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Boiling the immiscible water/*n*-nonane system from a tube bundle

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Abstract—A series of experiments is described in which water and the C_9 alkane *n*-nonane (b.p. 150.5°C, s.g. 0.72) was boiled in a short electrically heated shell and tube arrangement at heat fluxes up to 110 kW m^{-2}. Vapour composition, temperatures of vapour and liquid and the boiling curves were measured over the whole range of boiler liquid compositions. Systematic variations are discussed. The nature of the boiling process is described. Provided that at least the bottom row of tubes is immersed in water the boiling heat transfer coefficient based on the temperature difference between tube wall and t_{sat} water was very close to that for boiling pure water. The paper concludes with recommendations for design.

INTRODUCTION

SINCE the early work of Bonilla and Perry [1] on boiling the partially soluble *n*-butanol/water system over a horizontal plate a number of investigations have been carried out on immiscible liquid boiling over horizontal plates [2, 3, 4, 5], a horizontal wire [6] and a single horizontal tube [7]. Systems using mercury were aimed at enhancing heat transfer to an immiscible upper boiling phase [8, 9] and are dissimilar to the other studies in that mixing of the two liquids is always slight due to the high specific gravity and low volatility of the mercury. Other than the mercury systems all the systems boiled water and an organic liquid with water as the lower [1, 2, 4, 5, 6, 7] or upper phase [3, 4, 7].

In the quiescent state two immiscible liquids in a boiler shell separate into layers. When heated, the resultant pattern of boiling depends on the relative volatility of the two liquids and the position of the heating surface relative to the liquid/liquid interface. Sump and Westwater [7] identified 18 different heat transfer patterns according to the type of heat transfer in each phase and the position of the heating surface. When two immiscible liquids boil in equilibrium the boiling point is depressed below that of either pure component and the vapour composition is unique, independent of liquid composition. This is the azeotropic condition. In practice the complete mixing required to obtain this equilibrium condition is not often achieved resulting in a boiling point which lies between the azeotropic and one of the pure component values. The vapour is rich in that component compared with the azeotropic condition [2, 3, 7]. In this case the vapour composition is likely to depend on the relative volatility of the liquids and which liquid is in contact with the heating surface.

The heat transfer characteristics also depend strongly on which liquid is in contact with the heating surface. The boiling heat transfer coefficient is generally higher when water is in contact with the heating surface. For example Bonilla and Eisenberg [2] noted that as the increased agitation due to boiling the water/styrene system brought the upper less volatile styrene into contact with the heating surface at the bottom of the boiler there was a step reduction in the heat transfer coefficient. The degree of mixing in boiling experiments so far has not been clearly defined. This is a complicated effect because of the range of liquid pairs and position and type of heating surface. None of the previous published work studied the boiling characteristics likely over a tube bundle when the heating surface is positioned in both liquids simultaneously.

This paper describes a study of boiling from a bundle of tubes in the *n*-nonane/water system. Nonane is a C_9 alkane with a boiling point of 150.5°C and a specific gravity of 0.72 [10]. At atmospheric pressure this liquid combination forms an azeotrope at 94°C with a vapour of steam mass fraction, $y_w = 0.39$. The study arose from the requirement for design data on a boiler to produce steam/nonane vapour using steam as an indirect heat source in connection with laboratory evaluation of the immiscible liquid Rankine cycle [11]. Both azeotropic and steam rich vapour conditions are investigated.

EXPERIMENTAL APPARATUS

The boiling chamber represents a section of a shell and tube boiler (BC), Figs. 1 and 2, 230 mm in diameter and 58 mm deep, with the tube bundle situated at the bottom. The bundle consists of 12 × 56 mm tubes, 19 mm in diameter, on a 25.4 mm square pitch. The boiler tubes and shell were of aluminium alloy construction. A glass plate covered the front of the cell allowing visual and photographic studies of the boiling process and direct measurement of the liquid depth and interface position. Each tube contained a 400 W cartridge heater. The power supply to the heaters was set using variable transformers in conjunction with a Wattmeter. A chromel–alumel thermocouple, *t*, Fig. 2, was positioned

NOMENCLATURE

q	heat flux per unit area [kW m^{-2}]
t	temperature [°C]
δt	temperature difference [K]
δt_a	$(t_w - t_a)$ [K]
δt_{act}	$(t_w - t_{act})$ [K]
δt_{sat}	$(t_w - t_{sat})$ [K]
x	liquid mass fraction
y	vapour mass fraction.

Subscripts

a	azeotropic
act	actual
l	liquid
sat	saturated water
t	tube
v	vapour
w	water.

in the wall, at the top of each tube enabling, after a small correction for radial conduction, the surface temperature at the mid-point of the tubes to be measured. This was assumed to represent the temperature over the whole tube surface. Little circumferential variation would be expected due to the high thermal conductivity of the aluminium alloy. Four thermocouples were positioned in the liquid and one in the vapour phase. Thermocouple voltages were processed by a data transfer unit on to punch tape and analysed by computer.

During tests the chamber was filled to a depth of 140 mm, Fig. 2, a liquid volume of 1500 ml. Vapour produced in the chamber, Fig. 1 (BC), was condensed (MC) and entered a simple gravity separator (MS). This divided the condensate into streams of water and nonane. Each stream then passed into a flow measurement section (NMC)(WMC) which maintained the flow of liquid returning to the boiling chamber during the measurement process. This ensured that the boiler conditions remained steady throughout the experiment. The two condensate streams then passed into the constant volume preheaters (NPH)(WPH). The temperature of the feeds leaving the preheaters via the overflow pipes was maintained by temperature controllers, controlling the power input to the cartridge heaters within the preheaters. In all tests the water and nonane feed entered at the base of the boiler at the azeotropic temperature. Fibre glass lagging throughout the apparatus minimised heat losses. A heat balance was carried out over the whole system and showed a total heat loss from the boiling chamber of 100 W. Under 30 W was lost directly from the backplate of the boiler, only 5% of the power input at the lowest heat flux studied. Only part of this represents direct loss of power from the heaters to the backplate by conduction along the boiling tube.

