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Steam Condensation on Vertical, Inclined and Horizontal Surfaces Faced Up or Down in the Presence of Noncondensable Gases

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Abstract

Condensation of steam in the presence of noncondensable gas on a vertical, inclined and horizontal surface faced up or down is investigated using the MUCON(Manchester University CONdensation) facility. The MUCON work package was undertaken with the aim of extending the database currently available on the condensation of steam in the presence of noncondensable gases and thereby improving the empirical input to thermal-hydraulic codes which might be used for the design and safety assessment of advanced water-cooled nuclear reactors. A sand-blasted copper plate is used for filmwise condensation. One side of the copper plate is exposed to a steam / air mixture with various inclination angles. The condensing surface is installed face-up or face-down so that condensation can occur on the upper side or underside of a plate surface, respectively. The condensing plate can be adjusted to have different inclinations of 0^o, 5^o, 20^o, 45^o and 90^o. Given the inclination and surface installation, i.e., face-up or face-down, various air mass fractions up to 6.5% have been covered.

1 Introduction

In the future, passive decay heat removal systems will play an important part in improving the safety of advanced water-cooled reactors. Design studies for nuclear reactors utilising such new concepts have indicated that there is a need to improve our understanding of a number of aspects of heat transfer and thermal hydraulics, and to extend existing databases and produce better correlations. The influence of noncondensable gas on the condensation of steam is one such area where additional research is needed. A typical example is given by the PCCS(Passive Containment Cooling System) of the AP600, where steam released during an unanticipated transient or accident condenses on a cold wall with noncondensables. One is especially interested in determining the effect of orientation on condensation heat transfer coefficient because the containment has many cold surfaces with large areas at different angles of orientation.(Huhtiniemi et al. (1989), Cho and Stein (1989), Gerstmann and Griffith (1967)) Such particular effects of orientation on condensation heat transfer with a noncondensable was not fully investigated in the past. To determine this particular type of condensation phenomenon a series of experiments have been carried out in a controlled method using a steam/air mixture. This paper describes the experimental results for the first test series of the program.

