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Film-wise and drop-wise condensation of steam on short inclined plates

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Abstract

Film-wise and drop-wise condensation experiments were carried out at atmospheric pressure varying the condensing plates, their inclinations and orientations (upward or downward facing), and the air concentrations. As expected, drop-wise condensation showed much higher heat transfer rates than corresponding film-wise condensation in the pure steam cases. However, with the presence of air, both modes of condensation showed similar heat transfer rates due to the high thermal resistance of the air-rich layer. Both modes of condensation showed systematic decreases in heat transfer as the angle of the plate to the horizontal decreased and as the concentration of air increased. A noteworthy observation made during the tests on the plate orientation showed that condensation heat transfer rates on the upward facing plate were slightly higher than those beneath the downward facing plate in the pure steam cases but that the trends were reversed in the steam and air mixture cases.

Keywords: Film-wise condensation; Drop-wise condensation; Steam; Air; Inclination; Orientation; Short plate

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1. Introduction

Condensation has attracted many researchers' interests [1]. Numerous experimental and analytical studies have been devoted to explore the complexity of the phenomenon: its non-equilibrium characteristics, the different modes of condensation, the vapor mixture and the condensate flow regimes, the various kinds of vapors, the number of components, the geometrical configurations, etc. [2].

Following the pioneering analysis performed by Nusselt [3] on laminar free convection film-wise condensation, a number of studies were reported involving refinements to his assumptions concerning the effects of sub-cooling, the temperature profile in the condensate film, the effects of inertia and drag [4-6]. And his theory has been extended to condensation with the presence of a non-condensable gas [1, 6].

The identification of new mode of condensation by Schmidt et al. has led many experimental and theoretical researches on drop-wise condensation. Most of the drop-wise condensation experiments so far have been focused on the exploration of the promoters or surface conditions to achieve the stable formation of drop-wise condensation or the measurements of the absolute heat transfer rates on relatively simple geometrical configurations of vertical or horizontal plates or pipes [7-10].

The measured heat transfer coefficients of drop-wise condensations have been widely scattered, and only recently it was agreed that the heat transfer coefficients of the drop-wise condensation of steam are around 10 to 20 times higher than those of film-wise condensation [10]. Rose reported a detailed paper on various errors engaged in the measurements of drop-wise condensation heat transfer coefficients [11].

Among the tremendous number of studies, a limited number are addressing the fundamental characteristics of the phenomenon such as the effects of

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plate orientation, drop-wise condensation with the presence of air, and drop-wise condensation on inclined plates. Surprisingly few compare both modes of condensation in the same test facility.

Chung et al. reported a series of fundamental experimental results using a short condensing plate focusing on waveless leading edge phenomena. They investigated the effects of a slow flowing mixture on the water film and air-rich layer experimentally [12]. Also, they proposed the experimental evidence of dealing with drop-wise condensation of a steam/air mixture as film-wise condensation where the air-rich layer forms high thermal resistance [13]. The effects of plate orientation to the condensation heat transfer were also discussed [14].

This paper presents experimental results comparing the film-wise and drop-wise condensation of steam and mixtures of steam and air at atmospheric pressure. Using the same test rig, but different condensing plates specially made to promote one mode of condensation, both film-wise and drop-wise condensation heat transfer rates were measured by varying the air concentrations and plate inclination and its orientation (upward or downward facing). The originality of the work is to compare both modes of condensation in various test conditions in the same test rig.

2. Experimental apparatus

2.1 General description

A schematic diagram of the MUCON (Manchester University CONdensation) test facility is shown in Fig. 1. Water is supplied to the steam boiler by a degassing system that controls the air concentration of the water to ppm level. The boiler generates steam steadily at a rate that is controlled by the power input to the electrical immersion heaters. On leaving the boiler and passing through a separator section, the steam flows into a mixing chamber where it joins a flow of air that has been preheated so as to cause the vapor in the resulting mixture to be in the dry saturated condition when it enters the test section. The mixture of steam and air leaving the test section passes to a shell and tube heat exchanger where the residual steam is fully condensed. The condensate collected from the test section, the shell and tube heat exchanger and the separator is returned to the water degassing system. A more detailed description of the MUCON facility is found in the paper by Jackson et al. [15].