The nonane as received from the supplier was > 99% pure and both nonane and water were distilled before addition to the apparatus. Boiling, draining and refilling with distilled liquids was repeatedly carried out

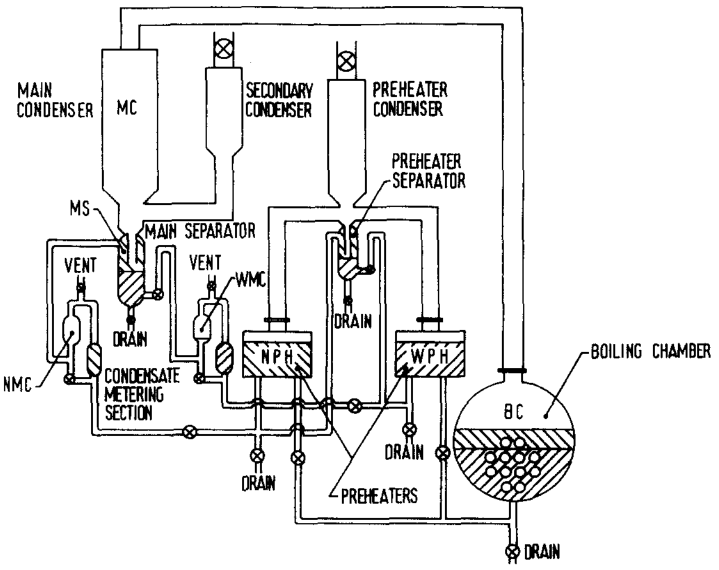

Fig. 1. Sketch of apparatus.

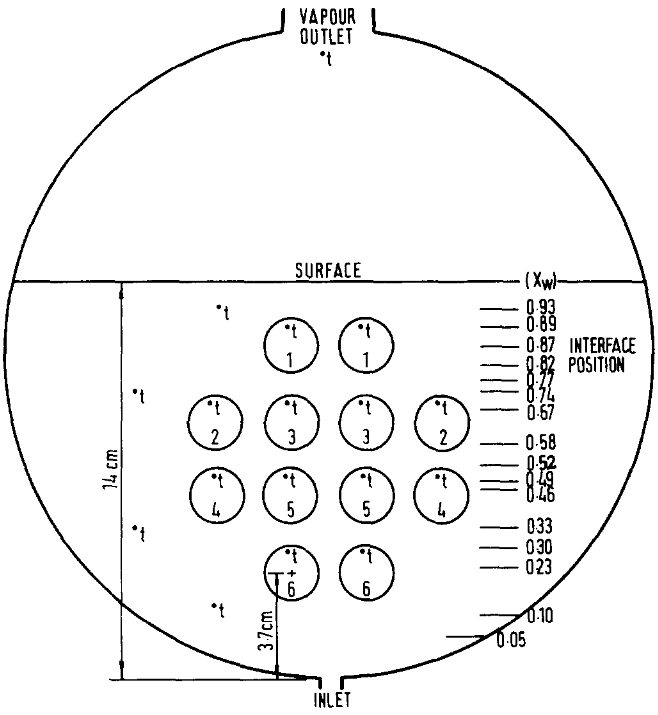

FIG. 2. Sketch of boiling chamber showing the relationship between x_w and the interface position.

until all impurities were removed from the system. Throughout the subsequent tests, the boiling surfaces remained clean.

EXPERIMENTAL PROCEDURE

Each boiling test was carried out over a range of heat flux from 15 to 110 kW m^{-2}, with equal power per tube. At each condition temperatures of the tubes, liquid and vapour were recorded as was the condensate flowrate. All experimentation was carried out at atmospheric pressure which was recorded to allow the calculation of t_{sat} and t_a. Tests were first carried out on pure water and pure nonane to ascertain the boiling curves for the pure liquids. Additional tests were then carried out on pure water to enable the liquid circulation between the shell and the bundle to be measured. In the latter tests high speed film was taken at four different heat fluxes. Small discs of paper were added to the fluid and circulated about the boiling chamber. Analysis of the discs' movement allowed liquid velocities throughout the boiling chamber to be estimated.

A series of sixteen tests using water/nonane mixtures at different boiler water mass ratios, x_w, from 0.93 to 0.05 were carried out, each over the same range of heat flux as the pure fluid tests. Again high speed films were taken at some ratios, in some cases using paper discs.

RESULTS AND DISCUSSION

Pure fluid boiling

Initial tests boiling water only, resulted in curves for the bundle as shown in Fig. 3. The heat transfer displayed the usual characteristics, a combination of boiling and convection. The symmetry about the central column of the bundle allowed an average value for tubes in symmetrical pairs to be used, Fig. 2. The total liquid circulation around the bundle was estimated [10] by analysis of the high speed film. The mass flux of water which entered the boiler below the central gap between the tube columns is a very small fraction of the circulation flux. The measured circulation rates varied less than 10% over the range of heat flux used.

Generally the upper rows of the bundle had the higher heat flux for a given δt. Tube pair 4 had the poorest heat transfer at low heat fluxes improving as heat flux increased. On tube pair 4 at low heat flux, the natural convection induced upflow on the outer surface of the tubes was opposed by the downward bulk circulation between the tubes and the shell of the boiler. Nucleate boiling was least assisted by convective heat transfer. As the heat flux increased bubble motion past the tube increased the convective element of the heat transfer, relative to some of the other tubes.