2 Experimental Work

2.1 Loop description

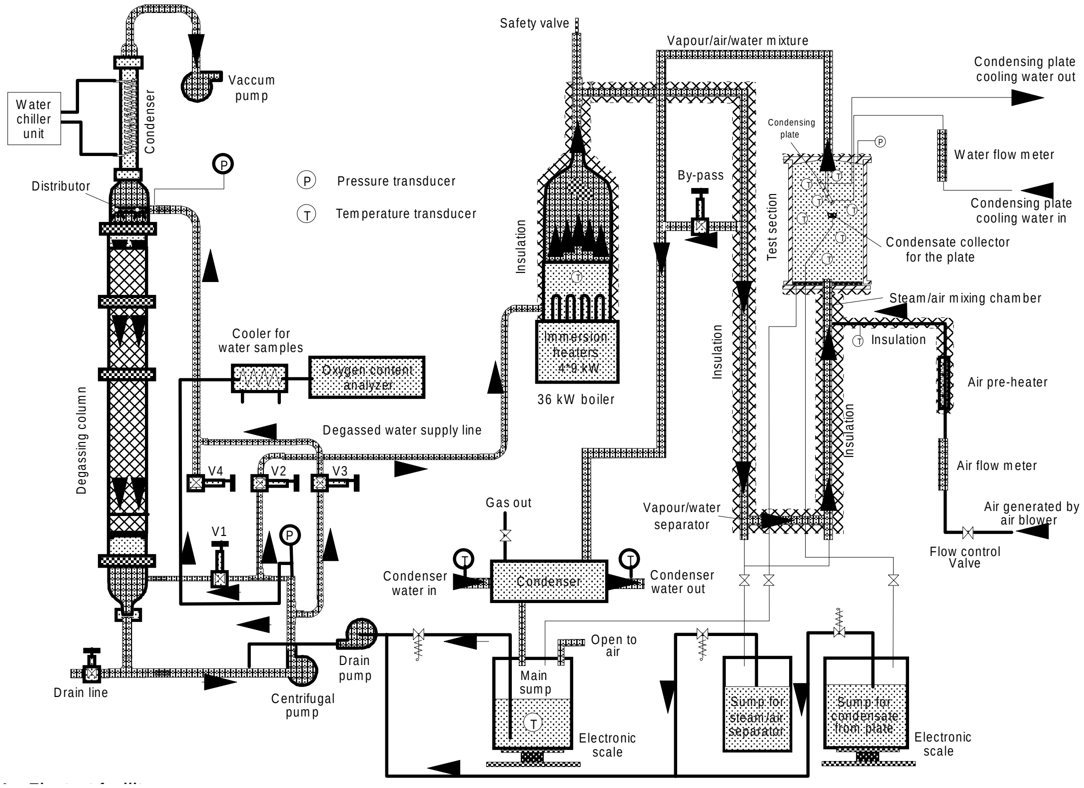


Figure 1 Schematic diagram of the test rig

A schematic diagram of a test facility called MUCON is shown in Figure 1. The rig consists of a water degassing and supply system, a boiler having a maximum power of 27kW to generate steam, an air supply system, a test section and a shell and tube condenser. The degassing system is used to extract dissolved gases from water and is connected to a vacuum pump. The boiler generates steam at a steady rate which is controlled by the electrical power input to the electrical immersion heaters in it. On leaving the boiler and passing through a separating section, the steam flows into a chamber where it mixes steadily with the flow of air which has been preheated to a temperature such that the vapor in the resulting mixture is dry saturated. The mixture of steam and air then flows into the test section. This is a cylindrical Pyrex shell closed at the top and bottom sides by two aluminum discs. The water-cooled condensing plate is suspended in it. The mixture of residual steam and air leaving the test section passes to the shell and tube condenser where the remaining vapor is fully condensed. The condensate from the test section and the shell and tube condenser is pumped back to the water degassing system. A more detail description of the MUCON facility can be found in the article by Jackson et al. (1998).

2.2 Water supply system

The water supply system consists of a degassing column, a vacuum pump, a water-circulating pump, and associated pipelines. The degassing column has a height of 3.0 m and diameter of 0.24 m. It is made of Pyrex glass, as are the other pipelines in the system. The column contains small stainless steel rings; 2 cm in diameter, stacked in the form of a cylindrical packed bed which has height of 1.5 m and diameter of 0.229 m. The water delivered by the circulating pump is sprayed from a distributor at the top of the degassing column onto the ring bed. A Pyrex coil that works as a condenser is mounted vertically above the degassing column. It is supplied with cooling water from a chiller unit. The top of the condensing section is connected to a vacuum pump. The degassing system, which operates under vacuum with the water continuously circulating, is capable of reducing the air concentration to a fraction of a milligram of air per kilogram of water.

2.3 Steam supply system

The boiler shell is a cylindrical vessel of 0.3 m in diameter and 1.4 m in height, with a domed top. It is made of Pyrex glass. The vessel contains three electrical immersion heaters; each rated at 9 kW, mounted vertically on a stainless steel base. The power supplied to these heaters can be controlled independently. The electrical power system is equipped with safety overload and over-temperature protection circuits. An over-pressure safety valve set at 0.2 bar gauge differential pressure is fitted to the top of the boiler. Degassed water is supplied to the boiler, as needed, via a feed line made of Pyrex glass. Under the conditions of a maximum power input of 27 kW, water is evaporated at the rate of about 0.015 kg/s. The temperature and pressure of steam delivered are measured. The steam produced in the boiler passes through a thermally insulated U shaped section of Pyrex glass tubing which acts as a separator. Water collected in the separator at the bottom of the downward leg drains

