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# Effect of downward inclination on two-phase flow structure during condensation of steam inside in a tube

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## 1. Introduction

In nuclear industry, condensation of steam inside tubes is a very important phenomenon that happens in many scenarios and systems such as passive cooling systems included in improvement of overall reactor safety. A lot of configurations where in-tube condensation takes place apply a horizontal and nearly horizontal orientation. Nonetheless, no literatures are available that prove that horizontal orientation during a process of condensation of steam provides the best performance over other inclination angles. The aforementioned performance varies according to two-phase flow structure which depends on the inclination angle [1].

Nowadays, still there is work to carry out to predict which orientation angle gives the best performance for both heat transfer coefficient and void fraction that seem to have some kind of relation between each other [2]. In-tube condensation is characterized by being generally film condensation in which a condensate layer is formed on the inner surface and vapor is condensed at the interface of the liquid-vapor mixture, at steady conditions the temperature at the interface may be approximated to the steam saturation temperature at the local steam partial pressure [3]. A condensate film is formed at the bottom of the tube and flows in the axial direction, which is produced due to its initial momentum and interfacial shear. Gravity force has significant effects on this phenomenon as condensate film may run down the inner surface of the tube and be accumulated. As liquid layer acts as a resistance to transfer heat, the heat transfer rate will depend the geometric structure formed by the liquid-vapor mixture which is identified at the interface. The distribution of liquid-vapor around the cross sectional area of a tube is called cross sectional two-phase flow structure and some condensation models for calculation of heat transfer coefficient suggest that information of such geometrical structure is important to model and define such two phase flow regimes [4].

A proper visualization technique needs to be developed to observe the detailed geometric structure of the cross sectional liquid-vapor distribution around the tube during an in-tube condensation process as the importance of such recognition may help to understand more the interaction between liquid and vapor phases during condensation inside tubes.

The motivation and aim of this research is to study the application of a proper visualization technique for the low mass flow rate systems in two-phase flow condensation such as the air-cooled passive cooling system and the effects of downward inclination on condensation of steam inside tubes. In order to obtain the aforementioned structure image, application of the concept of axial viewing technique is used [5].

## 2. Methods and Results

### *2.1. Experimental setup*

The schematics of the experimental facility is presented on Fig. 1. The experimental setup consists of a steam generator with capacity 2 kW capacity in order to obtained a desired mass flow rate, a superheater in charge of supplying necessary energy to obtain saturated steam at a temperature of 100 °C and 0.1 Mpa at the entrance, a precooler which consists of a parallel flow heat exchanger with inner tube diameter of 19.05 mm and annular tube diameter of 25.4 mm. A cooling loop was implemented where included a circulatory heated bath and a flowmeter in order to remove a desired amount of heat from the above mentioned precooler with objective to change steam quality at the outlet. The test section consists of an axial viewer and a glass pipe of inner diameter of 16.55 mm, the glass pipe is covered with black tape in order to leave a small section of 10 mm which is illuminated by a lightning system, a high speed camera is fitted in front of the axial viewer and the two-phase flow structure is recognized at the desired focal point. The high speed video camera used during the present work was a Phantom v7.3 image resolution 512x512, 1000fps, spatial resolution 50 μm/pixel.

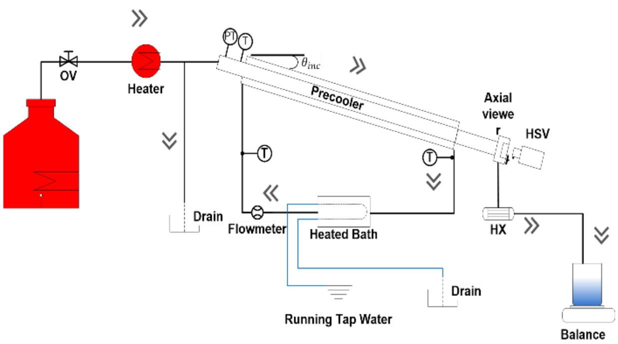


Fig. 1. Schematics of experimental facility.

The local quality at the outlet of the precooler was calculated based on energy balance by Eq. 1.

$$x = 1 - \frac{\dot{m}_{CW} * C_p * \Delta T}{\dot{m}_{Steam} * h_{fg}} \quad (1)$$

where $x$ is the steam quality at the outlet of the precooler, $\dot{m}_{CW}$ is the mass flow rate for cooling water, $C_p$ is the specific heat at constant pressure, $\Delta T$ is the temperature difference between the inlet and outlet parts for the cooling water, $\dot{m}_{Steam}$ is the mass flow rate of steam coming from the steam generator and $h_{fg}$ is the vaporization enthalpy for steam at 100°C and 0.1 Mpa.

