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EXPERIMENTAL INVESTIGATION ON THE LOCAL PROFILES OF HEAT TRANSFER COEFFICIENT DURING THE STEAM CONDENSATION IN A HORIZONTAL ANNULUS PIPE

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Abstract

The objective of the research is to investigate the heat transfer profiles by using a measurement of the temperature distributions during condensation in a horizontal annulus pipe. The circumferential temperature distribution along the annulus pipe wall were measured in order to investigate the heat transfer characteristics around the annulus pipe. An annulus pipe with inner section test pipe made from copper material ($d_{in} = 17.2$ mm, $d_o = 19$ mm) with a length of 1.8m and outer section test pipe made from a Galvanized Iron Pipe ($d_{in} = 108.3$ mm, $d_o = 114.3$ mm) with a length of 1.6m covered by 10 mm thick insulation was used in this experiment.

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Temperature were measured by five variations of inlet steam flow rate ranging from 1.6×10^{-3} to 7.6×10^{-3} kg/s. It was found that the local heat transfer coefficient is influenced by the radial and axial positions of the inlet, and it was highest on the top, and followed by those on the side and the bottom.

1. Introduction

As one of numerous types of heat exchangers, horizontal condensation heat exchangers have many industrial applications such as refrigeration and air conditioning [2]. In nuclear power plants, horizontal heat exchangers are widely used in advanced nuclear reactors and have been proposed for passive containment cooling systems (PCCS) of future water reactors. Many factors affect the heat transfer coefficient during this process, such as physical and chemical properties of steam and geometry of annulus pipe [1].

Condensation of steam in a horizontal heat exchanger with the present of a noncondensable gas has been experimentally studied by Vierow and Wu [5]. The annulus tube inner surface, outer surface and annular coolant channel temperature profiles were measured along the top and the bottom of the test section along with the annulus tube centerline. For the annulus tube inner surface temperature, an innovative thermocouple design was developed that allowed for nonintrusive measurements. From these and other data, local heat fluxes were obtained for a variety of pressures, steam inlet velocities and noncondensable gas mass fractions. The local heat fluxes are essential for development of analytical models of horizontal condensation heat exchangers but have not been reported elsewhere. In particular, it is important to distinguish the difference in performance between the top and bottom of the annulus tube. The experimental results also identified that the major flow regimes in the horizontal annulus tubes are generally wavy and stratified flow, with annular flow occurring only for a steam/air mixture velocity greater than approximately $35\,\text{m/s}$. The overall effect of non condensable gas on the heat transfer rate was investigated by comparing the centerline temperature profiles and the overall heat transfer rates. For the low inlet air mass fraction conditions, the effect is not as significant as previously expected. The effect of the local air mass fraction, air concentration distribution, liquid film characteristics and the turbulent mixing on the local heat transfer coefficient were qualitatively analyzed. The top and bottom show different dependencies on these factors due to the local flow conditions.

Nagae et al. [4] conducted research in relation to the condensation heat transfer coefficient on a vertical pipe. The test section consisted of a vertical, double-pipe cylinder made of stainless steel SUS304. The inner tube was the heat transfer tube with inside diameter of 19.3 mm, wall thickness of 3.04 mm and height of 1.8 m. The mixture of steam and air floweds into the tube from the bottom inlet. The coolant water flows along the outer surface of the heat transfer tube. The temperature distribution in the axial direction under pressure of 0.1 MPa, at an inlet steam flow rate of $1.23\,\mathrm{g/s}$ is found. Since the steam condenses and its partial pressure drops as it flows downstream, 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.

Based on the above description, many things can still be explored to explain the phenomena of heat transfer, especially related to condensation, both in the geometry, orientation or position of the pipe, and condensation process. From those facts, the author conducted an experimental study to investigate the heat transfer characteristics of this important phenomenon by using the measurement of the temperature profile and local heat transfer coefficient distributions during condensation in a horizontal annulus pipe.

