Int. J. Engng Ed. Vol. 8, No. 4, pp. 309–316, 1992
Printed in Great Britain.

0742–0269/91 $3.00+0.00

Teaching Pool Boiling by Using a Computerized Experiment

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A computer based experiment test rig has been developed for teaching boiling phenomenon. The experimental method allows for transient temperature measurements of a small heated body as it is quenched in a pool of liquid. A personal computer is used for data acquisition, heat transfer analysis and graphical presentation of data. The experiment provides an ideal teaching tool for fast and cost-effective teaching of boiling heat transfer. Sample results obtained during quenching of a 20 mm copper sphere in a pool of Refrigerant 11 are presented. Comparisons of the measurements with predictions from available empirical correlations are very good.

SUMMARY OF EDUCATIONAL ASPECTS OF THE PAPER

1. The paper discusses material for a course in: Mechanical Engineering and Chemical Engineering.
2. Students of the following departments are taught in the course: Mechanical Engineering and Chemical Engineering.
3. Level of the course: 4th year undergraduate and postgraduate.
4. Mode of presentation: 3 hours of class/week for one session (14 weeks) + 6 hours of laboratory per session.
5. Is the material presented in a regular or in an elective course: Elective course.
6. Class hours required to cover the materials: Forty-two hours for the total course.
7. Student homework and revision hours required for the materials: 3 hours/week for 14 weeks.
8. Description of the novel aspects presented in the paper: Integration of computer with the boiling experiment. Ease of collecting the data and the portable nature of the setup.
9. The standard text recommended for the course in addition to author's notes: No text is used. 150 pages (typewritten) notes of author.
10. The material is/is not covered in the text. The discussion in the text is different in the following aspects: The material is not thoroughly discussed in the textbooks but only the results are given. With this method and approach the students can see how the results are obtained.

INTRODUCTION

BOILING processes which are associated with very high heat transfer rates cover a numerous range of applications. In teaching two-phase flow and heat transfer, boiling phenomenon requires special attention because of its importance and complex nature. For a better understanding, it is essential that experiments are performed to demonstrate the physical phenomenon and relate these to heat transfer measurements.

Pool boiling occurs when the temperature of a solid surface adjacent to an initially quiescent liquid exceeds the saturation temperature corresponding to the liquid surface. There are several regimes of pool boiling which can be identified on a plot of heat flux versus the difference between the solid surface and liquid saturation temperatures.

Leidenfrost in 1756 [1] reported the existence of minimum and maximum rates of boiling heat transfer. In 1934, Nukiyama [2] was the first to publish clear scientific results indicating that there are different modes of boiling. The simplest way to classify the various regimes of pool boiling is to refer to the so-called boiling curve, i.e. a graphic relationship between the heater wall surface temperature (or wall superheat, ΔT_{sat}) and the surface heat flux. A typical boiling curve is shown in Fig. 1. The four main regimes on the boiling curve are natural convection, nucleate boiling, transition boiling and film boiling. The transition from natural convection to nucleate boiling is referred to as onset of nucleate boiling (ONB), the transition to the next stage is identified by a maximum known as critical heat flux. At the end of the transition boiling regime there exists a minimum (Leidenfrost point).

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* Paper accepted 12 April 1992.