*2.2 Results*

Table 1 summarizes the experimental conditions investigated in this study. Uncertainty analysis results are presented in Table 2.

Table 1. Experimental conditions

| Downward Inclination Angle (°) | Steam quality | | |
|---|---|---|---|
| | 0.17 | 0.34 | 0.78 |
| 3 | × | × | × |
| 45 | × | × | × |
| 75 | × | × | × |

Table 2. Summary of statistics of measurement errors

| Variable | Error | Error % | Standard deviation |
|---|---|---|---|
| $\dot{m}_{cw}$ | ±0.57 g/s | 2.02 | 0.22 g/s |
| T | ± 1 °C | 1.19 | 0.17 °C |
| $\dot{m}_s$ | ±0.0193 g/s | 2.11 | 0.09 g/s |
| x | ± 0.006 | 3.48 | 0.03 |
| $\theta_{inc}$ | ± 0.1 | 3.33 | 0.04 |
| $\alpha$ | ±0.02 | 3.08 | 0.04 |
| $\theta_{wet}$ | ±0.2° | 2.03 | 0.5° |
| $\delta_{Thickness}$ | ±0.025 mm | 2.75 | 0.3 mm |

The cross sectional two phase flow structures for three different steam qualities are shown with its respective behavior as inclination angle is changed in Fig. 2, starting from top to bottom, the first line in white-gray scale represents the liquid-vapor interface, some other white areas may be observed below the aforesaid line which are pure reflection from the light source that appear when the phenomena is recorded. It was observed that the bottom liquid film thickness had a tendency to decrease its length as inclination angle varies from 3° to 75°. This may be interpreted as an increase on the values for void fraction as inclination angle increases. However, a significant change was observed when the inclination angle was between 45° to 75°, the bottom film thickness had a significant drop for the steam qualities of 0.17 and 0.34 but for the steam quality of 0.78 it didn't affected the behavior significantly, this is because the gravitational forces have a significant effect at low steam quality condition but as quality increases along with inclination angle, the behavior of the condensation phenomenon is not affected greatly by the aforementioned gravitational forces. The shape of the interface was completely changing from having the geometry almost like a perfect arc to a streamline. Nonetheless, the liquid-vapor interface shows the flow regime type observed in the experimental matrix can be considered as a stratified wavy flow type, this type of flow regime is well known due to its variations on the liquid film height and wetted angles that are caused due to the difference of velocity between the liquid and vapor phases that are flowing together along the pipe during the condensation process, the high surface tension of water and the gravitation effects on flow structure [6].

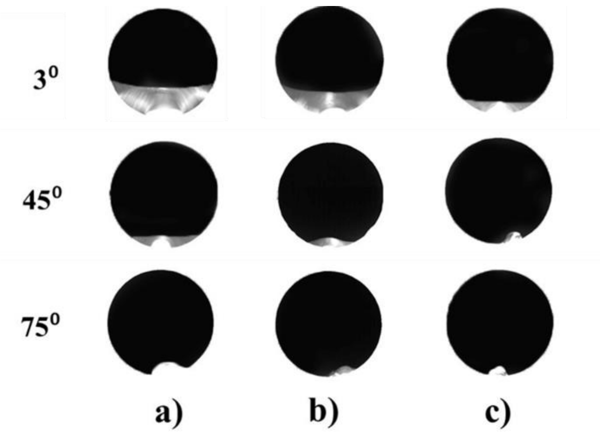


Fig. 2. Cross sectional two phase flow structure images: a) x=0.17, b) x=0.34 and c) 0.78

From the structure of the cross sectional image, important parameters can be measured such as, void fraction, wetted angle and bottom liquid film thickness which are important to calculate heat transfer coefficient. These parameters are measured by using a computer software. On Fig. 3, the values for the void fraction are presented in terms of a changing steam quality and changing inclination angle. An interesting comparison can be seen in the aforementioned figure which is the effects of inclination angle on condensation parameters, as the inclination angle increases it can be seen that values from void fraction tend to increase. The values of the void fraction measured are the averaged values of the total measurements. In order to find the aforementioned values for every void fraction point, a total of 100 measurements corresponding to a different image structure within the same test was performed.

