Pergamon

Heat Recovery Systems & CHP Vol. 14, No. 5, pp. 507–515, 1994
Elsevier Science Ltd
Printed in Great Britain
0890-4332/94 $7.00 + .00

0890-4332(94)E0004-4

REFRIGERANT-OIL MIXTURES BOILING IN A PLANAR CONFINED SPACE

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(*Received* 16 *September* 1993)

Abstract—In the frame of the JOULE 1 R&D programme of the Commission of the European Communities a project has been carried out on enhanced evaporation heat transfer surfaces. A specific investigation has been realised on refrigerant oil mixtures boiling in a planar confined space.

An experimental investigation of the boiling phenomenon in the confined space between a 30 mm wide × 120 mm high, heated plate and an opposing, adiabatic plate was carried out. The heated surface was made of a copper–aluminium–nickel alloy (Ra = 1 micrometer) and a saturated R-113/SUNISO 3GS oil mixture at atmospheric pressure was used as the boiling fluid.

The maximum heat flux tested was approximately 90% of CHF. The parameters investigated were the gap size (1–5 mm) and the oil concentration (1–7% by weight). It was again observed that confinement does not improve the nucleate boiling performance of pure R-113 in any significant way, whereas the CHF decreases with decreasing gap size. In addition, while the presence of oil was observed to have only a relatively minor effect on low flux nucleate boiling, it caused a serious degradation of the high flux boiling performance. This deterioration increased with increasing oil concentration and was more severe for smaller gap sizes. However, for a given gap size, the CHF increased with increasing oil concentration accompanied by increasingly larger surface superheats.

1. INTRODUCTION

Pool boiling in open spaces has been studied extensively in the past, but knowledge on the effect of confinement on pool boiling heat transfer is still very limited [1–6]. Nevertheless, pool boiling in confined spaces may occur in many practical situations. A few examples include immersion cooling of densely packed electronics, heat transfer from the plate-type fuel element in a nuclear reactor and, of more immediate interest of the present research project, plate heat exchangers. In some applications, because the confinement under certain conditions will enhance heat transfer, heat transfer equipment is intentionally designed to confine the boiling process.

An important aspect in the problem of confined boiling concerns boiling of mixtures of volatile and non-volatile fluids in confined spaces. For instance, in the petrochemical industry boiling of mixtures of hydrocarbons (volatile) with oil (non-volatile) is often encountered. In the refrigeration industry, contamination of the refrigerant with lubricant oil from the pumps, compressors, etc., is inevitable. As a result, some amount of oil is always present in the evaporator, the typical concentrations ranging from 5% to 10% by weight. In addition, oil is often intentionally added to the refrigerant to act as a lubricant as the fluid flows around the system. In these cases, the mixed oil is bound to affect the transport properties of the volatile fluid and may well have a significant effect on the boiling mechanisms and, consequently, the heat removal. As yet, no comprehensive model is available to describe this phenomenon, but heat exchanger designers must still be provided with accurate and reliable information regarding the heat transfer characteristics of mixtures of volatile and non-volatile fluids.

In the present investigation, the nucleate boiling and CHF behaviour of pure R-113 and mixtures of R-113 and SUNISO 3GS oil in a confined space is studied. The heated planar surface is treated so as to obtain a surface finish more representative of industrial applications (Ra = 1 μm).

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus used in the investigation is shown schematically in Fig. 1. The boiling chamber is made of double stainless steel walls and is equipped with three viewing windows,

