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THE EFFECTS OF PRESSURE AND ACCELERATION ON THE POOL BOILING OF WATER AND ARCTON 11

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Abstract—This paper describes an experimental study of the effects of high pressure and acceleration on pool boiling using water and Arcton 11. Boiling is from an electrically heated stainless steel tubular test section of 0·035 in O.D. and 1·25 in long arranged so that the resultant acceleration is at all times perpendicular to the axis of the tube. The test section is mounted in a pressurized centrifugal pool boiler.

Tests using water are reported for the pressure range 25–405 lb/in^2 and accelerations in the range 2·5–65·3 g. Tests using Arcton 11 are reported for pressures of approximately 20 and 90 lbf/in^2 and accelerations of 2·5, 16·3 and 65·3 g. The results for water show variations which are attributed to variable wetting of the boiling surface; those for Arcton 11 display considerable temperature overshoots with temperature differences of up to 120 degF attained under natural convection conditions before boiling took place. The results are discussed on the basis of a hypothesis concerning the contamination of the cavities in a boiling surface.

NOMENCLATURE

a, test section acceleration [ft/s^2];
g, acceleration due to Earth gravity [ft/s^2];
P, absolute pressure [lbf/in^2];
ΔP_H, hydrostatic pressure increment at the test section [lbf/in^2];
$\dot{q}$, rate of heat transfer per unit area of the heated surface [Btu/h ft^2];
T, temperature [°F];
ΔT, temperature difference between heated surface and the bulk liquid [degF];
ΔT_{sat}, temperature difference between heated surface and the liquid saturation [degF];
ΔT_{sub}, subcooling at the test section $\Delta T_{sub} = \Delta T - \Delta T_{sat}$ [degF];
v, specific volume [ft^3/lb];
Gr, Grashof number;
Nu, Nusselt number;
Pr, Prandtl number.

INTRODUCTION

THIS study concerns natural convection and nucleate boiling at high pressure and acceleration. A number of studies of heat transfer in these regimes at accelerations higher than earth gravity are reported in the literature.

Merte and Clark [2] used a pivoted boiler mounted on a rotating arm to boil water from an electrically heated flat surface with a normal acceleration vector. Experiments in the range one to twenty-one times earth gravity showed a decreased temperature difference, ΔT_{sat} in the nucleate boiling regime up to heat fluxes of about 50000 Btu/h ft^2 which was attributed to an increased natural convection heat-transfer component. This effect was absent at higher heat fluxes. Graham and Hendricks [3] used a pivoted centrifugal boiler to give an acceleration range of one to nine times earth gravity. Water was boiled from an electrically heated thin chromel ribbon mounted in tension over a bakelite block and provision was made for photographic studies. Increased acceleration delayed the onset on boiling until higher heat fluxes were reached and reduced the temperature difference, ΔT for some way into the nucleate boiling regime. In addition, increased acceleration gave a reduction in the number of active bubble nucleation centres near to the incipient boiling condition. These effects were attributed to an increase in the natural convection component and a thinning of the thermal sublayer under increased acceleration. Hysteresis of the temperature difference, ΔT was evident; values of this quantity recorded for increasing heat flux were larger than those for decreasing heat flux. Similar trends were observed by Graham.

Hendricks and Ehlers [4] in a study of pool heating of liquid hydrogen carried out on an apparatus similar to that used in [3]. Repetition of tests at seven times earth gravity with low heat flux nucleate boiling showed that a fresh fill of hydrogen gave a larger temperature difference, ΔT than for a subsequent similar test. It was thought that vapour nuclei still attached to the surface after the first test became active at lower temperature differences in the second test. This is of particular interest in view of the effects observed in the present study.

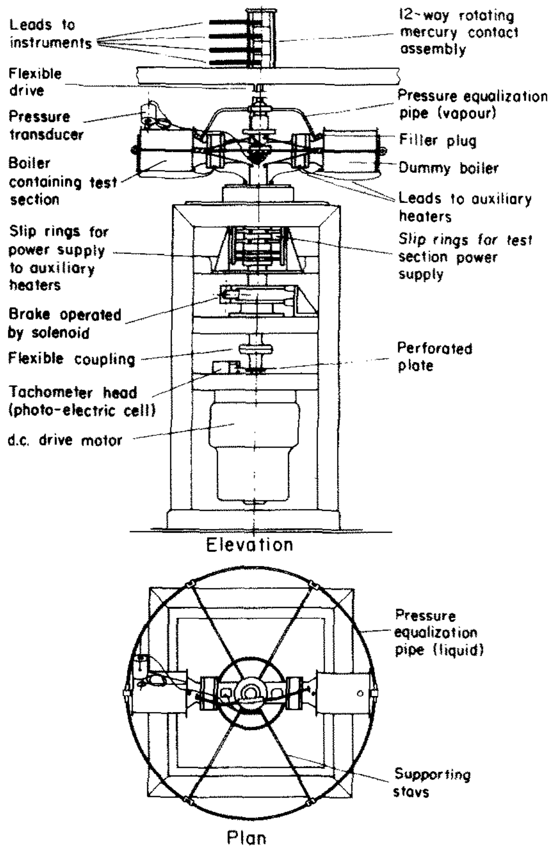

FIG. 1. Arrangement of centrifugal pool boiler assembly.

APPARATUS AND EQUIPMENT

The boiler used in this series of tests was the same as that used by Beasant and Jones [5] but with some modifications. Two similar boilers (as shown in Fig. 1) of welded steel construction were mounted rigidly in a horizontally opposed position on a vertical central shaft which was coupled to a d.c. motor. The boiler pressures were equalized by communication through two stainless steel pipes. One carried liquid and was attached to each boiler at its outer end; the other acted as a vapour link between the inner end of each boiler. In order to maintain water purity all wetted components were of stainless steel.

One boiler contained an electrically heated test section assembly which was supported in the horizontal position on electrical conductors at a nominal radius arm of 14·375 in, see Fig. 2. The test section was a straight length of hard drawn austenitic stainless steel tube of 0·035 in O.D. and 0·023 in I.D. with a heated length of 1·25 in. Horizontal mounting of the test section gave a uniform depth of immersion with a uniform subcooling due to the effects of hydrostatic pressure over the test section length. The acceleration vector was normal to the test section axis. There was considerable heat loss from the rotating boilers to the surrounding air and auxiliary electrical heaters were used to maintain and control the the boiler pressure. These were wound non-inductively round the cylindrical surface of each boiler and its outer end and were supplied with a maximum of 30 A at 250 V a.c. through a variable transformer and brush gear mounted on the central shaft.

