EFFECTS OF NON-CONDENSIBLE GAS ON THE CONDENSATION OF STEAM

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Abstract

The experimental work reported here was undertaken with the aim of extending the database currently available on the condensation of steam in the presence of non-condensable gases and thereby improving the empirical input to thermal-hydraulic codes which might be used for design and safety assessment of advanced water-cooled nuclear reactors. Heat was removed from flowing mixtures of steam and air in a test section by means of a water-cooled condensing plate. The test facility constructed for the study incorporates a degassing unit which supplies water to a boiler. This delivers steam steadily to a mixing chamber where it joins with a flow of preheated air. The mixture of steam and air is supplied to the bottom of a cylindrical test section in which it flows upwards over a double sided condensing plate which can be vertical, inclined or horizontal. The rate at which heat is removed by cooling water flowing through internal passages in the plate can be determined calorimetrically knowing the flow rate of the water and its temperature rise. After commissioning experiments had shown that reliable measurements of condensation heat transfer rate could be made using the test facility, a programme of development work followed in the course of which three different designs of condensing plate were evaluated in turn. The version eventually used in the main programme of experiments which followed was made from copper. However, its surfaces were coated with a thin layer of nickel and then with one of chromium. It was found that such a surface consistently promoted dropwise condensation and showed no signs of deterioration after lengthy periods of use. The rate of heat removal from pure steam and from mixtures of steam and air in varying proportions was measured as a function of plate sub-cooling for a variety of plate orientations.

1. Introduction

Passive decay heat removal systems will play an important part in the future in improving the safety of nuclear reactors of advanced design. Feasibility studies for nuclear reactors utilising such concepts have highlighted the need to improve our understanding of a number of aspects of heat transfer and thermal hydraulics. The influence of non-condensable gas on steam condensation is one of the topics on which further research is needed.

The inhibiting effect of non-condensable gas on the condensation of steam has long been recognised (see Ref. [1]) and much has been written on this topic. Some relevant papers on the influence of gas on the condensation of steam on plane surfaces are listed at the end of this paper (Refs. [2] to [23]). However, it is clear that there is a need for further basic experimental data. The present study was initiated to extend the existing database.

Work began on the project in 1996 with the design and construction of a test facility. That task was completed by the end of 1996. Calibration of the instrumentation and the commissioning of the test facility began in 1997 and by the middle of that year some preliminary experiments had been carried out. Photographs of the test facility at that stage of the project are shown on Plates 1 and 2. In the light of the experience obtained in the course of those experiments some modifications were made to the test facility and condensing plates of improved design were developed. A detailed programme of experiments was then carried out.
2. Description of the test facility

2.1. General description

Figure 1 shows a schematic diagram of the test facility. The degassing system is used to provide a supply of water for use in the steam boiler. 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 the mixing chamber where it joins a flow of air which has been preheated so as to cause the vapour in the resulting mixture entering the test section to be in the dry saturated condition. The test section is a cylindrical vessel with a water-cooled condensing plate suspended within it. The mixture of air and steam leaving the test section passes to a shell and tube heat exchanger where the residual steam is fully condensed. Condensate collected from the test section, the shell and tube heat exchanger and the separator is returned to the water degassing system.

2.2. Degassing system

The degassing system consists of a cylindrical packed bed column, a vacuum pump, a circulating pump, associated pipelines and an oxygen content analyser. The column is made of pyrex glass, as also are the various pipelines. It contains many small stainless steel rings stacked in the form of a bed of height 1.5 m and diameter 0.23 m. Water delivered by the circulating pump is sprayed onto the bed of rings from a distributor at the top. Mounted vertically above the degassing column is a condenser which is supplied with cooling water from a chiller unit. 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. Sampled water can be passed to an oxygen content analyser (type Kent EIL-9435) for the purpose of checking the amount of oxygen in it.