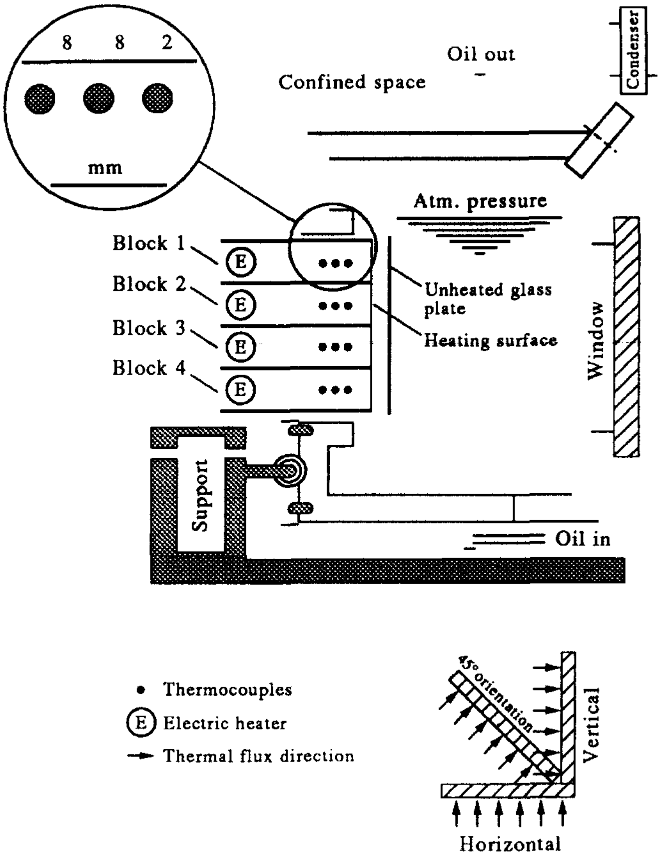

Fig. 1. View of the test rig.

one facing the heated surface and one on each side wall. Sealing of the windows was accomplished with R-113 resistant Teflon tape. The chamber is mounted on a horizontal axis which allows it to be rotated. Oil from the circulating heater flows in the space between the double walls, so as to keep the working fluid at a previously selected temperature; a thermocouple inside the chamber is used to monitor the bulk fluid temperature. A water-cooled, reflux condenser is used to condense the vapours back to the pool.

The test section itself is made of four copper–aluminium–nickel alloy blocks stacked together. The exposed face of the blocks is 30 mm square, thus making a 30 mm wide and 120 mm high test surface. Each block is independently heated by a 400 W cartridge heater located at the rear. Three thermocouples in each block, located at 2, 10 and 18 mm from the exposed surface, allowed for the determination of the temperature gradient in the block. The sides and rear of the block assembly were insulated in order to minimize the heat losses.

An HP 3421A Data Acquisition/Control Unit equipped with a 44462A 10 Channel Multiplexer and interfacing a computer system was used to take and reduce data automatically. In order to avoid the boiling curve hysteresis, all runs were made for decreasing heat fluxes. Once the maximum heat flux had been entered, the computer code checked for the attainment of prescribed conditions in the pool (determined by the oil jacket temperature), gave power to the test section and proceeded to the 30 min degassing period; thereafter, data collection started. The data acquisition system read and stored the temperatures in the blocks for a given power, after steady-state conditions had been verified. The power was then decreased in 10 W steps until the 10 W minimum had been reached. Before each run, the boiling surface was cleaned with R-113, so as to keep the same surface condition in all runs.

The wall temperature was obtained through extrapolation of the temperature profile in the blocks and the wall superheat was calculated using tabulated values for the saturation temperature of the boiling fluid. The average heat transfer coefficient over each block was then simply the ratio between the calculated heat flux (from the electrical input) and the block wall superheat. The average heat transfer coefficient over the entire surface was obtained by averaging the heat fluxes and the block wall superheats. The uncertainty in the temperature measurements was ±0.1°C and the uncertainty in the heat flux, as calculated from the electric power supplied, was approximately 4%. In addition, repeatability of the boiling curve was within 10%.

In the experimentation work, the maximum heat flux tested was within the CHF scatter range and the confined space was kept vertically oriented with all four edges open. The parameters varied were the gap size (2–5 mm) and the oil concentration (1–7% by weight). The latter parameter was measured before and after each run and the mean value taken as the nominal concentration. The measuring procedure consisted simply of taking a sample of known mass from the mixture, heating it to make the R-113 evaporate and then measuring the remaining mass of oil. The maximum uncertainty in the measurements, at low concentrations, was approximately 7%, whereas the deviation of the measured concentrations around the nominal value was approximately 2%. Finally, the wall superheat for boiling of the mixtures was simply referenced to the saturation temperature of pure R-113, as the expected increases in this parameter were within the uncertainty range of the temperature measurements.