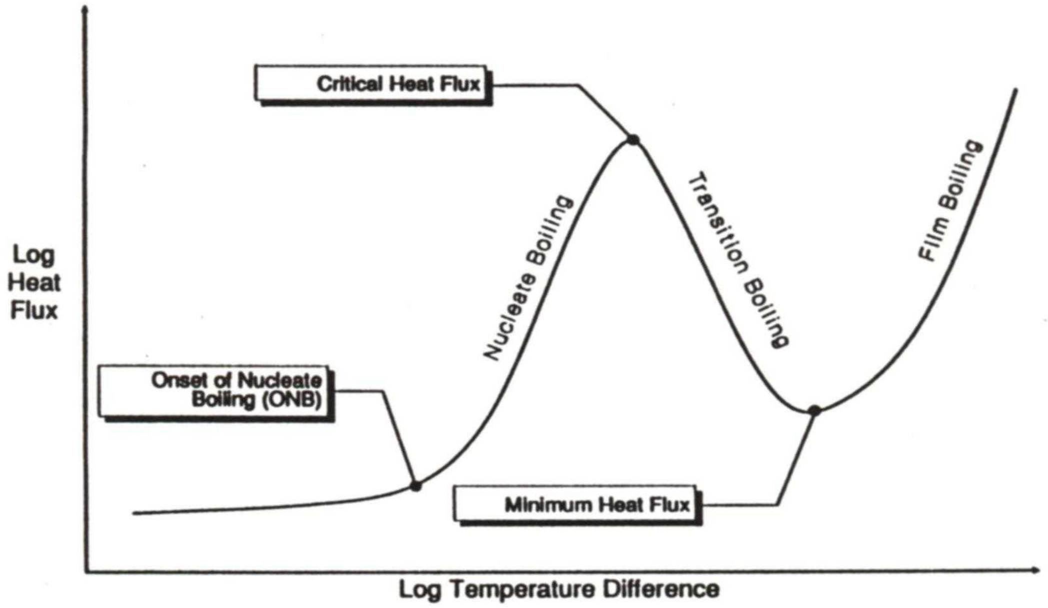


Fig. 1. Typical Pool Boiling Curve

The impetus for developing this experiment was to demonstrate to students the different regimes of pool boiling phenomenon and to produce boiling curves in a simple, fast and cost-effective manner. A personal computer was used to record the temperature history during boiling and perform an on-line analysis to produce the boiling curve. The data was plotted by the computer as the heat flux versus temperature difference. Also, the heat transfer coefficient was calculated and plotted. The boiling curve can be produced for a range of different fluids, however water and some refrigerants are best for demonstration purposes. The experiment illustrates the importance of different boiling regimes and the variation of heat transfer coefficient as well as the usefulness of personal computers for data-logging and performing on-line analysis in an integrated system.

BACKGROUND

There are three different ways of performing a pool boiling experiment.

1. Heat flux is controlled by, say, passing an electric current through a wire. The heat flux is obtained from the electric power requirement of the wire and the temperature can be determined by using the wire as a resistance thermometer (the original Nukiyama experiment). In this type of experiment the transition boiling regime cannot be achieved. It is also possible to substitute the wire by a heating body with a larger thermal mass [3].
2. Temperature is controlled by condensing a vapour on the inside of a tube and boiling the liquid on the outside of the tube. Surface temperature is directly measured by temperature probes and the heat flux is calculated by an energy balance on the condensing vapour. This is the most common technique for investigating the transition boiling regime [4].
3. Neither the temperature nor the heat flux is controlled; instead transient temperature measurements are made during quenching of a preheated metal body. Heat transfer rates can be calculated by numerical techniques or 'the lumped capacitance method' if it applies. Different techniques can be used for recording of temperature and time. The advantage of this type of experiment is that all boiling regimes are accessible, however due to the transient nature of the measurements, the boiling curve which is obtained is not a steady-state one. This problem can be overcome by a proper choice of the liquid as well as the solid material and dimensions [5].

The third method is probably the simplest to set up as a demonstration and teaching tool. Florscheutz [6] developed a test rig based on this method using an analogue computer. However, as these computers are being used less and with the present availability of digital personal computers, the analogue system is not very appealing.

EXPERIMENT

The major component of the experimental apparatus is a personal computer equipped with an analogue to digital converter (A/D) card. The computer is used to record the quenching body and fluid temperatures versus time. The computer is also used for analysis of the data as well as plotting and printing it.

A copper sphere was chosen for the quenching body. The size of the sphere was determined from a preliminary design calculation for quenching the

Refrigerant 11. The smaller the size of the quenching body is, the more accurate the heat transfer analysis used here would be. However, a small quenching body also means a short duration experiment. As a compromise between ease of boiling visualization and accuracy of the analysis, a diameter of 20 mm was chosen. The sphere was machined from free machining (grade 147) copper. A well of 2 mm diameter was drilled to the centre of the sphere. A fine (0.5 mm wire diameter) teflon insulated, copper–constantan thermocouple was then placed into the hole with its junction contacting the centre of the sphere. The hole was then filled with copper powder and a highly conductive heat transfer paste. The thermocouple lead wires were encased by a 3 mm O.D. stainless steel tube which was insulated and screwed into the sphere. Details of the sphere and thermocouple assembly are shown in Fig. 2. Another similar thermocouple immersed in the liquid was used for measuring the fluid temperature during the experiment.

A multi-channel variable gain amplifier was used to amplify the thermocouple outputs to produce signal levels suitable for the computer. The gain for each thermocouple was selected such that maximum sensitivity was achieved without saturating the 12 bit A/D converter. Both thermocouples were calibrated *in situ* over their desired temperature ranges by collecting temperature versus A/D readings. The data was used to produce polynomials of best fit (calibration equations) using a least squares regression program. The liquid was contained in a 2 litre pyrex beaker. A two flame gas burner was used for heating the sphere and the liquid. A camera equipped with a close-up lens was used to take photographs for visual recording of different boiling regimes.