2. Experimental Apparatus and Procedures

The experiment apparatus used in present experimental study is shown Figure 1 and the detail of the test pipe is in Figure 2. Tested liquid was water. The experiment apparatus consists of an inner annulus pipe made from copper $(d_{\mathrm{in}} = 17.2\,\mathrm{mm},\ d_{\mathrm{o}} = 114.3\,\mathrm{mm})$ with a length of 1.8 m. The outer pipe annulus is a galvanized iron pipe $(d_{\mathrm{in}} = 108.3\,\mathrm{mm},\ d_{\mathrm{o}} = 114.3\,\mathrm{mm})$ 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 direction along the pipe. The measurement ranged from -50 to $260^{\circ}C$ with an accuracy of $260^{\circ}C$. A data logger of RX 40 serial (OMRON, 20 Channels) was used to record the temperature data with a sampling rate of 5Hz. In the experiment, 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 horizontal pipe. On the other hand, the water was used as a coolant in the outer of annulus pipe.

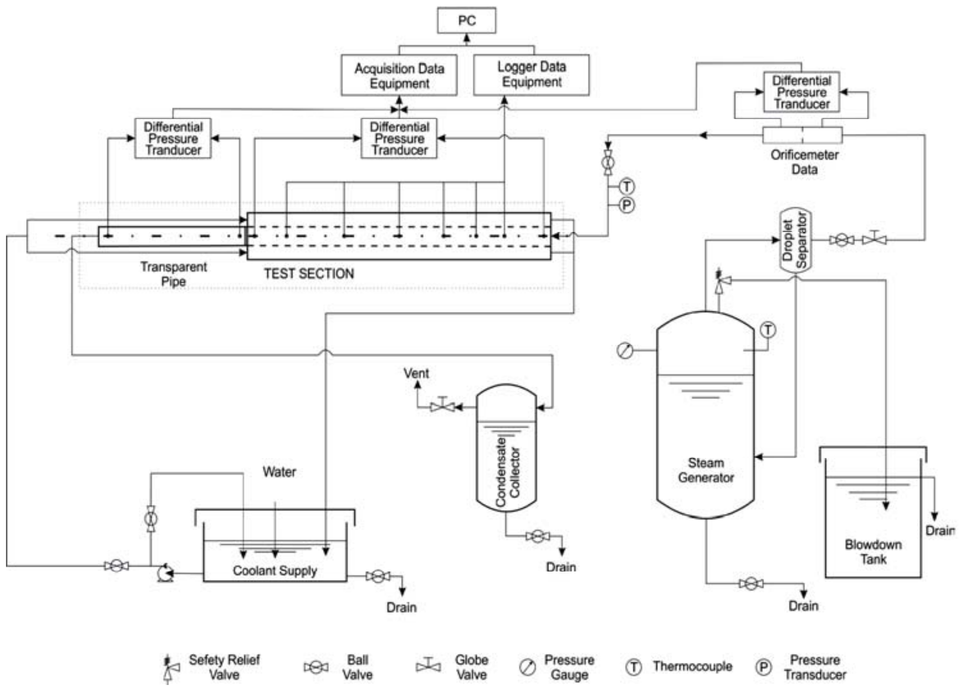

Figure 1. Experiment apparatus.

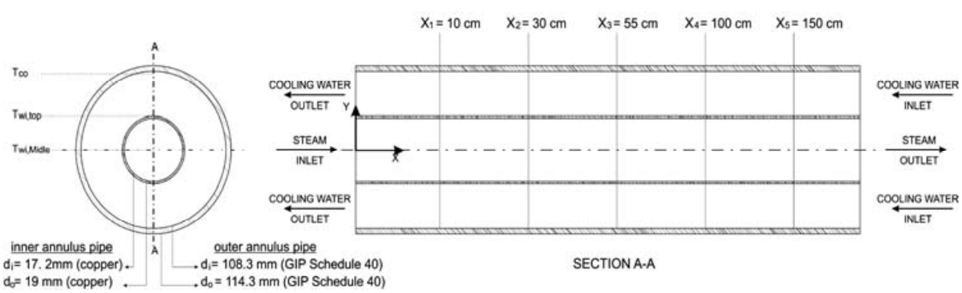

Figure 2. Temperature measurement in cross-section.