The boilers were rotated by a d.c. shunt connected drive motor of 3 hp and motor speed control was by an auto transformer in the armature circuit. Power was supplied to the test section via heavy brush gear (250 A) from a 10 kW

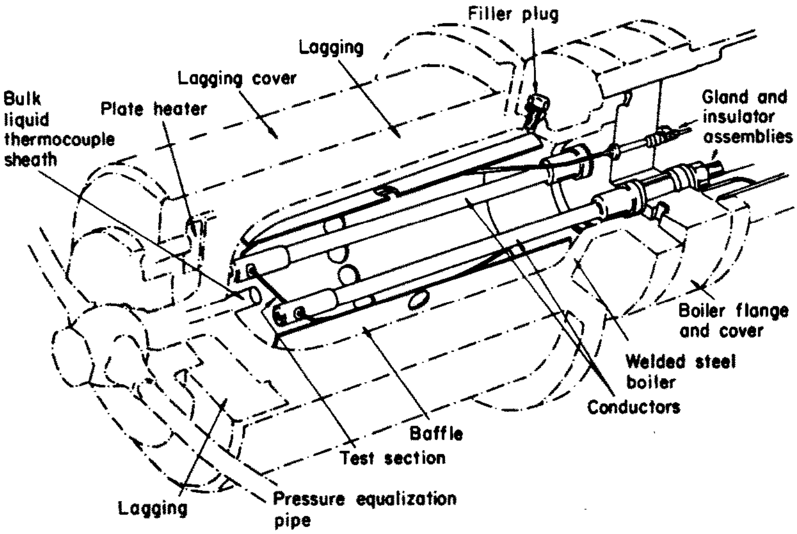

FIG. 2. Test section and boiler assembly.

d.c. generator set. The field voltage to the generator was regulated by a voltage stabilizer and an auto transformer and then rectified to give full range control over the power supplied to the test section. The power to the auxiliary heaters was from a 230 V a.c. mains supply via a 30 A mercury contact relay and a 30 A auto transformer.

Instruments were used to make the following measurements:

(i) The test section current was measured by a p.d. measurement across a measured resistance in series with the test section.
(ii) The test section p.d. was measured directly.
(iii) The boiler bulk liquid temperature was measured by a chromel–alumel thermocouple situated in a sealed pocket and at the same radius of rotation as the test section.
(iv) The temperature of the inner wall of the test section was measured by a fine wire butt welded thermocouple, fibreglass covered and insulated with silicone varnish, which was threaded through the test section.
(v) The speed of rotation of the boilers was measured by a photoelectric cell tachometer.
(vi) The boiler pressure was measured at low accelerations by a strain gauge transducer mounted on the boiler at the same radius of rotation as the test section and excited by a 5 V supply from dry batteries.

A d.c. potentiometer was used to obtain the readings (i–iv). The test section p.d., thermocouple, pressure transducer and burnout detector leads were taken from the rotating boilers via a twelve channel rotating mercury contact assembly which was driven by a flexible coupling from the main shaft.

At rotational speeds above 50 rev/min it was not possible to use the pressure transducer due to an inaccurate reading when under conditions of high radial acceleration. At high accelerations, the boiler pressure was estimated from the saturation pressure corresponding to the bulk liquid thermocouple reading with allowance for subcooling at the test section due to the effect of hydrostatic pressure.

PREPARATION OF THE BOILERS AND TEST SECTION

A careful cleaning and rinsing procedure using a strong detergent solution was carried out several times during the course of the experiments. This was done when a change was made in the boiling substance or when cleaning was thought to be necessary from the electrical resistivity of boiler water samples. If the electrical resistivity fell to near $5 \times 10^4\ \Omega$ cm the boilers were refilled. Measurements of the surface tension of a sample taken from the distilled deionized water supply gave 74 dyn/cm at 20°C. This indicated that the supply of distilled deionized water was free of surface active agents.

For the water tests the boilers were filled with distilled deionized water which had been degassed by boiling in a filling flask for 1 h immediately before filling. In order to expel air from the boilers and to ensure efficient degassing this water was then boiled from the auxiliary heaters at slightly above atmospheric pressure for a further period of 30 min with one filler plug left loose for venting purposes. To remove absorbed gasses from the test section surface, boiling from the test section at a moderate heat flux was carried out for a short time during this period if the test section had not previously been used or had dried out. Pressure transducer and bulk liquid thermocouple readings were noted and at the end of this period the boilers were sealed while at saturation temperature.

Arcton 11, which is a volatile liquid at room temperature, was poured into the boiler from the pressure cylinder in which it was supplied. It did not require degassing and because of its volatility was quickly brought up to saturation temperature in the boilers and, with one filler plug loose, it was held at saturation for about 15 min to drive off residual air from the boilers. The boilers were then sealed while at saturation temperature.

Each test section was stored in distilled deionized water until required. Final preparation of the test section consisted of polishing the boiling surface with 4/0 emery polishing paper.

TEST PROCEDURE

Test runs were carried out to determine the relationship between the temperature difference, ΔT and the heat flux for water and Arcton 11 in turn. Each run was made at a selected pressure and acceleration and the same test section was used throughout the series of tests.

An initial pressure reading was taken from the pressure transducer before each run and with the boilers rotating at a low speed (up to 50 rev/min). If the run was at a higher rotational speed the pressure during the run was estimated from the bulk liquid temperature reading with allowance for subcooling. The rotational speed of the boilers was set to the selected value for each run, as measured by the tachometer, and the pressure was maintained at a constant value, within practical limits, throughout each run by adjustment of the power input to the auxiliary heaters.

Each set comprised test section thermocouple, bulk liquid thermocouple, test section p.d. and current readings. The electrical power supply was adjusted to give an estimated initial heat flux of about 5–10 per cent of the critical value and the power was increased by a small step between each set of readings until the heat flux was, by estimation, about 50–75 per cent of the critical value.

Then the power was decreased by a number of steps and an additional set of readings was taken after each step. However, to obtain a more complete investigation there was some variation in the order in which the readings were taken in some of the runs.

