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SOUND EMISSION AND HEAT TRANSFER IN LOW PRESSURE POOL BOILING

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Abstract—Heat transfer rates and the accompanying sound intensities are reported for pool boiling of water on a tubular stainless steel heater at pressures in the range 760–90 torr and liquid subcoolings of up to 60°C. When nucleate boiling occurs with the regular formation of similarly sized bubbles from fixed nucleation sites, as when water boils under atmospheric conditions, a progressive decrease in the sound intensity is produced by a decrease in the heat flux. A transition from this regular process occurs at low pressures and in this region the sound intensity is not uniquely related to the heat flux.

A review of reported work on sound emissions accompanying pool boiling is included.

NOMENCLATURE

Hz,	frequency, T^{-1};
q/a,	heat flux, MT^{-3};
T,	temperature, θ;
Δ,	finite difference operator.

Subscripts

bubble,	relating to bubble;
exp.	experimental value;
n.c.,	natural convection component;
sat.,	difference between wall value and saturation value.

INTRODUCTION

THE ONSET of local boiling on a submerged surface is often accompanied by audible sounds emitted probably as a result of the collapse of vapour bubbles in the subcooled liquid. The changes in these boiling sounds that occur as the nature of the boiling changes through the boiling curve is sufficiently audible to be noted by a casual observer.

The sound emission is caused by the propagation of pressure waves within the boiling liquid, and since these boiling sounds appear to coincide with the commencement of nucleation on the heated surface it is reasonable to assume that the bubbles are the source of the pressure waves. During the lifetime of a bubble there are various stages at which pressure variations could occur and audible sounds could be emitted. The most obvious source is the collapse of the vapour bubbles in the body of the liquid. The formation of a bubble and fluctuations in the size of the bubble are other potential sound generators.

The possibility that the sound level may be related to the heat transfer rate could be of importance in detecting ebullition in liquid cooled systems where vapour formation is undesirable.

LITERATURE REVIEW

It is apparent from photographic studies of nucleate boiling by Kirby [1] and from the measurement of temperature fluctuations during bubble formation made by Moore [2] and Morin [3] that the initial growth rate of a vapour bubble is extremely rapid, so that a bubble "appears" on the heated surface. One

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consequence of the fast growth of a void in the liquid phase is the propagation of a pressure pulse directed away from the nucleus of the vapour bubble. Jameson and Kupferberg [4] have presented an analysis of the pressure transients following the departure of a bubble and Garg and Patten [5] have reported measurements of such transients during the saturated pool boiling of water at subatmospheric pressures. The frequency and amplitude of these pulses is determined by the bubble formation frequency and the initial growth rate. Ellion [6] has described the growth and collapse cycle of a bubble formed on a heated surface in a subcooled pool of liquid. It was observed that the bubbles pulsated on the surface, due to the continuous cycle of formation and collapse without departure from the surface. Such a pulsating system produces cyclic pressure variations in phase with the cycle of bubble formation and collapse.

Minnaert [7] showed that radial pulsations in an air bubble immersed in water can produce audible sounds with a frequency related to the size of the bubble and Nesis [8, 9] has presented an analysis of sound emission by the radial pulsation of bubbles.

These analyses were concerned with pulsating gas bubbles of fixed mass and are therefore not directly applicable to the process of vapour bubble formation in a boiling system. However, they are pertinent in as much as they indicate that should radial pulsations occur in a vapour bubble with the required amplitude and frequency the emission of audible sounds could result. The total collapse of a bubble, either on the solid surface or in the bulk of the liquid, may cause a pressure transient directed towards the centre of the bubble sufficient to result in sound emission. The condensation of the vapour causing a void in the liquid will result in an inrush of water and the kinetic energy of the water will be dissipated as it fills the void. One possible form of energy dissipation is in sound emission. Thus in vapour bubble collapse there are two potential sound sources, the pressure transient caused by the collapse of the bubble and dissipation of the kinetic energy of the inrushing liquid.

Sound emission from a film boiling system differs from the nucleate boiling case since the concept of the regular formation of similar bubbles from fixed sites on the heated surface is invalid for film boiling. Marx [10] postulated a mechanism for the sound emitted when a massive hot body was quenched. A process of vapour blanket formation and collapse, which would decrease in frequency as the body cooled, was stated to be the source of the sound. It was observed that the frequency of the sound did in fact decrease as the body cooled.

Since the sound emitted from a boiling system appears to be derived from the bubbles it is of interest to study the effects of parameters which effect the bubble dynamics, on the sounds. Two important factors influencing the number and lifetime of bubbles are the heat flux and the liquid temperature. In general an increase in the heat flux in nucleate boiling increases the number of bubbles formed unless accompanied by a change in the mode of boiling. It might therefore be expected that an increase in the sound level would accompany an increase in the heat flux, for a constant liquid temperature. Osborne and Holland [11] related the total sound intensity in the range 1–10 kHz to the power input to a wire immersed in water. The level of the sound increased to a "saturation value" and remained or fell below it when subjected to a further increase in heat flux. The heat flux at the "saturation value" of the sound level did not correspond to the systems critical heat flux. Westwater [12] compared the total sound emitted in the range 25–7500 Hz to the rate of heat transferred from a horizontal copper bayonet heater to boiling methanol. Figure 1 summarises the published results. During nucleate boiling, an increase in the temperature excess was accompanied by an increase in both the heat transfer rate and the sound level. Increasing the temperature excess through the transition boiling region caused a steady in-

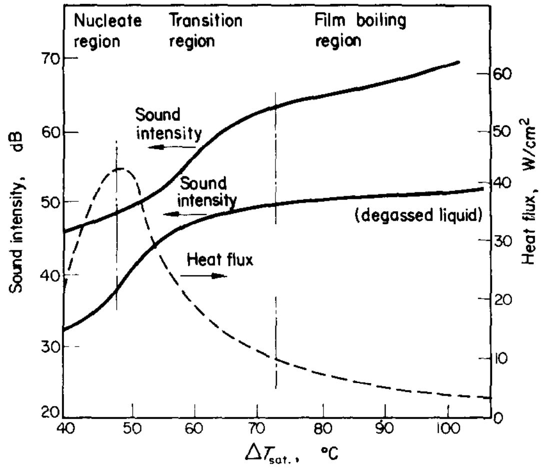

FIG. 1. The relationship between the boiling curve for water and the sound level. (After Westwater [12]).

crease in the sound level although the heat flux was decreasing. The intensity of sound emitted during film boiling was appreciably constant. Schwartz [13] related sound emitted from boiling water to the rate of heat transfer from an electrically heated stainless steel heater. The analysis of the sound showed that it approximated to white noise (i.e. all the frequency components were at similar levels), in the frequency range 25–700 Hz and that the contribution to the total emitted sound of frequency components in the range 1–3 kHz was minimal. Figure 2 relates the intensity of sound in the range 25–700 Hz to the temperature excess and shows a relationship of the same form as the boiling curve.

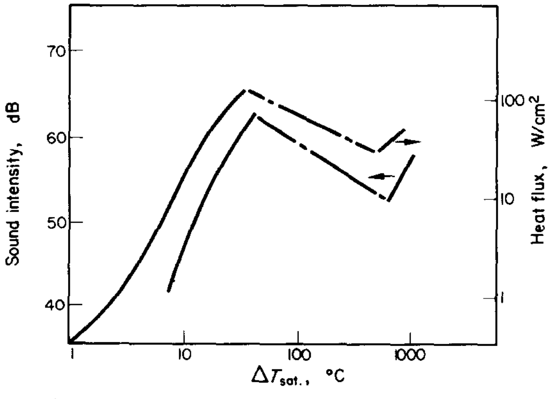

FIG. 2. The relationship between the boiling curve for water and the sound level. (After Schwartz [13]).

Since a change in the heat flux has no appreciable effect on the life cycle of individual bubbles in the liquid phase, it could be expected that the change would also not affect the frequency components of the sound emitted. An increase in the overall power level of the sound frequency spectrum would be expected since the number of bubbles produced in a boiling system is influenced by the heat flux. Tokmakov [14] showed a linear relationship between the sound intensity and heat flux in nucleate pool boiling at a fixed liquid superheat.