2.3. Steam supply system

The boiler shell, which is also made of pyrex glass, is a cylindrical vessel of diameter 0.3 m and height 1.4 m having a domed top. It contains four 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 electrical system is equipped with safety overload and over-temperature protection circuits. An over-pressure safety valve set at a gauge pressure of 0.2 bar is fitted to the top of the boiler. Degassed water can be supplied to the boiler, as needed, via a feed line made of pyrex glass. The boiler is instrumented so that the steam delivery temperature and pressure can be measured. Under conditions of maximum power input, water is evaporated in the boiler at a rate of about 0.015 kg/s. 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.

2.4. 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. It 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.

2.5. Test section

Figure 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. Figure 3 shows the cooling water system for the condensing plate.

The steam/air mixture enters the test section through the base and flows upwards over the condensing plate. On the base there are two condensate collectors. The outside one collects any
Figure 1: The test facility
Figure 2: The test section

Figure 3: Condensing plate cooling system
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. These are made using an electronic scale. 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 in which the steam is completely condensed.

2.6. Condensing plates

Three different designs of condensing plate have been used in the course of this study. The initial one (see Figure 4) was manufactured from aluminium. When, after some time, it was found that the surface condition was showing signs of deteriorating the aluminium plate was replaced by one made of copper with nickel coated surfaces (see Figure 5). The internal passages for cooling water were modified so as to reduce flow resistance and improve the uniformity of cooling. In the course of further tests the surface condition of this plate was also found to be deteriorating. A third type of plate, was designed and manufactured (see Figure 6). The material was again copper but this time the surfaces were first coated with a thin layer of nickel and then with one of chromium. Also, a novel arrangement of internal passages was used with a view to achieving improved cooling. Commissioning tests showed this plate to have a stable surface condition and also to be satisfactory from the point of view of uniformity of temperature.

2.7. Cooling water system

In the case of the tests performed using the initial plate, the cooling water was taken directly from the laboratory cooling water system. The sub-cooling of the plate was varied by adjusting the water flow rate. This arrangement was later replaced by another one (see Figure 3, earlier) which enabled the sub-cooling to be controlled by varying water flow rate and water temperature independently. The various condensing plates were each instrumented to enable the temperature rise of the cooling water flowing through them to be measured using thermocouples situated at entry and exit. Thus, knowing the cooling water flow rate and its temperature rise the rate of heat transfer could be determined.

2.8. Shell and tube heat exchanger

The residual vapour in the mixture of steam and air leaving the test section is completely condensed in a water-cooled shell and tube heat exchanger made of stainless steel. The condensate produced passes to a sump. When the contents exceed a certain value, a pump and magnetic valve is activated causing the water in it to be returned to the degassing column.

2.9. Measurements

The measurements made are listed below:

- Rate of flow of condensate from the shell and tube condenser to the main sump. This is measured using a load cell in conjunction with the data acquisition system.
- Rate at which condensate is produced on a condensing plate. This is also measured using a load cell in conjunction with the data acquisition system.
- Rate of flow of cooling water through the condensing plate. This is measured using a rotameter and a flow turbine.
- Pressures in the steam delivery line and the test section. These are measured using pressure gauges.
- Temperature of the condensing plate. This is measured using several calibrated K-type thermocouples.
- Temperatures of the steam/air mixture flowing into and out of the test section. There are measured using two calibrated K-type thermocouples.
10 mm thickness

1.5 mm hole for thermocouple

Cooling water inlet

Fixing arm

Cooling water flow path

Cooling water outlet

Figure 4: Initial condensing plate

Copper

Nickel plated surface

10 mm thick

0.000104 m

0.0000283 m

100 mm

Figure 5: Second condensing plate

Low thermal conductivity resin

Water out

Water in

8 mm

8 mm

90 mm

24 mm

8 mm

5 mm

Figure 6: Final condensing plate
• Temperature of condensate leaving the test section. This is measured using a calibrated K-type thermocouple situated in the condensate collector.
• Rate of flow of air injected into the steam. This is measured using a rotameter and a flow cell.
• Temperature of the air injected into the steam. This is measured using a calibrated K-type thermocouple situated near the air injection nozzle.
• Temperatures of the cooling water at inlet to and outlet from the condensing plate. These are measured using two calibrated K-type thermocouples mounted in the flow passages at inlet and outlet.
• Electrical power supplied to the boiler immersion heaters. This is determined from measurements of current and voltage.