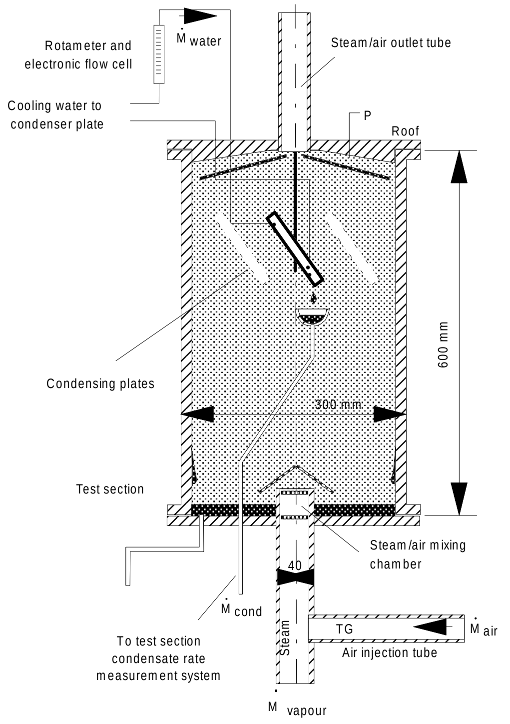


Figure 2 Schematic diagram of the test section

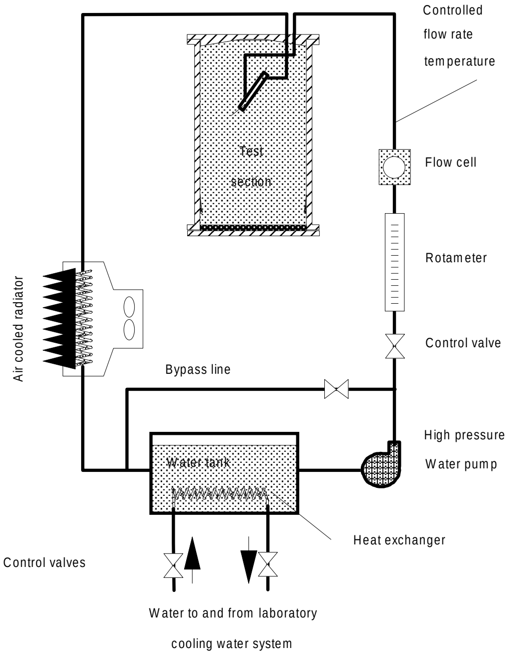


Figure 3 Condensing plate cooling system

to a sump. The steam passes upwards from the separator to a steam / air mixing chamber.

2.4 Air supply system and mixing chamber

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

2.5 Test section and cooling system

A test section is schematically shown in Figure 2. It consists of a cylindrical Pyrex glass shell 0.3m in diameter and 0.6m in height. Within the test section, a condensing plate cooled by water is suspended from the top by a specially designed support. The arrangement allows the plate to be mounted at various angles. The cooling water system for the condensing plate is shown in Figure 3. The steam / air mixture enters the test section centrally through its base and flows upward over the condensing plate. There are two condensate collectors on the base. The edge collector collects any condensate, which is formed on the test section wall and top. This is found to be negligible because heat losses to the surroundings are small. The central collector catches the condensate falling from the condensing plate and passes it to a sump. The rate at which the condensate is produced on the plate can be determined from measurements of the weight of the sump. A residual mixture of vapor and air leaves the test section from its top venting and is ducted through Pyrex glass piping to a shell and tube heat exchanger, which serves as a supplementary-final condenser. In the stainless steel shell and tube condenser the residual steam, which remains in the steam / air mixture after leaving the test section, is completely condensed, while the air is vented to the atmosphere. When the condensate level exceeds a certain level a pump and a magnetic valve are activated returning the water to the degassing column. The shell and tube condenser is cooled by water from the laboratory cooling water system.