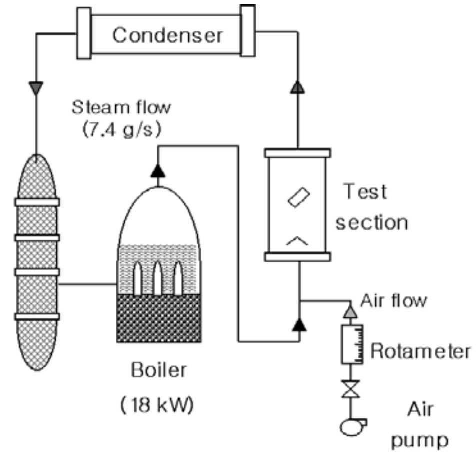

Fig. 1. Schematic diagram of MUCON test facility.

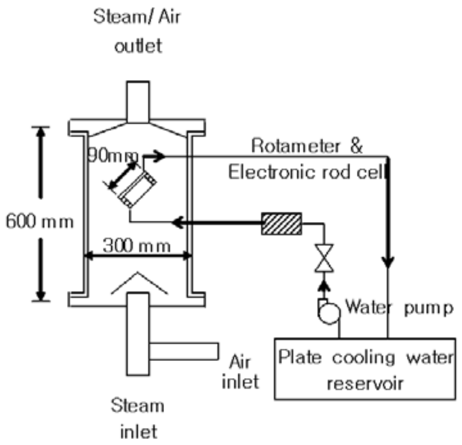

Fig. 2. Test section.

2.2 Test section

Fig. 2 shows a schematic of the test section, which is of diameter 0.3 m and height 0.6 m and is made of Pyrex glass. A water-cooled condensing plate with a plate angle adjustable arrangement is located in the test section. A mixing plate covers the steam/air mixture inlet in order to prevent direct exposure of steam/air mixture flow to the plate. Two thermocouples located within the test section at the top and bottom measure the vapor temperatures at these locations. The steam/air mixture enters the test section through the base and flows upwards slowly over the condensing plate.

2.3 Condensing plates

The condensing plates are made of two copper

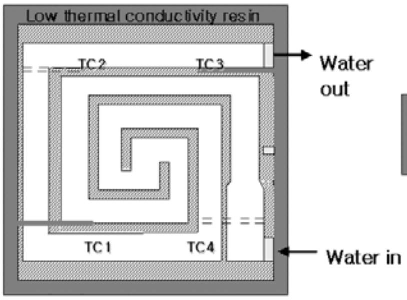

Fig. 3. Condensing plate geometry.

shells brazed together. The internal consists of a spiral channel as shown in Fig. 3 that guarantees high surface temperature uniformity and high turbulence for the whole range of cooling water flow rates. The four edge sides of the plate are covered with a 5 mm thick low thermal conductivity resin. One side of the plate was covered with perspecs which acted as thermal insulation and the other side of the plate was exposed to the steam/air mixture.

A variety of suitable treatments were tried with a view to pioneering film-wise condensation over the full area of the condensing plate. The approach finally adopted was to shot blast the surface and then expose it to a flowing mixture of steam and air for more than 50 hours to get a stable oxidation layer on the surface. After the treatment, the surface was found to promote a film-wise condensation uniformly and in a stable and repeatable manner.

The drop-wise condensing plate was also made of copper. Its surface was coated firstly with a thin layer of nickel and then with one of chromium. This surface promotes drop-wise condensation of steam in a very stable manner over an extended operational time of about 600 hours.

Four thermocouples are embedded 0.5 mm below the condensing surface in order to measure the surface temperature. Thermocouples are located in the cooling water flow channel at the inlet and outlet to enable the temperature rise of the coolant to be measured. The rate of heat transfer is reliably measured calorimetrically as follows:

$$Q = mC_p(T_{out} - T_{in}) \qquad (1)$$

where m is the cooling water flow rate measured both by an electric flow cell and a rotameter, C_p is the specific heat of cooling water and T_{in}, T_{out} are inlet and outlet temperatures.

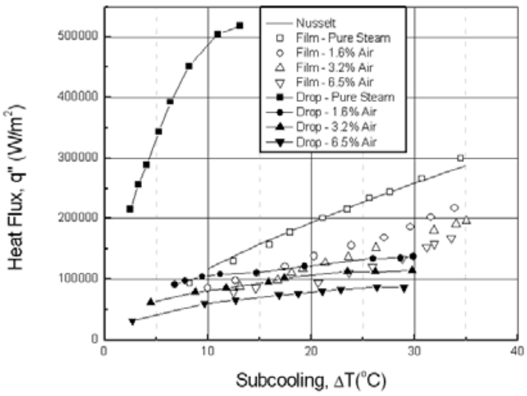

Fig. 4. Vertical condensing plate.

