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EXPERIMENTAL INVESTIGATION OF SLUGGING AS INITIATING WATER HAMMER PHENOMENON THROUGH INDIRECT CONTACT STEAM CONDENSING IN A HORIZONTAL PIPE HEAT EXCHANGER

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ABSTRACT

Slugging as a water hammer initiator is a fascinating topic because it has a strategic impact on equipment safety in industrial systems, i.e. pressurized water reactors (PWR), heat exchangers, etc. The present research's objective was to investigate slugging as initiating the water hammer phenomenon through indirect contact steam condensing in a horizontal pipe heat exchanger. The experiment apparatus used in the present experimental study consisted of an inner annulus pipe made of copper (d_{in} = 17.2 mm, d_o = 19 mm) with a length of 1.8 m and an outer annulus pipe of galvanized iron (d_{in} = 108.3 mm, d_o = 114. 3 mm) with a length of 1.6 m. The tested liquid was water. The experiments were conducted at a static pressure of P_s = 108.825 kPa and the temperature of T = 119.7°C. The obtained experimental data of temperature and differential pressure fluctuations were analyzed using statistical analysis. The results were as follows: 1) the flow pattern area of non-slugging (stratified and wavy flow), transition (wavy-slug flow), and slugging (slug and large-slug) were determined, with the transition flow pattern of slug and large-slug defined as initiating water hammer; 2) transition area ranges for the wavy-slug flow pattern are from $\dot{m}_{co}=1\times10^{-1}$ kg/s to $\dot{m}_{co}=6\times10^{-1}$ kg/s for $\dot{m}_{st}=6\times10^{-3}$ kg/s to $\dot{m}_{st}=7.5\times10^{-3}$ kg/s, and $\dot{m}_{co}< 3\times10^{-1}$ kg/s for $\dot{m}_{st}=8\times10^{-3}$ kg/s to $\dot{m}_{st}=9\times10^{-3}$ kg/s. These obtained data are very important in order to develop a database for the input of an early warning system design in a safe, two-phase flow installation piping system during steam condensation.

Keywords: Heat exchanger; Horizontal pipe; Slugging; Steam condensation; Two-phase flow

1. INTRODUCTION

Condensation plays an important role in nature, where it is a crucial component of the water cycle, and in chemical processing or nuclear power plants (Ghiaasiaan, 2008). The condensation of an induced water hammer is a rapid event that could be aptly termed a "rapid steam bubble collapse." It occurs when a steam pocket becomes totally entrapped in a subcooled condensate. As the steam gives up its heat to the surrounding condensate and pipe walls, the steam changes from a vapor to a liquid state. As a liquid, the volume formerly occupied by the steam shrinks by a factor of from several hundred to over a thousand, depending on the saturated steam pressure. If the steam pressure is high, the condensate is subcooled, non-condensables are absent, and the void is large enough for a slug to pick up some

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velocity; the overpressure resulting from such an event can easily exceed 1000 psi. This is high enough pressure to fracture a cast iron valve, blow out a steam gasket, or burst an accordion type expansion joint. And, in fact, failure on each of these components in separate condensation-induced water hammer accidents has resulted in operator fatalities (Kirsner, 1998).

The research was conducted in relation to the condensation heat transfer coefficient on a vertical pipe (Nagae et al., 2005). The test section consisted of a vertical, double-pipe cylinder made of stainless steel SUS304. The inner tube was the heat transfer tube with an inside diameter of 19.3 mm, wall thickness of 3.04 mm, and height of 1.8 m. The mixture of steam and air flowed into the tube from the bottom inlet. The coolant water flowed along the outside surface of the heat transfer tube. Temperature distribution in the axial direction under pressure of 0.1 MPa at an inlet steam flow rate of 1.23 g/s was determined. Since the steam condenses and its partial pressure drops as it flows downstream, the steam–air mixture temperature decreases accordingly. While the enthalpy of the steam is higher near the inlet, and thus the temperature decrease rate is low, the enthalpy decreases with the temperature decrease, and the temperature decrease rate tends to grow higher.