DISCUSSION

Readings were obtained in the natural convection non-boiling region in most of the test runs. These results are plotted in Fig. 3 in the form Nu against the product $Gr\,Pr$ along with the similarity relationships of Nusselt [6] and McAdams [7]. It can be seen that the Arcton results follow the same form of curve as the similarity relationships but give higher values of the Nusselt number. For $Gr\,Pr > 10^4$ the Arcton results can be correlated by the expression:

$$Nu = 0{\cdot}725\ Gr\,Pr^{0.25}.$$

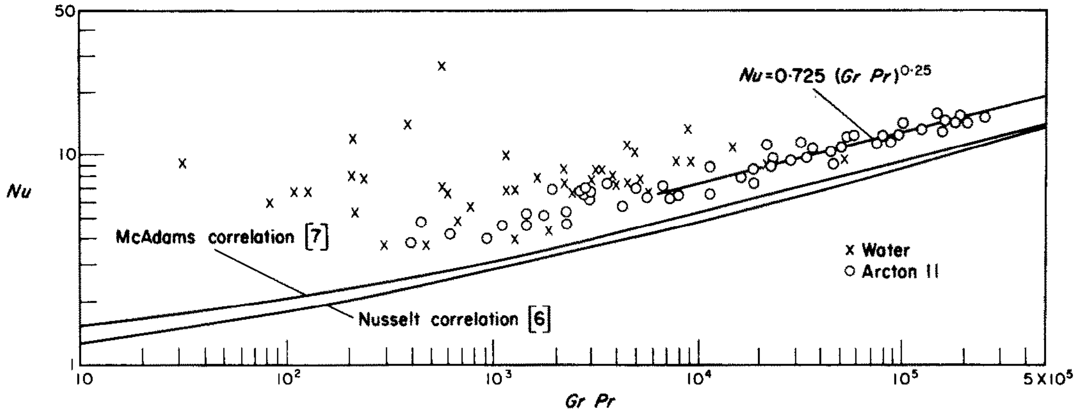

FIG. 3. Water and Arcton 11: natural convection heat transfer.

Similar expressions have been proposed by previous investigators but there is wide variation in the values of the constant. This is illustrated by the value of 0·47 for $Gr\,Pr > 10^5$ given by Fishenden and Saunders [8] and the value of 1·4 found to correlate the results of Hall and Hatton [9] lying in the range $10^2 \leqslant Gr\,Pr \leqslant 10^4$.

The results for water are more scattered than those for Arcton and indicate higher values of Nusselt number for $Gr\,Pr < 10^4$ although there is agreement between the two fluids at higher values of $Gr\,Pr$. The measured temperature differences were mostly small (down to 1·9 degF) and the results for water are of limited significance on account of the possible errors involved in the measurements. An estimate of errors is given in the Appendix.

Results of test runs with distilled deionized water are plotted for the purpose of comparison in Figs. 4–10. Figures 4–6 show the effects of change of pressure at various accelerations. In each case a reduction in the temperature difference at high pressure is evident in the nucleate boiling region, a result which is in agreement with previous investigators and which is predicted by the theory of bubble nucleation from vapour filled cavities. This reduction is present at high accelerations within the experimental range.

Figures 7–10 show the effects of increased acceleration at various pressures. At high accelerations there is an increase in the heat-transfer coefficient, with a reduction in the temperature difference, in the natural convection region. In the nucleate boiling region the temperature difference is increased at high acceleration; this is most probably due to the subcooling at the test section induced by the hydrostatic pressure which is estimated at approximately 8 lbf/in² at 65·3 g. The experiments of Fritz and Homann [10] suggest that the temperature difference throughout the depth of liquid, that is, perpendicular to its free surface, does not follow the saturation temperature distribution but, due to mixing, is more uniform with a superheated region near the surface and a subcooled region at a greater depth. The bulk liquid temperature measurements of Merte and Clark [2] for a high acceleration system indicated a near uniform temperature distribution. As a working basis for the estimation of test section subcooling the saturated liquid condition was taken at half the test section depth with the temperature at this position equal to the measured bulk liquid temperature at the test section. Hence the test section subcooling may be expressed in the form

$$\Delta T_{\text{sub}} = \frac{\Delta P_H}{2}\left(\frac{\mathrm{d}T}{\mathrm{d}P}\right)_{\text{sat}}.$$

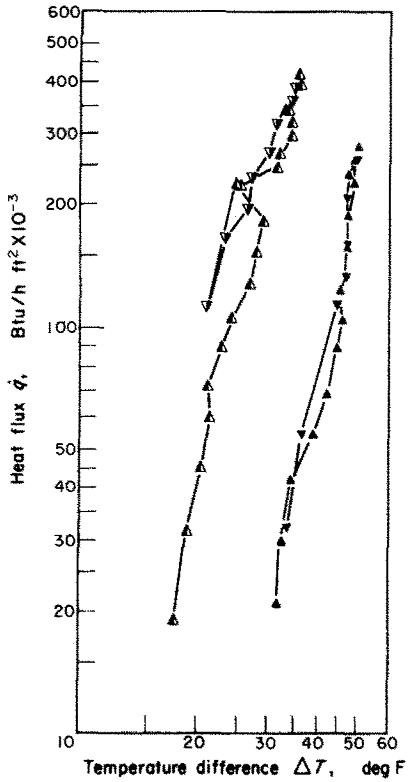

FIG. 4. Water: effect of pressure at acceleration, $a = 2{\cdot}5g$.

Run No. 18
Fill No. 2. $\Delta T_{sub} = 3{\cdot}5$ degF
Pressure: 25 lbf/in^2
▲ increasing heat flux
▼ decreasing heat flux

Run No. 19
Fill No. 2. $\Delta T_{sub} = 0{\cdot}4$ degF
Pressure: 378 lbf/in^2
▲ increasing heat flux
▼ decreasing heat flux

The increase in the temperature difference, ΔT due to high acceleration was more marked at lower than at higher pressures and this may be attributed to the large subcooling at low pressures arising from larger values of $(\mathrm{d}T/\mathrm{d}P)_{sat}$.

The results of Merte and Clark [2] showed a reduction in the temperature difference at increased acceleration well beyond the incipient boiling point up to a heat flux of about 50000 Btu/hft^2 and a slight increase at higher heat fluxes.

This was explained on the grounds of a significant free convection non-boiling component of heat transfer well into the nucleate boiling regime. The author's results do not show the same effect; leaving aside the higher degree of scatter the cross over in the boiling curves

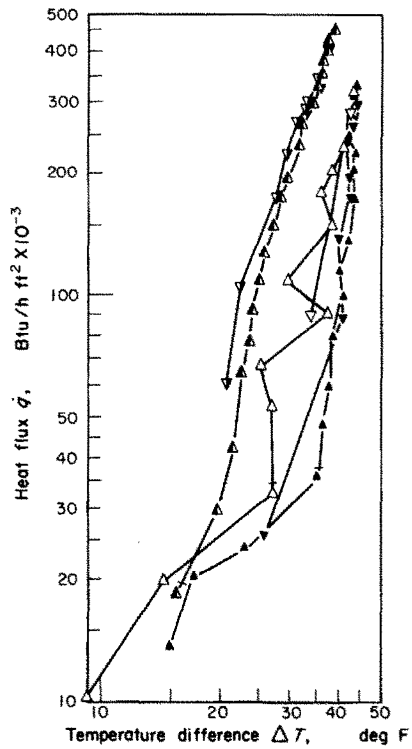

FIG. 5. Water: effect of pressure at acceleration, $a = 16{\cdot}3g$.