As q increased, the slope $B = d(\ln q)/d(\ln \delta t_{sat})$ of the boiling curves for all the tubes tended to a constant value of 2.9, close to the value for nucleate boiling in a pool which may be represented by equation (1), ref. [12] with $B = 3.5$.

$$q = A(\delta t_{sat})^B. \quad (1)$$

At high heat flux in the bundle the heat transfer was increasingly dominated by boiling and that due to

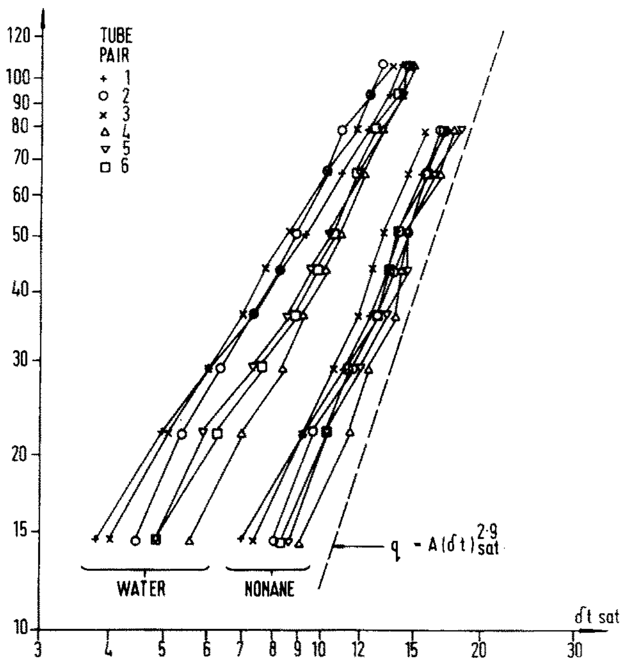

FIG. 3. Nucleate boiling curves for the six tube pairs for pure water and *n*-nonane.

convective flows in the bundle became relatively negligible [13].

Tests using nonane exhibited boiling curves of a similar nature with the same limiting slope, $B = 2.9$, positioned to the right of the water curves, Fig. 3. It was noticeable that the bubble size was much smaller giving a more stable flow within the tube bundle. Convective effects were less than for water boiling as the many small bubbles covered most of the tube surface.

Water/nonane boiling

Boiling characteristics in the mixture depended markedly on the liquid/liquid interface level in the quiescent state. Figure 2 shows the relationship between this level and the mass fraction of water in the boiler, x_w. The boiling curves are shown in Figs. 4 and 5. In Fig. 4 the results are shown for all tubes at $x_w = 0.52$ and the bundle mean values for the more significant mass fractions in Fig. 5. Vapour composition y_w is shown as a function of q and x_w in Fig. 6 and as function of the difference $(t_v - t_a)$ between actual vapour temperature and azeotropic temperature in Fig. 7. Variation in liquid temperature throughout the bundle was negligible. The excess of liquid temperature t_l over t_a is plotted as a function of q and x_w in Fig. 8.

In Figs. 4 and 5 the abscissa is $\delta t_{sat} = (t_t - t_{sat})$ the difference between tube temperature and water boiling temperature at the system pressure. More orderly curves, more easily compared to pure water boiling are obtained than when the q vs δt_{act} representation is used. The use of δt_{sat} is equivalent to potting vs t_t [7]. From a design standpoint this is the most useful representation since the liquid temperature is indeterminate. If the liquid is subcooled the heat transfer coefficient, $q/\delta t_{sat}$, is higher than that based on δt_{act}. However, experimental evidence showed that the boiling initiated in water contacting the tubes. Tubes were either entirely immersed in water occasionally containing nonane droplets or immersed in nonane above the interface. In the latter case a film of water could be seen on the surface of the tubes. Size and frequency of departure of the bubbles from the surface were similar to those observed for pure water, entirely unlike the high frequency departure rates observed for the small bubbles in boiling pure nonane. Further, when the boiler was switched off the water layer remained coating the tubes and formed a droplet beneath the tube clearly visible in the surrounding nonane, Fig. 9 (a). The water layer on the tubes above the interface, level with the second row from the bottom, forms a characteristic reflecting surface. In cases where the boiler was switched on, after filling in such a way that no water contacted the tubes above the interface, boiling started initially only on tubes at the interface. On subsequent start-ups when the tubes above the interface were coated with water remaining from the previous test, boiling started on all tubes on or above the interface simultaneously.

Circulation rates in the immiscible system could not be obtained from the high speed film. Visibility was reduced by the dispersed droplets of nonane. However, circulation rates were clearly lower than in pure water boiling with only a few paper discs carried up into the flow. The nonane restricted the circulation of water below it. The effect of this on convective heat transfer in the bundle is a factor tending to reduce heat transfer

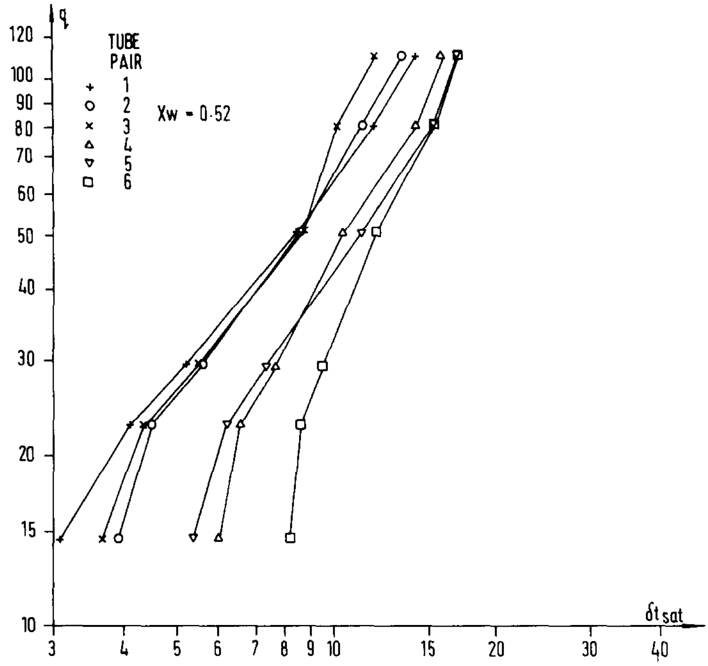

FIG. 4. Nucleate boiling curves for the six tube pairs for a water/n-nonane mixture of $x_w = 0.52$.

compared with the pure water boiling. However, this proved to be a secondary effect.