2.4 Test program

The experiments were performed at atmospheric pressure. The mass flow rate of the steam was fixed at 7.4 g/sec and the air mass fractions were varied 0, 1.6, 3.2, and 6.5%. The plate inclinations were varied 5 and 20 degrees and vertical and for the inclined plates, the plate orientations were adjusted either upward or downward facing. Heat transfer rates were measured for a range of sub-cooling of the surface from about 10 to 35 °C using two types of condensing plates promoting film-wise or drop-wise condensation respectively. As the plate surface temperature was maintained by the heating from the steam-air mixture and cooling from the coolant flow, the sub-cooling temperature was controlled by both coolant reservoir temperature and coolant flow rate to the condensing plate.

3. Results and discussions

The experimental results on the film-wise and drop-wise condensation heat transfer rates on vertical plates along with Nusselt prediction are presented in Fig. 4. The horizontal axis shows the sub-cooling temperature, which is defined by the temperature difference between the steam and the condensing plate surface, and the vertical axis shows the measured condensation heat flux calculated by the heat transfer rate from equation (1) divided by the condensing plate surface area. The solid line denotes the predictions from Nusselt analysis, which was re-evaluated by Rohsenow to account for the nonlinear temperature distribution [4]:

$$h = 0.943\left[\frac{\rho(\rho-\rho_V)gk^3(h_{fg}+0.68C_p\Delta T)}{L\mu\Delta T}\right]^{1/4} \qquad (2)$$

where h is the condensation heat transfer coefficient, ρ, ρ_v the densities of water and vapor, g the acceleration of gravity, k the thermal conductivity of water, h_{fg} the latent heat of condensation, ΔT the sub-cooling temperature, μ the viscosity of water, L the length of the condensing plate. The effect of variation of viscosity with temperature was also approximated by using above equation with properties k, ρ and C_p evaluated at the temperature suggested by Minkowycz and Sparrow [6].

The film-wise condensation heat transfer rate in the pure steam case shows broad agreement with the Nusselt predictions. The heat transfer seems unaffected by the slow steam flow over the condensing plate. The drop-wise condensation in the pure steam cases showed 3 to 6 times higher heat transfer rates than film-wise condensation, which should be up to 10 to 20 times according to Rose [11]. Based upon his discussions on the accuracy of the measurements, this difference seems to be caused by a few ppm of non-condensable gas in the vapor, as it can lead to a significant additional temperature difference in the vapor near the condensate surface. As the test apparatus allows ppm order of air despite the degassing column, the discrepancy between the results in this study and Rose's figures are probably due to steam containing a few ppm of non-condensable gases. However, in the air injection cases, the effects of the ppm order of non-condensable gas are negligible.

The maximum sub-cooling temperature of only about 13 °C could be achieved in the drop-wise condensation tests as the high drop-wise condensation heat transfer rate to the condensing plate in the pure steam case overwhelmed the cooling from the plate cooling water system.

In the steam-air mixture cases, both film-wise and drop-wise condensation heat transfer rates were similar in range and heat fluxes show systematic decreases as the mass fraction of air increases in both film-wise and drop-wise condensations. As the condensation heat transfer rates with the presence of air are more limited by the thermal resistance of the air rich layer than the mode of condensation, it is not surprising that the differences in the condensation modes do not result in large differences in heat transfer rates. The drop-wise condensation showed even lower heat transfer rates than film-wise condensation except for the small sub-cooling ranges, and this trend seems to be stronger at higher air concentrations. As the sub-cooling increased, due to the differences in the disturbances of the condensate flows (wide and slow water film vs. narrow and fast water rivulets) to the air rich layer, the film-wise condensation showed slightly higher heat transfer rate increases than the drop-wise condensation [13].

Figs. 5 and 6 show the drop-wise and film-wise condensation test results with the plate inclined at 20°. The solid and open symbols, corresponding to FU and FD in the legend, present the test results for the upward and downward facing plate, respectively, and the solid line denotes the prediction from Nusselt analysis for the 20° inclined plate. Both modes of condensation, except for the absolute heat fluxes, show a similar pattern depending on the test conditions. The heat transfer rates are smaller than those of the vertical cases for corresponding air concentrations.