Run No. 24
Fill No. 3. $\Delta T_{sub} = 1{\cdot}9$ degF
Pressure: 26 lbf/in^2
▲ increasing heat flux
▼ decreasing heat flux

Run No. 17
Fill No. 1. $\Delta T_{sub} = 0{\cdot}5$ degF
Pressure: 166 lbf/in^2
△ increasing heat flux
▽ decreasing heat flux

Run No. 21
Fill No. 2. $\Delta T_{sub} = 0{\cdot}3$ degF
Pressure: 400 lbf/in^2
▲ increasing heat flux
▼ decreasing heat flux

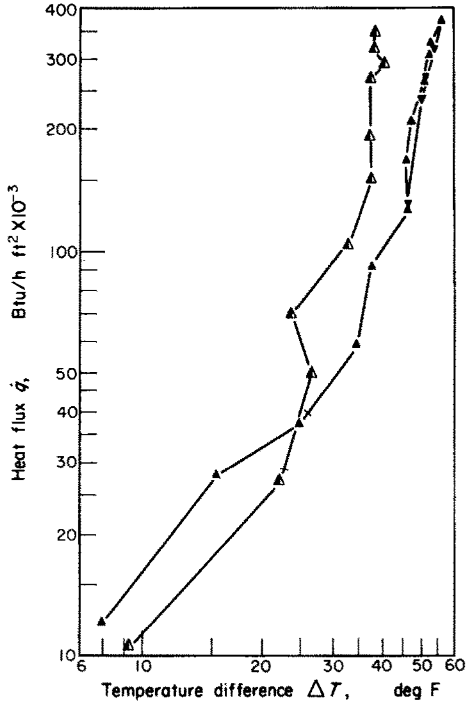

FIG. 6. Water: effect of pressure at acceleration, $a = 65{\cdot}3g$.

Run No. 25
Fill No. 3ΔT_{sub} = 6·9 degF
Pressure: 36 lbf/in^2
▲ increasing heat flux
▼ decreasing heat flux

Run No. 27
Fill No. 3. ΔT_{sub} = 1·0 degF
Pressure: 400 lbf/in^2
▲ increasing heat flux

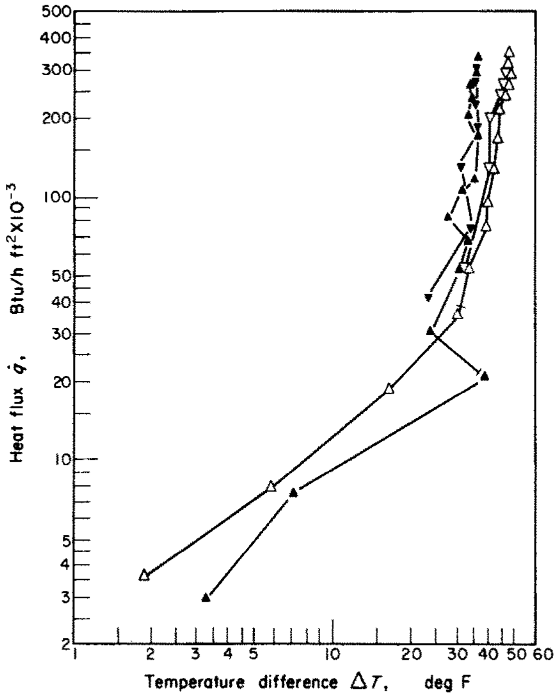

FIG. 7. Water: effect of acceleration at nominal pressure, 25 lbf/in^2.

Run No. 8
Fill No. 1. ΔT_{sub} = 0·6 degF
Acceleration, a = 4·2 g
▼ increasing heat flux
▲ decreasing heat flux

Run No. 10
Fill No. 1. ΔT_{sub} = 3·5 degF
Acceleration, a = 25·4 g
△ increasing heat flux
▽ decreasing heat flux

usually occurs in the region of the incipient boiling point. The divergence between the present results and those of [2] may be due to different heater geometry and subcooling effects. The results of [2] are presented in terms of ΔT_{sat} whereas the present results are based on the temperature difference, ΔT.

At high accelerations the heat flux at the incipient boiling condition is increased. Although the onset of boiling could not be determined visually in the present tests, an estimation could be made from the change of slope of the boiling curve and a departure from the natural convection relationship. Table 1 gives the range of the heat flux values at the first reading after the estimated onset of boiling in increasing heat flux. All the runs in which convection occurred are included.

The estimated onset of boiling is marked in the figures by a bar across the connecting line between the appropriate points.

In several of the runs using water the onset of boiling is marked by an abrupt change of slope of the boiling curve and in run No. 8 (Fig. 7)

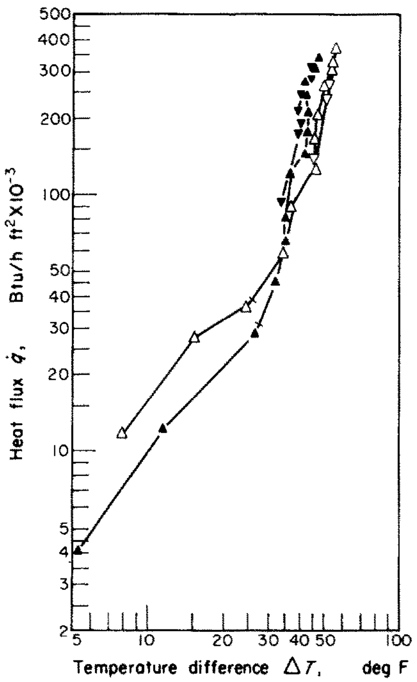

FIG. 8. Water: effect of acceleration at nominal pressure, 35 lbf/in^2.

Run No. 9
Fill No. 1. $\Delta T_{sub} = 1{\cdot}7$ degF
Acceleration, $a = 16{\cdot}3\ g$
▲ increasing heat flux
▼ decreasing heat flux

Run No. 25
Fill No. 1. $\Delta T_{sub} = 6{\cdot}9$ degF
Acceleration, $a = 65{\cdot}3\ g$
△ increasing heat flux
▽ decreasing heat flux

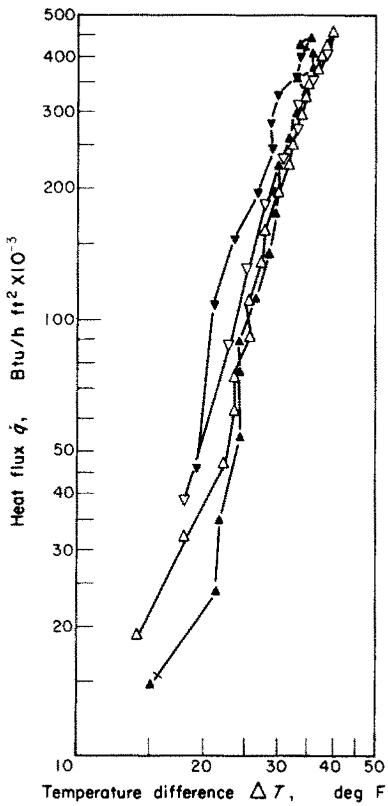

FIG. 9. Water: effect of acceleration at nominal pressure, 400 lbf/in^2

Run No. 20
Fill No. 2. $\Delta T_{sub} = 0{\cdot}1$ degF
Acceleration, $a = 9{\cdot}2\ g$
▲ increasing heat flux
▼ decreasing heat flux

Run No. 22
Fill No. 2. $\Delta T_{sub} = 0{\cdot}4$ degF
Acceleration, $a = 25{\cdot}4\ g$
△ increasing heat flux
▽ decreasing heat flux

and No. 15 (Fig. 10) there is a reduction of temperature difference after the onset of boiling, i.e. a temperature "overshoot". The reduction of 5 degF in run No. 8 was noticed as an abrupt change at the time of reading and was too large an effect to be put down to instrument error. The phenomenon of overshoot is discussed more fully in connection with the results for Arcton 11.