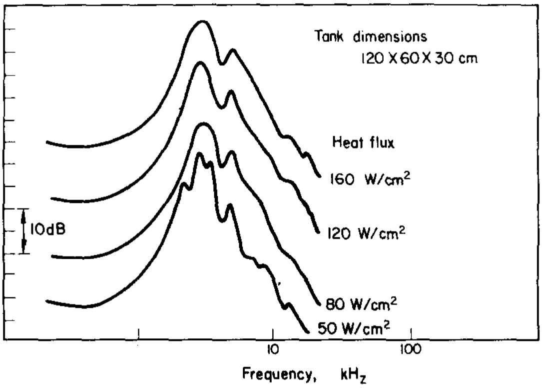

FIG. 3. Acoustic spectrum as a function of heat flux. (After MacLeod [15]).

An increase in the heat flux of a pool boiling system was found to modify the power level of the acoustic spectrum although the general shape was maintained. Figure 3 from MacLeod [15] shows the acoustic spectra of sound emitted during boiling in a vessel of dimensions 120 × 60 × 30 cm as a function of the heat flux. Similar results have been published by Walton [16] for a flow boiling system.

Acoustic spectra as a function of heat input have also been reported by Osborne and Holland [11]. A slight change in the frequency at which the peak sound intensity occurred was noticed in boiling experiments using thin wires. For other wires, the frequency at which the maximum sound intensity occurred was appreciably constant. The sound intensity increased with an increase in the power input to the heater. The temperature of the liquid in which boiling is occurring has a considerable influence on the lifecycle of a vapour bubble. In view of this observation it is to be expected that the sound level emitted from a boiling system would similarly be affected by the liquid temperature.

Little work of a comparative nature has been reported for sound generation in a subcooled boiling system. Reference to the boiling of a domestic kettle, which has a constant power input, should indicate the effect of liquid temperature as the bulk temperature increases. It will be observed that the sound exhibits a maximum level before saturated conditions exist, that is with a water temperature in the region of 95°C. This condition of low subcooling corresponds to the condition in which the bubble size is approaching a maximum and where all the bubbles collapse within the bulk of the liquid. Saturated boiling does not involve the collapse of the vapour bubbles in the liquid and it is observed that the sound is emitted at a relatively lower level.

Osborne [17] noted that when the heat flux was barely sufficient to sustain nucleate boiling on a heater surface an increase in the liquid temperature was accompanied by an increase in the sound intensity. This may be attributed to the greater rate of formation of vapour bubbles at the elevated temperature due to the reduction in the convective component of the heat transfer. At elevated heat fluxes this effect was not apparent.

Several variables in the heater construction affect the rate of formation of vapour bubbles on the heater during nucleate boiling. The material of construction, dimensions and orientation of the heater affect the boiling characteristics to different extents. Osborne and Holland [11] have reported experiments which demonstrated the change in the boiling sounds caused by variations in these factors. It was reported that a slight increase in the sound intensity accompanied a change from a vertical to a horizontal orientation and that the effect of doubling the heated length was to increase the sound intensity by almost 3dB as predicted from nucleation site theory.

Osborne and Holland [11] showed that the intensity of the sound emitted from a hot wire immersed in an extensive volume of water at 5°C followed an inverse square distance relationship. Analysis of the sound showed a broad irregular maximum in the spectrum.

Janes [18] reports the results of experiments on boiling noise, with emphasis on the isolation of selected components of the acoustic spectrum, for the detection of boiling in reactor coolant channels.

Boiling sounds emitted from few liquids other than water have been analysed. Westwater [12] has reported a study of the sound emitted from boiling methanol. Osborne [17] reported that the boiling of castor oil was inaudible and that the process of bubble formation was slow enough to be followed by the naked eye. These observations support the theory that sound emission is closely allied to the bubble forming properties of a boiling system.

For bubble formation to be initiated on a heated surface some gas must be present in the cavities on the surface and so the resulting bubbles will contain a proportion of noncondensible material. Osborne [17] has found that the intensity of sounds emitted from a degassed system was higher than for boiling in a liquid containing dissolved gas. MacLeod [15] has attributed this effect to the damping of sound waves in the liquid by the residual gas bubbles. Westwater [12] has conversely reported a decrease in the intensity of boiling sounds when care was taken to ensure that the liquid was degassed. These two observations are not incompatible since the process of bubble formation is retarded and hence sound emission is at a low level. In liquids containing a proportion of dissolved gas, the sound emitted by the bubbles is absorbed by the residual gas bubbles.

Studies of acoustic emissions in high pressure flow boiling installations have been reported by Goldman [19] and by Firstenberg [20].

APPARATUS

The apparatus was designed to study the relationship between the sound intensity, the heat transfer rate and the liquid temperature in a low pressure pool boiling system and is fully described in [21]. A schematic diagram is given in Fig. 4. The vessel comprised a 33 in. deep cylinder, $21\frac{1}{2}$ in. i.d. fabricated from $\frac{3}{16}$ in. stainless steel. Three optical ports of armour plate glass allowed observation of the interior of the vessel. Boiling was induced on the outside surface of a thin walled stainless steel tube (6 in. length, 0·23 in. dia. and 0·015 in. wall thickness) mounted in the vessel in the plane of the lowest of the optical ports. The heater mountings acted as power carriers and were insulated from the vessel by P.T.F.E. inserts. Expansion of the heater was compensated by a flexible mounting between one test piece carrier and the vessel. The vessel was designed to withstand vacuum conditions given by the "Edwards" high vacuum pump. Conditions within the vessel were maintained by manual control of cooling water passing inside the two elliptical cooling coils, seen in Fig. 5, and by control of the flow to the condenser. A thermocouple assembly shown in Fig. 6 enabled the water temperature in close proximity to the heater to be measured.

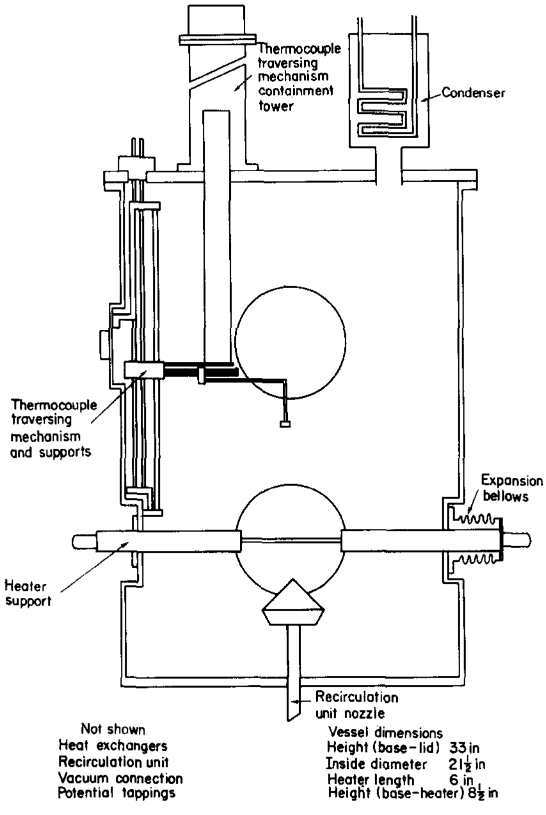

FIG. 4. Schematic representation of low pressure boiling facility.

Electrical power was supplied from a "Variac" controlled, three phase transformer (415 V, 50 Hz input) feeding a three phase bridge rectifier supplying up to 1000 amp d.c. at a potential of 12 V with a maximum peak to peak ripple content of 5 per cent. Early studies employing a.c. power had been unsatisfactory owing to a considerable mains frequency 'peak' appearing in the acoustic spectra. A 50 amp triple pole "Arrow" contactor was included in the primary circuit which was activated by a 110 V supply signal from a burnout detection/prevention circuit. The sounds were detected using a cylindrical lead zirconate pressure transducer (Calibration constant 7μV/μbar), immersed in the water at a position 2 in. below the horizontal plane of the heater and 3 in. away in the horizontal plane. The actual location of the transducer below the heater was found to be unimportant.