3. Results and Discussion

3.1. Axial temperature profiles

Axial temperature profiles on the top, side and bottom of the inner pipes of the horizontal tube annulus as a function of the inlet steam mass flow rate $(\dot{m}_{st})$ are respectively shown in Figures 3, 4 and 5. As shown in Figure 3, axial temperature profile at the bottom of pipe, for some variation of the inlet steam flow rate $(\dot{m}_{st})$ and under a constant cooling water mass flow rate of $\dot{m}_{co} = 4.23\,\text{kg/s}$, the highest temperature profile was observed at the largest $\dot{m}_{st}$ of $7.6\,\text{kg/s}$, and further it decreases with decreasing rate of $\dot{m}_{st}$, and the lowest temperature was noticed at the smallest $\dot{m}_{st}$ of $1.6\,\text{kg/s}$. Further observation from the Figure 3 at location of 10 cm to 30 cm from the inlet, temperature profile is close to saturation temperature for $\dot{m}_{st} = 2.6\,\text{kg/s}$ up to $7.6\,\text{kg/s}$. These data indicate condensation process. Meanwhile, at a position of 30 cm to 100 cm from the inlet, the temperature profile also shows the same tendency then rapidly decreases. Temperature at each point will be lower for $\dot{m}_{st}$ is smaller. This condition indicates that at this location the steam has been condensed and formed a layer with relatively similar thickness for all of $\dot{m}_{st}$ on the bottom. Meanwhile, at distance of 100 cm and 150 cm from the inlet, the temperature profile decline rapidly. This means that the thickness of an unstable condensate happens continuously and or one to the next location. From this analysis it can be deduced that the variation of the $\dot{m}_{st}$ from $2.6\,\text{kg/s}$ up to $7.6\,\text{kg/s}$ the thickness of condensate is relatively constant. It indicates that the flow pattern is wavy or wavy to slug. This condition is different compare to the smallest $\dot{m}_{st}$ of $1.6\,\text{kg/s}$. In this $\dot{m}_{st}$, temperature profile form a straight-lined decline, which indicates that the temperature decrease occurs linearly which means that the thickness of the condensate was formed more orderly and relatively constant. In comparison between Figure 3 and Figure 4, it is revealed that there are significant differences. In Figure 4, the variation of $\dot{m}_{st}$ of $2.6\,\text{kg/s}$ up to $7.6\,\text{kg/s}$, the temperature showed a similar trend at points located between 10 cm and 100 cm from inlet. This means that the conditions at the midpoint of the side of the annulus pipe is relatively similar for some of $\dot{m}_{st}$ variations, and start to change at point 150 cm from the inlet, where the smaller $\dot{m}_{st}$, local temperature is the lowest. For $\dot{m}_{st} = 1.6$ kg/s, the temperature has begun to decrease sharply between 55 cm to 150 cm from inlet. This condition indicates a layer of condensate began to fill the section of the pipe, such that the thermocouple was wetted by condensate. If Figures 3 and 4 are compared with the Figure 5, there are also very significant differences. Figure 5 describes the temperature profile at the top. From this figure, it can be explained that the profiles show a similar trend, and differ only after passing a point of 100 cm. The temperature profile at the point from 10 cm to 100 cm was relatively constant at saturation point. This means that the steam was condensing, except for the lowest $\dot{m}_{st}$ (1.6 kg/s) which has begun to slight down after a point 55 cm, that indicates that for the smallest $\dot{m}_{st}$, the steam was condensed earlier and closer to the inlet.