2.10. Data acquisition system

A computer-based system consisting of a 16 channel scanner, a precision digital voltmeter and an IBM compatible PC is used for signal monitoring and data acquisition. It takes the signals from the test facility, stores them, and displays updated information on a monitor.

3. Commissioning of the Test Facility

3.1. Commissioning tests

In the course of commissioning the test facility, checks were carried out to ensure that all the measurement devices were functioning properly and to assess the accuracy with which the measurements could be made using them. A number of calibration tests were performed. Particular care was taken in the case of temperature measurement. All the thermocouples on the test facility were calibrated against a standard platinum resistance thermometer.

The test facility was first brought into service with the aluminium condensing plate installed in the test section. It was initially operated with a fixed electrical power input to the boiler supplying steam steadily at atmospheric pressure to the test section without air injection. Condensate from the condensing plate was collected in the test section and from the sump of the shell and tube heat exchanger which condenses the residual steam leaving the test section. No water was supplied to the boiler whilst this test was in progress. The whole procedure was repeated for a number of values of electrical power input to the boiler covering the full working range. These measurements enabled the total rate of heat removal from the condensing plate and the heat exchanger to be determined for each value of power input to the boiler. By subtracting this from the electrical power input to the boiler, the heat loss from the test facility to the surroundings was found. This turned out to be quite small (about 1 kW) and did not vary much from test to test because the temperature of the boiler and test section did not change. These tests demonstrated that the rate of production of steam in the boiler could be readily determined from a knowledge of the electrical power input to the boiler by simply subtracting the estimated rate of heat loss from it and assuming that the remainder was used to evaporate water in the boiler.

Next, 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. Figure 7 shows a comparison of the rates of heat transfer determined by the two different methods. It can be seen that they are in very good agreement with each other.

4. Preliminary Experiments Using the Initial Condensing Plate

4.1. Condensation heat transfer measurements with pure steam

(i) Effects of varying the steam flow rate and the plate orientation

Initially experiments were performed with the plate vertical supplying pure steam at atmospheric pressure to the test section at 3.5 g/s by applying a power of 9 kW to the immersion heaters in the
boiler. The subcooling of the plate was varied by adjusting the flow rate of cooling water passing through it. Figure 8 shows the results. Further experiments were then performed with the power input to the boiler increased to 18 kW, giving a steam flow rate of 7.2 g/s. Next, similar experiments were carried out with the plate inclined at 45° and then, finally, with the plate in the horizontal position. Figure 9 shows the results obtained for all three cases. It can be seen that there is a clear difference between the rate of heat transfer for the three different orientations of the plate. As might have been anticipated, the rate of heat transfer is highest for the vertical case, slightly reduced for the inclined case and very much reduced for the horizontal case. Some effect of varying the steam flow rate can be seen, but this is small.

(ii) Effect of reducing the steam pressure

Experiments to study the effect of reducing the steam pressure were performed next. Measurements were made at pressures of 0.75 bar and 0.60 bar. The results are shown on Figure 10 where it can be seen that there was a systematic reduction of rate of heat transfer as the steam pressure was reduced.

Some limitations of the initial condensing plate design became apparent in the course of these tests. Only a very limited range of subcooling could be covered and it was clear, therefore, that larger cooling passages were needed. A further cause for concern was the fact that the two thermocouples on the plate gave readings which differed significantly. However, in spite of these limitations, it was decided to continue to use this condensing plate for further commissioning tests.

4.2 Measurements with mixtures of air and steam

Experiments were performed next supplying mixtures of air and steam at atmospheric pressure to the test section. Results were obtained for the vertical, inclined and horizontal cases with values of air flow rate of 0.5 g/s, 1.0 g/s and 1.5 g/s and steam flow rates of 3.5 g/s and 7.2 g/s. They are shown on Figures 11 and 12, where it can be seen that for each inclination there is a strong and systematic reduction of heat transfer with increase of air concentration. These experiments demonstrated that the air supply system was functioning satisfactorily and that the test facility was capable of yielding useful information. However, they highlighted the limitations of the arrangement for cooling the condensing plate referred to earlier. Also, visible stains became apparent on the condensing plate indicating that its surface condition was changing. This gave rise to concern about the repeatability of the results which could be obtained using this plate.
Figure 8: A typical result for initial plate in vertical position with power input to boiler 9 kW (vapour flow rate: 3.5 g/s)