The relationships between the rate of boiling heat transfer and the level of emitted sound were studied at the four pressures, 760, 405, 210 and 90 torr corresponding to water saturation temperatures of 100, 80, 65 and 50°C. Measurements were taken with a decreasing heat flux and checks on readings were made under increasing heat flux conditions. The following comments apply to all the data discussed. Measurement of the heating current and the potential drop across the test section allowed calculation of the heat transfer rate. Measurement of the tube inside wall temperature by chromel/alumel thermocouples spot welded to the surface, with reference junctions at 40°C, together with computation of the temperature increase through a tube with uniform internal heat generation enabled the temperature excess to be evaluated. Acoustic measurements were made using a "Bruel and Kjaer" type 2107 frequency analyser.

DISCUSSION OF RESULTS

It is most convenient to study the boiling at each pressure individually before assessing the data *in toto*. It should be noted that the temperature excess $\Delta t_{\text{sat.}}$ refers to the difference between the wall temperature and the liquid saturation temperature *at the depth of immersion.*

Pressure 760 *torr*

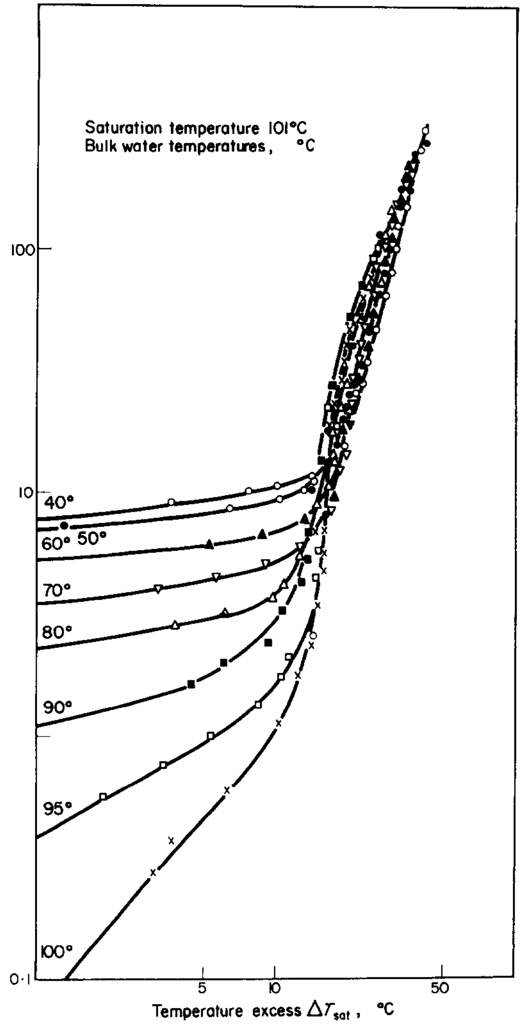

FIG. 7. Experimental values of the rate of heat transfer from an electrically heated stainless steel tube to a quiescent pool of water at a pressure 760 torr.

Figure 7 presents the boiling curves for water boiling at atmospheric pressure with bulk temperatures up to 60°C below the saturation value. The data compares favourably with existing data on the rate of heat transfer to water in pool boiling. The intensity of the sound accompanying the boiling is shown, as a function of the total heat flux, in Fig. 8. The increased heat flux at which nucleate boiling commences in sub-cooled boiling, shown clearly in Fig. 7, causes a reduction in the sound intensity at low heat flux values but as the heat flux is increased the rate of increase in sound level is greatest in the case of the coldest water so that the greatest sound intensity accompanies the boiling at the highest heat flux in the coldest water. Since Rallis [22] has demonstrated that the total heat transferred in a boiling process can be expressed as the sum of the bubble induced heat transfer and the natural convection component, the experimental data can be expressed in terms of the bubble induced heat transfer rather than the total heat flux. The convective component of the heat transfer may be estimated by extrapolation of the convective data into the boiling region and the bubble induced heat transfer is thus

$$\frac{q}{a_{\text{bubble}}} = \frac{q}{a_{\text{exp.}}} - \frac{q}{a_{\text{n.c.}}}\,. \tag{1}$$

This equation does not imply that all the bubble induced heat transfer is via a latent heat path but assumes that the convective relationships valid prior to ebullition are equally applicable

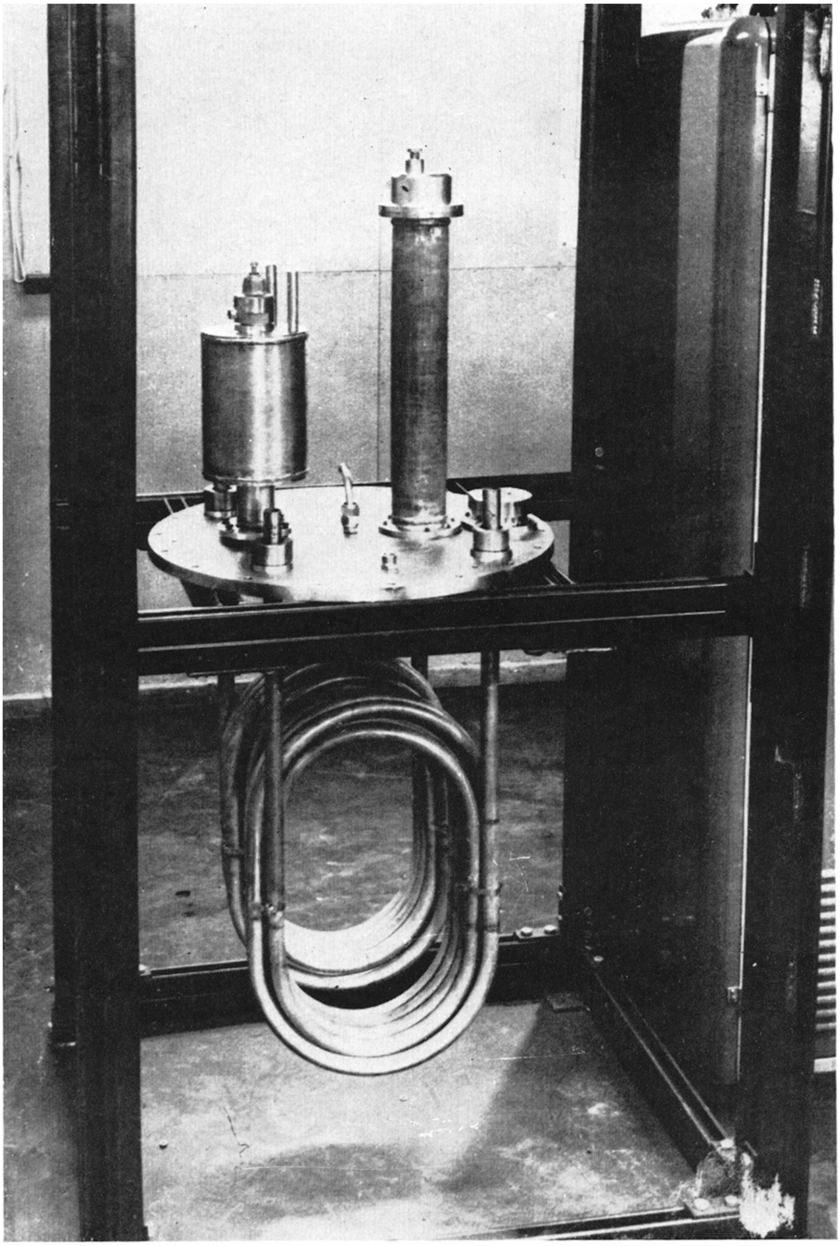

FIG. 5. Lid assembly showing elliptical heat exchangers, the condenser and thermocouple housing.