Measurements involving a two-phase flow, particularly for the case of vapor-condensation, are critical for industrial applications, as well as for basic scientific development. Such applications range from process control in chemical production plants, oil-gas exploration, the transportation of oil-gas mixtures in pipes, nuclear reactors, etc. For more than five decades, studies have attempted to understand the mechanism of two-phase flow; however, there remains no consensus on its complex nature. Many investigations have postulated that the mechanisms are different for each flow regime or pattern. Accordingly, there has been some success in formulating models for different flow regimes, and several corresponding flow maps for horizontal flow have been developed, and a well-known pattern map has been proposed (Mandhane et al., 1974). However, many of the maps are the product of visual observations and are, therefore, subjective in nature. By far the most commonly used method to discriminate flow regimes, particularly in the early years, was the application of high-speed cameras.

More modern methods use time series analysis of the experimental data. In most cases, analysis of the power spectrum density (PSD) function is employed to extract the periodic feature of a signal. The PSD and probability density function (PDF) of the transient pressure drop signal was calculated to identify the flow pattern of two-phase flow in a vertical pipe (Mastui, 1986), and PSD and other fractal techniques for flow pattern identification were employed, as well (Cai et al., 1996). Nonlinear analysis was used to analyze differential pressure fluctuations of two-phase flow through a T-junction, with the aim of clarifying the two-phase flow splitting behavior at a T-junction. These results may be significant for better understanding the flow structure and also for establishing valid models different from conventional viewpoints (Wang et al., 1998; Wang et al., 2003).

Based on the above description, an investigation of steam condensation and two-phase flow is wide-ranging. Many aspects can still be explored to explain the phenomenon of two-phase flow, particularly when related to condensation, both in the position of the pipe and in the condensation process. The objectives of this research are to use pressure difference statistical analysis to study the two-phase flow interfacial behavior of the condensation steam.

2. METHODOLOGY

The tested liquid was water. The experiment apparatus consisted of an inner annulus pipe made from copper (d_{in} = 17.2 mm, d_o = 19 mm) with a length of 1.8 m and an outer annulus pipe of galvanized iron (d_{in} = 108.3 mm, d_o = 114.3 mm) with a length of 1.6 m. Thermocouples, type

K 36 TT OMEGA with chromel (+) and alumel (-) materials, were used as temperature sensors to detect the spread of temperature in radial or axial directions along the pipe. The measurements ranged from -50 to 260^{o}C, with an accuracy of 0.01°C. An RX 40 serial data logger (OMRON, 20 Channels) was used to record the temperature data with a sampling rate of 5 Hz. In the present experimental study, the water was heated using a boiler to generate steam, which was then flowed and condensed inside the annulus pipe to form a steam-condensate, two-phase flow in a horizontal pipe. The experiments were conducted at a static pressure of P_s = 108.825 kPa and a temperature of T = 119.7°C. Water was used as a coolant in the outer annulus pipe. The pressure drop in the axial direction of the test was measured by a differential pressure transducer with a sampling rate of 7.353 kHz.

3. RESULTS AND DISCUSSION

3.1. Two-phase Flow Pattern based on Pressure Difference Fluctuation and Power Spectra Density Analysis

There are no measurement fluctuations on the pressure difference and/or the power spectra density for both the small inlet steam mass flow rate and the highest cooling water mass flow rate ($\dot{m}_{st}$= 1. 6×10^{-3} kg/s and $\dot{m}_{st}$= 2.8×10^{-3} kg/s, $\dot{m}_{co}$= 5.78×10^{-1} kg/s). This indicates there was no condensate passing wave (CW), meaning that the physical flow pattern formed is stratified. The condensate flows at certain layers, while the steam flows separately above the condensate without a Bernoulli effect. The absence of dominant frequency value of the power spectra density supported this analysis. Figure 1 shows the pressure difference fluctuation when the inlet steam mass flow rate was significantly improved ($\dot{m}_{st}$= 6.8×10^{-3} kg/s up to $\dot{m}_{st}$= 8.1×10^{-3} kg/s). It can be seen that the mean pressure difference fluctuated with a small amplitude (±5 kPa), demonstrating a small passing condensate wave that indicated there was no significant additional mass flow of condensate in the test pipe (<5 Hz). From these data, it can be interpreted that the condensate flows with small wavy patterns.