Figure 9: Effect of plate inclination on rate of heat transfer
5. Development of an Improved Condensing Plate

As a result of the experience gained with the initial condensing plate, it was decided to manufacture a new one using copper rather than aluminium. Four thermocouples were embedded within it to measure the surface temperature and the arrangement of internal cooling passages was changed to reduce the flow resistance. The outside of the plate was coated with nickel with a view to improving the stability of its surface condition. In addition, a new cooling system was installed on the test facility which enabled the temperature of the cooling water to be controlled. Once this was done the test facility was brought into service again. Figure 13 shows the results of commissioning experiments to check the accuracy of heat transfer measurement using the new plate and the new cooling system.

A lengthy programme of experiments followed, firstly supplying pure steam and then mixtures of steam and air. Some typical results (obtained with plate inclined at 45°) are shown on Figure 14. It was found that a much greater range of subcooling could be covered. However, the plate temperature did not prove to be as uniform as expected. Furthermore, after quite a number of tests had been completed there was again evidence of discolouration of the plate and lack of repeatability of results due to deterioration of surface condition.

An interesting feature of the results obtained is that with pure steam supplied to the test section the rate of heat transfer increases very rapidly as the subcooling is increased up to about ten degrees after which it suddenly stops changing. A further feature is the very large reduction of heat transfer caused by injecting small amount of air into the steam. It became obvious that more sensitive control over air injection was needed.

After careful analysis of the plate-cooling problem, a new condensing plate having a very different arrangement of internal cooling passages was designed, manufactured and installed in the test section (see Figure 6, earlier). It was manufactured in two halves using copper. These were brazed together in a furnace after the grooves for the cooling passages had been machined on them. To address the problem of obtaining a stable surface condition the condensing surfaces were firstly coated with a thin layer of nickel and then with one of chromium. The air injection arrangements were
Figure 11: Effect of air injection on rate of heat transfer (Power input to boiler: 9kW, Vapour flow rate: 3.5 g/s)
Figure 12: Effect of air injection on rate of heat transfer (Power input to boiler: 18kW, Vapour flow rate: 7.4 g/s)
Figure 13: Comparison of heat transfer measured by the carlorimetric and the direct condensation collection method.

Figure 14: Rate of heat transfer for inclined condensing plate with and without air injection (Vapour flow rate: 3.5 g/s)
modified to enable greater control to be exercised at low flow rates. Commissioning tests were then carried out to study the effects of these changes. These experiments showed that the uniformity of temperature was significantly improved with this plate and that accurate and repeatable heat transfer results could be obtained. The mode of condensation promoted on the surfaces was dropwise and there was no evidence of any deterioration of surface condition after a lengthy period of use. In the following section of this report a series of investigations of condensation heat transfer made using this plate are reported.

6. Main Programme of Experimental Work

6.1. Experiments promoting condensation on both surfaces

In the first investigation, experiments were performed promoting condensation on both surfaces of the plate. Measurements were made using pure steam and also mixtures of steam and air. Power inputs of 9 kW, 18 kW, and 27 kW were supplied to the boiler, giving steam flow rates $\dot{m}_s$ of 3.5 g/s, 7.4 g/s and 11.4 g/s. Air was injected into the steam at rates in the range 0.02 g/s to 1.0 g/s. Results were obtained for three different orientations of the plate, vertical, inclined at 45° and horizontal. The results are presented on Figures 15, 17 and 19, respectively, as rate of heat transfer $\dot{Q}$ versus subcooling $\Delta T$ for a number of values of air injection rate $\dot{m}_a$. On these figures, the curves for condensation with mixtures of steam and air were produced using an equation of the form $\dot{Q} = C \Delta T^p \dot{m}_a^q$, with values of the coefficient C and the indices p and q chosen to give the best fit to the experimental data for each steam flow rate $\dot{m}_s$ and plate orientation. Comparisons between the experimental and curve-fitted values of $\dot{Q}$ for the three different orientations are shown on Figures 16, 18 and 20, respectively, along with the corresponding equations. It can be seen that in general the fit to the data is good.