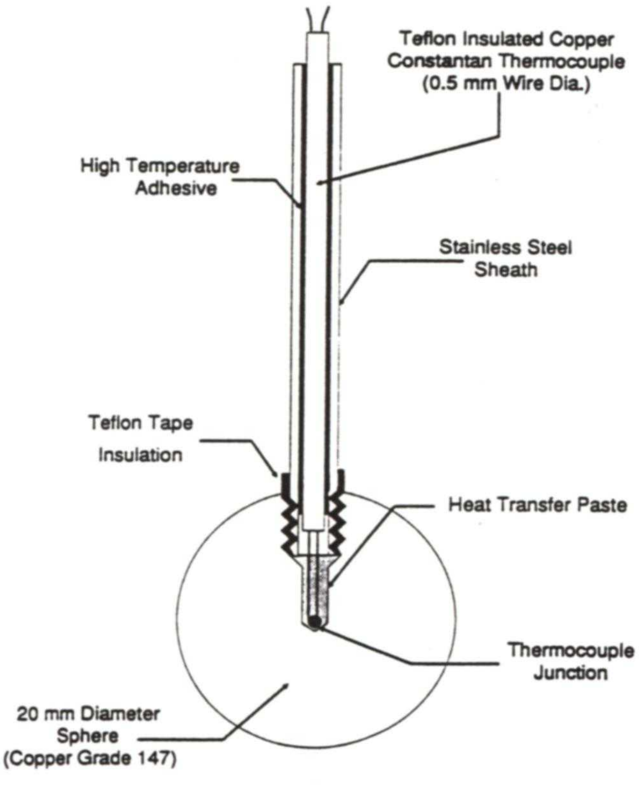


Fig. 2. Diagram of Copper Sphere Design

ANALYSIS

Suppose that the sphere is preheated to a given temperature and then dropped into a liquid. Assuming that the temperature of the sphere is spatially uniform at any instant (i.e. no temperature gradient in the sphere—'lumped capacitance method' [7]) then the rate of heat transfer can be determined from the rate of change of the internal energy,

$$Q' = -mc\frac{\mathrm{d}T}{\mathrm{d}t} \tag{1}$$

where Q' is the rate of heat transfer, m, c and T are the mass, specific heat capacity and temperature of the sphere, respectively; t denotes time. Heat flux can be determined from:

$$q' = -\frac{mc}{A}\frac{\mathrm{d}T}{\mathrm{d}t} \tag{2}$$

where A is the surface area of the sphere. For a constant specific heat capacity, the heat flux is simply proportional to the rate of change of temperature with time:

$$q' = -C\frac{\mathrm{d}T}{\mathrm{d}t} \tag{3}$$

where $C = \dfrac{-mc}{A}$

The assumption of a uniform temperature throughout the body is clearly an idealization, for if no temperature gradient existed then conduction of heat through the body would not be possible. However, if the resistance to heat transfer through the body due to conduction is small compared to the resistance to heat transfer from the body surface to its surroundings (convective resistance) then the temperature gradient through the body would be small. In this case, the lumped capacity heat transfer analysis can be used with a reasonable accuracy. The error associated with this analysis depends on the value of the dimensionless Biot number, which for a sphere is defined by:

$$\mathrm{Bi} = \frac{\mathrm{h}D}{6\mathrm{k}} \tag{4}$$

where h is the convective heat transfer coefficient, D and k are the diameter and thermal conductivity of the sphere respectively. The error is negligible when Bi is very small [7], say less than 0.1. This suggests that it is best to use a highly conductive solid material with the smallest possible dimensions. Of course, for ease of visualisation of different boiling regimes a compromise was made on the size of the sphere used here.

The heat transfer coefficient can be determined from the Newton's law of cooling:

$$h = q'/(T - T_f) \qquad (5)$$

where T_f is the bulk fluid temperature. It is noted that the calculation of heat flux (eqn. 3) requires the differentiation of an experimentally derived temperature history curve. Differentiating such a curve will invariably produce a scattering of results due to the inherent non-smoothness of the curve caused by errors in the measuring system, and analogue to digital conversion. Numerous numerical differentiation procedures are available to approximate the instantaneous slope of such a curve using forward, backward or central difference formula.

COMPUTER PROGRAM

A computer program was written in Basic for data acquisition and analysis. It was possible to record the temperatures for 1950 timesteps before filling up the data buffer of the particular personal computer used for this experiment. The sampling rate was interactively determined between 0.5 and 36 scans per second. In each scan, seven consecutive readings of the sphere temperature as well as a single reading of liquid temperature were recorded. The A/D data was continuously written to the data buffer. The A/D data could then be saved on a floppy disk as a binary file for permanent data storage. The analysis was done using the buffer data directly or by loading the previously stored data into the buffer. The thermocouples calibration equations were used to convert the raw A/D readings to actual temperatures.

Heat flux calculation (eqn. 3) was performed by determining the instantaneous rate of temperature change. At each timestep, the temperature of the sphere was calculated by numerically averaging the seven sphere temperature readings collected in each scan. This averaging reduced data scatter. The instantaneous rate of temperature change was estimated by using a five point central difference formula. This smoothed out the differentiation process. The temperature history for each run was plotted simultaneously as the analysis was being performed.