Description of boiling process

Typically for $x_w = 0.52$, Fig. 4, at $q = 15\,\mathrm{kW\,m^{-2}}$ the interface level was relatively undisturbed and there was noticeably more boiling on the two rows above the interface than below. The liquid was subcooled by about 1 K below t_{sat}, Fig. 8. The steam fraction in the vapour leaving the boiler, y_w, at this heat flux was 0.40, about azeotropic, Fig. 6. At $q = 22\ \mathrm{kW\ m^{-2}}$, the interface at the sides of the shell moved down level with the top of the third tube row as water was drawn up the centre of the bundle, the vapour bubbles breaking up the interface there. This effect became progressively more marked as q increased. At $36\,\mathrm{kW\,m^{-2}}$ the nonane

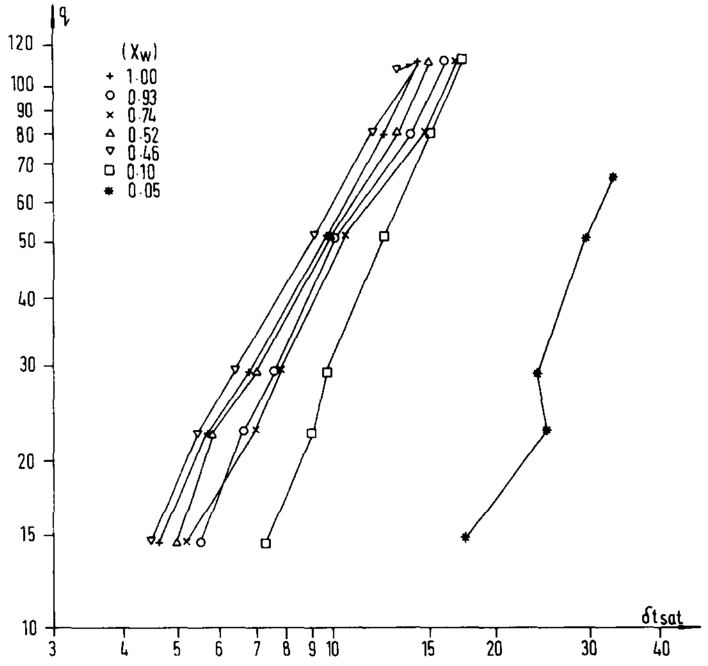

FIG. 5. Mean boiling curves for water/n-nonane mixtures between $x_w = 1.0$ and $x_w = 0.05$.

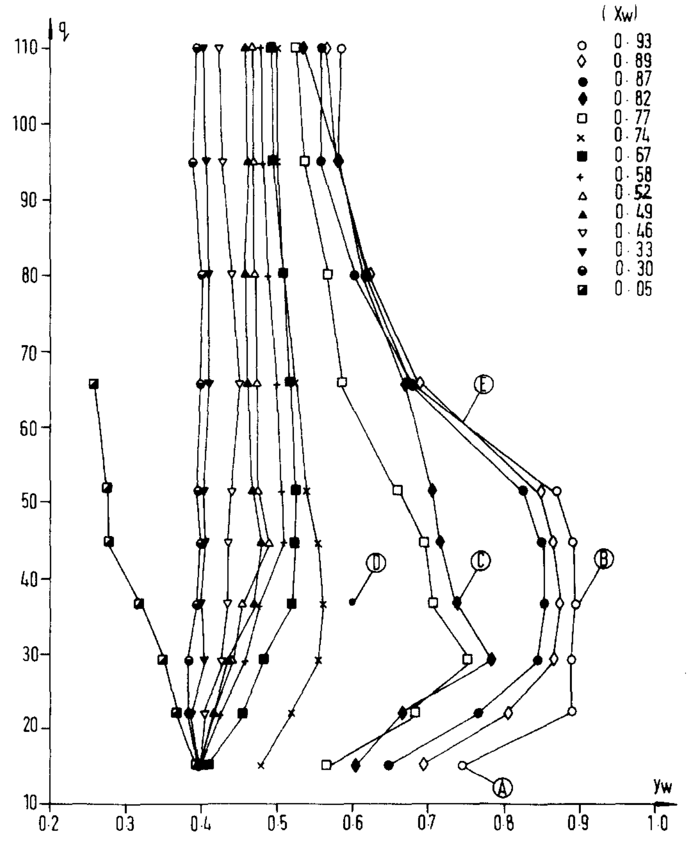

FIG. 6. Variation of vapour composition with boiler ratio and heat flux.

at the sides of the shell was composed of droplets of different sizes—small at the interface and larger nearer the surface—interspersed in a continuous phase of water and entrained vapour bubbles. In the centre a fountain of vapour and liquid emanating from the bundle was just starting to deform the liquid surface. Increasing the heat flux still further moved the interface at the sides further down allowing nonane to pass into the bundle below the third row of tubes. At the interface the nonane droplets were smallest and there was more entrained vapour. Below the interface the small nonane droplets passed into the water and circulated with the continuous phase of water into the bundle. These effects can be seen on Fig. 9 (b). Above the bundle a plume of vapour broke through the surface. Subcooling of the liquid increased to a maximum of 2.7 K at the highest heat flux, Fig. 8. As heat flux was increased y_w rose to a maximum of 0.49 at $q = 45\,\mathrm{kW\,m^{-2}}$ and then stabilised at about 0.47 at higher heat fluxes, Fig. 6.

At greater boiler water contents—thinner nonane layers—there was a tendency for the nonane layer to be pushed aside at lower heat fluxes by the column of water and steam breaking through the surface. Much less vapour was entrained in the nonane above the interface. Less nonane penetrated into the bundle and there was less subcooling in the liquid. Vapour composition varied more at high x_w, Fig. 6. Steam content y_w of the vapour was generally greater for all heat fluxes. Initially when q was increased, y_w rose to a maximum coinciding with the nonane layer separation by the column of steam and water breaking through the surface. At the highest q values where mixing was most complete y_w fell, Fig. 6.

With thicker nonane layers, $x_w < 0.52$, the nonane became the continuous phase above the interface coinciding with less water circulating up through the bundle. Below the interface there was very little entrainment of nonane droplets. The liquids in the boiler were less mixed. The central plume contained more nonane and vapour composition tended to azeotropic at all heat fluxes. Nonane rich vapour was obtained only at very low boiler water contents, $x_w = 0.05$. Subcooling in the liquid became progressively lower the thicker the nonane layer.

Vapour separation

Heat flux was not restricted up to the maximum available value of 110 kW m^{-2} by vapour entrainment induced rise in surface level into the vapour space. Steam separation from pure water boiling occurred without difficulty. Difficulty of separation of vapour from the boiling liquid increased with increasing nonane content in the boiler up to the point where nonane became the continuous phase ($x_w = 0.49$).

