 illustrates a typical case of constant temperature boundary conditions imposed by external condensation of steam on the test tube. The test section shown in this case is the place where external condensation and internal flow boiling occur simultaneously. The test section therefore functions as a cross flow heat exchanger whose both sides are manipulated with phase-change heat transfer processes. The test apparatus for this arrangement is to consist of two closed loops, including: external condensation loop (i.e. steam condensation over a horizontal tube) and internal boiling loop (i.e. two-phase flow boiling inside the tube).

Within the external condensation loop, saturated vapor of water at saturation temperature and pressure of $T_{sat,steam}$ and $P_{sat,steam}$ is provided by a steam generator and then enters the test chamber. After condensation of steam on the horizontal test tube due to the temperature difference between the saturated vapor and the tube surface (called subcooling), the condensate is driven by gravity and collected in a condensate reservoir to feed the steam generator and set a steady flow circulation in the external condensation loop. Regarding the internal boiling loop, the fluid is warmed up by the SP-Heater in order to reach the saturated liquid state ($x = 0$) at the saturation temperature and pressure of T_{sat} and P_{sat}, respectively ($T_{sat} < T_{sat,steam}$). Using the Pre-Heater located right before the test section, the saturated liquid therefore reaches a certain vapor quality at the inlet of the test section (x_{in}) and is afterwards exposed to the latent heat released from the external condensation side to reach an unknown higher vapor quality at the outlet (x_{out}).

The unknown outlet vapor quality can be measured by adding a calibrated heat-supplying unit (After-Heater) with power controller installed right after the test section in order to take the two-phase flow with unknown outlet quality to the known state of saturated vapor (i.e. $x = 100\%$) at the same saturation temperature of T_{sat}. In this case, the energy balance is dictated as follows:

$$Q_{calib-after} = \left(Q_{suppl-after} - Q_{loss-after}\right) = \dot{m}\left(h_{g(x=1)} - h_{x[out]}\right) \tag{4}$$

where $Q_{suppl-after}$ stands for the heat experimentally supplied by the After-Heater, $Q_{loss-after}$ is the corresponding heat loss from this heat-supplying unit, and $Q_{calib-after}$ accounts for the calibrated heat which is actually transferred to the boiling flow. Having the enthalpy of saturated vapor ($hg_{(x=1)}$) known, the only unknown parameter in Eq. (4) is the enthalpy at the outlet of the test section ($h_{x[out]}$) from which the outlet vapor quality can be extracted at the operating saturation temperature and pressure. Similar to the case of constant wall heat flux boundary conditions stated earlier, the inlet vapor quality can independently be measured and controlled by adjusting the calibrated heat supplied by the Pre-Heater using the Eq. (2).

In this approach, to ensure the state of saturated vapor, the After-Heater located after the test section is adjusted to supply the required latent heat for the two-phase flow with a certain outlet quality to reach a temperature slightly higher than the constant saturation temperature, which would be the starting point of the superheated vapor state. As shown in **Figure 3**, using the sight glass installed after the

After-Heater, the state of saturated vapor is also directly observed in order to check whether or not there is any liquid droplet and/or humidity in the gas stream at the beginning of superheated state. Unlike the earlier approach to measuring local vapor quality at the outlet of test section under uniform wall heat flux conditions, this approach does not contain any accumulated errors arising from earlier measurements of inlet vapor qualities.

4.2 Approach II: auxiliary heat exchanger

In the second methodology for variable wall heat flux conditions, a tube-in-tube or shell-and-tube heat exchanger installed at the test section may be used for measuring and controlling local vapor quality at the outlet of test tube. Analogous to the earlier cases, the inlet vapor quality is measured and controlled by monitoring the calibrated heat supplied by the Pre-Heater using the Eq. (2).