3. EXPERIMENTAL RESULTS AND DISCUSSION

As mentioned before, boiling of mixtures of a volatile and a non-volatile fluid is often encountered in industrial applications. Examples were the petrochemical and the refrigeration industries. In this part of the investigation, efforts were directed towards identifying the basic boiling behaviour of such mixtures in the rectangular channel at hand. Data were taken for boiling

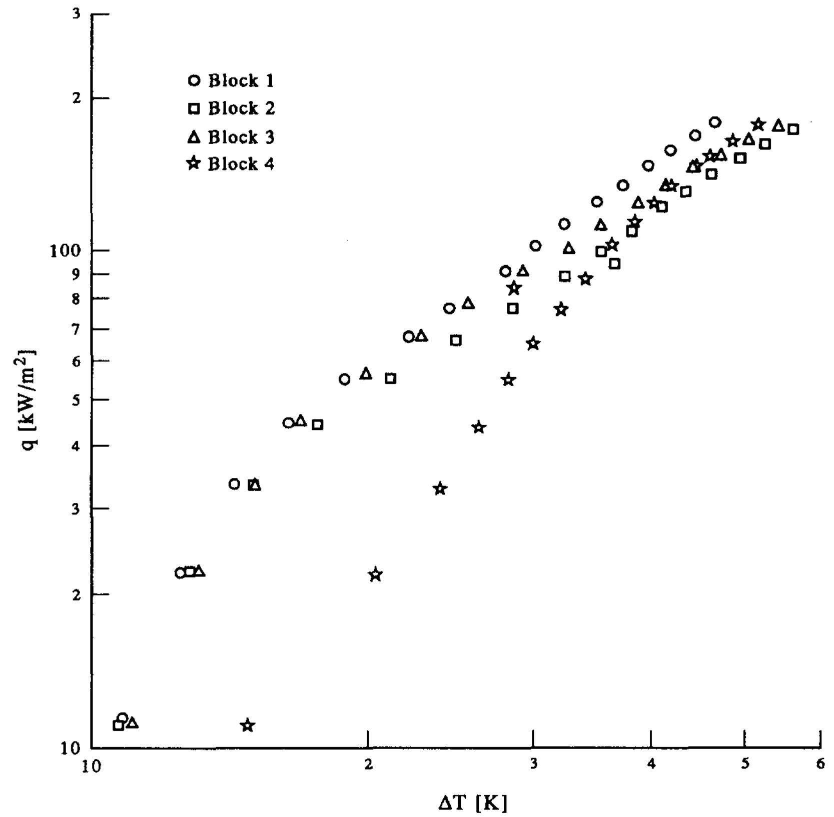

Fig. 2. Performance of the individual blocks for unconfined boiling of a 7.2% concentration R-113/oil mixture.

of saturated R-113 and mixtures of R-113 and SUNISO 3GS oil on the uncoated, smooth surface. The maximum heat flux tested was within the CHF scatter range of pure R-113 and the confined space was kept vertically oriented with all four edges open. The parameters varied were the gap size (2–5 mm) and the oil concentration (1–7% by weight).

Even though R-113 is not used in actual applications and a wide variety of oils is encountered, it is believed that the data obtained here reveal the trends in boiling mixtures of hydrocarbons and oil and of refrigerants and oil. It is acknowledged, though, that a quantification of the heat flux dissipations occurring in these cases would require testing the fluids actually used or testing fluids with similar values of the pertinent properties.

3.1. *Unconfined boiling of R113/oil mixtures*

Preliminary experiments were run for boiling of mixtures under unconfined conditions in order to dissociate the effects of confinement from the effects of oil. An analysis of the data was done first to check the representativeness by averaging parameters of heat transfer conditions over the entire surface.

Figure 2 shows the performance of the individual blocks at the 7% oil concentration. The variations in the heat transfer coefficient decrease from approximately 50% at low heat fluxes to 20% at high heat fluxes. Hence, caution should be employed in reading the discussion below, in terms of the average parameters. Whenever local temperature differences and/or heat fluxes are important, a separate analysis should be done.

Figure 3 shows the data for the effect of oil concentration on the overall performance. For low concentrations ($W < 4\%$) and low heat fluxes ($q < 65\,\mathrm{kW/m^2}$), a slight increase in heat transfer occurs. For higher heat fluxes, a serious deterioration in performance relative to the pure fluid is anticipated, even though no difference is expected between the different concentrations. However, a sharp deterioration in performance is observed for the 7% oil mixture.