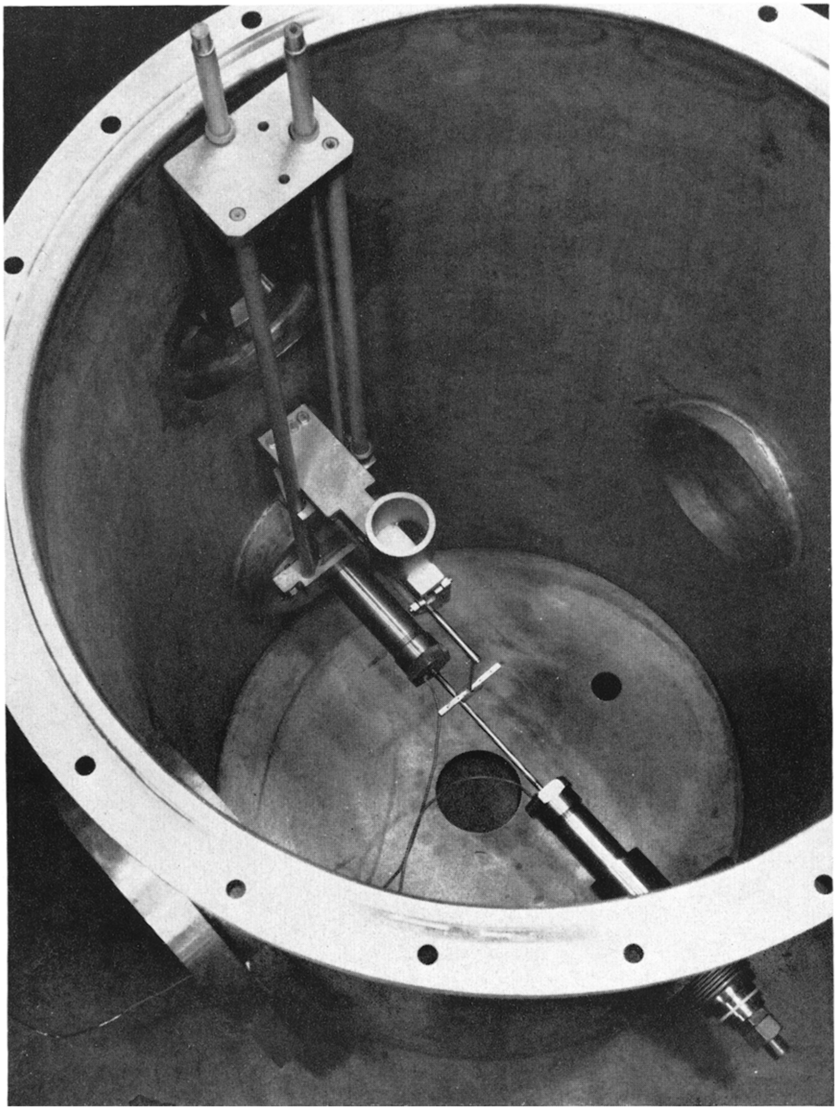

FIG. 6. Location of heater and thermocouple traversing mechanism with boiler vessel prior to assembly.

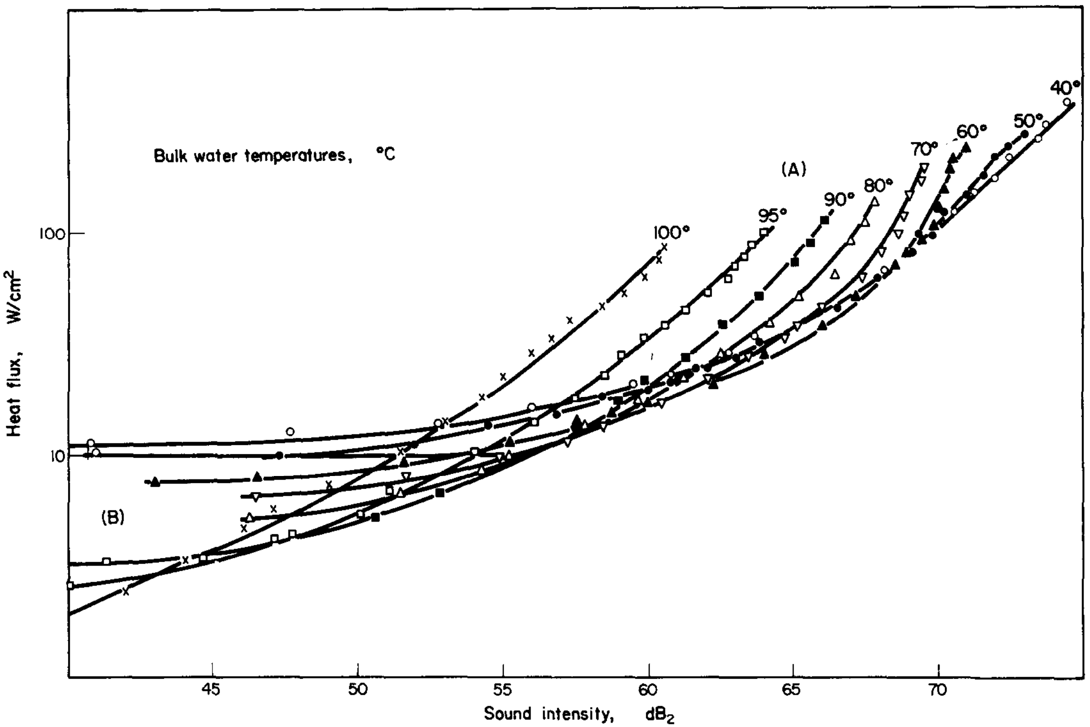

FIG. 8. Sound intensity accompanying nucleate boiling in water at a pressure of 760 torr, as a function of water temperature and total heat flux.

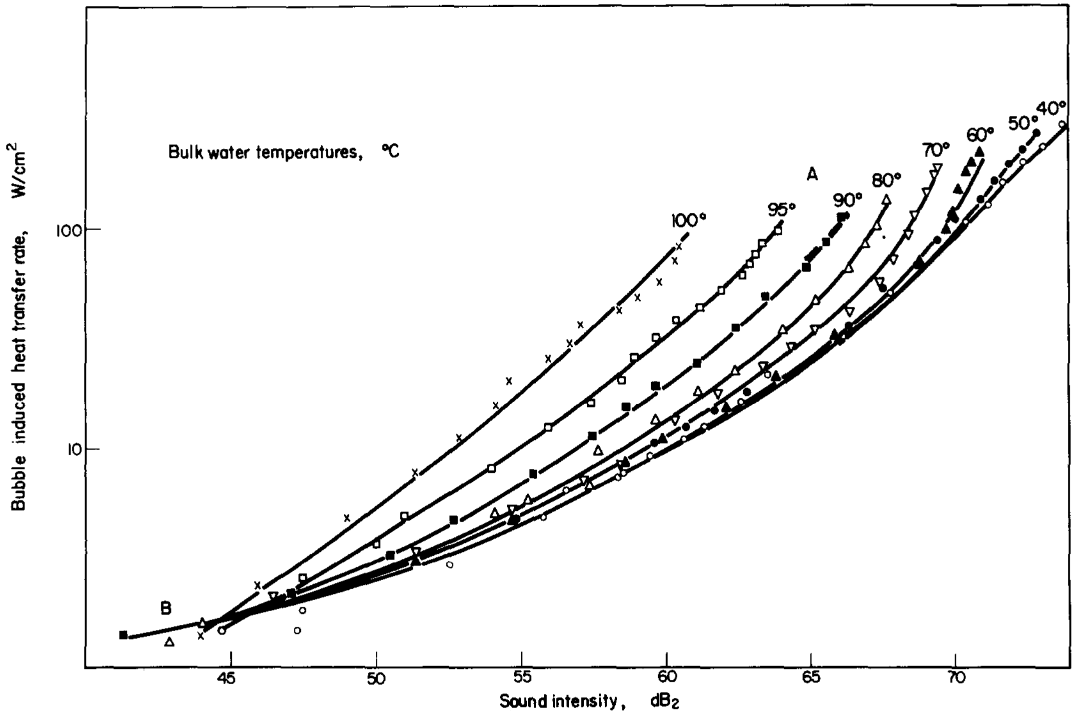

FIG. 9. Sound intensity accompanying nucleate boiling in water at a pressure of 760 torr, as a function of water temperature and bubble induced heat transfer rate.

after the start of nucleation and that the bubble induced heat transfer is superimposed onto the convective mode.