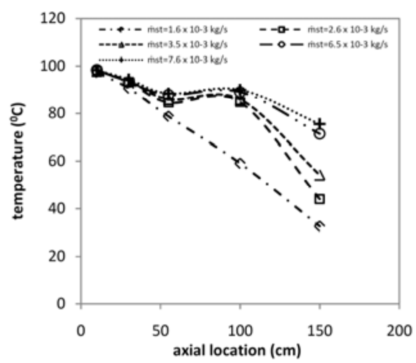

Figure 3. Axial temperature profiles at the bottom of the horizontal condenser pipe of the $\dot{m}_{st}$ variation.

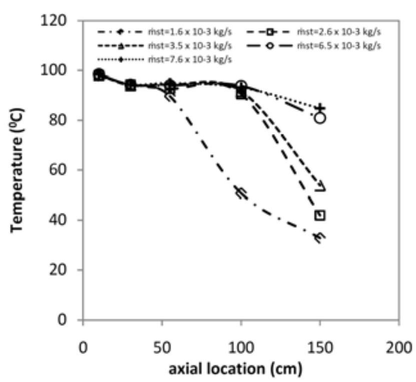

Figure 4. Axial temperature profiles at the side of the horizontal condenser pipe of the $\dot{m}_{st}$ variation.

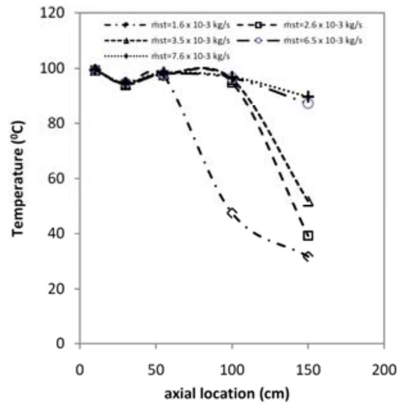

Figure 5. Axial Temperature Profiles at the top of the horizontal condenser pipe of the $\dot{m}_{\text{st}}$ variation.

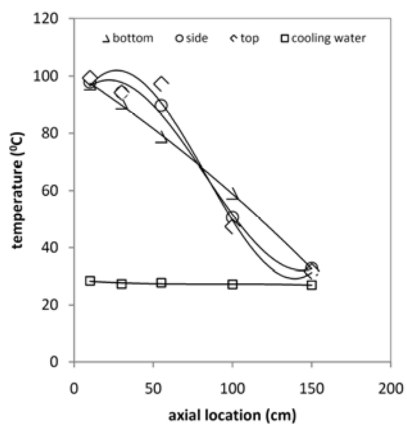

Figure 6. Temperature profile on the cross-section pipe test ($\dot{m}_{\text{st}} = 1.6 \times 10^{-3}\,\text{kg/s}$, $\dot{m}_{\text{co}} = 4.23\,\text{kg/s}$).

Figures 6 to 9 describe the temperature distribution in the test pipes at several locations. Close observation of Figure 6 reveals that the location of the point at the bottom of the annulus pipe, temperature profile decline linearly starting from 10 cm to 150 cm from the inlet, while at the location of the point on the side and top temperatures were relatively the same condition at the point 10 cm to 30 cm from the inlet, which indicates that condensation was taking place at this location, and then the temperature dropped at 30 cm to 150 cm from the inlet which shows that there has been additional layer forming of condensate. At 100 cm from the inlet, the temperature at the top is lower than that of the bottom. This is due to the location of condensation has occurred first and grains of condensate still stuck on the wall above the annulus pipe before falling down, thus condensate grain temperature being measured by the thermocouple is lower than the temperature of the condensate film at the bottom. According to Koch [3], the condensation droplets (drop wise condensation), as happened at the top of the heat transfer coefficient, has a value higher than that of the condensation layer (film condensation), as happens at the bottom, thus it becomes logical that for the case. This temperature is lower than that of the bottom. While at the same location (100 cm from the inlet), the temperature on the side were also lower compared with that of the bottom, it expresses that on this side thermocouples were more frequently touching the condensate rather than in contact with steam.