As represented in **Figure 4**, a hot liquid single-phase flow with known mass flow rates and known temperatures and pressures at the inlet and outlet passes through

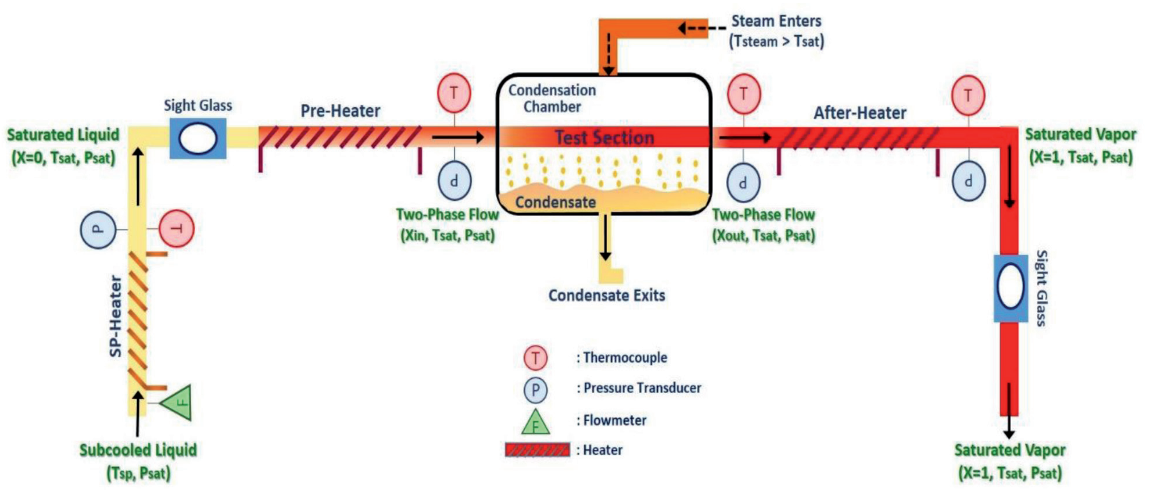

Figure 3.
The experimental approach to measuring vapor qualities for uniform wall temperature boundary conditions.

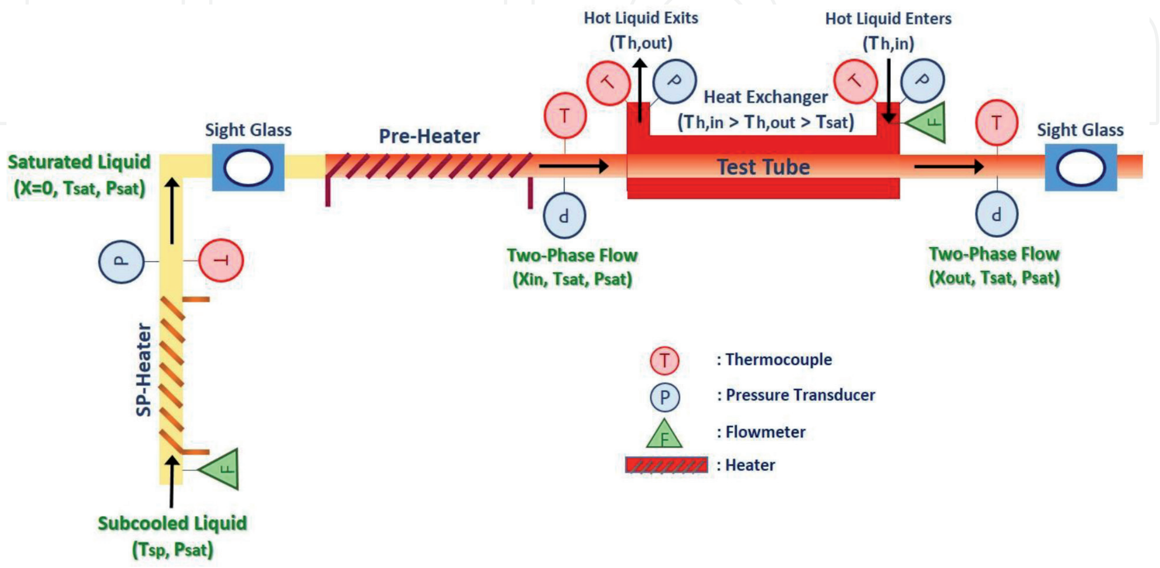

Figure 4.
The experimental approach to measuring vapor qualities for variable wall heat flux boundary conditions.

the outer tube (shell side), while the boiling flow of a known inlet vapor quality with a saturation temperature (T_{sat}) lower than that of the heating liquid (T_h) enters the inner tube of the counter-flow heat exchanger. After latent heat acquisition from the hot-side fluid, the internal boiling flow undergoes an unknown increase in vapor quality at the outlet of test tube whereas the heating liquid in the shell side experiences a temperature reduction as a result of sensible heat rejection yet its temperature at the outlet remains higher than the constant saturation temperature of internal boiling flow. The vapor quality at the outlet of the test tube can therefore be controlled by adjusting the mass flow rate of the hot liquid single-phase flow $\left(m_h\right)$ at the shell side of the counter-flow heat exchanger.