With the plate vertical or inclined at 45° droplets of condensate formed very rapidly at many points on the surfaces and coalesced to form rivulets. These ran off the plate leaving the surface clear so that further dropwise condensation could occur. The process was repeated continuously all over the surface in a very dynamic manner. When pure steam was supplied to the test section the rate of heat transfer increased steadily with increase of subcooling and then remained constant beyond a certain value because it was no longer possible for additional steam to reach the condensing plate.

When mixtures of steam and air were supplied to the test section, the presence of a very small amount of air inhibited the heat transfer process markedly. The rate of heat transfer continued to fall as the concentration of air was raised, but less and less strongly. The limit on heat transfer found with pure steam as subcooling was increased was not reached in the experiments with air present in the steam.

A good overall description of the results shown on Figures 15 and 17 from the experiments with mixtures of steam and air for the vertical and inclined cases is given by the equation.

$$\dot{Q} = C \Delta T^{0.36} \dot{m}_a^{-0.38} \dot{m}_s^{0.65},$$

(1)

with the coefficient C taking the value 63.7 for the vertical plate and 60.1 for the inclined one. Comparing these values it can be seen that the total rate of heat transfer with the plate inclined is only slightly lower than with it vertical. The dependence of rate of heat transfer on air injection rate is very similar for these two orientations ($\dot{Q}$ varying with $\dot{m}_a$ in a rather non-linear manner). The same can be said of the variation with steam flow rate (this time with $\dot{Q}$ increasing almost in proportion to $\dot{m}_s$). A measure of the effectiveness of heat transfer is provided by the ratio $\dot{Q}/\Delta T$ and, it can be seen from Equation 1 that this falls with increase of subcooling as $\Delta T^{-0.64}$.

With the plate horizontal, condensate was not able to leave the plate so readily and parts of the upper and lower surfaces were covered with liquid for a significant proportion of the time. Whereas the rates of heat removal for the inclined case were only slightly smaller than for the vertical case they were much lower when the plate was horizontal. For this orientation, the trends with increase of steam flow rate and air injection rate were not completely systematic.
Figure 15: Effect of subcooling, air injection rate and vapour flow rate on rate of heat transfer for the double-sided vertical case with the final plate.
Figure 16: Comparison of experimental and curve-fitted values of heat transfer
Figure 17: Effect of subcooling, air injection rate and vapour flow rate on rate of heat transfer for the double-sided inclined at 45° case.
Figure 18: Comparison of experimental and curve-fitted values of heat transfer.
A satisfactory overall description of the set of results for mixtures of steam and air shown on Figure 19 is given by the equation

\[ \dot{Q} = 73.3 \Delta T^{0.33} \dot{m}_a^{-0.32} \dot{m}_s^{0.7} \]  

(2)

From this it can be seen that the influences of air injection rate and steam flow rate are both slightly weaker than for the vertical and inclined cases. The overall rate of heat transfer for the horizontal case is generally lower by about 20% than for the vertical and inclined cases.

These experiments with a double-sided plate did not allow the contributions of the upper and lower surfaces to be separated. Clearly, in the case of condensation on horizontal or slightly inclined surfaces the process of condensation will be different on the two surfaces and the upward facing and downward facing cases should be studied separately. It was with this in mind that the experiments reported in the next section were conducted with the plate only promoting condensation on one surface.

6.2. Experiments promoting condensation on one surface only

The condensing plate was thermally insulated on one face by covering it with a sheet of perspex 5mm thick. A programme of experiments was then carried out with the plate horizontal, inclined at 5° and inclined at 20°, firstly with the condensing surface facing upwards and then with it facing downwards. Experiments were only performed for one value of steam flow rate (7.4 g/s, boiler power input 18 kW). The results for the upward and downward facing cases are shown on Figures 21 and 23, respectively.