Figure 7 shows the same tendency for top, side and bottom, namely at the point of temperature measurement results were approximately constant for a point located at 10 cm to 100 cm from the inlet, and were still at a temperature of saturation, this indicates that process of condensation was taking place in that location. While the temperature on the side and bottom points are still in saturation temperature. This indicates that condensate has been formed at this location. Next, at points located at 100 to 150 cm from the inlet, conditions at the three locations possess the same trend that was downward sharply, this means that there has been a significant additional amount of condensate at this location.

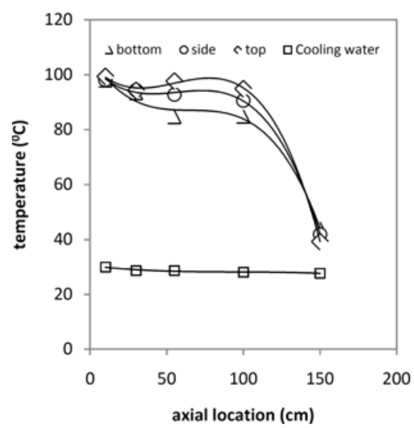

Figure 7. Typical of Temperature profile on the cross-section pipe test ($\dot{m}_{st}$ = 2.6 kg/s, 3.5 kg/s, 4.3 kg/s, 5.1 kg/s and $\dot{m}_{co}$ = 4.23 kg/s).

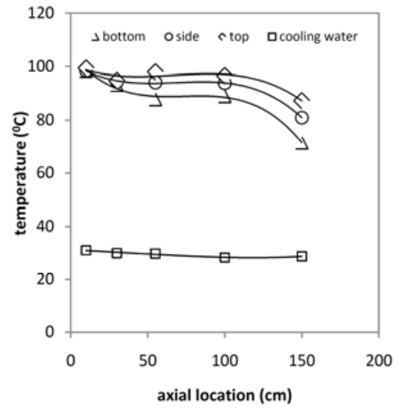

Figure 8. Temperature profile on the cross-section pipe test ($\dot{m}_{st} = 6.5\,kg/s$, $\dot{m}_{co} = 4.23\,kg/s$).

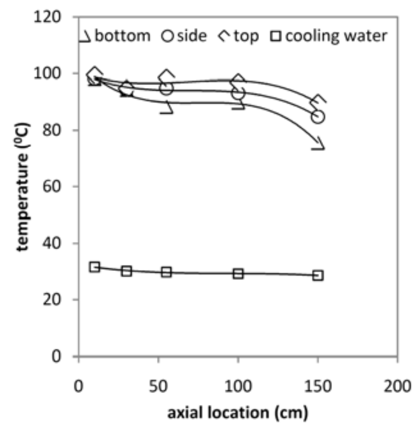

Figure 9. Temperature profile on the cross-section pipe test ($\dot{m}_{st} = 7.6\,kg/s$, $\dot{m}_{co} = 4.23\,kg/s$).

Next, Figures 8 and 9 show the different tendencies at the end, especially at 100 cm to 150 cm from the inlet. At 10 cm to 100 cm from the inlet have the same trend with Figure 7 relatively. From Figure 9, it can be explained that the temperature at the point of 100 cm and 150 cm from the inlet for the three position (bottom, side and top), was still quite high. These data indicate that the vapor dominates the flow rate that occurred in the condenser pipe, resulting in the instability of the flow of steam-condensate, causing the flow of condensate to be wavy. With increasing $\dot{m}_{st}$ it will increase the effects of larger instability or wave that occurred so and start to form a flow to slug wavy (wavy-slug) or even slugging and waterhammer. Cooling water discharge was kept constant $(\dot{m}_{co} = 4.23\,\text{kg/s})$, as well as its temperature distributions possess the same trend pattern, where the farther from the inlet temperature decreased linearly, the highest temperature of 31.67°C (at a point 10 cm from inlet) and the lowest 27.02°C (at a point 150 cm from the inlet) and the mean of 28.96°C.