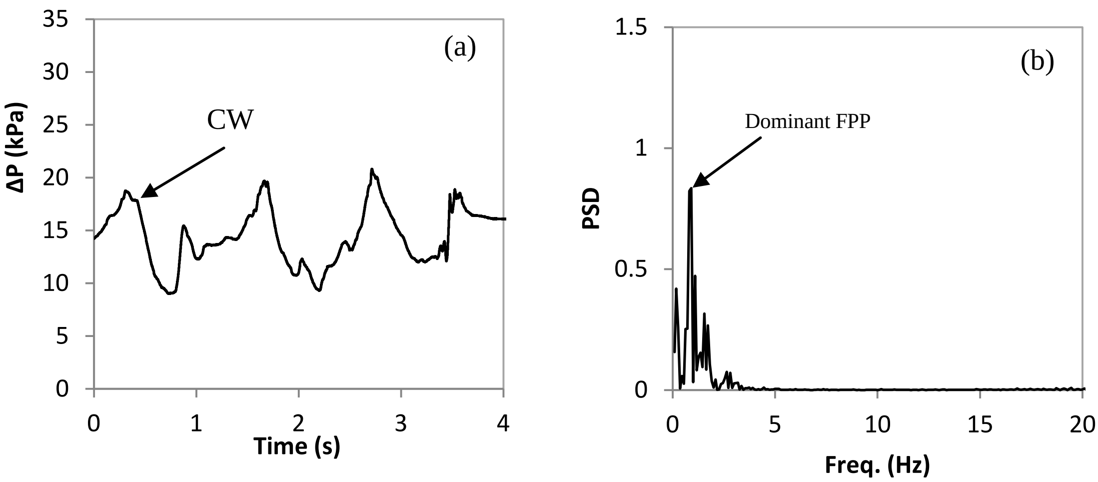

Figure 1 (a) Typical pressure difference fluctuation; (b) PSD of pressure difference, ($\dot{m}_{st}$= 6.8×10^{-3} kg/s to $\dot{m}_{st}$= 8.1×10^{-3} kg/s), $\dot{m}_{co}$= 5.78×10^{-1} kg/s)

When the inlet steam mass flow rate was increased to $\dot{m}_{st}$= 8.4×10^{-3} kg/s or $\dot{m}_{st}$= 8.6×10^{-3} kg/s, the pressure difference fluctuation is significantly increased, as shown in Figure 2. The pressure difference fluctuated with significant mean amplitude (±10 kPa). This indicates that the condensation dominated the flow in the test pipe, as there is a large amount of passing wave formation. From this data, it can be interpreted that the condensate flowed with large wavy patterns and formed vapor lock, where the vapor is trapped in the condensate. This is called the slug flow pattern, and it is capable of initiating the occurrence of water hammer.

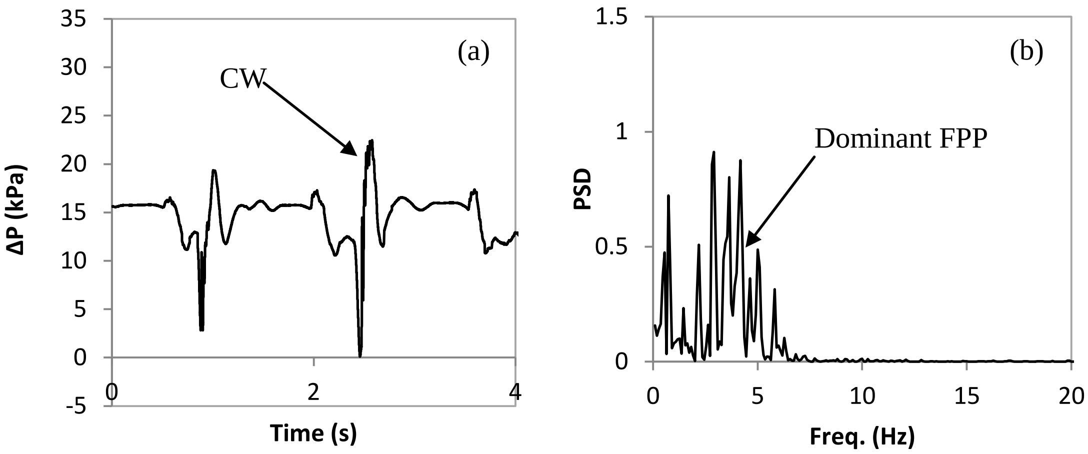

Figure 2 (a) Typical pressure difference fluctuation; (b) PSD of pressure difference, ($\dot{m}_{st}$=8.4×10^{-3}kg/s to $\dot{m}_{st}$= 8.6×10^{-3} kg/s), $\dot{m}_{co}$=5.78×10^{-1}kg/s)

3.2. Two-phase Flow Pattern based on Temperature Profiles

Figure 3 shows the same temperature tendencies for the top, side, and bottom of the pipe, with approximately constant measurement results indicating a saturation temperature at 10 cm to 100 cm from the inlet. This indicates the process of condensation had taken place. The temperatures at the side and bottom points still being at a saturation temperature indicate condensation formed at these locations. At points located 100 cm to 150 cm from the inlet, conditions at the three locations possess the same trend, i.e. downward sharply, meaning there has been a significant additional amount of condensation at this location.