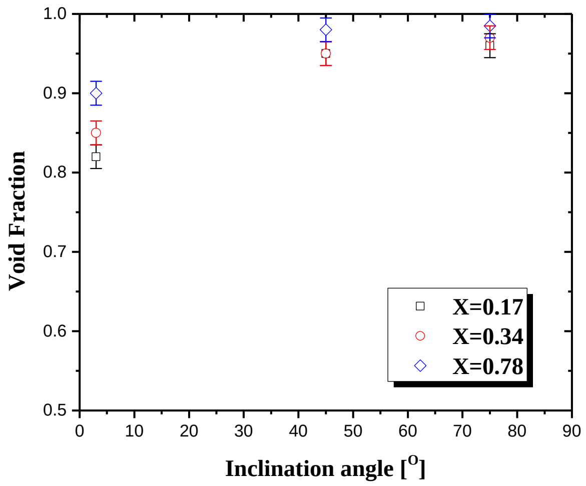


Fig. 3. Inclination effects on void fraction.

Other parameters that were affected by the inclination angle were wetted angle and bottom film thickness that presented a similar behavior, as the inclination angle increases, both parameters tend to decrease its values as shown in Fig. 4 and 5. Both wetted angle and bottom film thickness showed also a trend and a decreasing path for the whole range of inclination angle from 3° to 75° confirming that inclination angle had a significant on such parameters. On the steam quality of 0.17, the drop on both values was significant while for the high steam quality condition of 0.78, the values maintained almost a constant value as gravitational force seemed not to affect greatly this condition.

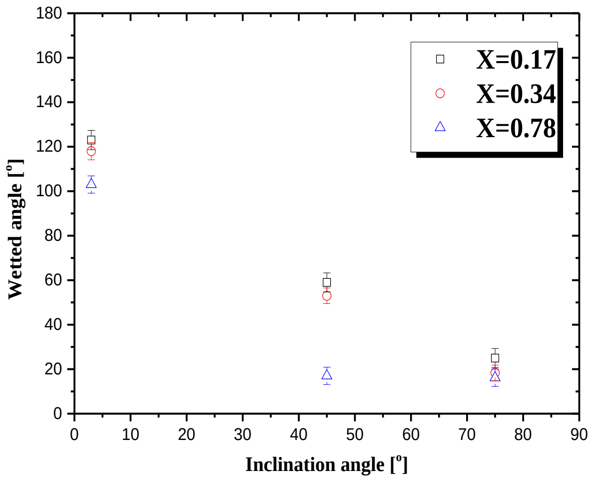


Fig. 4. Inclination effects on wetted angle

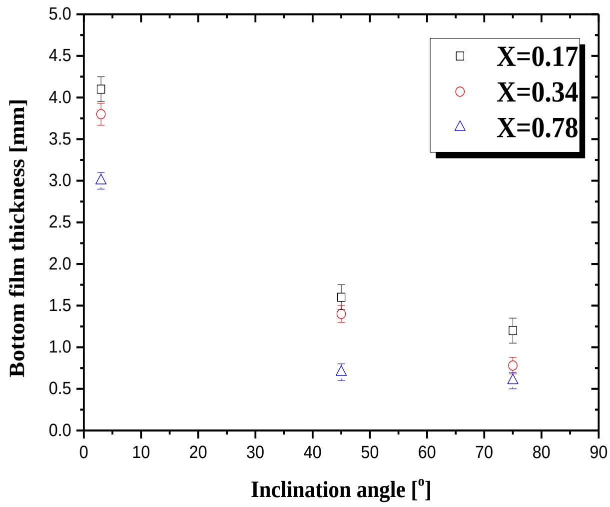


Fig. 5. Inclination effects on bottom film thickness.

## 3. Conclusions

An experimental study of the application of axial-viewing for visualization of cross-sectional two-phase flow structure during condensation of steam inside tubes was conducted. The test matrix for the present study was performed according to the following summary: pure steam was used at a saturation temperature of 100 °C and atmospheric pressure. Mass flux of the present work was 3.43 kg/$m^2$s and three vapor qualities with values of 0.17, 0.34 and 0.78 were tested for three downward inclination angles with values 3°, 45° and 75°. The key findings from this study are following:

- By using axial-viewing technique, it was possible to visualize and recognize the two-phase flow structure from cross sectional view during condensation of steam inside an inclined tube.
- Condensation parameters encountered in two-phase flow that include: void fraction, wetted angle and bottom film thickness were possible to measure from structure images obtained during the present work.
- The results obtained showed that the variation of inclination angle during condensation of steam inside tubes had a significant effect on condensation parameters, especially at the low quality condition where seems that gravitational forces affect significantly such condition and an optimum angle may be found depending on the configuration.

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