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An Experimental Study of the Effects of Inclination and Air Concentration on Film Condensation on a Flat Plate Facing Upwards and Downwards

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응축판의 기울기와 공기함량이 필름응축에 미치는 영향에 관한 실험적 연구

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ABSTRACT

Rates of heat transfer have been measured on a water-cooled flat plate promoting film condensation as steam and mixtures of steam and air flowed over it. The rates of heat transfer decreased as the angle of the plate to the horizontal was reduced and as the concentration of air was increased. A notable observation was that comparison of results for the upward and downward facing cases showed that the heat transfer rates with pure steam are higher for an upward facing plate than for a downward facing one. However, with air present in the steam, this trend is reversed. In the case of pure steam, the test results show good agreement with predictions made using the Nusselt theory.

Key Words : Film, Condensation, Inclination, Plate, Steam, Air, Heat transfer

Ⅰ. Introduction

Condensation has been an important and challenging area of heat transfer research since the appearance of the first steam surface condenser for a marine engine in 1860[1]. The complexity of the phenomena involved stems from the different modes of condensation depending on the wetting characteristics of the surface(film-wise vs. drop-wise), the vapour mixture flow patterns(free convection vs. forced convection), the condensate flow regimes(laminar vs. turbulent), the various kinds of vapour and the number of components, and the different geometrical configurations[2].

Following the pioneering analysis performed by Nusselt on film condensation, a number of studies were reported involving refinements to his assumptions

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concerning the effects of sub-cooling. the temperature profile in the condensate film. the effects of inertia and drag. etc.[3-7].

It soon became apparent that even a small quantity of non-condensable gas in the condensing vapour had a profound influence on the resistance to heat transfer through the region of the liquid-vapour interface[8. 9].

Difference in geometrical configuration leads different balance of forces and energies and results in different heat transfer. So far. not many different configurations were tried. Most of condensation researches were devoted to vertical or horizontal plates/pipes. As to the effects of the plate inclination on condensation. the present state of knowledge simply suggests the use of a reduced gravitational acceleration caused by the inclination of the plate[8. 9].

Relatively few studies concerned with downward facing surfaces have been reported. Gerstmann and Griffith observed film condensation phenomena using a horizontal and inclined downward facing plate. They identified three distinct condensate flow regimes : glassy and smooth flow. developing wave flow. and ruptured interface. However the observations from a long plate could not deal with the waveless near edge phenomena in detail and the observations were only from downward facing plates[10].

Anderson and Corradini performed condensation tests using a mixture of steam and non-condensable gas in an environment simulating an AP-600 nuclear reactor containment. But as the study was aimed developing an experimental correlation readily applicable to the accident analyses. it dealt with overall aspects of behavior and did not provide information concerning the detailed independent phenomena[11].

In the present investigation. as an extended study on the effect of geometrical configurations. we focused on identifying the variations in film condensation heat transfer at various inclinations comparing the upward and downward facing plates.

II. Apparatus and Experiments

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 the degassing system. The boiler generates steam steadily at a rate. which 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 which has been preheated so as to cause the vapour in the resulting mixture to be in the dry saturated condition when it enters the test section. The test section is a cylindrical vessel which has a water-cooled condensing plate suspended in it. 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 can be found in the paper by Jackson et. al.[12].

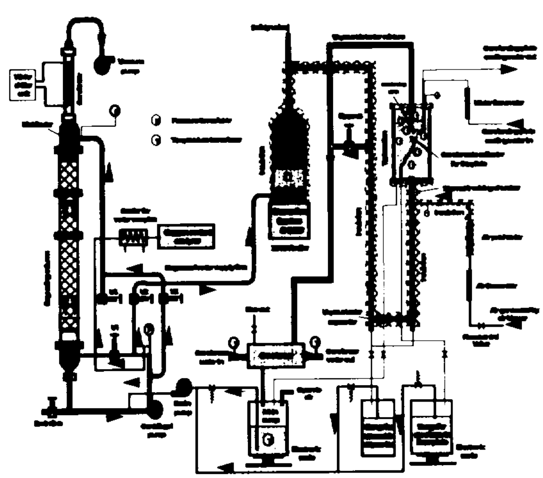

Fig. 1. A Schematic Diagram of MUCON Test Rig.

2. Degassing System

The water supply system consists of a degassing column. a vacuum pump. a water circulating pump. associated pipelines and an oxygen content analyser. The column is of diameter 0.24 m and height 3.0 m and is made of pyrex glass. as also are the various pipelines. It contains a packed bed of small stainless steel rings. Water delivered by the circulating pump is sprayed onto the bed of rings from a distributor at the top. A condenser. which is supplied with cooling water from a chiller unit. is mounted vertically above the degassing column. The top of the condenser is connected to a vacuum pump. The degassing system is able to reduce the oxygen concentration in the water to a fraction of a milligram of oxygen per kilogram of water.