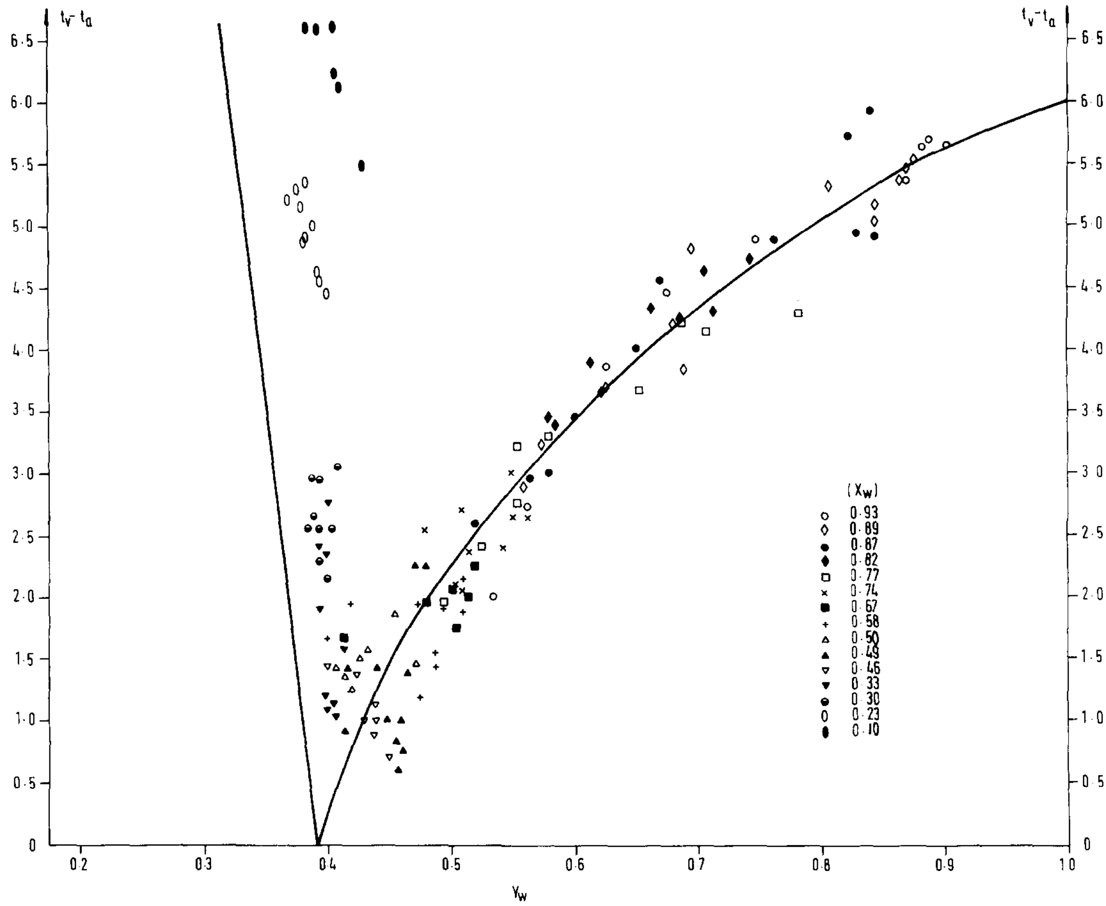

FIG. 7. Variation in vapour temperature above the azeotropic temperature with boiler ratio and heat flux and superimposed the water and nonane dew lines.

Further increase in nonane content improved separation. These effects are due to the amount of vapour entrained in the liquid above the interface discussed above. At $x_w = 0.52$ at the highest heat flux available, $q = 110$ kW m^{-2} the entrained vapour caused the liquid surface level to rise about half way up the vapour space between the boiler outlet and quiescent liquid level. It was evident that further increase in heat flux would have led to difficulties in separation.

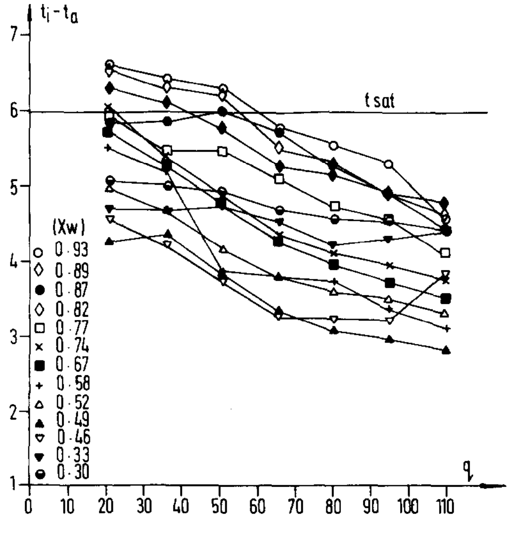

FIG. 8. Variation in liquid temperature above the azeotropic temperature with heat flux for a range of boiler ratios.

Effect of interface level on boiling curves

The principal effect on the boiling curves was the amount of nonane in the boiler. This affected circulation, mixing of nonane and water and the amount of subcooling, which, in turn affected the heat transfer. The same general trends were observed at all heat fluxes, Fig. 5. Heat transfer improved as x_w was reduced from 0.93 to 0.46. At $x_w = 0.46$ the heat transfer coefficient was greater than when boiling pure water. Contact between water and nonane improved with increasing nonane content. Although the liquid temperature was always more than 2.8 K above t_a, the system tended towards equilibrium as nonane content increased. Nucleation of steam bubbles continued at the tube wall, whose mean temperature was always at least 4.5 K above t_{sat}, Fig. 5 Subsequent growth of the bubbles improved with increased quantities of nonane in the vicinity of the tubes.