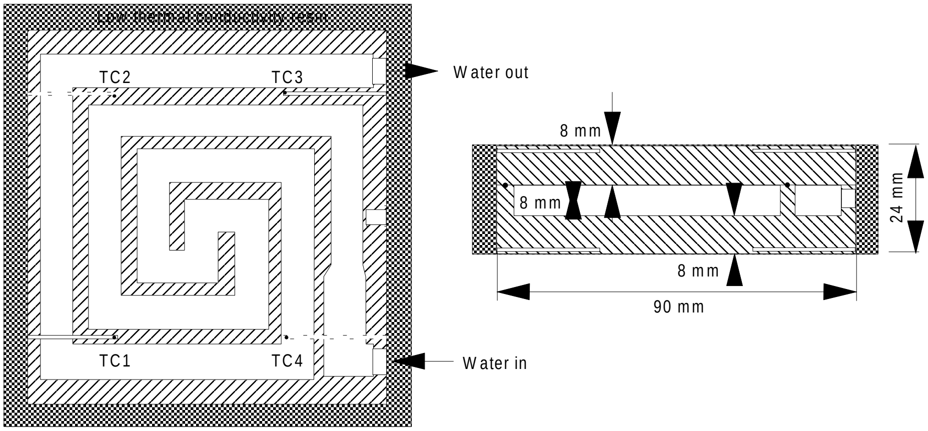


Figure 4 Internal structure of the condensing plate

In order to achieve the required uniformity in the surface temperature of the condensing plate, a particular solution has been adopted to achieve high conductivity and stability of the condensing surface, which is shown in Figure 4. The plate is made of two copper shells welded 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 5mm thick low thermal conductivity resin. Four thermocouples are planted 0.5 mm below the condensing surface in order to measure the surface temperature, and two thermocouples are located at the inlet and outlet of the cooling water flow channel to measure the temperature rise of the coolant.

The condensing plate is originally plated with a layer of Nickel-Chromium over a copper plate. This surface promotes the drop-wise condensation of steam in a very stable manner over an extended operational time of about 600 hours. In order to get a fully film-wise condensation on the full area of the condensing plate even at low subcooling and in the vertical position, an extensive testing of different surface treatments has been carried out.(Finnicum

Table I Experimental Test Matrix

Air mass fraction	Inclination angle				
	0^o	5^o	20^o	45^o	90^o
0%	FU / FD	FU / FD	FU / FD	FU / FD	FU / FD
1.6%	FU / FD	FU / FD	FU / FD	FU / FD	FU / FD
3.3%	FU / FD	FU / FD	FU / FD	FU / FD	FU / FD
6.5%	FU / FD	FU / FD	FU / FD	FU / FD	FU / FD

and Westwater (1989)) Microscopic photography method to measure the contact angle between the droplets of water and the surfaces for several surface conditions has been performed to find a high wettable condition of the surface.

1. The copper surface was painted with an inorganic zinc powder to promote an electrochemical reaction with the copper surface. However, the condensing film does not fully cover the upper region of the plate.

2. The copper was oxidized in a furnace at different temperatures and for different periods of time to achieve oxidation layers on the plate surface. However, the results were not satisfactory.

3. The copper surface was sand-blasted to get a minute irregular surface. After this treatment, the surface was found to promote a stable film condensation and to give repeatability of the experiments.

One side of the plate was covered with Pyrex glass and the other side of the plate was exposed to the steam / air mixture to prevent different condensing heat transfer on both sides.

2.6 Test matrix and experimental procedures

As mentioned in the previous section, only one side of the condensing plate is exposed to the steam / air mixture, so the experiments are carried out with two geometric adjustments; face up or down. Another geometric parameter is the inclination angle of the condensing plate. The inclination angle varies from a horizontal to vertical configuration with five steps as shown in Table I. In the present study, the steam flow rate is supplied by the immersion heater with an electrical power of 18kW, which gives a constant steam mass flow rate of $7.4g/sec$. The air flow rates are varied to get various air mass fractions from zero up to 6.5%. Preliminary experiments were performed to study the accuracy with which condensation heat transfer could be determined. Measurements of the rate at which condensate was collected from the condensing plate enabled a check to be made on the accuracy of the calorimetric method of determining heat removal from the plate. It was shown that the two different methods are in very good agreement with each other. Therefore, the condensation heat transfer rates in this work are determined by a calorimetric method as follows:

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

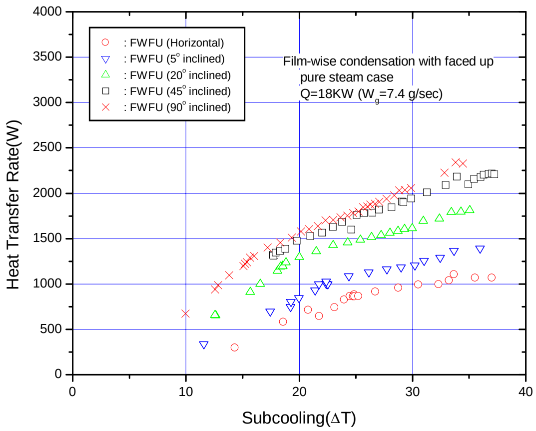
where $\dot{m}$ is coolant flow rate, and T_{in}, T_{out} are the coolant temperatures at the inlet and outlet, respectively.