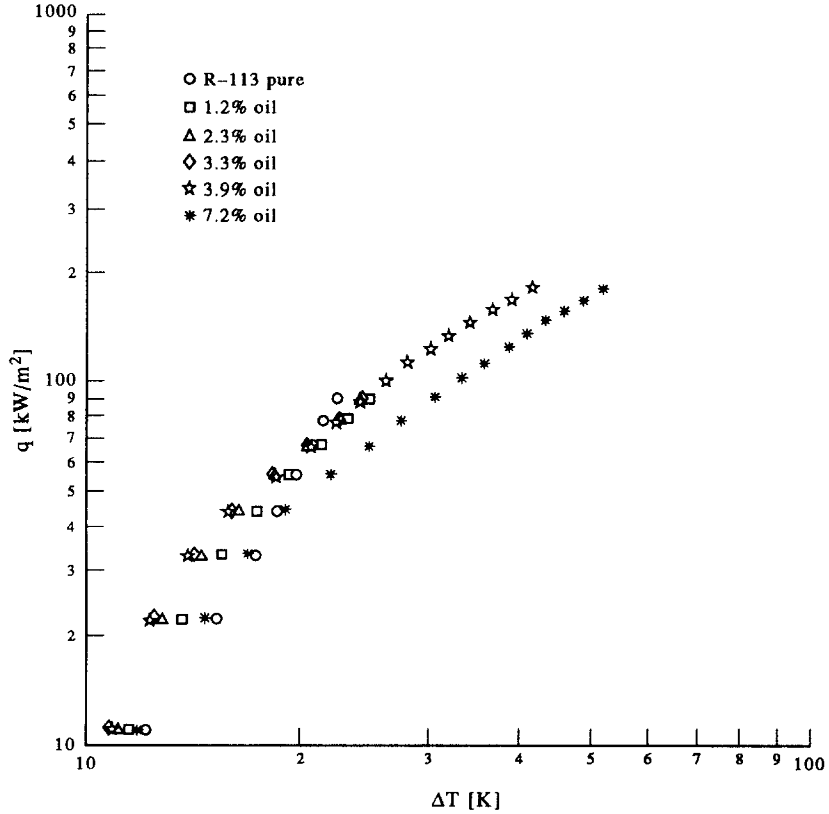

Fig. 3. Effect of oil concentration on the surface overall performance for unconfined boiling of R-113/oil mixtures.

It is believed that the main effect of oil on the mixtures at hand is to impose a mass diffusion resistance. Thus, the degradation in performance, even at low concentrations, would indicate that substantially less vapour is being generated, with a consequent reduction in heat removal.

3.2. *Confined boiling of R113/oil mixtures at 5 mm gap size*

The next step in the experimentation was to combine the effects of oil and confinement. The data for the boiling behaviour of the individual blocks at the 7% oil concentration and 5 mm gap size are shown in Fig. 4. The confinement was seen to have made heat transfer conditions over the surface rather uniform for low and moderate heat fluxes. For high heat fluxes, differences among the blocks of about 30% still occur. Accordingly, caution should be exercised in reading the discussion below when high heat fluxes are involved. The data for the effect of oil concentration on overall performance at the 5 mm gap size are shown in Fig. 5. For heat fluxes up to 60 kW m^{-2}, the performance is essentially the same for all concentrations tested and within the scatter range of the pure fluid boiling curves. For higher heat fluxes, the performance deteriorates markedly, the superheat continuously increasing with increasing oil concentration.

Comparison of Figs 4 and 5 indicates that the effect of confinement on boiling of mixtures is to accelerate the detrimental effect of oil on heat transfer. In this regard, deterioration in performance, with respect to the pure fluid, started slightly earlier for confined boiling than it did for unconfined boiling (60 kW m^{-2} and 65 kW m^{-2}, respectively). This effect could be due to the formation of increased areas of thin film evaporation, with the resulting increase in the rate of vapour generation. The oil mass diffusion resistance would then be more strongly felt in this case than in situations where sensible heat transfer plays a more important role. By the same token, for low heat fluxes, where the vapour generation is not very high either under confined or unconfined conditions, no significant differences in the intensity of the oil effect are observed.