Next, Figure 4 shows different tendencies, where the temperature at the points 100 cm and 150 cm from the inlet for all three positions (bottom, side and top) was still quite high. These data indicate the vapor dominates the flow rate that occurred in the condenser pipe, resulting in instability of the steam-condensate flow, causing a wavy flow of condensation. Increasing $\dot{m}_{st}$ will increase the effects of the instability or wave that occurred and start to form a slug wavy flow (wavy-slug) or even slugging and water hammer. Cooling water discharge was kept constant ($\dot{m}_{co}$= 4.23×10^{-1} kg/s), and its temperature distributions possess the same trend pattern, where the inlet temperature decreased linearly, with the highest temperature at 31.67°C (at a point 10 cm from the inlet), the lowest at 27.02°C (at a point 150 cm from the inlet), and the mean at 28.96°C.

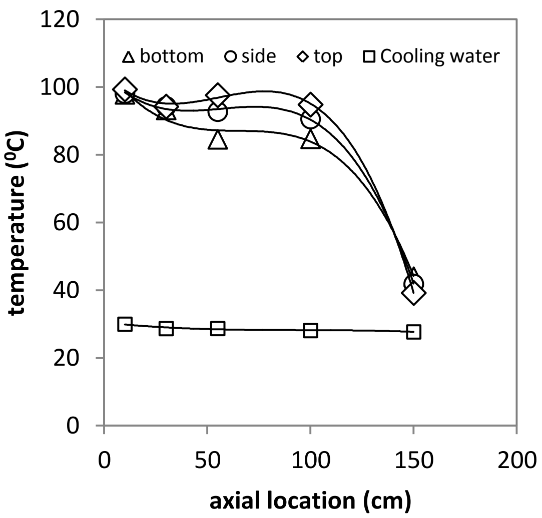

Figure 3 Typical temperature profiles on the cross-section pipe test ($\dot{m}_{st}$= 2.6 kg/s, 3.5×10^{-3} kg/s, 4.3×10^{-3} kg/s, 5.1×10^{-3} kg/s, and $\dot{m}_{co}$= 4.23×10^{-1} kg/s)

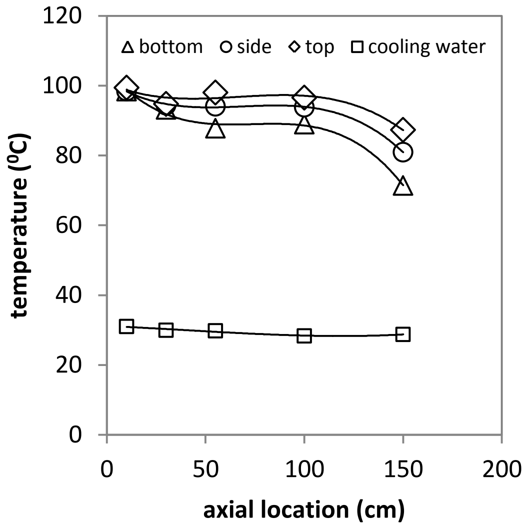

Figure 4 Temperature profile on the cross-section pipe test ($\dot{m}_{st}$=6.5×10^{-3} kg/s, $\dot{m}_{co}$=4.23×10^{-1}kg/s)

3.3. Normal Distribution Analysis of Pressure Difference Fluctuation

The normal distribution of pressure difference data presents further analysis. Figure 5 presents a graph of the normal distribution of pressure difference for variations of the inlet steam mass flow rate and five variations of the cooling water flow rate $\dot{m}_{co}$= 1.24×10^{-1} kg/s to $\dot{m}_{co}$= 5.78×10^{-1} kg/s.