Given the required test condition and the thermohydraulic capability of the test rig, different experimental procedures have been applied to obtain the needed range of subcooling for the pure steam and air / steam mixture cases. Heat transfer rates are measured for various subcooling of the surface from about 5 ^oC to 35 ^oC. In the pure steam case, the temperature of the cooling water tank has been brought to be about 70^oC to get low subcooling. For each data acquisition, the subcooling of the condensing surface is continuously increased by cooling the coolant temperature in the supply tank. On the other hand, in the case of a steam / air mixure, it was very time-consuming to wait until the steam heated up the temperature of the coolant to get the low subcooling condition. Therefore, the subcooling of the plate is varied reducing the cooling flow rate through the condensing plate.

3 Results and Discussions

3.1 Effects of inclination angle

Figures 5 and 6 show the effects of inclination angle on condensation heat transfer rates for the pure steam cases. As can be seen in these figures, the heat transfer rate increases as the inclination angle increases. As the inclination angle increases from the horizontal plane, the condensate film thickness is apt to be thin due to gravitational force. This makes the condensation heat transfer rates greater. However, the rate of increase of the condensation heat transfer rates gets to be small and the heat transfer rates do not increase any more at the inclination angle of about 45^o in the case of the face up configuration. It is noteworthy that, in the face down case, we can still see the difference of the condensation heat transfer rates between the 45^o and 90^o cases. Figures 7 and 8 also show the effects of inclination angle on the condensing heat transfer rate for air injection cases. In these figures, it can be seen that the maximum heat transfer rates can also be obtained at a vertical inclination. However, when face down, enhancement of the heat transfer rate with an increase of inclination becomes larger with high subcooling. This means that the heat transfer rates, when the plate is nearly horizontal face downward, are very low especially for the high subcooling region. The reason for that can be inferred from the following experimental observation. When the condensing plate is face down, several droplets of condensate, which are hanging on the condensate film, are observed to move around the surface until they grow enough to detach from the plate. This makes a very nonuniform and unstable condensate film thickness. Due to this dynamic random phenomenon occurring on the condensing surface, the measured



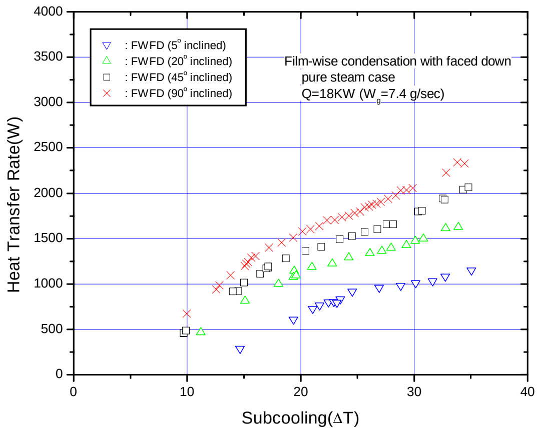
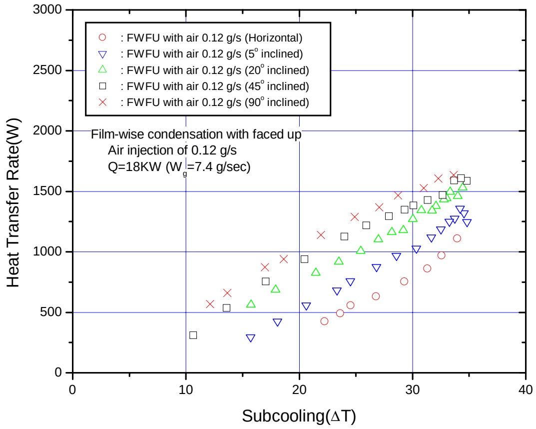