Considerable scatter in the temperature difference results can be observed for water fill No. 1. Again, the effects were too large to be put down to instrument or reading error and in any event there was much less scatter in the results obtained with subsequent charges of water. However, in many of the runs using water fill No. 2 or No. 3 slow fluctuations in the specimen temperature reading were noted during otherwise steady conditions.

The fluctuations were most severe (± 3 degF) during increasing heat flux readings at a little

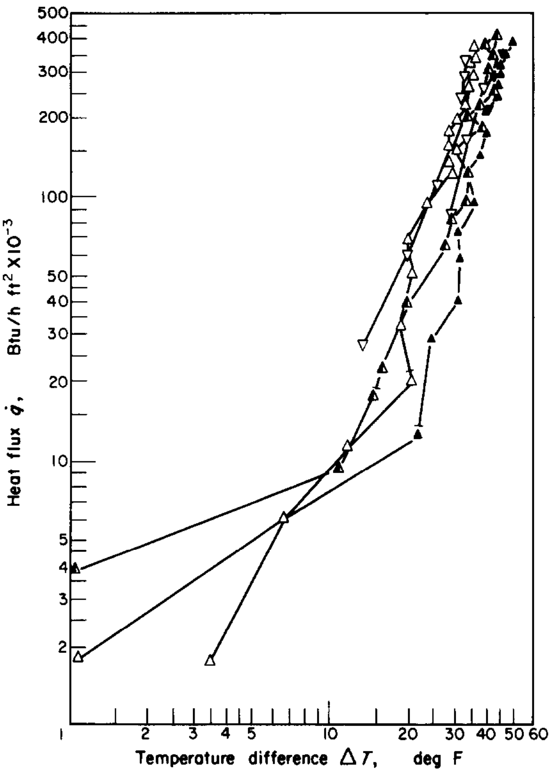

FIG. 10. Water: effect of acceleration and 19 day waiting period at nominal pressure 165 lbf/in^2.

Run No. 14
Fill. No. 1. ΔT_{sub} = 0·1 degF
Acceleration, a = 4·2 g
▲ increasing heat flux
▼ decreasing heat flux

Run No. 15
Fill No. 1. ΔT_{sub} = 0·3 degF
Acceleration, a = 9·2 g
△ increasing heat flux
▽ decreasing heat flux

Run No. 16
Fill No. 1. ΔT_{sub} = 0·8 degF
Acceleration, a = 25·4 g
▲ increasing heat flux
▼ decreasing heat flux

higher than the incipient boiling value and declined gradually at higher heat fluxes. It is possible that fluctuations were also present in the case of fill No. 1, though of much longer period. Mesler and Banchero [17] observed fluctuations in the pool boiling of organic liquids from a stainless steel tube of 0·064 in O.D. and noted that the fluctuations were more prominent at lower heat fluxes in the nucleate boiling region. Madsen and Bonilla [18] measured fluctuations of considerable intensity with boiling surface temperature changes of up to 25 degF for pool boiling of a sodium–potassium alloy.

Table 1

Acceleration (a/g)	Heat flux range (Btu/h ft^2)
1·4	24600–28800
4·2	28360–30330
9·2	23940–32400
16·3	29530–48140
25·4	22100–53820
65·3	49530–58710

An hysteresis effect can be seen in several runs and this was particularly noticeable in runs 19 and 20: values are given in Table 2 for a heat flux of 300000 Btu/h ft^2:

Table 2

Run No.	$T_{inc} - T_{dec}$ (degF)
19	+4·0
20	+4·5

Both runs used water fill No. 2. In run No. 19, Fig. 4 an unusually low value of the temperature difference was obtained for increasing heat flux at a value of 220000 Btu/h ft^2 and this was found to be repeatable in a spot check after completing the run. It is difficult to advance a satisfactory explanation of this effect.

Figure 10 shows a sequence of runs using water fill No. 1. A period of 19 days intervened between runs No. 14 and 15 during which period the boiler was closed. The temperature difference in the nucleate boiling regime for run No. 15, after this period, was considerably less than that for run No. 14. This effect could be explained on the grounds that the vapour filled cavities left in the test section surface had become regassed during the waiting period. Ellion [11] has shown that this would have reduced the superheat required for nucleation but it would be expected that the cavities would be purged of gas during the degassing procedure. Run 16, at an acceleration of 25·4 g, is also shown in Fig. 10 and the temperature difference, although higher than in run No. 15 (probably due to increased subcooling) does not attain the values of run No. 14. Therefore, it is difficult to explain this effect on the basis of regassing of the cavities. An alternative explanation, that during the waiting period the boiling surface became less wetted due to contamination, is preferred. Such contamination would increase the effective cavity size and reduce the superheat required for nucleation.

The test runs using Arcton 11 are plotted individually in Figs. 11–16. The most striking feature of each of these runs is the presence of a large "overshoot" of temperature in the natural convection boiling region, well beyond the values at which incipient boiling might be expected to occur. Similar overshoots are reported in the literature. Corty and Foust [12] obtained temperature differences of about 50 degF for n-pentane and almost 60 degF for diethyl ether in the natural convection region during a succession of test runs although the temperature differences in nucleate boiling were much lower. Sabersky and Gates [13] obtained overshoots of almost 100 degF above the normal boiling temperature difference for water which had been prepressurized to 15000 lbf/in^2 for not less than 15 min. Marto [14] found that the surface superheats necessary to initiate boiling of sodium were considerably in excess of those required to maintain nucleate boiling. Results due to Long [15], published in a review paper by Zuber, for dichloretetrafluoroethane show a considerable overshoot up to a temperature difference of 53 degF.

The sequence in which the results were obtained in run No. 28 is significant, see Fig. 11.