3.2. Local heat transfer coefficient

The local wall heat fluxes on the annulus pipe were calculated by the wall inner surface-to-outer surface temperature measurement. Ideally, a heat covection and conduction calculation as in equation (1) should give the local wall heat flux:

$$h_{cl-wi}(r_{wi})(T_{cl} - T_{wi}) = \frac{(k_{wi-wo})(T_{wi} - T_{wo})}{\ln\frac{(r_{wo})}{r_{wi}}} = h_{wo-co}(r_{co})(T_{wo} - T_{co}). \quad (1)$$

Temperature on the top $(T_{wi,\,top})$, side $(T_{wi,\,side})$ and bottom $(T_{wi,\,bott})$ of inner wall of the annulus pipe and at inner wall of outer annulus pipe were measured, while temperature on the top $(T_{wo,\,top})$, side $(T_{wo,\,side})$, bottom $(T_{wo,\,bott})$, of outer wall of the annulus pipe and centerline (T_{cl}) were calculated. Conduction heat transfer of copper (k_{wi-wo}), can be found from data table, while the inner (d_i) and outer diameter (d_o) of pipe can be measured. Thus, the local heat transfer coefficient (h_{cl-wi}) can be calculated and shown in Figures 10 and 11.

Average heat transfer coefficient in the test pipe is calculated using the below equations

$$Q_{TS} = \dot{m}c_{p,\,st}(T_{st,\,out} - T_{st,\,in}), \quad (2)$$

$$h_{av} = \frac{Q_{TS}}{A_{inside}(T_{sat} - T_{wall})}, \quad (3)$$

$$A_{inside} = \pi d_i L. \quad (4)$$

Figure 10 illustrates the profiles of local heat transfer coefficient near the inner wall of the annulus pipe. From these figures it can be explained that the local heat transfer coefficient was influenced by the axial position of the inlet. The closer to the inlet the value of local heat transfer coefficient was larger.

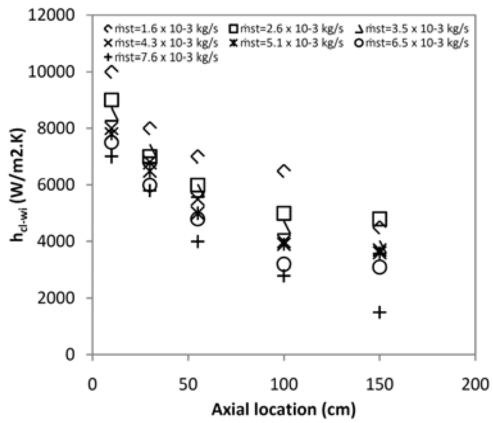

Figure 10. Typical of profile local heat transfer coefficient for $\dot{m}_{\mathrm{st}}$ variation.

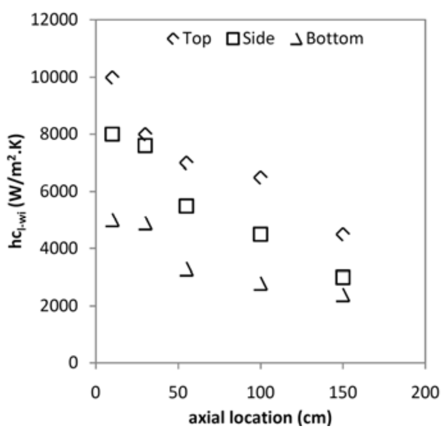

Figure 11. Typical of profile local heat transfer coefficient for radial position.

Local heat transfer coefficient $(h_{\mathrm{cl-wi}})$ on the top, side and bottom were shown in Figure 11. From this figure, it can be explained that the $h_{\mathrm{cl-wi}}$ was influenced by the radial and axial positions of the inlet. The closer to the inlet, the value was larger. Thus, the $h_{\mathrm{cl-wi}}$ on the top were highest, and followed by those on the side and the bottom.