When the data are presented in terms of the bubble induced heat transfer, the effect of different nucleating heat fluxes is removed and the sound intensity increases regularly with an increase in the bubble induced heat transfer rate as shown in Fig. 9. The scatter in the data at low heat fluxes is caused by the ordinate being the difference between two experimentally determined quantities of comparable orders of magnitude.

Boiling at a pressure of 405 *torr*

Experimental data on the rate of boiling heat transfer from stainless steel to sub-cooled water at a pressure of 405 torr are presented in Fig. 10.

The intensity of the sounds accompanying the boiling are shown in Fig. 11 where the data exhibits essentially the same trends as the data of Fig. 8. Expressing the data in terms of the bubble induced heat transfer rate (equation (1)) again brings order into the data in the lower nucleate boiling regions as in Fig. 12. An abnormality appears in the data at high subcoolings ($\Delta t_{\text{sub.}} > 30°\text{C}$) when a reduction in the heat flux from the highest value is accompanied by an initial increase in the intensity of the sound followed, on a further reduction in heat flux, by a rapid drop in the sound intensity. This is in contrast to the regular decrease in sound intensity which accompanies a reduction in the heat flux at higher water temperatures and at all water temperatures during boiling at 760 torr. The data in this region were entirely reproducible even after vigorous degassing by boiling under reduced pressure had ensured that the gas content at these water temperatures was no greater than the gas content at other temperatures. It was concluded that this change in the pattern of the sound level was possibly the result of a change in the boiling process under these conditions and this was supported by experimental studies outlined later.

Boiling at a pressure of 210 *torr*

The experimental data of Fig. 13 were obtained during boiling at a system pressure of 210 torr. Similarity in trends observed during boiling at higher pressures are apparent. A new feature is the increase in the heater temperature that accompanies a reduction in the heat flux at the point of cessation of nucleation. This continuity is particularly noticeable under highly sub-cooled conditions, and the data of Raben [23] for the saturated boiling of water at a

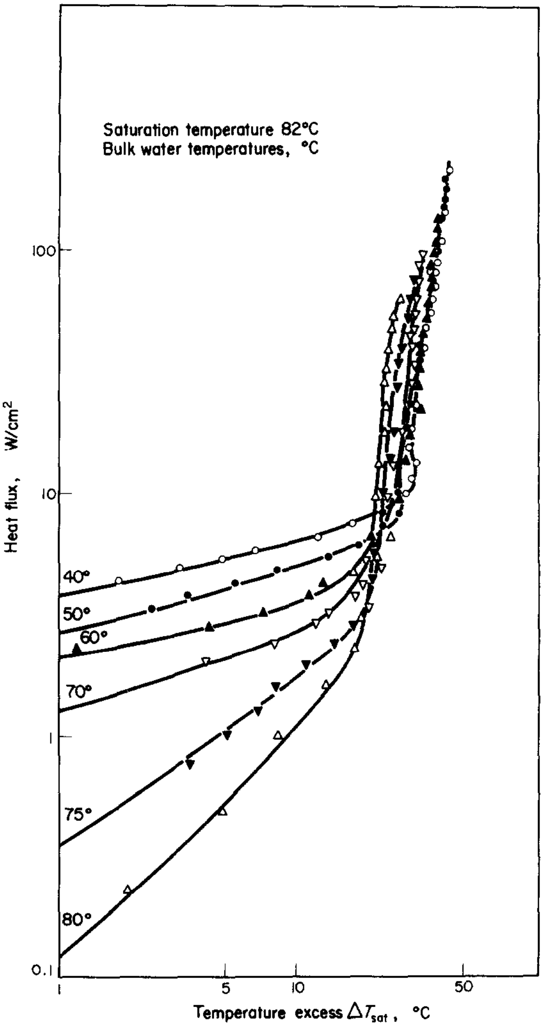

FIG. 10. Experimental values of the rate of heat transfer from an electrically heated stainless steel tube to a quiescent pool of water at a pressure of 405 torr.

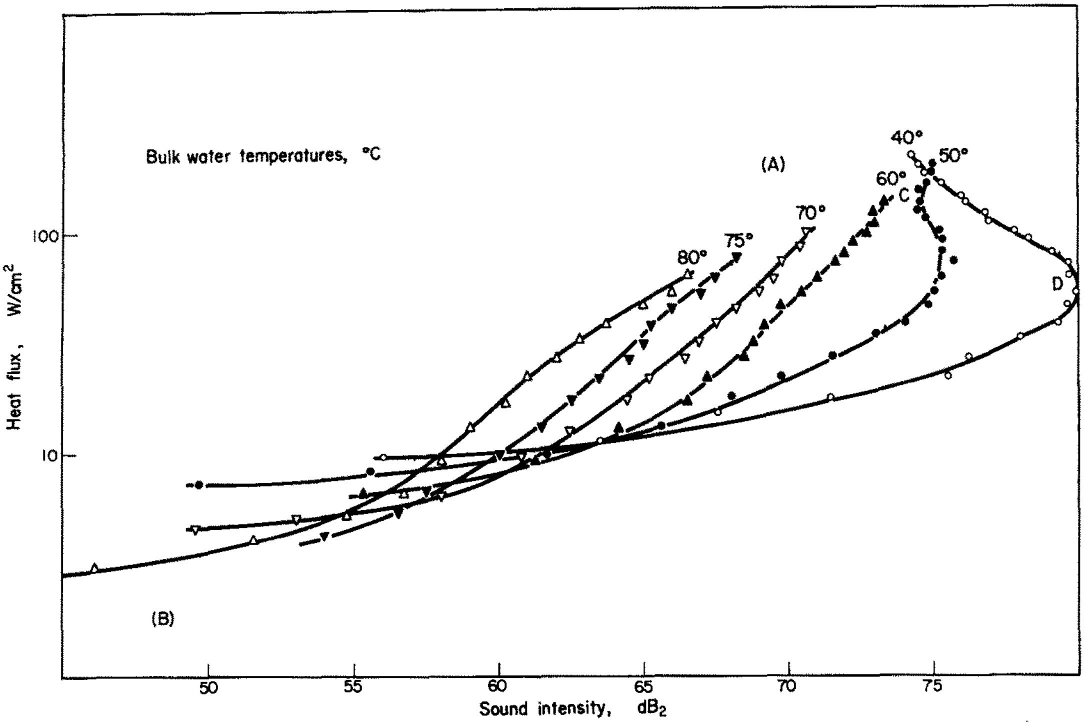

FIG. 11. Sound intensity accompanying nucleate boiling in water at a pressure of 405 torr, as a function of water temperature and total heat flux.