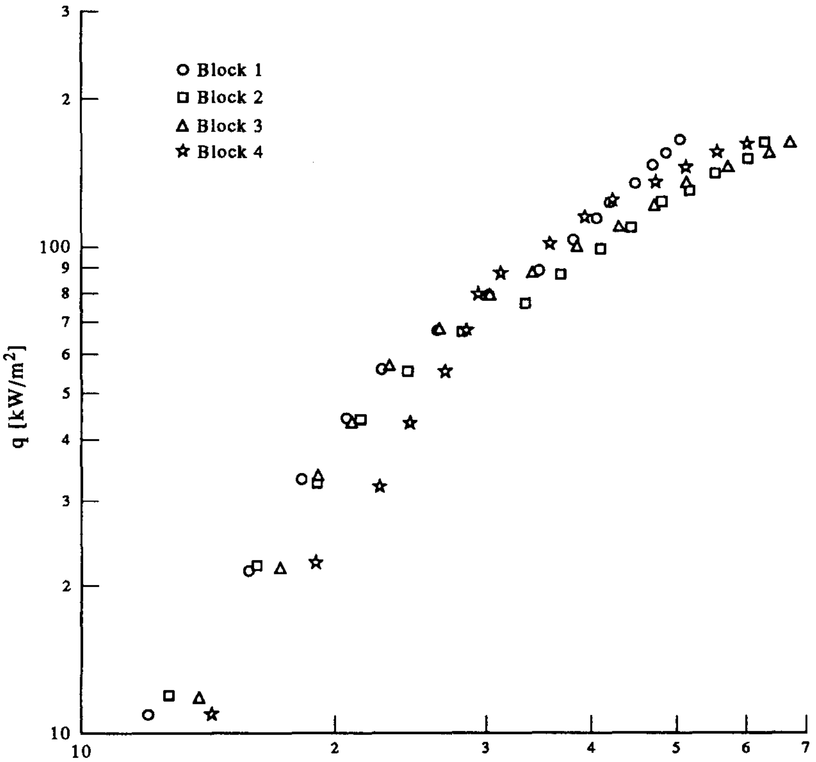

Fig. 4. Performance of the individual blocks for confined boiling of a 7.0% concentration R113/oil mixture at the 5 mm gap size.

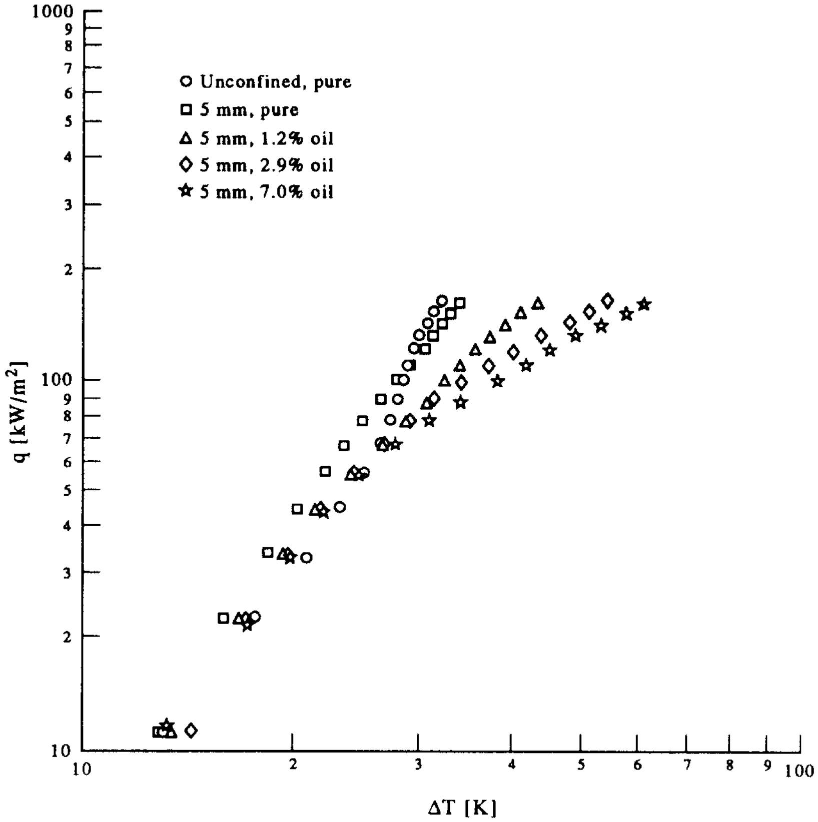

Fig. 5. Effect of oil concentration on the surface overall performance for confined boiling of R113/oil mixtures at the 5 mm gap size.