The amounts of heat exchanged between the internal boiling flow and the heating liquid can be measured by writing down an energy balance as follows:

$$Q_{rejected} = \dot{m}_h C_p \left(T_{h,in} - T_{h,out}\right) = Q_{gained} = \dot{m}\left(h_{x[out]} - h_{x[in]}\right) \tag{5}$$

Aside from $h_{x[out]}$, all the other parameters in Eq. (5) are known. The enthalpy at the outlet of the test section ($h_{x[out]}$) can thus be calculated and the vapor quality at the outlet of the test tube can be measured and controlled subsequently. Similar to the approach engaged to the uniform wall heat flux boundary conditions, the outlet vapor quality derived from this approach contains an accumulated error arisen from earlier measurement of the inlet vapor quality.

To keep the boiling fluid recirculated, this is evident that other components are required for the internal boiling loop, which are not shown in **Figures 2–4**. Subsequent to the test section or the After-Heater, the two-phase flow with a certain outlet quality or the saturated vapor is required to be condensed in a heat exchanger to reach the state of saturated liquid which is followed by a drop in temperature and pressure after passing through an expansion valve to reach the state of subcooled liquid prior to entering the pump in order to avoid the cavitation phenomenon. The liquid flow is then squeezed by a gear pump up to the desired saturation pressure to enter the SP-Heater.

5. In-situ measurement for any thermal boundary conditions

Regardless of the type of thermal boundary conditions governed on the test section, the local vapor quality of a two-phase flow boiling may be obtained through in-situ measurements.

Using the experimental approaches and/or instruments introduced here, first, the local density of two-phase flow at either of the inlet or outlet of a test section can be measured in-situ for any thermal boundary conditions that might be imposed on the test section. After obtaining the density, two independent thermodynamic properties of the flow at either inlet or outlet are known (*i.e.* density and either of saturation temperature or corresponding pressure) in order to look up the enthalpy of the two-phase flow at either inlet or outlet ($h_{x[in]}$ or $h_{x[out]}$). Having the local enthalpies known, the local vapor quality (x) can be readily obtained via $h_x = h_{f(x=0)} + x\,h_{fg}$ as the only unknown parameter left here. However, this is important to note that the accuracy of this approach is lower than those of the earlier approaches described so far in the present study due to the less accuracy of the limited experimental methodologies [16] and instruments [17–19] introduced to date to measure density of a two-phase flow.

Interest in the determination of two-phase flow density has brought about the design and development of various instruments to measure density in cryogenic flow systems. The more promising of the methods suggested are based on either (i) measurements of the average dielectric constant or capacitance of the two-phase fluid or (ii) measurements of the nuclear radiation attenuation properties of the two-phase fluid. In principle, both of these measurable quantities are associated with the fluid density.

Turney and Snyder [17] used a capacitance density meter to measure the density of liquid and two-phase hydrogen flow. Most of their measured and calculated values of density exhibited a deviation up to ±15% of the full-scale density. The advanced Coriolis meters have also been investigated for measurement of two-phase flow density [18, 19]. In this context, Reizner [18] has addressed the issues concerned to metering two-phase flow using the Coriolis meters. Technically, this is hard to retain flow-tube oscillations within two-phase flow due to the high and rapid damping of oscillations which is, by far, up to three orders of magnitude higher than that of the single-phase flow. Once the transmitter is not capable of maintaining the oscillations, the Coriolis meter is found to be "stalled", and no measurements are provided. Even in the case of averting the stalling, large errors in measurements of mass flow and density are induced.

Although there is no specific instrument to accurately measure density of a two-phase flow, the technique(s) recently introduced by Boltenko [16] can measure the density with a reasonable accuracy. The range of uncertainty reported for his technique(s) is between 3% and 5%.