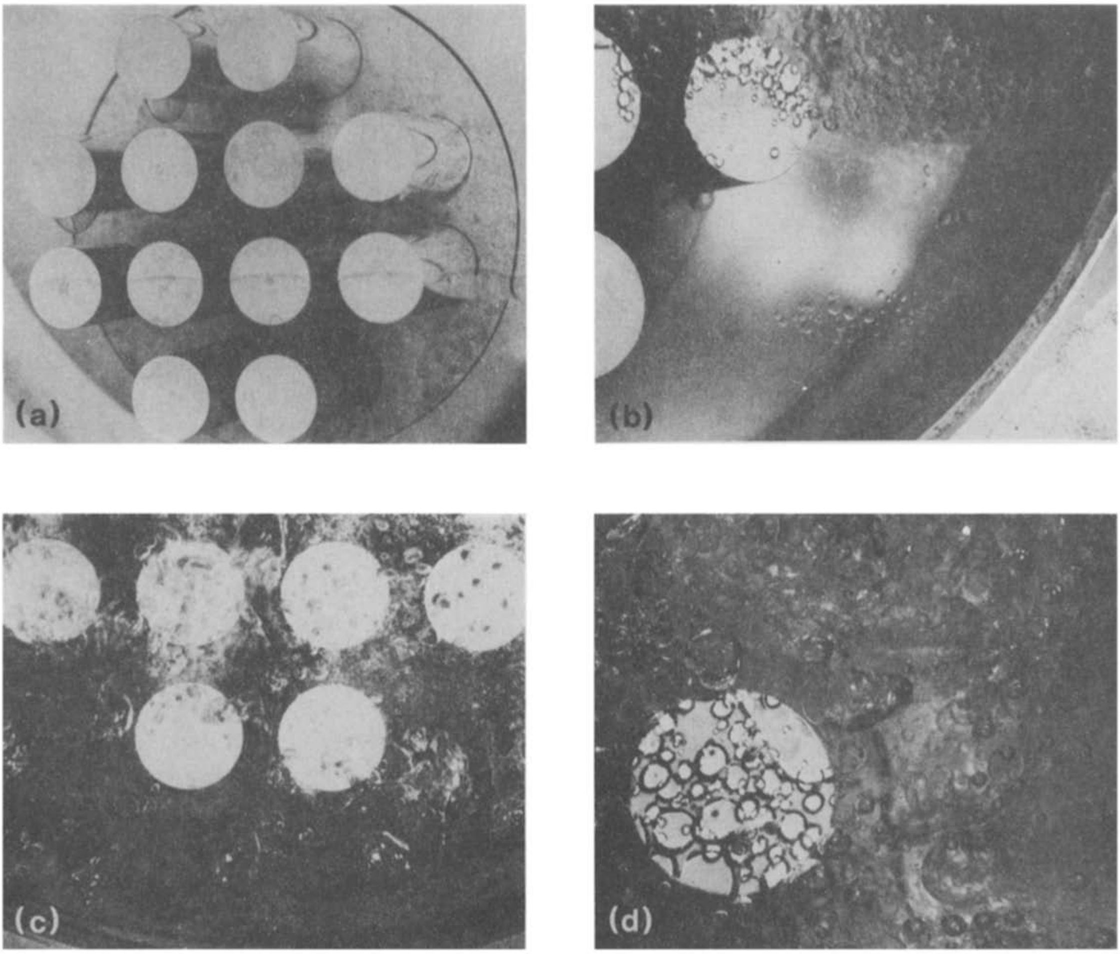

FIG. 9. (a) Water film on tubes above interface $q = 0, x_w = 0.46$; (b) circulation of nonane droplets into water $q = 15$ kW m^{-2}; $x_w = 0.46$; (c) boiling from water/nonane interface $q = 51$ kW m^{-2}; $x_w < 0.05$; (d) water droplets attached to vapour bubbles in nonane phase, $q = 51$ kW m^{-2}.

Further increase in nonane content from $x_w = 0.46$ to 0.05 decreased the rate of heat transfer. At this stage most of the tubes were above the interface and convective heat transfer to nonane replaced boiling on an increasing number of tubes as x_w decreased. At very low water contents, $x_w < 0.05$, only convective heat transfer to nonane occurred on the tubes. Boiling took place at the base of the boiler wherever the nonane came into contact with the remaining water, Fig. 9 (c). The boiling curve, Fig. 5, moved in a step change to a lower rate of heat transfer. Further reductions in water content resulted in explosive boiling of the water feed entering the boiler into the hot nonane. This resulted in unstable flow through the apparatus caused by variations in vapour production. In all tests using higher water content the flow through the apparatus was stable.

Liquid temperature

In most of the tests, tubes below the interface were surrounded by water below its saturation temperature at the boiler pressure. Liquid temperatures rose above t_{sat} only when nonane layers were thin and the heat flux below 70 kW m^{-2}, Fig. 8. Then the thin film of nonane remained unbroken and under operating conditions all the tubes were immersed in water. With subcooling, growth of nucleated steam bubbles can continue only if nonane vapour enters the bubble to raise its vapour pressure above the surrounding liquid pressure. Otherwise the nucleated bubbles will collapse. Bubble collapse was observed on the high speed film generally in regions of the boiler where there was evidently no nonane. For example this occurred on the bottom row of tubes at $x_w = 0.52$, at a heat flux of 15 kW m^{-2}, Fig. 4, where the liquid subcooling was only 1 K.

For boiler compositions up to $x_w = 0.49$ subcooling was greatest at the highest heat flux. Maximum subcooling of 3.2 K was observed at $x_w = 0.49$, Fig. 8. At each heat flux subcooling increased with increasing thickness of the nonane layer up to this value of x_w and thereafter decreased. Agitation and hence mixing of the liquids in the boiler, controlled the amount of subcooling. This mixing improved as the nonane layer increased in thickness to $x_w = 0.49$ and thereafter decreased as nonane became the continuous phase above the interface. The more mixed the liquids near the tube surface, the nearer the azeotropic equilibrium boiling was approached although it was observed that there was always a water film around the tube. The boiler composition was always nonane rich when azeotropic vapour was formed. Sump and Westwater [7], boiling the water/hexane system observed water boiling below the interface at subcooling up to 35 K while any hexane at all remained in the boiler. Under these circumstances no visible droplets of hexane approached the boiling tube. It appears that the significant difference between this and the water/nonane system which concerns subcooling is the small but greater solubility of hexane than nonane in water. Presumably sufficient hexane is dissolved in the water to provide the hexane vapour pressure necessary for the nucleating bubbles to grow. Under these conditions the characteristics of subcooled boiling were not evident [7]. For the same δt_{sat} the heat flux was the same as when boiling pure water despite the large amount of subcooling. In the steam/nonane system however, when no droplets of nonane were near the tubes, nucleated steam bubbles did not grow, or collapsed if the water was subcooled.