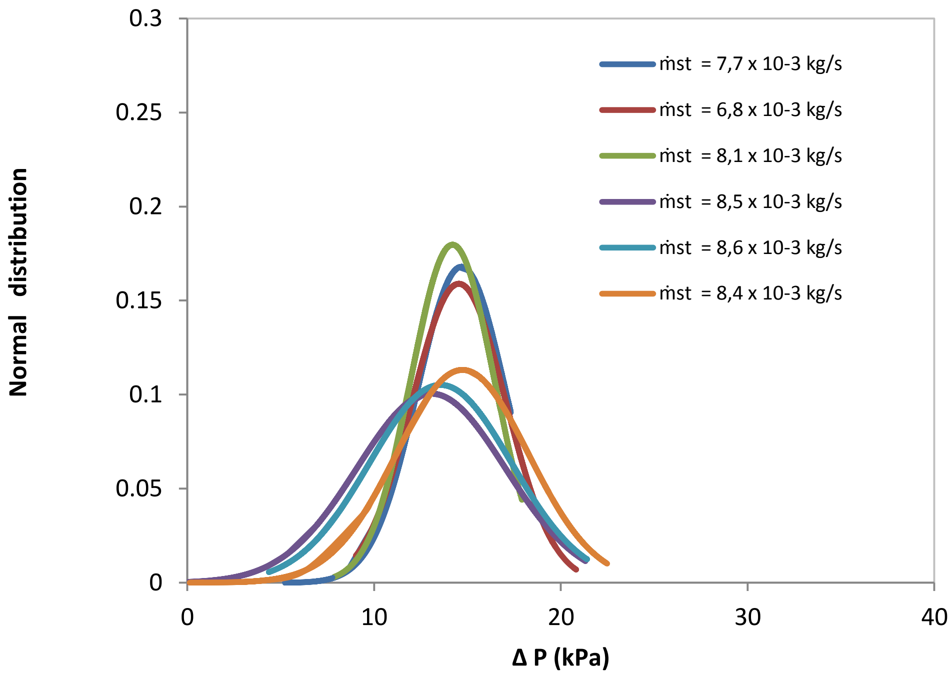

Figure 5 Normal distribution of pressure difference fluctuation ($\dot{m}_{co}$= 5.78×10^{-1} kg/s)

From Figure 5, the curve's shape is classified into two groups. The first group is a bell-shaped curve; it is slim, tall, and tapered ($\dot{m}_{st}$= 6.8×10^{-3} kg/s to $\dot{m}_{st}$= 8.1×10^{-3} kg/s), indicating the pressure difference distribution is concentrated in the mean area with a relative standard deviation smaller than the second group. This implies that pressure difference fluctuation was not significant at the time; thus, there were few passing condensate waves. This analysis predicted the flow patterns to be wavy or slug flow. For the inlet steam with a mass flow rate of $\dot{m}_{st}$= 8.4×10^{-3} kg/s to $\dot{m}_{st}$= 8.6×10^{-3} kg/s, the curve is short, broad, and blunt, meaning the pressure difference is not centered on the mean value with a large standard deviation. This also means the pressure difference fluctuation is very striking; thus, the passing condensate waves were increased. This data predicted the flow pattern to be slug or large.

4. CONCLUSION

This study's findings were as follows: 1) the flow pattern area of non-slugging (stratified and wavy flow), transition (wavy-slug flow), and slugging (slug and large-slug) were determined. The transition flow pattern of slug and large-slug is defined as initiating water hammer; 2) transition area range of wavy-slug flow pattern was from $\dot{m}_{co}$=1×10^{-1} kg/s to $\dot{m}_{co}$=6×10^{-1} kg/s for $\dot{m}_{st}$=6×10^{-3} kg/s to $\dot{m}_{st}$=7.5×10^{-3} kg/s and $\dot{m}_{co}$< 3×10^{-1} kg/s for $\dot{m}_{st}$=8×10^{-3} kg/s to $\dot{m}_{st}$=9×10^{-3} kg/s. Those obtained data are very important to develop database input for the early warning system design in a safe, two-phase flow installation piping system during steam condensation.

Nomenclature

co	:	coolant water
d	:	diameter (m)
i	:	inner
$\dot{m}$	:	steam mass flow rate (kg/s)
o	:	outer
sat	:	saturated
T	:	temperature (^{o}C)

5. ACKNOWLEDGEMENT

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