3.3. *Confined boiling of R*113/*oil mixtures at* 2 *mm gap*

In order to further characterise the effect of confinement on boiling of mixtures, data were also taken for the 2 mm gap size. In this case, the power was increased until the onset of CHF started to take place, at which point the power was decreased and data taking was initiated. Because, for unconfined boiling and 5 mm gap size, the onset of the critical condition was expected to occur at exceedingly high heat fluxes, the detection of the CHF was restricted to the 2 mm gap size.

The data for the boiling behaviour of the individual blocks at the 7% oil concentration and 2 mm gap size are shown in Fig. 6. The performance of block 1 is seen to be very similar to that for the 5 mm gap size (Fig. 4), whereas the lower blocks exhibited a poorer performance relative to the previous case. At the highest heat fluxes, the differences in the heat transfer coefficients among the blocks attained 36%. Hence, caution is once again recommended in applying the conclusions drawn from the averaged data to other situations.

The data for the effect of oil concentration on the overall performance at the 2 mm gap size are shown in Fig. 7. It should be noted, first of all, that a serious degradation in heat transfer with increasing oil concentration occurs throughout the entire heat flux range. This fact corroborates the previous proposition that the confinement accelerates the oil detrimental effect. Granted that, at 2 mm gap size, areas of thin film evaporation are already formed at relatively low heat fluxes, the oil mass diffusion resistance is then felt earlier. In addition, increases in this resistance due to a higher concentration would also be more noticeably felt, due to the relatively more important role now played by latent heat transfer.

The noticeable increase in the CHF (indicated by the arrows) with increasing oil concentration is thought to be due to a delay in the formation of dry patches. Because it becomes increasingly difficult to generate vapour and because the oil itself remains on the surface as the R-113 boils off,

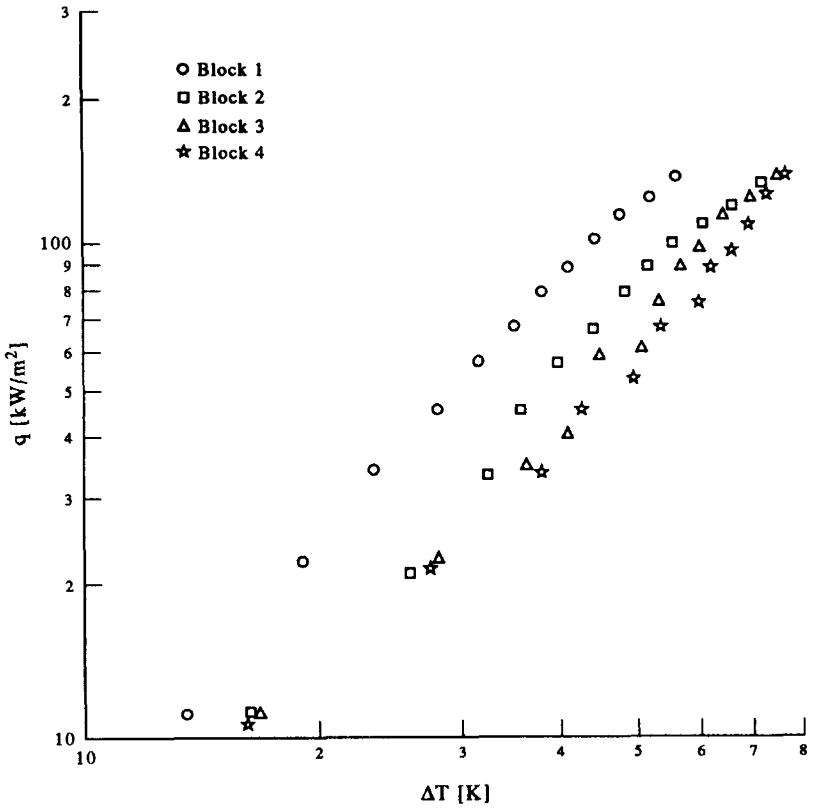

Fig. 6. Performance of the individual blocks for confined boiling of a 7.0% concentration R113/oil mixture at the 2 mm gap size.

dry patches are not easily formed and propagated. This resistance to the inception and propagation of local areas of film boiling translates into a delay to the onset of film boiling over the entire surface. The increasingly higher surface superheats are also easily explained if it is considered that heat transfer through an oil rich liquid layer is less efficient than boiling heat transfer of R-113.