For the pure steam case, comparison of the solid and open squares in Figs. 5 and 6 reveals that the upward facing plate shows higher heat transfer rates than the downward facing one even though the downward facing plate meets the steam flow directly from below. In the pure steam cases, the only thermal resistances of the condensation heat transfers are due to the thickness of the condensate film and droplets, respectively. It was observed during tests that the condensate film and rivulets run down along the downward facing plate and fall down in the edge of the plates instead of falling down by the gravity at their places of generation due to an adsorption or a surface tension effect by the molecular forces. With this effect together with the gravitational force, the condensate film and droplets upon the upward facing plate seem to spread more while that beneath the downward facing one is prolonged. Thus, the higher heat transfer rate of the upward facing plate may be

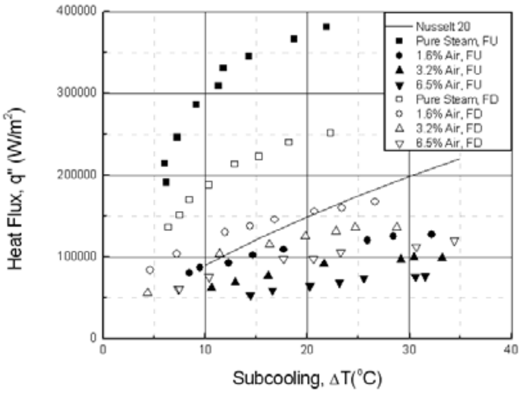

Fig. 5. Inclined condensing plate (20 degrees, Drop-wise).

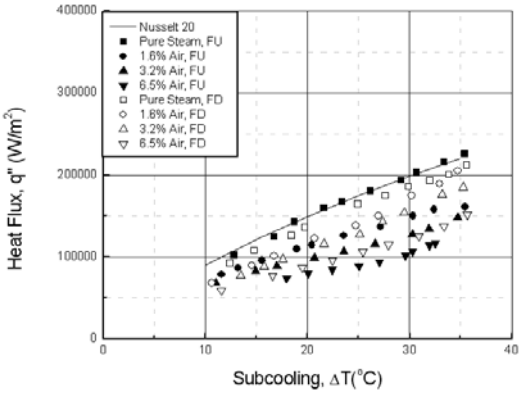

Fig. 6. Inclined condensing plate (20 degrees, Film-wise).

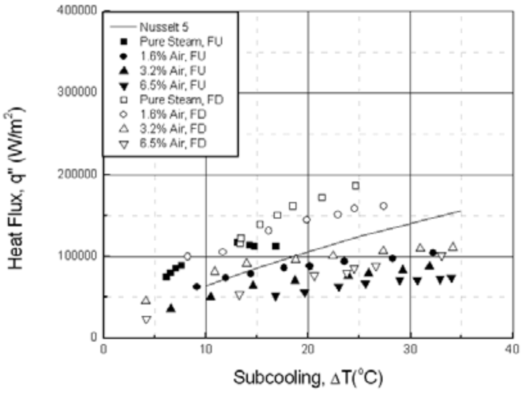

Fig. 7. Inclined condensing plate (5 degrees, Drop-wise).

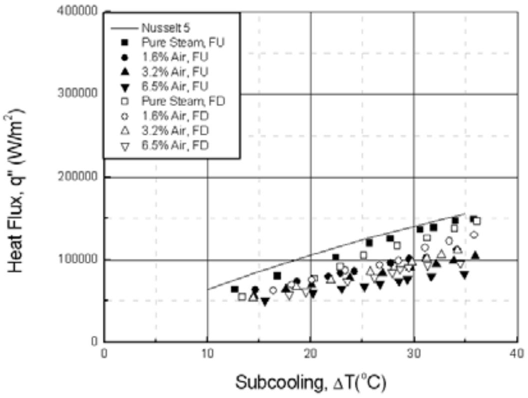

Fig. 8. Inclined condensing plate (5 degrees, Film-wise).

Table 1. Summary of experimental observations.