3. Steam Supply System

The pyrex glass boiler shell is a cylindrical vessel of diameter 0.3 m and height 1.4 m which has a domed top. It contains three electrical immersion heaters. each rated at 9 kW. which are mounted vertically within it on a stainless steel base. The power supplied to these heaters can be controlled independently. The boiler is instrumented to enable the steam delivery temperature and pressure to be measured. Under conditions of maximum power input. water is evaporated in the boiler at a rate of about 0.015 kg/s. The steam produced by the boiler passes through a thermally insulated U shaped section which acts as a separator. Water collects at the bottom of the downward leg from where it drains to a sump. The steam passes upwards from the separator to the steam/air mixing chamber.

4. Air Supply System and Steam/Air Mixing Chamber

Air drawn from the laboratory by a small centrifugal blower passes through a filter and an electrical preheater. The flow rate can be adjusted manually using a control valve and is measured using a rotameter. Dry steam from the boiler and hot air from the preheater flow into a pyrex glass tube containing number of horizontal perforated plates which serves as a mixing chamber.

5. Test Section

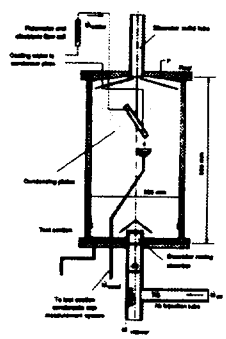

Fig. 2 Test Section.

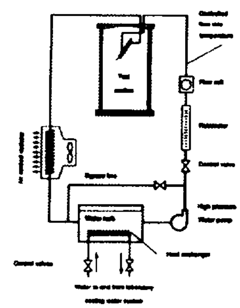

Fig. 3 Plate Cooling System.

Fig. 2 shows a schematic of the test section. which is of diameter 0.3 m and height 0.6 m and is also made of pyrex glass. Within it. a water-cooled condensing plate is suspended from the top by an arrangement which allows the plate orientation to be varied. Two thermocouples are located within the test section at the top and bottom to measure the vapour temperature at these locations. The steam/air mixture enters the test section through the base and flows upwards over the condensing plate. On the base of the test section there are two condensate collectors. The outside one collects any condensate which is formed on the test section wall. This is minimal because the heat loss to the surroundings is small. The central collector catches condensate which falls from the condensing plate. This drains to a sump. The rate at which condensate is produced can be determined from measurements of the weight of the sump and contents. After a series of commissioning tests, it was concluded that the rate of heat transfer could also be reliably measured calorimetrically as follows:

$$Q = \dot{m} C_p (T_{out} - T_{in}) \qquad (1)$$

The mixture of residual vapour and air leaves the test section at the top and is ducted through pyrex glass tubing to a water-cooled shell and tube heat exchanger.

6. Condensing Plate

Fig. 3 shows the cooling water system for the condensing plate. The condensing plate is shown in Fig. 4. The plate is made of two copper shells brazed together. The internal consists of a spiral channel that guarantees high surface temperature uniformity and high turbulence for the whole range of cooling water flow rates. It helps the internal side heat transfer coefficient to be almost constant during the experiments. 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.

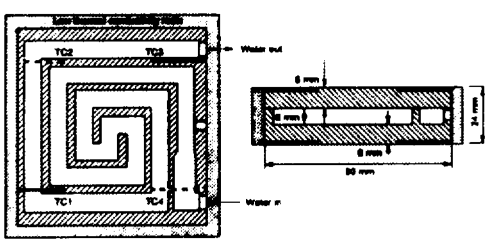

Fig. 4. Condensing Plate Geometry.

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 which finally adopted was to shot blast the surface and then expose it to a flowing mixture of steam and air for 50 hours to get stable oxidation layer on the surface. After this treatment, the surface was found to promote a film condensation uniformly and in a stable and repeatable manners.

7. Test Matrix and Experimental Procedure

A programme of experiments was carried out varying the plate inclination and its orientation (facing upwards or facing downwards). The inclination was varied from 5 degrees from the horizontal to vertical as shown in Table 1. Keeping the steam flow rate constant at 7.4 g/s maintaining the electrical power of 18 kW, the air flow rate was varied to give air mass fractions from 0 to 6.5 %.