Vapour temperature

Figure 7 shows vapour temperature as a function of vapour composition, y_w. The dew lines for the steam/nonane system at the boiler pressure are superimposed. In all cases the vapour temperature was lower than the bulk liquid temperature. The two temperatures were closest at high heat flux when the liquid was most subcooled. Sump and Westwater [7] measured a temperature drop of about 6 K close to the surface with liquid and vapour temperature equal at the surface, in an R113/water system. The system was relatively unmixed. The water/nonane system was well mixed, particularly at high heat flux. Since a thermocouple positioned only 10 mm below the surface registered the same temperature as the others positioned throughout the liquid it is unlikely that there was any substantial fall in temperature near the surface. Steam bubbles leaving the tubes exchange heat and mass with the bulk liquid as they rise. Nonane evaporates into the bubbles which can therefore sustain a temperature lower than the liquid until they reach the surface. Water droplets were carried with the bubbles so that the state of the vapour tends towards the observed dew point equilibrium of the mixed vapours with water. Droplets of water could be seen attached to bubbles during the experiments, Fig. 9 (d). Shimada *et al.* [4], studied vapour bubbles rising through an interface between the condensed phase of the liquid and another less volatile liquid. They also noticed that the bubbles of vapour carried droplets of the lower liquid within them through the interface and into the upper phase. In the present system the vapour leaving the boiler is a combination of the vapour bubbles rising from different parts of the bundle and some mass transport of vapour at the surface due to the temperature gradient between bulk liquid and vapour.

It was noticeable, Figs. 7 and 8, that subcooling first increased as vapour composition approached azeotropic, from the steam-rich side, and then decreased when the vapour was azeotropic as x_w fell further from 0.46 to 0.10. The subcooling was sustained by the evaporation of nonane into the bubbles as they rose through the liquid. In cases where azeotropic vapour was produced as the bubble formed on the tube there was insufficient water in the boiler to maintain the same level of subcooling. This resulted in a reduction in subcooling of the liquid and in superheated azeotropic vapour leaving the boiler.

DESIGN CONSIDERATIONS

Vapour composition

From a design point of view the object is to raise vapour of a specified composition at a known heat flux. In the steady state, composition of feed to the boiler and vapour raised will be the same at a particular but usually different boiler liquid composition, Fig. 6. It is impossible to produce vapour more rich in nonane than azeotropic vapour with stable boiler conditions but all vapour compositions between azeotropic and pure steam may be produced. To boil very water rich vapours at 110 kW m^{-2}, it is necessary to have very small amounts of nonane in the boiler. Adding only 7% by mass of nonane to pure water results in a change of y_w from pure steam to 0.6. Referring to Fig. 6 it can be seen that this effect occurs at other heat fluxes and higher nonane contents. For example, a reduction of x_w by 4% at $x_w = 0.77$ produces a 25% change in the steam content of the vapour at $q = 29$ kW m^{-2}. This effect is caused at those critical nonane layer thicknesses where a small increase in boiler nonane content allows nonane to circulate into the tube bundle. At high heat fluxes the nonane always circulates into the bundle.

Continuously pumped feeds

Normally feed is supplied to boilers by pumping. To obtain a specified vapour composition with a continuously pumped steady feed supply it is necessary only to ensure that the liquid feed composition is the same as the desired vapour composition. Vapour composition is insensitive to small changes in feed composition even when the variation of y_w with the boiler composition is most sensitive. This is because the volume of liquids in the boiler is very large compared with the feed rates. For example, Fig. 6, point B, at $y_w = 0.9$ and $q = 36$ kW m^{-2} to change y_w to 0.6, point D, by altering the boiler feed composition to 0.6, Fig. 10, curve 3, would take over 35 min, curve 2. Of course the proportion of nonane evaporating alters as the feed rate is changed at the same heat flux making it necessary under continous pumping conditions to alter

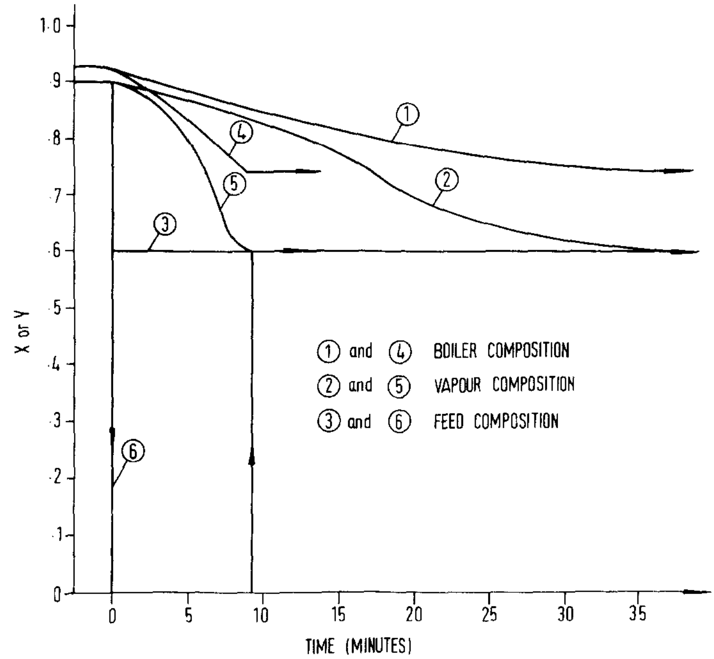

Fig. 10. System response required for a change in y from 0.9 to 0.6 at 36 kW m^{-2}. Curves 1 to 3 by changing boiler feed to $x_w = 0.6$ and curves 4 to 6 to all nonane.

the total feed volume from an initial flowrate of 2.9 to 4.1 $dm^3\ h^{-1}$ as the change takes place. The boiler composition changes to $x_w = 0.75$, curve 1, Fig. 10.