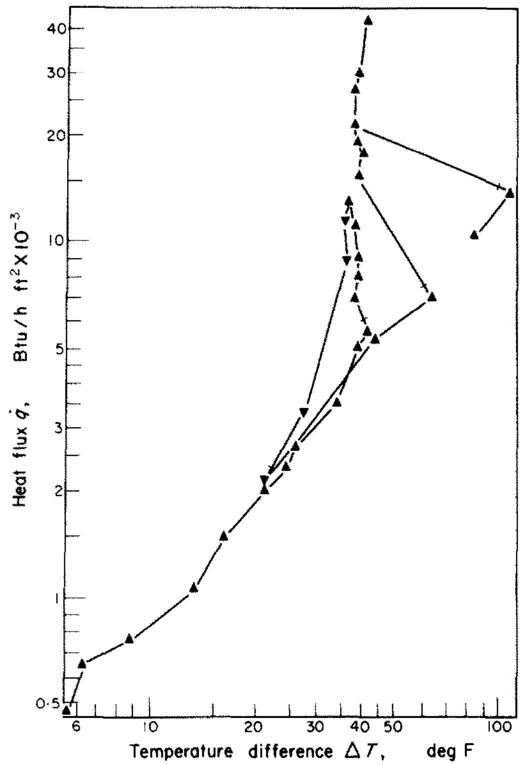

FIG. 11. Arcton 11, run No. 28. Pressure, 18·5 lbf/in^2, acceleration, a = 2·5 g.

▲ increasing heat flux
▼ decreasing heat flux
ΔT_{sub} = 0·6 degF

This was the first run after filling with Arcton 11 and no prior boiling had taken place from the test section. The heat flux was increased from zero and no marked overshoot occurred. Incipient boiling was estimated to occur at a temperature difference of about 40 degF and there was a small reduction in the temperature difference to 36 degF during the subsequent nucleate boiling period. The heat flux was then decreased to less than the incipient value. When the heat flux was again increased it gave a considerable temperature overshoot, ΔT = 62 degF followed by a near vertical boiling curve. After a time interval a further check on the readings was taken by increasing the heat flux

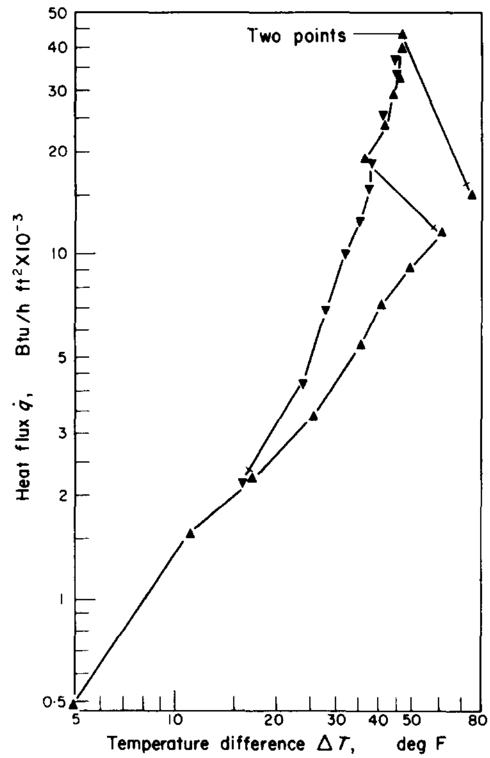

FIG. 12. Arcton 11, run No. 29. Pressure, 19·5 lbf/in^2, acceleration, a = 16·3 g.

▲ increasing heat flux
▼ decreasing heat flux
ΔT_{sub} = 3·7 degF

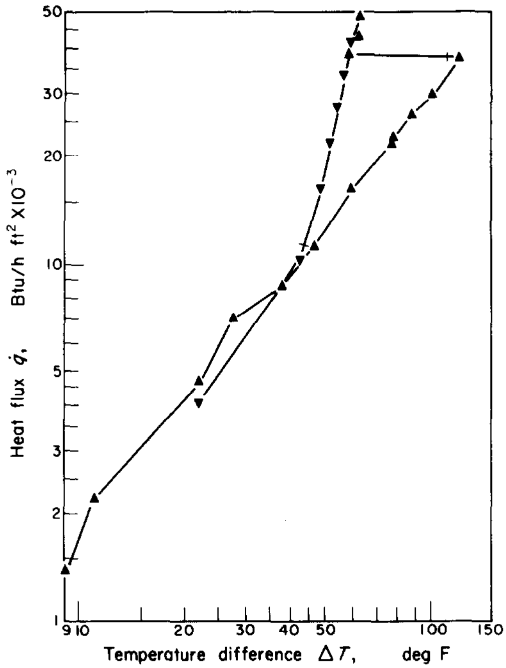

FIG. 13. Arcton 11, Run No. 30. Pressure, 22 lbf/in^2, acceleration, a = 65·3 g.

▲ increasing heat flux
▼ decreasing heat flux
ΔT_{sub} = 14 degF

from zero; in this case the temperature difference exceeded 100 degF before boiling commenced.

These results may be explained in the following way. When the boiler was filled with Arcton 11 numerous pockets of air were trapped in cavities in the test section surface. These air pockets were readily available as nucleation centres and boiling commenced when the test section was heated to the temperature required for nucleation. The boiling action purged the cavities of air which was replaced by Arcton 11 vapour. On the cessation of boiling, this vapour condensed and liquid entered and wetted the cavities, dissolving oily or greasy contaminants and leaving only very small pockets of vapour in small irregularities within the cavities or at the cavity bottom. In further heating, boiling did not commence until the temperature necessary to promote nucleation from the remaining small vapour nuclei was attained but, once boiling had begun again, larger quantities of vapour were left behind by the first departing bubble and the nucleation of subsequent bubbles took place from effectively larger nuclei at lower superheats.

This hypothesis supports the view that nucleation takes place from vapour filled cavities but it suggests that for boiling surfaces with a normal engineering finish, the temperature differences, both in incipient and sustained boiling, are not solely governed by the microscopic geometry of the boiling surface, e.g. on cavity mouth radius.

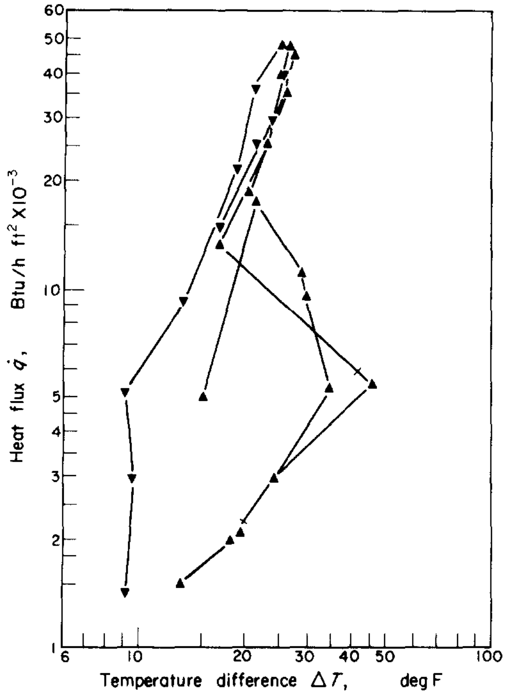

FIG. 14. Arcton 11, run No. 31. Pressure, 88 lbf/in^2, acceleration, a = 2·5 g.