The following is a brief explanation of the proposed techniques to measure local density of a two-phase flow:

i. *Gamma-raying Technique:* The method of Gamma-raying makes it possible to measure density of a two-phase flow both in steady and transient flow regimes as well as makes it possible to carry out ongoing record of $\rho(t)$ with averaging over the time intervals which are remarkably shorter than the typical duration of an unsteady process (τ > 0.1 s) [20].

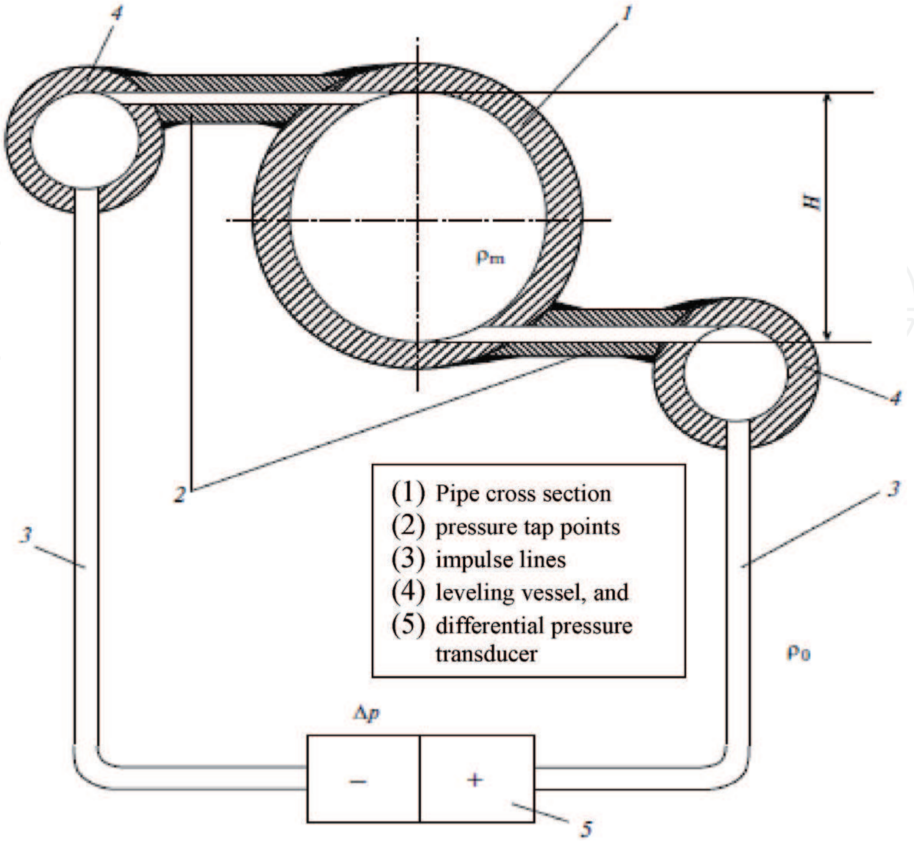

Figure 5.
Schematic of the hydrostatic method to determine density of a two-phase flow [16].

ii. *Hydrostatic Technique:* The hydrostatic method to determine the density of a two-phase flow is performed by the measurement of static pressures at two points of a channel. After measuring the static pressure difference between these two pressure tapping points, the average density of the two-phase flow can be obtained by the following correlation [21]:

$$\bar{\rho} = \frac{\left(\Delta P_{st} - \Delta P_{hyd}\right)}{g\,H} \tag{6}$$

in which g is the gravitational acceleration, H is the pipe diameter, ΔP_{hyd} accounts for the hydraulic resistance between the pressure tap points, and ΔP_{st} stands for the hydrostatic pressure difference between the pressure tap points.

As can be seen from Eq. (6), it is possible to obtain $\bar{\rho}$ only if ΔP_{hyd} is known. Hence, the hydrostatic technique may be employed to measure $\bar{\rho}$ for test sections with horizontal orientation. In the case of horizontal test tube $\Delta P_{\mathrm{hyd}} = 0$, and then Eq. (6) reduces to:

$$\bar{\rho} = \frac{\Delta P_{st}}{g\,H} \tag{7}$$

Figure 5 depicts schematics of the hydrostatic technique to measure the average density of a two-phase flow in a horizontal pipe.