Effect	Cases	Heat Transfer	Cause
Orientation	Pure steam	$q''_{FU} > q''_{FD}$	Condensate spreading
	Mixture	$q''_{FU} < q''_{FD}$	Air-rich layer stability
Condensation mode	Pure steam	$q''_{Drop} >> q''_{Film}$	Wetting characteristics
	Mixture	$q''_{Drop} \sim q''_{Film}$	Air-rich layer controls

explained by the thinner water film and flat droplets.

Now, if we focus our attention on the solid and open triangle curves in both figures, which are for 6.5% air mass fraction, the open triangles are always above the solid ones, which means that the downward facing plate shows higher heat transfer rates.

The presence of non-condensable gas will result in an additional thermal resistance by the formation of an air-rich layer. As it has much larger thermal resistance than the condensate film or water droplets, the condensation heat transfer is controlled more by the thermal resistance of the air-rich layer. The molecular weights of air and steam are 28.97 and 18.0005, respectively, which means the air-rich layer is heavier than the bulk mixture of air and steam. Hence, the air-rich layer on the upward facing plate is stable, while that beneath the downward facing plate is unstable. Also, steam from below has negligible drag effect on the water film, but the steam-air mixture does disturb the relatively light air-rich layer. The important observations are summarized in Table 1.

Similar trends are observed in the inclined plates at 5 degrees shown in Figs. 7 and 8. At low inclinations, due to the low heat flux and condensate flow rate, the factors not considered by Nusselt analysis, such as surface tension, become important and affect the heat flux. The test result for the pure steam showed slightly lower heat flux than that predicted by Nusselt analysis.

The measurement errors were estimated to be less than 10% through the tests, which is calculated by expanding Equation (1) and assuming 5% measurement error for flow rate and 0.1 °C error for temperature.

$$\delta Q = m C_p \Delta T \left[\left| \frac{\delta m}{m} \right| + \left| \frac{\delta(\Delta T)}{\Delta T} \right| \right] \qquad (3)$$

However, the calorimetric measurement of heat transfer rates permits larger error in low sub-cooling temperatures when there is small difference in inlet and outlet cooling water temperatures. Thus, larger measurement errors were engaged in small sub-cooling ranges. Also, maximum 5% of temperature differences were observed in the four thermocouples embedded in the condensing plates, which means that the plate surface temperature was not perfectly uniform.

4. Conclusions

A program of drop-wise and film-wise condensation experiments was carried out at atmospheric pressure varying the plates, plate inclinations, the orientations and the air concentrations. For all inclinations, the film-wise condensation test results for pure steam showed good agreement with the predictions of the Nusselt analyses for the corresponding inclinations and the small steam flow does not affect the heat transfer.

In the pure steam cases, the drop-wise condensation showed only 3 to 6 times higher heat transfer rates than film-wise condensation due to the ppm order of air contained in the steam as pointed out by Rose [11]. However, in the steam/air mixture cases, the film-wise and drop-wise condensation showed similar range of heat transfer rates, as the heat transfer rates are governed more by the thermal resistance of the air-rich layer than by the mode of condensation. Hence, it is modestly concluded that for the steam and air mixture cases, the drop-wise heat transfer can be reasonably approximated by the film-wise condensation heat transfer correlations.

Systematic reductions in heat transfer rates were observed as the air concentration increased and as the angle of the condensing plate to the horizontal decreased in both modes of condensation.

A noteworthy observation was made as to the effect of plate orientation. In the pure steam case, the upward facing plate shows higher heat transfer rates than the downward facing one for all inclinations due to the spreading of water film or water rivulets. However in the steam and air mixture cases, the downward facing plate shows higher heat transfer rates than the upward facing one for all inclinations, which seems to result from both the buoyancy effect caused by the density difference between steam and air and the disturbance of the air-rich layer by the mixture flows.

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Nomenclature

C_p : Specific heat of condensing plate cooling water
g : Acceleration of gravity
h : Condensation heat transfer coefficient
h_{fg} : Latent heat of condensation
k : Thermal conductivity of water
L : Length of the condensing plate
m : Condensing plate cooling water flow rate
Q : Rate of heat transfer
Q'' : Heat flux
T : Temperature
ΔT : Sub-cooling temperature

Greek symbols

μ : Viscosity of water
ρ : Density of water
ρ_v : Density of vapor

Subscripts

Drop : Drop-wise condensation
Film : Film-wise condensation
FD : Downward facing
FU : Upward facing
in : Inlet
out : Outlet
v : Vapor

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