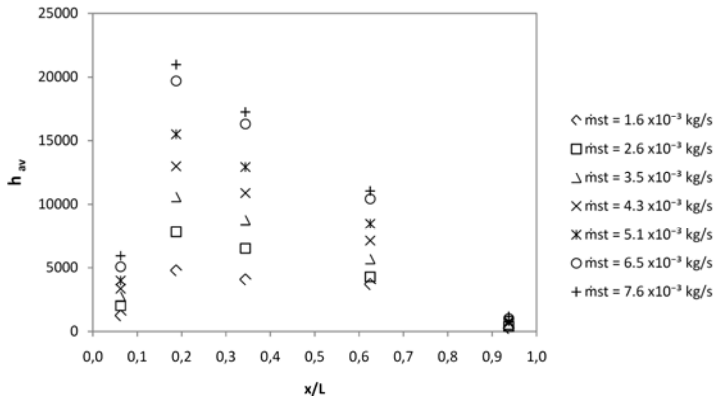

Figure 12. Average heat transfer coefficient in axial position.

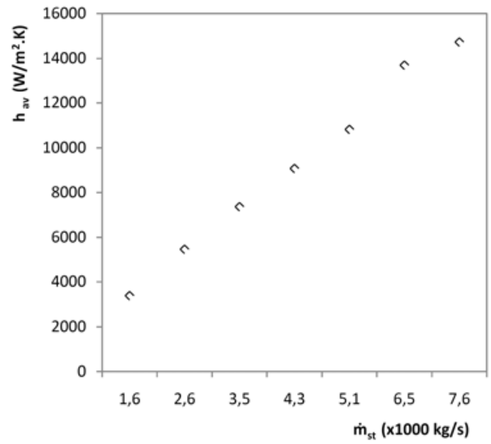

Figure 13. Average heat transfer coefficient.

Referring to Figure 12, it can be explained that the average heat transfer coefficient on the location of $x/L = 0.2$ to 0.6 are greater than $x/L = 0.0$ and $x/L = 0.8$. This indicates that in the location, the steam was being changed from vapor to liquid, so the coefficient of latent heat is dominant. While at the location $x/L = 0.0$, the steam was still at the superheated temperature and the location of $x/L = 0.8$, the steam has been changed to liquid. Thus, the amount of heat transfer coefficient on the location of $x/L = 0.2$ to 0.6 are greater than $x/L = 0.0$ and $x/L = 0.8$. Based on the Figure 13, it can be explained that the average heat transfer coefficient tends to increase linearly with increasing steam mass flow rate $(\dot{m}_{\mathrm{st}})$. These data revealed that the rate of heat transfer tends to be higher with increasing the $\dot{m}_{\mathrm{st}}$.

4. Conclusion

The local profiles of heat transfer coefficient during the steam condensation in a horizontal pipe were observed experimentally. The results are summarized as follows:

(1) Temperature profiles in the events of condensation in horizontal pipe were affected by the radial (cross-sectional) and axial positions along the annulus pipe, where the temperature of the upper radial position tends to be higher while farther away from the inlet temperature tends to be lower.

(2) The local heat transfer coefficient was influenced by the radial and axial positions of the inlet. The closer to the inlet, the value of local heat transfer coefficient was larger.

(3) The local heat transfer coefficients on the top were highest, and followed by those on the side and the bottom.

Nomenclature

d = diameter (m)

A = area (m^2)

Q_{TS} = Heat transfer rate (kW)

$\dot{m}$ = mass flow rate (kg/s)

sat = saturated

T = temperature $(^{\circ}C)$

h = local heat transfer coefficient $(W/m^2 \cdot K)$

k = conduction thermal coefficient $(W/m \cdot K)$

r = radius (m)

s = second

Hz = hertz

Subscript

i = inner

o = outer

w = wall

cl = centerline

co = coolant water

wo = wall-outer

wi = wall-inner

bott = bottom

st = steam

av = average

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