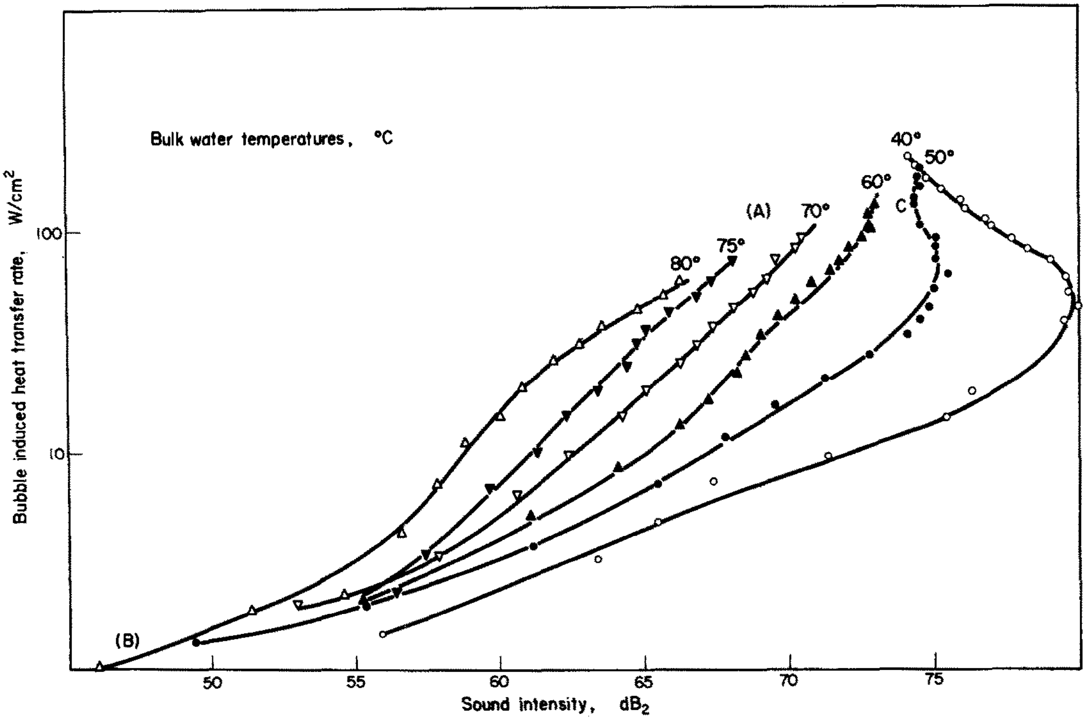

FIG. 12. Sound intensity accompanying nucleate boiling in water at a pressure of 405 torr, as a function of water temperature and bubble induced heat transfer rate.

pressure of 200 torr exhibits a similar discontinuity. Raben showed the discontinuity to be present at pressures of 200 torr and below but to be absent, or immeasurably small, at higher pressures.

The sound intensity accompanying the boiling described in Fig. 13 is shown in Fig. 14. It was not possible to obtain sound level data in the low heat flux nucleate boiling region owing to the intermittent nature of the boiling process and the accompanying sound emissions. Since little of the data of Fig. 14 relates to the low heat flux nucleate boiling region the data are not further presented in terms of the "bubble induced heat transfer rate" since it is in this region that the additive effect of the convective heat transfer component is most pronounced. The data for saturated (65°) and low sub-cooled (60°C) boiling systems take a similar form to previous data where a reduction in the sound level accompanied a reduction in the heat flux. The discontinuity occurring in highly sub-cooled boiling at 405 torr appears at a lower sub-cooling ($\Delta t_{\text{sub.}} = 10$°C) during this series of experiments and a further discontinuity is observed at a high sub-cooling ($\Delta t_{\text{sub.}} = 25$°C). In the highly sub-cooled case, a reduction in the heat flux is accompanied initially by a reduction in the sound level but this changes to an increase as the heat flux is further reduced. The maximum sound intensity in this latter region exceeds the sound intensity recorded at the peak heat flux. A further decrease in the heat flux causes a sporadic mode of bubble formation which is accompanied by a staccato sound emission and it was not possible to record the intensity of these sounds. Observation of the heater surface temperature during this mode of boiling indicated rapid variations accompanying the boiling. The indicated surface temperature often dropped to the temperature of the bulk of the liquid in the vessel and this was followed by a build up to a supersaturated condition.

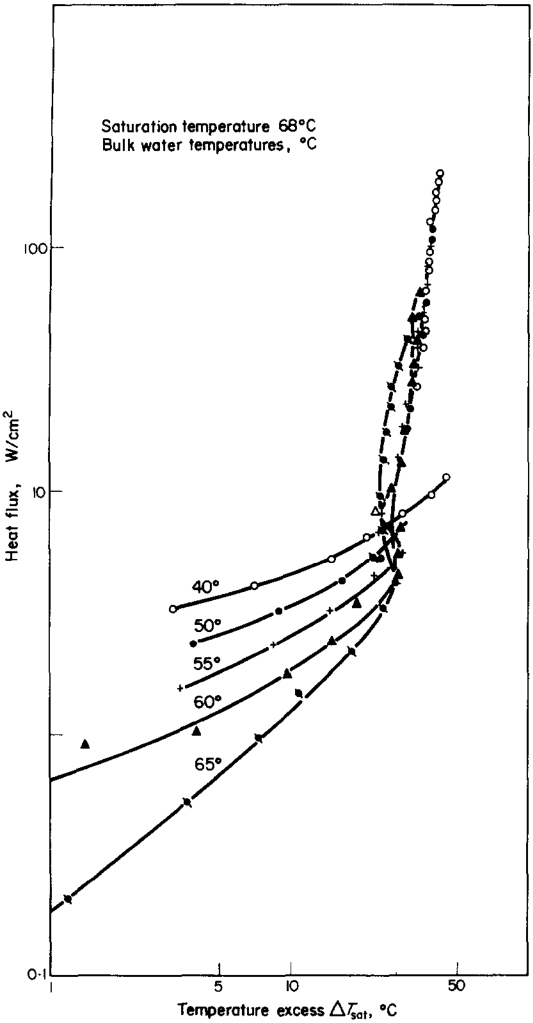

FIG. 13. Experimental values of the rate of heat transfer from an electrically heated stainless steel tube to a quiescent pool of water at a pressure of 210 torr.

Boiling at a pressure of 90 *torr*

The vapour pressure of water at 50°C is 90 torr and boiling heat transfer data obtained at this system pressure are presented as Fig. 15 where the discontinuity in the boiling curve accompanying the cessation of nucleation is apparent at all water temperatures. As in the previous case, it was not possible to obtain data in the low heat flux nucleate boiling region owing to the intermittent nature of the boiling process.

Measurement of the level of sound accompanying the boiling was restricted to the region in which sounds were emitted at a steady intensity. Figure 16 shows the "S" shaped curves commencing with a water temperature only 10°C below the saturation condition.

GENERAL DISCUSSION

The boiling curves, Figs. 7, 10, 13 and 15 are all of the general form expected as a result of the literature survey although several of the graphs show specific differences. The increase in the convective heat transfer component accompanying a reduction in the bulk temperature and the nondependence of the heat transfer rate in sub-cooled nucleate boiling on the bulk temperature may be observed in all the data.

A limited amount of data is available on the rate of heat transfer during the saturated boiling of water on the plane end of a vertical copper rod under reduced pressures (Raben [23]) and this data has been referred to above where appropriate but, since the geometries and heater materials differ, direct comparisons of the data cannot be made.

The authors' experimental data on the rate of heat transfer to boiling water under saturated conditions at the four system pressures studied are presented together as Fig. 17. From this set of curves the rate of heat transfer in the convective region appears to increase with a reduction in the saturation temperature. This observation is at variance with the data of Rallis [24], who observed no change in the rate of naturally convective heat transfer with a reduction in system pressure and also with the data of Raben [23] who found a decrease in the heat transfer rate accompanying a reduction in pressure. This apparent irregularity can be explained by noting that in the current study a finite depth of water (2 ft) was used whereas in the two other studies cited above the hydrostatic effect of the immersion depth was negligible