Figure 5 Effects of inclination angle in the case of pure steam: face up

Figure 6 Effects of inclination angle in the case of pure steam: face down

surface temperatures give large scattering. Practically, it is very difficult to get the averaged surface temperature. It seems that this complex phenomenon results in relatively low condensation heat transfer rates. When the steam / air mixture is condensed on the cooling surface, it is well known that the major heat transfer resistance lies on the gas phase above the water film. Therefore, the stability of the gas phase boundary layer becomes one of the most important factor governing the heat transfer rate. At the moment, it is very difficult to determine what is going on in this region. It needs further investigation.



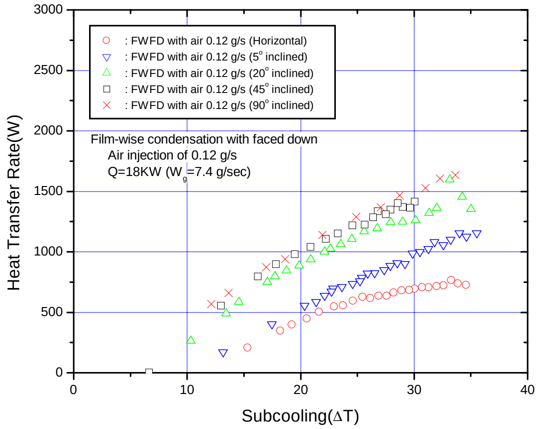


Figure 7 Effects of inclination angle in the case of air injection: face up

Figure 8 Effects of inclination angle in the case of air injection: face down

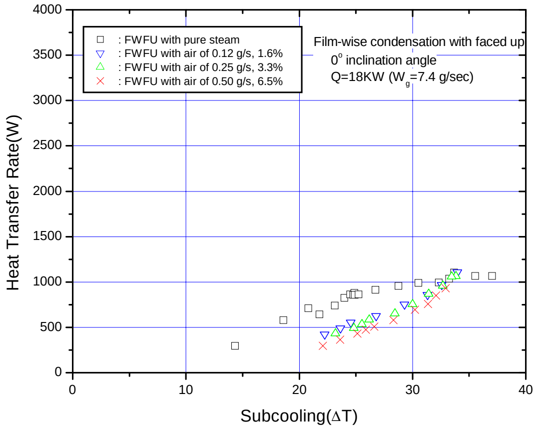


Figure 9 Effects of air mass fraction at 0^o

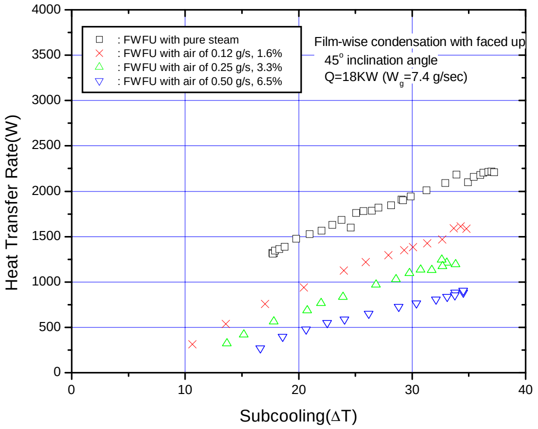


Figure 10 Effects of air mass fraction at 45^o

3.2 Effects of air mass fraction

Figures 9 and 10 show the effects of air mass fraction on condensation heat transfer at the inclination angle of 0^o, 45^o, respectively. As well known, the condensation heat transfer rate decreases with an increase of the air mass fraction, which is clear in Figure 10. However, as the inclination becomes horizontal, the decreasing rate of the heat transfer rates becomes small with respect to an increase in the air mass fraction. Figure 9 shows a typical result for the case of a horizontal plate. As you can see in this figure, the effects of an increase of the air mass fraction seem to be negligible. Three sets of data with the steam / air mixture fall into the range of experimental errors. The trend of the other sets of data for an inclination of 5^o and 20^o is between Figure 9 and Figure 10, showing the decreasing effects of air mass fraction with a decrease of inclination angle.