To speed up the response it is possible to pump in only the liquid component which is deficient in the vapour at the total volumetric rate of evaporation of the liquid of both components until the change is complete, curve 6, Fig. 10. The change referred to above would then take only 9 min, curves 4 and 5, Fig. 10. This method of control requires no preknowledge of the boiler composition necessary to produce the required y_w at a given heat flux provided it is based on measurement of the vapour composition.

At vapour compositions near azeotropic, change in demand for vapour without altering its composition can be achieved quickly because little change in boiler composition is necessary, Fig. 6. For higher y_w generally a considerable change in x_w with q is needed. Again the time required for the boiler to settle to equilibrium can be reduced by pumping in only the liquid temporarily deficient in the vapour until the necessary x_w is achieved. The delay in reaching steady state depends on the boiler composition change required to compensate for the change in heat flux imposed. For example at a required $y_w = 0.75$ a change in heat flux from 15 to 36 kW m^{-2}, Fig. 6, points A–C, would lead initially to $y_w = 0.9$, point B. An increase in boiler nonane content from $x_w = 0.93$ to 0.82, points B and C, is required to maintain $y_w = 0.75$. The delay in reaching this equilibrium condition is 6 min in the test boiler if only nonane is returned to the boiler. Due to the shape of the q vs y_w curves for steam rich vapours, the boiler composition is the same at two different heat fluxes, Fig. 6 points A and E, for example, producing the same vapour composition. In these specific cases a change in heat flux can be achieved without any alteration of x_w.

To obtain the most rapid response to changes in q or required y_w it may be possible to alter the boiler composition more quickly by making provision to remove the liquid in excess at the same time as the other is supplied. Again this may be controlled by sensing vapour composition or by coarse control based on preknowledge of the x_w required followed by fine control based on vapour composition. Control might also be based on sensing vapour temperature which is close to the dewline for water condensation for steam rich vapours. However, this can provide only coarse control of y_w as is clear from the scatter on Fig. 7. When boiling azeotropic vapours, superheated vapour is produced which makes this method of control unsuitable.

Intermittent feed

Usually an intermittent feed controlled by level in the boiler is employed in maintaining boiler output. In boiling immiscible liquids this leads to changes in x_w when the feed is cut off followed by a change in vapour composition. When x_w and y_w are close, the change in x_w will be slow and hence y_w will be only slightly altered in the period when feed is stopped. The effect is greater when x_w and y_w are greatly diffferent. At $x_w = 0.93$ and $q = 110$ kW m^{-2} feed cut off leads to a rise in y_w as the nonane liquid is depleted. Even at this condition the change in y_w will be small provided the level reduction permitted is small.

Heat transfer area

To transfer the same amount of heat to the immiscible liquid system as to pure water, roughly the same surface area is required provided that there is sufficient water in the boiler to circulate into the bundle. In the experimental boiler this implied that the interface had to be at or above the bottom row of tubes. Because of the entrainment effect at the surface the maximum heat flux is lower than that attainable in a similar water boiler. However, in the steam/nonane system studied a heat flux of over 100 kW m^{-2} could be accommodated easily.

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EBULLITION D'UN SYSTEME NON-MISCIBLE EAU-n-NONANE POUR UN FAISCEAU DE TUBES

Résumé—On décrit une série d'expériences dans lesquelles l'eau et le C_9 alkane n-nonane (ébullition à 150,5°C, 0,72) sont en ébullition dans un appareil chauffé électriquement à des flux allant jusqu'à 110 kW cm^{-2}. La composition de la vapeur, les températures de vapeur et de liquide et les courbes d'ébullition sont mesurées dans le domaine complet des compositions du liquide en ébullition. Des variations systématiques sont discutées. On décrit la nature du mécanisme de l'ébullition. Tant que la base de la rangée de tubes est immergée dans l'eau, le coefficient de transfert thermique à l'ébullition basé sur la différence de température entre la paroi du tube et t_{sat} de l'eau est très proche de celui de l'eau pure bouillante. Le texte se termine par des recommandations pour l'ingéniérie.

SIEDEN DES NICHTMISCHBAREN WASSER/n-NONAN-SYSTEMS AM ROHRBÜNDEL

Zusammenfassung—Es wird eine Reihe von Experimenten beschrieben, bei welchen Wasser und das C_9-Alkan n-Nonan (Siedepunkt 150,5°C, spez. Gew. 0,72 kg dm^{-3}) in einem kurzen, elektrisch beheizten Rohrbündelwärmetauscher bis zu Wärmestromdichten von 110 kW m^{-2} gesiedet werden. Über den gesamten Bereich der Zusammensetzung der zu verdampfenden Flüssigkeit werden die Dampfzusammensetzung, die Temperaturen des Dampfes und der Flüssigkeit sowie die Siedekurven gemessen. Die systematischen Variationen werden diskutiert. Der Verlauf des Siedeprozesses wird beschrieben. Vorausgesetzt, daß die untere Rohrreihe mit Wasser bedeckt ist, ergibt sich, daß der Wärmeübergangskoeffizient beim Sieden, bezogen auf die Temperaturdifferenz zwischen Rohrwand und Sättigungszustand des Wassers, sehr ähnlich ist dem Wärmeübergangskoeffizienten beim Sieden von reinem Wasser. Am Schluß werden noch Empfehlungen für die Konstruktion gegeben.

КИПЕНИЕ НЕСМЕШИВАЮЩЕЙСЯ СИСТЕМЫ ВОДА/Н-НОНАН, ИСТЕКАЮЩЕЙ ИЗ ПУЧКА ТРУБ

Аннотация—Описывается серия экспериментов, проводимых с кипящей системой вода/C_9 алкан н-нонана в мелкой нагреваемой электрическим током полости и системе труб при тепловых потоках до 110 кВт/м^2 (точка кипения 150,5°C, удельный вес 0,72). Состав пара, температуры жидкости и пара, а также кривые кипения измерялись во всем диапазоне изменений состава жидкостей в котле. Проводится обсуждение полученных результатов. Описывается природа процесса кипения. При условии, когда нижний ряд труб погружен в воду, коэффициент теплопередачи при кипении, построенный по разности температур между стенкой трубы и $t_{\text{насыщ.}}$воды, оказался весьма близок к значению коэффициента для кипения чистой воды. В конце статьи даны предложения для проектировщиков.