6. Merits and demerits

In this section, the experimental approaches are sought to be compared based on their level of accuracy in measurement, affordability, and simplicity in implementation. Remarks, including merits and demerits, are expressed for each experimental technique described in the earlier sections in sequence.

6.1 Remarks on the approach for uniform wall heat flux conditions

The approach described in Section 3 is restricted to the investigation of the impact of local vapor quality on the heat transfer performance under known constant wall heat flux boundary conditions. Although the method is very affordable and simple to be implemented, accuracy of this methodology to measure local vapor quality is reliant heavily on the accuracy in estimating heat losses and calibrating heat supplies. Furthermore, it is important to note that the measurement of local vapor quality at the outlet of test section using this technique contains an accumulated error arisen from earlier measurement of local vapor quality at the inlet according to Eq. (3).

On the other hand, the measurement of flow boiling heat transfer data for horizontal test tubes using electrical heating has always been a subject of debate [22], where hot fluid heating is preferred to be used. In this regard, the following concerns are needed to be addressed: (i) for different types of stratified flow pattern, hot fluid heating induces practically uniform wall temperature boundary conditions for the tube perimeter, whereas electrical heating contributes to the circumferential heat conduction for the tube perimeter from the hot, dry-wall conditions at the top to the colder, wet-wall conditions at the bottom of the tube, leading to unknown thermal boundary conditions, (ii) for annular flow pattern with partial dryout at the top of the tube, electrical heating is not also advised due to the axial heat conduction along the tube.

6.2 Remarks on the approach I for constant wall temperature conditions

Using the approach I described in Section 4.1, higher accuracy and lower uncertainty in vapor quality measurements can be achieved by conducting accurate estimation of heat losses as well as accurate calibration of heat supplies. Furthermore, measurement of local vapor quality at the outlet of test section using this technique does not contain any accumulated errors arising from earlier measurements of inlet vapor quality as represented in Eq. (4). This is while the approach is very affordable and simple in execution.

Taking advantage of the After-Heater located after the test section, this technique does not interfere with heat transfer data collected from the test section and does not pose the issues of circumferential and axial heat conduction caused by electrical heating for stratified and annular flow patterns within the test section.

6.3 Remarks on the approach II for variable wall heat flux conditions

The approach II described in Section 4.2 is more expensive than the earlier techniques presented. The method is also not as simple as the earlier techniques in implementation. Using this approach, there is still accumulated error in measurement of outlet vapor quality arisen from the earlier measurement of inlet vapor quality, according to Eq. (5).

Moreover, the main drawback is that the methodology is likely to pose a higher overall uncertainty in measuring the local vapor qualities as compared to the earlier techniques described in Sections 3 and 4.1 since there will be higher number of points to be measured for temperature, pressure, and mass flow rate as indicated in Eq. (5). In this technique, five more precision instruments are required to be in service in order to measure flow rate of the hot-side fluid (one flow sensor), pressures (two pressure transducers), and temperatures (two thermocouple probes) at the inlet and outlet of the shell side of heat exchanger.

6.4 Remarks on the approaches for any thermal boundary conditions

The major drawback of the in-situ measurements is that the techniques and/or instruments introduced to date pose a low accuracy to measure local density of a two-phase flow, which ultimately makes the overall uncertainty for vapor quality measurements undesirable. In addition, very accurate and expensive pressure transducers and/or expensive advanced Coriolis meters are required to be procured to implement this technique properly.

7. Conclusions

Vapor quality plays a key role in flow boiling heat transfer behavior and can noticeably affect the local flow boiling heat transfer coefficient. To accurately investigate the effect of vapor quality on flow boiling behavior, accurate measurement of local vapor quality is critical.

In the present study, various experimental techniques were presented to measure and control vapor quality for flow boiling tests and were classified based on the type of thermal boundary conditions induced on the test tube wall. Moreover, in-situ measurements and techniques were also investigated to measure local density of two-phase flow and subsequently local vapor quality regardless of the governing thermal boundary conditions.

To provide a deeper insight to select an appropriate technique depending on researchers' choices, the experimental techniques were also compared based on their level of accuracy in measurement, affordability, and simplicity in implementation through addressing their potential weaknesses and strengths.

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