The data for condensation of steam in the presence of air have again been fitted separately for each orientation of the plate by an equation of the form \( \dot{Q} = C \Delta T^p \dot{m}_a^q \). Comparisons between the experimental and curve-fitted values of \( \dot{Q} \) for the various orientations of the plate are shown on Figures 22 and 24 along with the corresponding equations.

It can be seen from Figures 21(a) and 23(a) that with pure steam and the plate inclined at 20° to the horizontal the rates of heat transfer are clearly higher for the upward facing case than for the downward facing one. This must be due to the rivulets of condensate running off the surface more readily. However, with the plate mounted horizontally, or inclined at only 5°, the rates of heat transfer are greatly reduced and there is no clear cut difference between the rates of heat transfer for the upward and downward facing cases. However, an irregular variation of rate of heat transfer with subcooling is evident in the upward facing case and this is indicative of flooding of the surface.

As can be seen from Figures 21(b), (c) and (d) and Figures 23(b), (c) and (d), the pattern of behaviour with mixtures of steam and air is quite different. There is a systematic reduction in rate of heat transfer with increase of air concentration and also with reduction of plate inclination. The values are consistently higher for the downward facing case, presumably as a result of the upward flow of steam towards the plate helping to control the build up of air near it.
Figure 19: Effect of subcooling, air injection rate and vapour flow rate on rate of heat transfer for the double-sided horizontal plate.
Figure 20: Comparision of experimental and curve-fitted values of heat transfer
Figure 21: Effect of subcooling, air injection rate and orientation on rate of heat transfer (upward facing single sided plate, power input to the boiler 18 Kw, vapour flow rate 7.4 g/s)
Figure 22: Comparison of experimental and curve-fitted values of heat transfer
Figure 23: Effect of subcooling, air injection rate and orientation on rate of heat transfer (downward facing single plate, power input to the boiler 18 Kw, vapour flow rate 7.4 g/s)
Figure 24: Comparison of experimental and curve-fitted values of heat transfer.
Conclusions

The chromium-plated condensing plate used in the present study proved to be very satisfactory. It consistently promoted dropwise condensation and the surface condition showed no signs of deteriorating after a lengthy period of use. The novel arrangement of cooling passages enabled a satisfactory uniformity of plate temperature to be achieved.

The experiments using pure steam with the plate mounted vertically in the test section promoting condensation on both sides showed that the heat transfer rate increased steadily up to a certain value as subcooling was increased after which ceased to increase as a result of a limit being reached on the rate at which steam could get to the plate. The degree of subcooling at which this occurred and the limiting value of heat transfer rate both increased as the rate of flow of steam through the test section was increased.

The associated experiments with mixtures of steam and air using the double-sided vertical plate showed that even a very small amount of air present in the steam caused a large reduction in rate of heat transfer. This influence varied in a very non-linear manner becoming less and less sensitive to the amount of air present as the concentration was increased.

With the plate mounted at 45° promoting condensation from steam or mixtures of steam and air on both sides, heat was removed at almost the same rate as for the vertical case and the pattern of behaviour with increase of steam flow rate and air concentration was very similar.

With the plate mounted horizontally the rates of heat transfer achieved were greatly reduced as a result of the condensate not draining easily from the plate. This was particularly evident in the case of condensation of pure steam where the rate of heat transfer actually fell as the steam flow rate was increased due to flooding of the upper surface with condensate.

With the plate promoting condensation on one surface only and mounted at an angle of 20° to the horizontal, the rate of heat transfer from pure steam was higher for the upward facing case. With the angle of inclination reduced from 20° to 5°, or with the plate mounted horizontally, the rate of heat transfer was considerably lower due to condensate not draining from the plate so readily. There was then no clear cut difference between the results for the upward and downward facing cases except that the variation with subcooling became rather irregular with the condensing surface facing upwards due to flooding of the surface.

Using mixtures of steam and air, the rates of heat transfer reduced systemically as the concentration of air was increased and also as the inclination of the plate was reduced. The rate of heat transfer was higher in the downward facing case as a result of the upward flow of steam towards the plate aiding the removal of air from the condensing surface.

Further Work

A follow on programme of experiments with the surface condition of the plate modified so that it promotes filmwise condensation under all conditions has been initiated.

REFERENCES