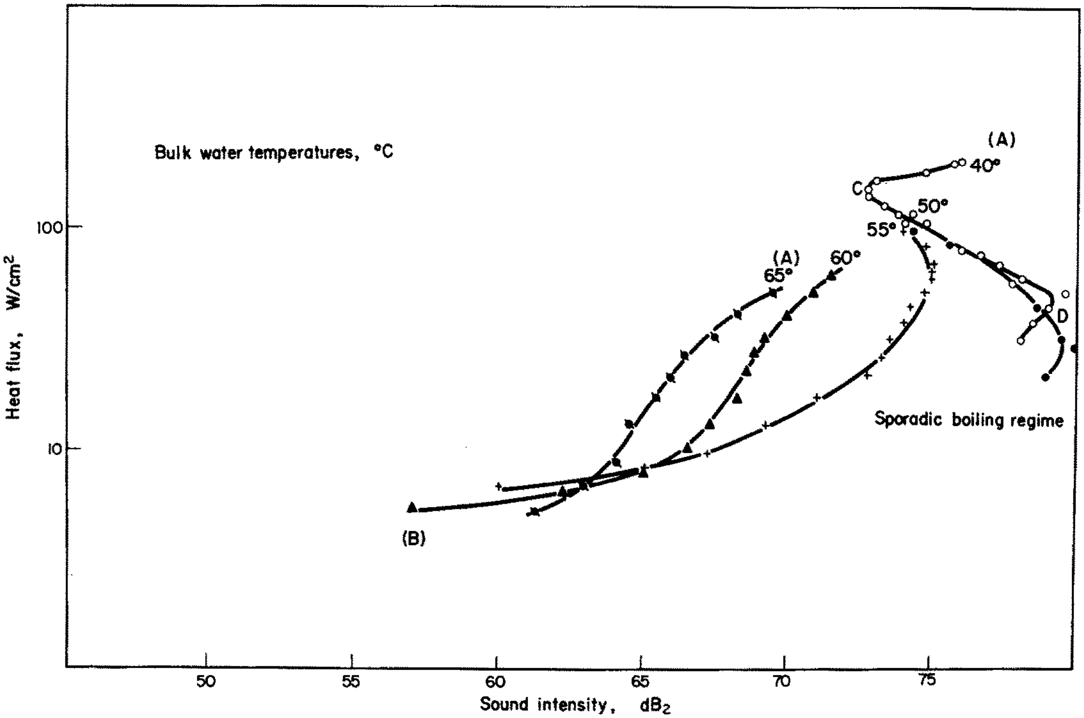

FIG. 14. Sound intensity accompanying nucleate boiling in water at a pressure of 210 torr, as a function of water temperature and total heat flux.

in comparison with the system pressure. In the case of a system pressure of 90 torr, where the maximum water temperature is 50°C as this is set by the vapour pressure of water under these conditions, the hydrostatic effect of the immersion of the heater in the water elevates the saturation temperature of the water on the heated surface to a value of 54·5°C, this causing an effective sub-cooling of 4·5°C despite the fact that the water is saturated with respect to the system pressure. This implies that the "saturated boiling" data of a system pressure of 90 torr should be more comparable to the case of sub-cooled boiling at 95°C with a system pressure of 760 torr than to the saturated boiling data at this pressure. Examination of Fig. 17 shows that the saturated boiling data at a pressure of 90 torr are offset from the data for a pressure of 760 torr by approximately 5°C in the convective region and that the rest of the data are offset by amounts which are comparable to the amounts of sub-cooling caused by the hydrostatic effect. These observations indicate that the rate of convective heat transfer in a saturated system is not affected by the pressure of the system.

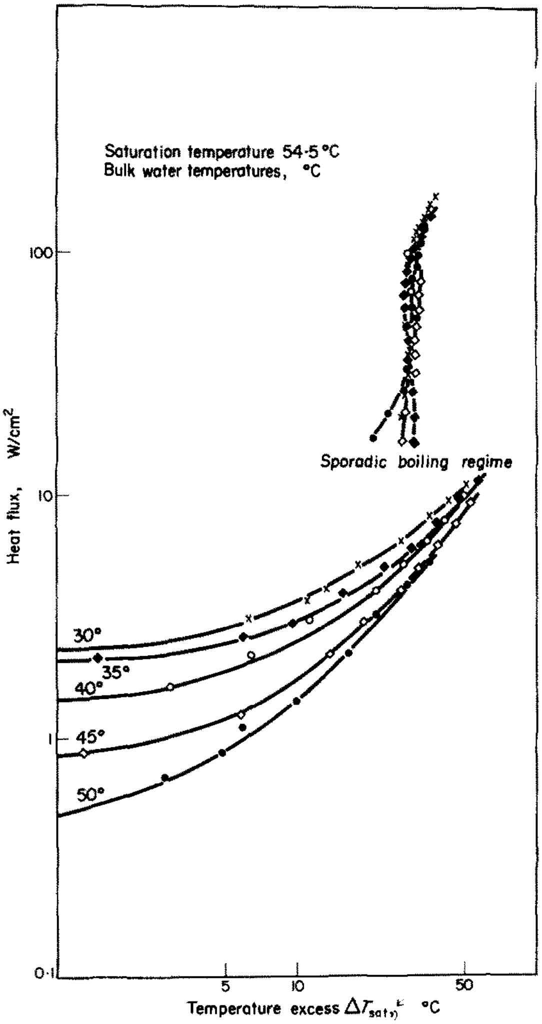

FIG. 15. Experimental values of the rate of heat transfer from an electrically heated stainless steel tube to a quiescent pool of water at a pressure of 90 torr.

In the nucleate boiling region of Fig. 17, the temperature excess required to sustain a given heat flux is increased by a reduction in the system pressure and this confirms the observations of Rallis and of Raben and follows the trend in data obtained at elevated pressures by Farber [25]. The increase in the required temperature excess can be attributed to the reduction in the number of potentially active nucleation sites due to the increase in the minimum cavity radius required for nucleation as predicted by Séméria [26] and by the analysis of Hsu [27].

The influence exerted by the heat flux, water temperature and system pressure on the intensity of the sound accompanying saturated and sub-cooled boiling in water is shown in Figs. 8, 11, 14 and 16. The data shows that when the boiling process is controlled by the mode of vapour formation in which bubbles form regularly from specific locations, the sound level decreases steadily with a decrease in the heat flux. More particularly, as in Figs. 9 and 12, the sound level can be associated with the bubble induced component of the total heat transfer rate and data presented in this manner exhibits a steady increase in the sound intensity accompanying a reduction in the water temperature at a fixed value of the bubble induced heat transfer rate. When the process of vapour generation differs from that of the regular evolution of similarly sized bubbles, the sound intensity changes with modification to the bubble formation process. In the diagrams referred to above, several regimes are identified, these being bounded by the extremities of the data and by the positions at which marked changes in the trends of the data appear. Visual and stroboscopic observation of the heated surface indicated that the regime boundaries apparent in the acoustic data are also boundaries in the bubble forming characteristics of the system and, thus, that the modification to the sound intensity is the direct result of changes in the number, size and lifetime of bubbles formed on the heater.

In regime AB, a reduction in the heat flux causes a reduction in the number of bubbles formed as a result of a decrease in the number of nucleating centres and is accompanied by a decrease in the sound level. For boiling water under atmospheric conditions this is the only region that is observed. In boiling under reduced pressure conditions, and under certain other conditions of high sub-cooling, before the point of total cessation of vapour formation is reached the process is modified at point C and the sporadic mode of vapour formation commences. A further decrease in heat flux causes an increase in the sound intensity as a result of an increase in the rate of vapour formation by the sporadic process at the expense of the regular mode of nucleation. At point D the majority of the vapour formation is by the sporadic process and a reduction in heat flux causes a reduction in the rate of vapour formation rather than a further change from regular to sporadic boiling. Ultimately, the non-boiling condition of B is attained.

The sporadic process of bubble formation under reduced pressure conditions would appear to be comparable to the mode of boiling observed in liquid sodium and sodium/potassium alloys as reported by Madsen [28] and Lyon [29].