3.3 Effects of face up/down configuration

Figures 11 and 12 show the comparison of heat transfer rates between two different plate configuration; face-up and face-down. It is noteworthy that, in the pure steam case, the face-up configuration gives a higher condensing heat transfer rate than the face-down case. However, in the presence of noncondensable gases, it becomes reversed as can be seen in Figure 12. The reason for such a reverse phenomenon may be inferred from the buoyancy effect of steam. As the steam is lighter than the air, the steam molecules are subject to a buoyancy force, which means that steam molecules have a higher upward velocity than air molecules. Therefore, air molecules form an air rich layer on the condensing surface face up, which works as a resistance to condensation. In the presence of air, the steam has less chances to condense on the plate faced up. However, in the face down case, the condensing surface gets a direct momentum of the mixture coming from the bottom and the steam molecules have more chances to reach the surface than in the face up case. On the other hand, for the pure steam cases, the major heat transfer resistance depends only upon the water film characteristics. Condensate film thickness for the face-down installation seems to be thicker due to the complex unstable phenomenon mentioned in the previous section. It is difficult to explain the exact difference between the two plate configurations due to the limitation of the current work. A wider range of experimental and analytical investigations on this particular subject is definitely needed for further understanding.

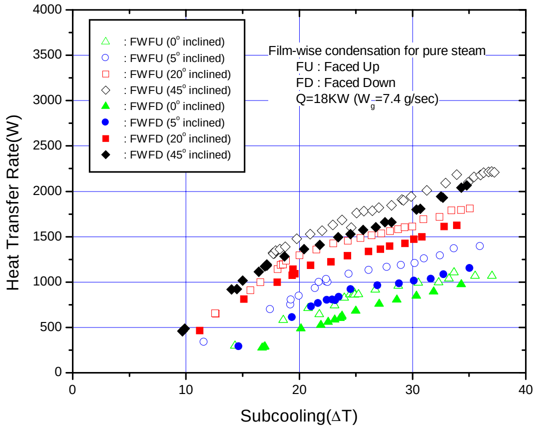


Figure 11 Effects of face up / down configuration with pure steam

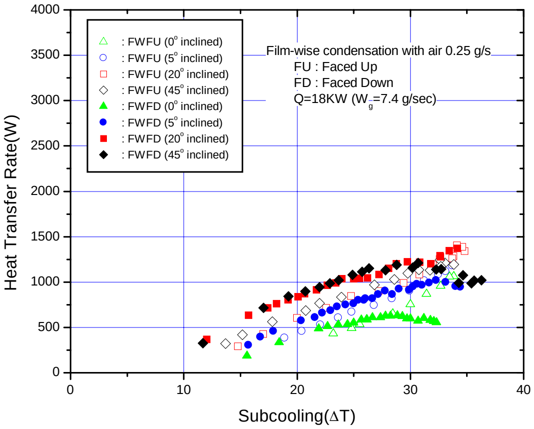


Figure 12 Effects of face up / down configuration with air

4 Conclusions

Filmwise condensation experiments for a square plate inclined at various angles from horizontal to vertical are performed with / without noncondensable gas by utilizing the MUCON facility. The effects of inclination angles, air mass fraction, and plate installation;face-up or face-down, are investigated experimentally. The following conclusion can be deduced from the present work

- The heat transfer rate increases with an increase of inclination angle. However, in the cases of face-up installation, the heat transfer rate does not increase any more for inclinations higher than 45^o. Meanwhile, a relatively large difference in the heat transfer rate can be expected between the inclinations of 45^o and 90^o in the case of a face-down installation.
- In the case of a face-down installation, especially for the inclination close to horizontal, the condensate film shows very unstable and nonuniform characteristics, resulting in nonuniform surface temperatures.

- The heat transfer rate reduces with an increase in the air mass fraction, as is well known in the literature.

- The difference of heat transfer rate between the two installations: face-up or face-down is investigated.In the case of pure steam, the face-up configuration gives a higher condensing heat transfer rate than the face-down case. However, in the presence of non-condensable gases, it becomes reversed. Such reverse characteristics seem to be attributed to the buoyancy effect of steam.

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