Table 1. Test matrix

Air mass fraction	Inclination Angle			
	5°	20°	45°	Vertical
0 %	FU/FD	FU/FD	FU/FD	FU
1.6 %	FU/FD	FU/FD	FU/FD	FU
3.3 %	FU/FD	FU/FD	FU/FD	FU
6.5 %	FU/FD	FU/FD	FU/FD	FU

* FU/FD : upward facing/downward facing

Heat transfer rates were measured for a range of sub-cooling of the surface from about 10 to 35 °C, which were controlled by varying the cooling water flow rate and reservoir temperature. During the test, as the heat is transferred to the condensing plate, the cooling water reservoir temperature increases. In the steam and air mixture cases, the condensation heat transfer rates were measured starting with a low reservoir temperature and high water flow rate by decreasing the flow rate with mild increase in the reservoir temperature. However in the pure steam cases, the reservoir temperature increased quickly due to relatively higher heat transfer rate. Thus in order to get enough data points, the heat transfer rates were measured starting with a high reservoir temperature and low water flow rate by increasing mass flow rate and by cooling the reservoir.

III. Results and Discussions

1. Vertical Case

Fig. 5 shows the results for the vertical case. The solid line denotes the prediction from the Nusselt analysis, which was reevaluated by Rohsenow to account for the nonlinear temperature distribution[9].

$$h = 0.943\left[\frac{\rho(\rho-\rho_v)(g\sin\theta)k^3(h_{fg}+0.68C_p\Delta T)}{L\mu(T_s - T_w)}\right]^{1/4}$$

The effect of variation of viscosity with temperature was approximated by using equation (2) with properties, k, ρ, and Cp evaluated at the temperature suggested by Minkowycz and Sparrow[9].

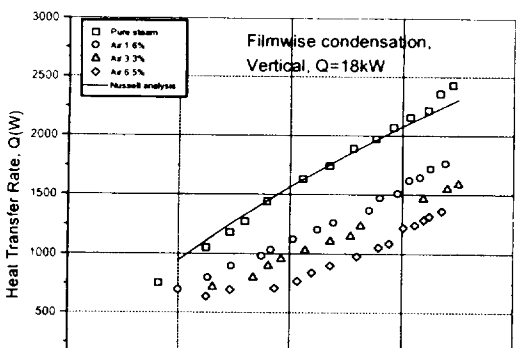

Fig. 5. Vertical Case.

As can be seen, the pure steam case shows good agreement with the Nusselt predictions.

As the air concentration increases, the heat transfer rates reduce systematically. With the 1.6% air concentration, the heat transfer rate at the sub-cooling temperature of 32 °C reduces about 500 W from that of pure steam case, and then subject to further increase in air concentration, the reduction rate in heat transfer is reduced.

2. 45 Degrees Case

Fig. 6 shows the results with the plate inclined at 45 degrees for both the upward and downward facing cases. The heat transfer rates are smaller than the vertical case for corresponding air concentrations.

For the pure steam case, it is observed that the upward facing plate shows higher heat transfer rates than downward facing one. With pure steam, the thermal resistance to the film condensation phenomena is due to the condensate film. Thus the heat transfer will be enhanced if the film thickness is reduced.

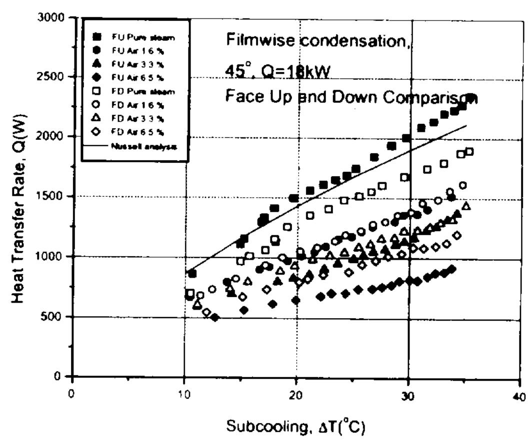

Fig. 6. 45 Degrees Case.

The experimental observation of the water film running down beneath the downward facing plate instead of falling by the gravitational force, shows that the surface tension force is larger than the gravitational force in this short plate experiments. where the condensate-vapour interface doesn't rupture. It is apparent that the condensate film upon the upward facing plate will spread more and form thinner water film than in the downward facing case. This can be an explanation on the reason why in the pure steam cases. the upward facing plates show slightly higher heat transfer rates than the downward facing ones.

Now. if we focus attention on the solid and open triangle curves. which are for 6.5% air concentration. 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 air rich layer in the vicinity of the liquid-vapour interface. It is well known that condensation in the presence of air is limited by the diffusion capability of the steam through air rich layer. Furthermore the thermal resistance of the condensate film is small compared to that of the air rich layer.