▲ increasing heat flux
▼ decreasing heat flux
ΔT_{sub} = 0·2 degF

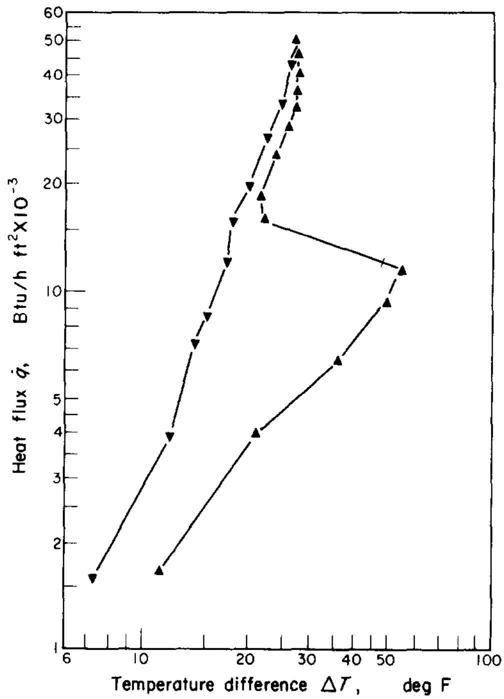

FIG. 15. Arcton 11, run No. 32. Pressure, 90 lbf/in^2, acceleration, a = 16·3 g.

▲ increasing heat flux
▼ decreasing heat flux
ΔT_{sub} = 1·1 degF

Other factors, such as the ability of the liquid to wet the surface, the degree of surface and particularly of cavity contamination, and the ability of the fluid to dissolve the contaminants must be taken into account. A representation of the contaminated cavity hypothesis, as applied to water and Arcton 11, is given in Fig. 17.

The onset of boiling from a temperature overshoot was usually sudden. In run No. 30 a reading was taken in the natural convection region which gave a temperature difference of 121·4 degF after which boiling commenced suddenly and the temperature difference dropped to 58·4 degF without adjustment of the controls. In contrast, in run No. 31, stability was obtained at intermediate temperatures between the natural convection and boiling curves.

In some instances very large temperature differences were measured before boiling of Arcton 11 commenced and the stability of the superheated liquid layer adjacent to the surface and the mechanism of nucleation are of interest. The largest measured temperature differences gave estimated surface superheats which approached 70 per cent of the limiting superheat calculated from the Van der Waals isothermals with $(\partial P/\partial V) = 0$. This is in approximate agreement with the results reported by Wismer [19]. Although within the limits of stability for the pure substance on the basis of the Van der Waals isothermals, such superheats are well outside the values normally encountered for nucleation from vapour filled cavities and it is possible that rupture of the solid liquid interface was the initial mechanism of vapourization prior to normal nucleation from vapour filled cavities.

Considerable hysteresis effects can be seen with reduced temperature difference under de-

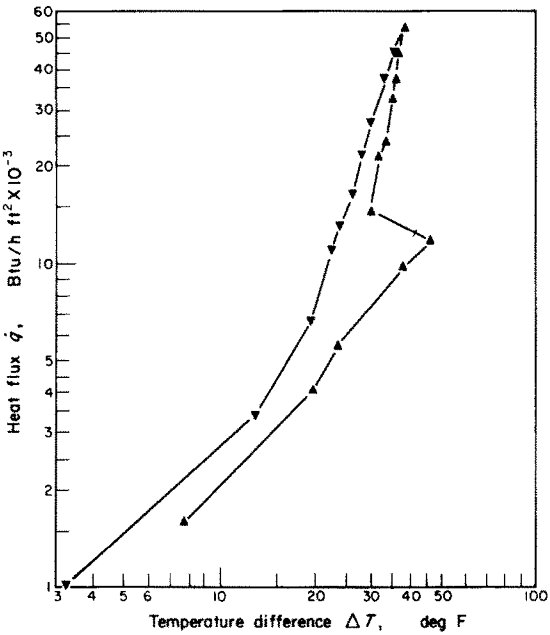

FIG. 16. Arcton 11, run No. 33. Pressure, 95 lbf/in^2, acceleration, $a = 65{\cdot}3\ g$.

▲ increasing heat flux
▼ decreasing heat flux
$\Delta T_{sub} = 4{\cdot}5$ degF

creasing heat flux conditions. It is possible that cavities become less wetted as the boiling action grows more vigorous during increase of heat flux and remain in this condition during decrease of heat flux until boiling ceases. Thus the boiling curves for increasing heat flux have a steeper slope, with the effective size of the nuclei increasing, than those for decreasing heat flux with stable nuclei.

Table 3 shows some effects of increase of pressure and acceleration for Arcton 11.

The trends are similar to those already discussed for water; the temperature difference is increased at high accelerations due, most probably, to the subcooling arising from the hydrostatic pressure at the test section and the temperature difference is decreased at high pressure. Values of heat flux at the cessation of boiling are given for the low pressure runs. This was estimated from the point at which the decreasing heat flux values rejoined the natural convection curve. It is interesting to note that at higher pressures (see Figs. 14–16) the natural convection curve was not rejoined even at very low heat fluxes. It is possible that weak boiling from very large nuclei persisted in these runs.

CONCLUSIONS

1. The results for heat transfer in the natural convection regime for Arcton 11 are correlated by the expression:

$$Nu = 0{\cdot}725\ Gr\ Pr^{0{\cdot}25} \text{ for } Gr\ Pr > 10^4.$$

2. The measured temperature differences in the nucleate boiling regime show considerably more variability for water than for Arcton 11. This is attributed in the case of water to variable wetting of the nucleating cavities due to the presence of contaminants which are not soluble in water.