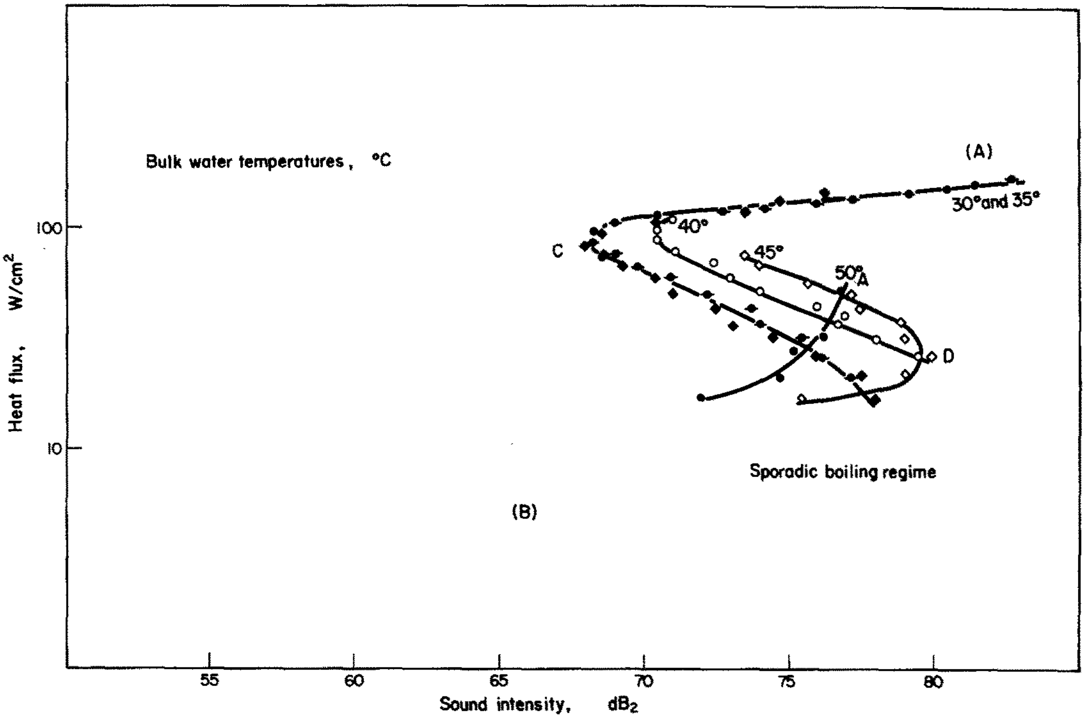

FIG. 16. Sound intensity accompanying nucleate boiling in water at a pressure of 90 torr, as a function of water temperature and total heat flux.

Observations made during the reduced pressure boiling of water may, therefore, be more pertinent to liquid metal cooled systems than observations made during boiling at atmospheric or higher pressures. The main feature of the low pressure boiling acoustic data is the intermittent sounds, of high intensity, that are emitted at low heat fluxes in the nucleate boiling region. Because of the intermittent nature of these sounds it was not possible to record sound levels using the existing equipment.

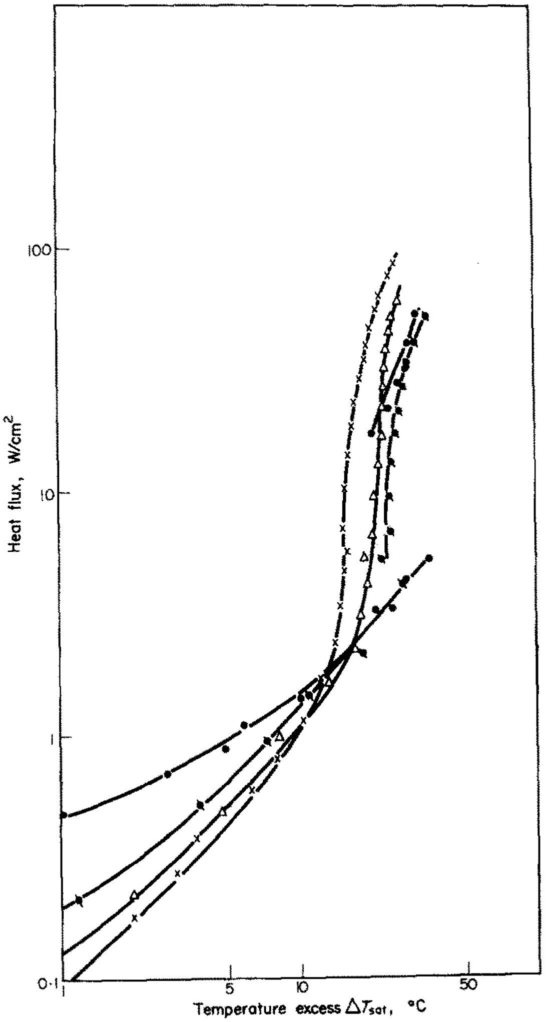

FIG. 17. Effect of pressure on rate of heat transfer in saturated boiling.

	Pressure	Water Temperature
×	760 torr	100°C
Δ	405 torr	80°C
●	210 torr	65°C
●	90 torr	50°C.

CONCLUSION

From the studies reported above, the following conclusions have been drawn.

(1) The initiation of boiling on a heated surface submerged in saturated or subcooled water at atmospheric pressure or below can be detected by an increase in the sound intensity in the audible range (20 Hz to 20 kHz) as detected by a cylindrical lead zirconate pressure transducer immersed in the water.

(2) Where the process of bubble formation is comparable to the process observed in the boiling of water at atmospheric pressure a regular decrease in the sound intensity accompanies a reduction in the heat flux. At low heat fluxes in the nucleate boiling region in subcooleed boiling, where the different heat fluxes at which nucleation commences cause a reduction in sound level with a reduction in water temperature, order can be brought into the data by expressing the sound level relative to the increased heat transfer rate over the natural convection component rather than to the total heat transfer rate.

(3) The intensity of sound accompanying a boiling process is co-dependent on the heat flux and water temperature so that measurement of the sound level together with one of the other parameters is not sufficient information uniquely to specify the boiling status.

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Résumé—Les densités de flux de chaleur et les intensités sonores qui les accompagnent sont données pour l'ébullition en réservoir de l'eau sur un réchauffeur tubulaire en acier inoxydable à des pressions dans la gamme 760–90 torr et des sous-refroidissements de liquides allant jusqu'à 60°C. Lorsque l'ébullition nucléée se produit avec la formation régulière de bulles de taille semblable à partir des sites fixes de nucléation, de même que lorsque l'eau bout sous des conditions atmosphériques, une décroissance progressive de l'intensité sonore est produite par une décroissance du flux de chaleur. Une transition à partir de ce processus régulier se produit aux faibles pressions et dans cette région l'intensité sonore n'est pas reliée uniquement au flux de chaleur.

Une revue des travaux publiés sur les émissions sonores accompagnant l'ébullition en réservoir est incluse.

Zusammenfassung—Es wird über den Wärmeübergang und die auftretenden Geräuschintensitäten beim Sieden in freier Konvektion von Wasser an einem rohrförmigen Heizelement aus rostfreiem Stahl bei Drücken im Bereich von 760–90 Torr und Flüssigkeitsunterkühlungen bis zu 60°C berichtet. Wenn Blasensieden mit regelmässiger Bildung von Blasen gleicher Grösse an festen Siedekeimen auftritt, wie beim Sieden von Wasser unter atmosphärischen Bedingungen, wird durch Verringerung der Wärmestromdichte eine fortschreitende Abnahme in der Geräuschintensität hervorgerufen. Ein Sprung in diesem regelmässigen Vorgang tritt bei geringen Drücken auf; in diesem Gebiet besteht keine eindeutige Geräuschintensität und Wärmestrom.

Eine Übersicht von erschienenen Arbeiten über Geräuschbildung beim Sieden in freier Konvektion ist angegeben.

Аннотация—Приведены интенсивность теплообмена и интенсивность звука для случая кипения воды в большом объеме в трубчатом нагревателе из нержавеющей стали при давлении от 760–90 торр и при недогреве жидкости до 60°C. Если пузырьковое кипение сопровождается периодическим образованием одинакового размера пузырьков на ядрообразующей поверхности при кипении воды в атмосферных условиях, то уменьшение теплового потока приводит к уменьшению интенсивности звука. Переход от этого регулярного процесса происходит при низких давлениях, и в этой области интенсивность звука неоднозначно относится к тепловому потоку.

Дается обзор работ по генерированию звука, которое сопровождает кипение в большом объеме.