The molecular weights of air and steam are 28.97 and 18.0005 respectively. That means that the air rich layer is heavier than the bulk mixture of air and steam. Thus for the upward facing plate. the air rich layer will be stable in the view point of gravity. However for the downward facing plate. the air rich layer will be unstable because the mixture is lighter than the air rich layer. Thus the thinner air rich layer beneath the downward facing plate will result in higher rate of condensation than for one on the upward facing plate.

Furthermore the mixture velocity of about 10 cm/sec seems to be strong enough to disturb the air rich layer underneath the downward facing plate together with the weight difference between steam and air. which is not enough to alter the heat transfer rate in the pure steam case because it is negligible compared to a characteristic vapour molecular velocity defined by $(2RT/M)^{1/2}$.

3. 20 and 5 Degrees Cases

Similar trends were observed for 20 and 5 degrees except that the absolute values of the heat transfer rate were smaller. The results are shown on Figs. 7 and 8. Once again it is notable that the Nusselt analysis predicts the test results for pure steam cases reasonably well.

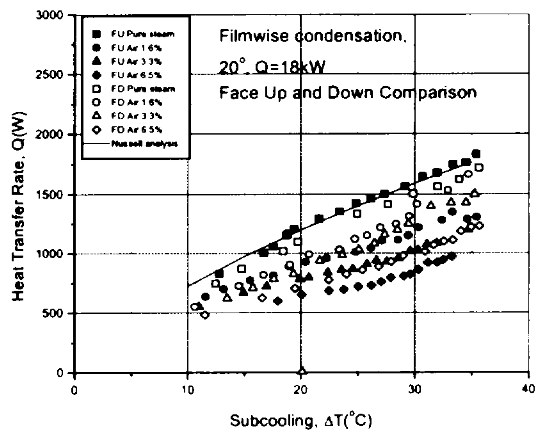

Fig. 7. 20 Degrees Case.

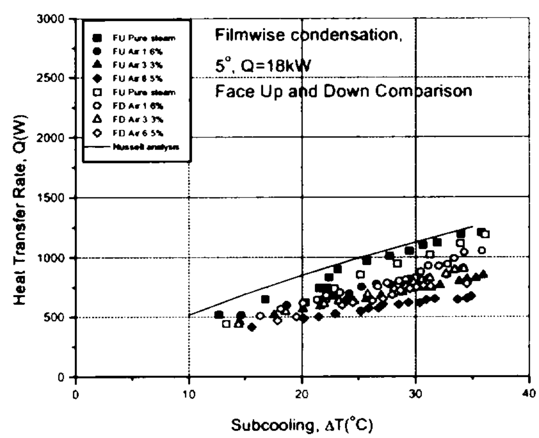

Fig. 8. 5 Degrees Case.

Ⅵ. Conclusions

A programme of film condensation experiments concerning the effects of plate inclination. orientation and air mass fraction were performed using a short plate in MUCON test facility.

The test results for pure steam show good agreement with the predictions of the Nusselt analysis. As expected. the heat transfer rates increase with the increase of sub-cooling and inclination to the horizontal and the heat transfer rates reduce with the increasing air mass fraction.

As to the effect of plate inclination and orientation. in the pure steam case. the upward facing plate shows higher heat transfer rates than the downward facing case for all inclinations due to the spreading effect of water film.

However in the steam and air mixture cases. downward facing plate shows higher heat transfer rates than the upward facing one for all inclinations. which seems to result from both the weight difference between steam and air and the disturbance of air rich layer underneath the downward facing plate by mixture blowing velocity.

Nomenclature

c_p : specific heat at constant pressure. liquid $[J \cdot kg^{-1} \cdot K^{-1}]$

g : acceleration of gravity $[m \cdot s^{-2}]$

h : heat transfer coefficient $[W \cdot m^{-2} \cdot K^{-1}]$

h_{fg} : latent heat of condensation $[J \cdot kg^{-1}]$

k : thermal conductivity of liquid $[W \cdot m^{-1} \cdot K^{-1}]$

L : length of the cooling plate $[m]$

M : molecular weight $[kg \cdot kmole^{-1}]$

$\dot{m}$: plate cooling water mass flow rate $[kg \cdot s^{-1}]$

Q : heat transfer rate $[W]$

R : gas constant $[J \cdot kg^{-1} \cdot K^{-1}]$

T : temperature $[K]$

Greek symbols

ρ : density of liquid $[kg \cdot m^{-3}]$

μ : viscosity of liquid $[kg \cdot m^{-1} \cdot s^{-1}]$

θ : angle from the horizontal

Subscripts

s : properties at saturation pressure

w : properties at wall temperature

ref : reference values

out : plate cooling water outlet

in : plate cooling water inlet

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