3. The tests support the view that nucleation from vapour filled cavities is normal in established nucleate boiling. However, Arcton 11

Table 3

Run No.	Pressure (lbf/in^2)	Acceleration a/g	Decreasing heat flux value at cessation of boiling (Btu/h ft^2)	Temperature difference at 40000 Btu/h ft^2 degF increase in heat flow (degF)	decrease in heat flux
28	18·5	2·5	2200	38	—
29	19·5	16·3	2200	45	44
30	22	65·3	10000	59	59
31	88	2·5	—	25	22–25
32	90	16·3	—	28	25
33	95	65·3	—	36	34

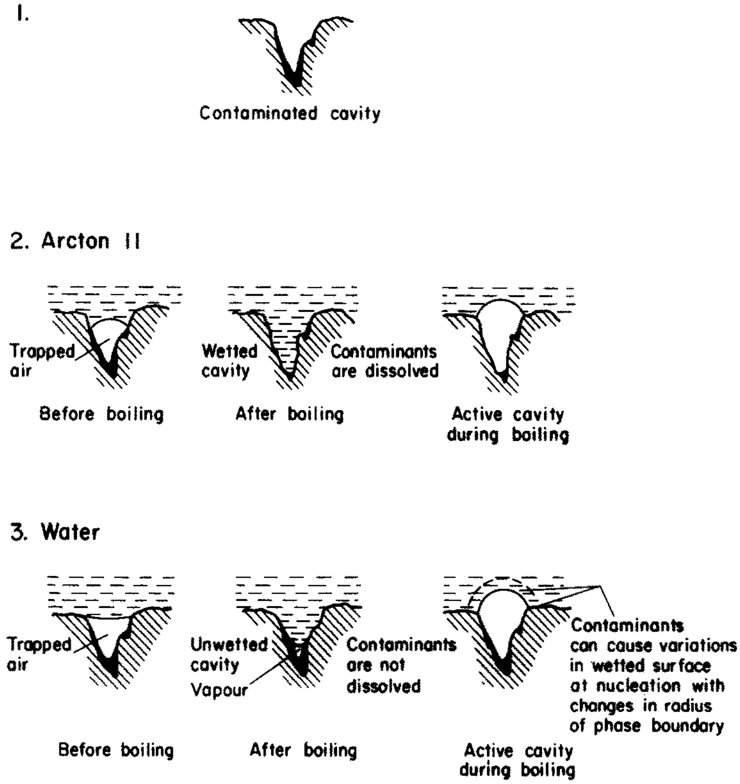

FIG. 17. Contaminated cavity hypothesis.

may completely wet the cavities after boiling. In subsequent heating, vapourization may be initiated by rupture of the liquid–solid interface at the high liquid superheats associated with a temperature overshoot.

4. Acceleration has little effect on the temperature difference in nucleate boiling.

5. Increase in acceleration results in an increase in the heat flux at the incipient boiling condition.

6. Increase in pressure results in a decrease in the temperature difference.

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APPENDIX

Computation of Results and Estimation of Errors

Calibrated chromel–alumel thermocouples were used to measure the bulk liquid temperature at the test section and the temperature inside the tubular test section. The thermocouple inside the test section measured the inside wall temperature on the assumption that the inner surface of the test section was adiabatic. It was necessary to estimate the temperature difference across the thickness of the test section wall. For this purpose the test section was regarded as a number of concentric elements of equal thickness and the equation of heat conduction and internal heat generation was expressed in numerical form for each element with the assumptions of steady temperatures and an axial direction of electrical current. A digital computer programme was used to compute the boiling surface heat flux and temperature.

The accuracy of the results was investigated and instrument accuracy and discrimination; personal and computational errors were accounted for. This investigation is reported in detail in [20] the results reported herein were found to lie between the following limits:

(i) Temperature difference between the boiling surface and the bulk fluid, ΔT at boiling surface heat fluxes of

(a) 100000 Btu/h ft^2: $\pm 1{\cdot}4$ degF.
(b) 400000 Btu/h ft^2: $\pm 2{\cdot}5$ degF.

(ii) Boiling surface heat flux

(a) At 20000 Btu/h ft^2: $\pm 7{\cdot}4$ per cent.
(b) At 100000 Btu/h ft^2: $\pm 4{\cdot}4$ per cent.
(c) At 500000 Btu/h ft^2: $\pm 3{\cdot}8$ per cent.

(iii) Test section acceleration: $\pm 2{\cdot}2$ per cent.

(iv) Boiler pressure: ± 6 lbf/in^2.

Item (iv) corresponds to the following limits of saturation temperature:

(a) Water at 25 lbf/in^2: ± 13 degF.
Water at 400 lbf/in^2: $\pm 1{\cdot}5$ degF.
(b) Arcton 11 at 18·5 lbf/in^2: ± 17 degF.
Arcton 11 at 95 lbf/in^2: ± 5 degF.

Résumé—Cet article décrit une étude expérimentale des effets d'une pression élevée et de l'accélération sur l'ébullition en réservoir en employant du l'eau et de l'Arcton 11. L'ébullition est obtenue à partir d'une section d'essai tubulaire en acier inoxydable et chauffée électriquement dont le diamètre extérieur est de 0,89 mm, et la longueur de 3, 175 cm, et disposée de telle façon que l'accélération résultante soit tout le temps perpendiculaire à l'axe du tube. La section d'essai est montée dans une chaudière centrifuge pressurisée.

Des essais employant de l'eau sont présentés dans la gamme des pressions de 1,725 à 27,9 bars et des accélérations dans la gamme de 2,5 à 63,5*g*. Des essais employant de l'Arcton 11 sont présentés pour des pressions égales approximativement à 1,38 et à 6,2 bars et des accélérations de 2,5; 16,3 et 65,3 *g*. Les résultats pour l'eau montrent des variations qui sont attribuées à une mouillabilité variable de la surface d'ébullition; ceux pour l'Arcton 11 présentent des dépassements de température considérables avec des différences de température allant jusqu'à 66,7°C atteintes dans des conditions de convection naturelle avant que l'ébullition ne commence. Les résultats sont discutés sur la base d'une hypothèse concernant la contamination des cavités dans une surface d'ébullition.

Zusammenfassung—Die vorliegende Arbeit beschreibt eine experimentelle Untersuchung des Einflusses von hohem Druck und Beschleunigung auf Behältersieden an Wasser und Arcton 11. Das Sieden erfolgt an einem elektrisch beheizten Versuchsrohr aus rostfreiem Stahl von 0,89 mm Aussendurchmesser und 31,8 mm Länge so, dass die resultierende Beschleunigung stets senkrecht zur Rohrachse verläuft. Das Versuchsrohr ist in einem als Zentrifuge ausgebildeten Siededruckgefäss befestigt.

Die Versuche mit Wasser werden für einen Druckbereich von 1,73–28 bar und für Beschleunigungen im Bereich von 2,5–65,3 g, die Versuche mit Arcton 11 für Drücke von etwa 1,38–6,2 bar und Beschleunigungen von 2,5, 16,3 und 65,3 g beschrieben. Die Versuche mit Wasser zeigen Schwankungen, die der unterschiedlichen Benetzung der Heizfläche zugeschrieben werden, die für Arcton 11 zeigen beträchtliche Überhitzungen, denn es wurden bei natürlicher Konvektion Temperaturunterschiede von 67 grd erreicht, ehe sieden eintrat. Die Ergebnisse werden aufgrund einer Hypothese, die die Verschmutzung der Poren in der Heizfläche betrifft, diskutiert.