Finally, in order to further establish the confinement "magnifying action" on the oil detrimental effect, Fig. 8 is presented. A clear degradation in heat transfer with narrowing confinement is seen throughout the entire heat flux range, whereas in Fig. 9 similar performances are observed for all gap sizes with pure R113.

4. CONCLUSION

For boiling of R113/oil mixtures on a smooth surface, the conclusions are:

(1) For unconfined boiling at low flux ($q < 6\,\mathrm{kW\,m^{-2}}$) and low oil concentrations ($w < 4\%$), no significant effect of oil on heat transfer is observed.

(2) For unconfined boiling at higher heat fluxes and higher oil concentrations, a serious deterioration in performance relative to the pure fluid can be expected.

(3) For 5 mm gap size and low heat fluxes ($q < 60\,\mathrm{kW\,m^{-2}}$), no significant effect of oil is observed for all concentrations tested.

(4) For 5 mm gap size and higher heat fluxes, a rapid deterioration in heat transfer occurs with increasing oil concentration.

(5) For 2 mm gap size, a degradation in heat transfer occurs throughout the entire nucleate boiling regime, the degradation being more serious at high heat fluxes.

(6) The CHF increases with increasing oil concentrations, even though accompanied by increasingly larger superheats.

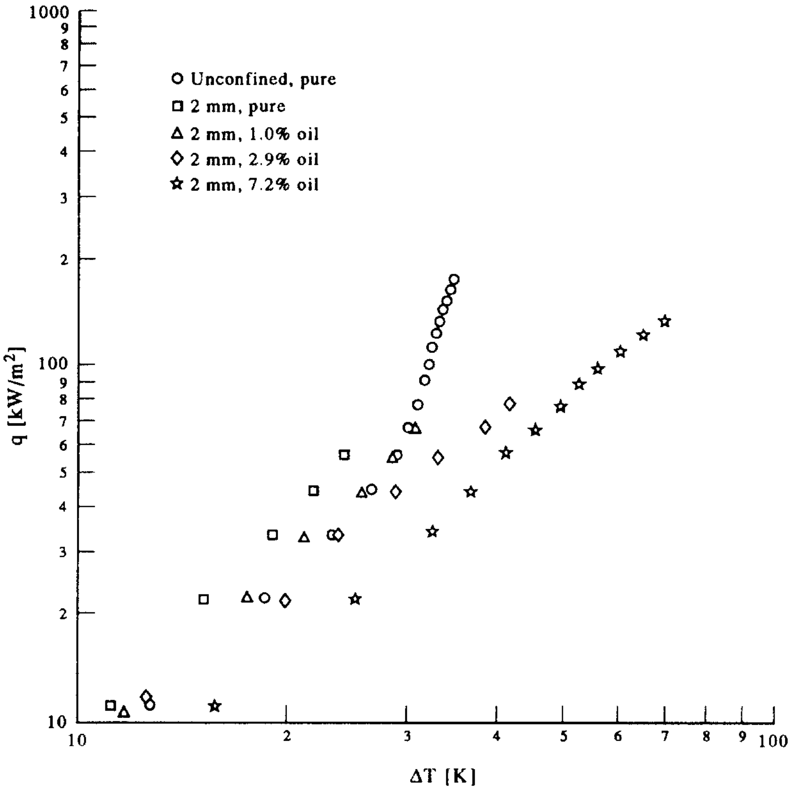

Fig. 7. Effect of oil concentration on the surface overall performance for confined boiling of R113/oil mixtures at the 2 mm gap size.

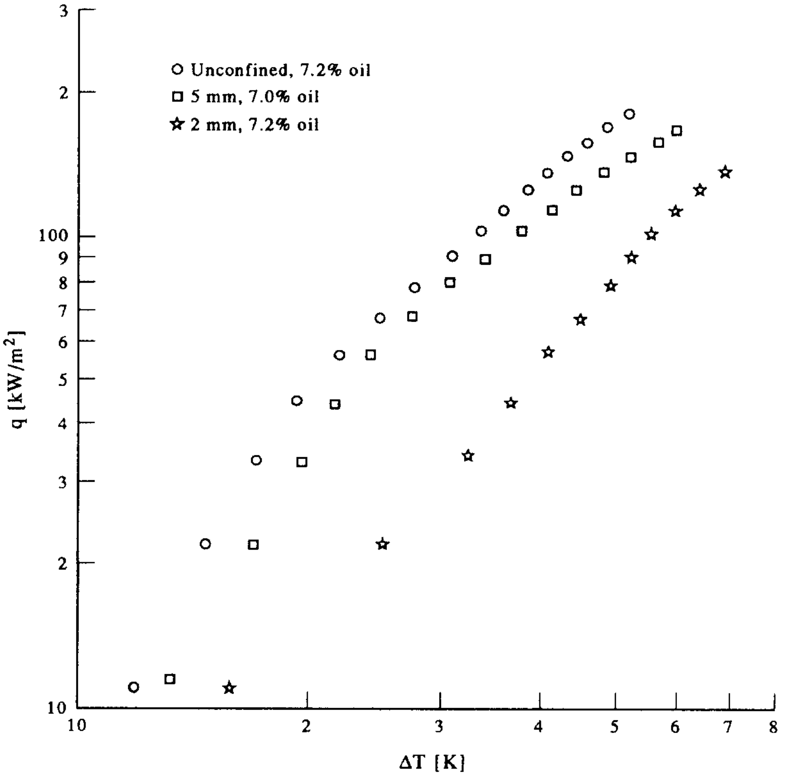

Fig. 8. Effect of confinement on the surface overall performance for boiling of 7% concentration R113/oil mixtures.

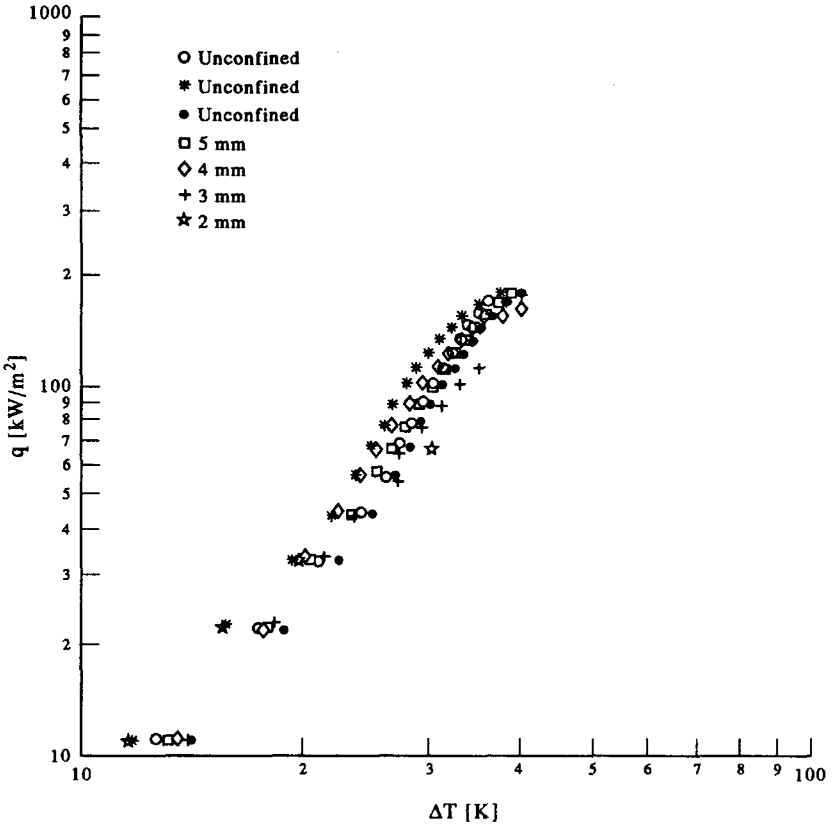

Fig. 9. Effect of confinement on boiling of pure R113.

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