Heat transfer analysis was performed on the temperature data, starting at the point where the sphere temperature decreased by more than 0.5°C per scan (quenching process was assumed to begin, t = 0). The analysis was terminated when the end of the data list was encountered or when the sphere superheat (sphere and fluid temperature difference) was less than 1°C. Test liquid temperature was obtained by numerically averaging liquid temperature data collected in all scans. The calculated heat flux was used to determine the heat transfer coefficient (eqn. 5) at each time step.

For presentation of results several options are incorporated in the program. After analysis has been performed, it is possible to list or plot the data. Data listings available include raw A/D data and temperature versus time, calculated heat flux and heat transfer coefficient data. Graphical output options are plots in the following form: (i) sphere superheat temperature versus time, (ii) heat flux versus temperature difference (boiling curve) and (iii) heat transfer coefficient versus temperature difference. The temperature-time history plot features automatic axis scaling for both temperature and time axes. The boiling curve and heat transfer coefficient plots are plotted on a log-log scale and ranges are user selectable. All the output options could either be displayed on the screen or printed.

Further details of the data acquisition system, software as well as a copy of the computer program can be obtained from the authors.

RESULTS

The experimental procedure consisted of slowly heating the sphere and test liquid on the two ring gas burner to the desired temperature. During heating, the sphere temperature was monitored (displayed on the computer screen) to ensure that the thermocouple teflon insulation was not damaged. This corresponded to a sphere temperature below 300°C. After selecting the appropriate sampling rate and reaching the desired temperatures, the sphere was dropped into the liquid and boiling initiated. Experiments were performed at atmospheric pressure with saturated and subcooled water and Refrigerant 11 ($T_{sat} = 23.8$°C). The different boiling regimes were observed and photographed. The total duration of boiling was of the order of 1–2 minutes.

Typical results obtained during saturated boiling of R-11 are presented here. The temperature history during boiling is shown in Fig. 3. The three boiling regimes are easily distinguished from the slope of the curve. The total elapsed time for boiling heat transfer is around 110 seconds with stable film boiling being exhibited for most of the time (approximately 85 seconds), film transition boiling for about 17 seconds, and nucleate boiling for about 8 seconds.

The boiling curve extracted from the temperature history is given in Fig. 4. It is noted that as the analysis is carried out on a time basis, the majority of points lie in the stable film boiling regime. The points of maximum and minimum heat flux, as well as the boiling regimes are evident. The value of maximum heat flux is very close to that predicted by Lienhard and Dhir [8] correlation. A relatively large scatter of data is evident in the single phase convective regime. This is due to the error in the temperature readings being of the same order as the temperature difference between two consecutive readings. Of course, this data scatter is magnified in the calculated heat transfer coefficient for this region (Fig. 5). Six sample photographs taken during this experiment are shown in Fig. 6. The

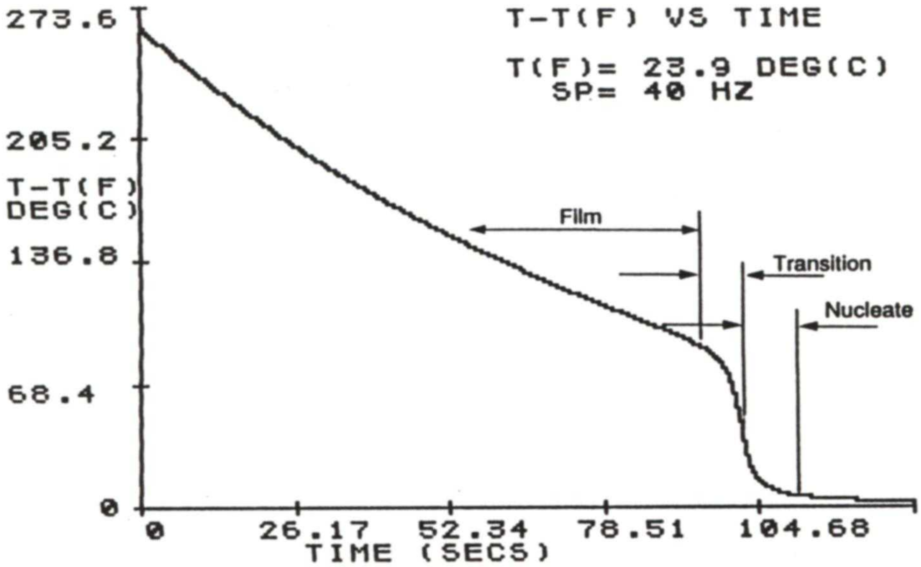


Fig. 3. Temperature History During Boiling of Refrigerant 11

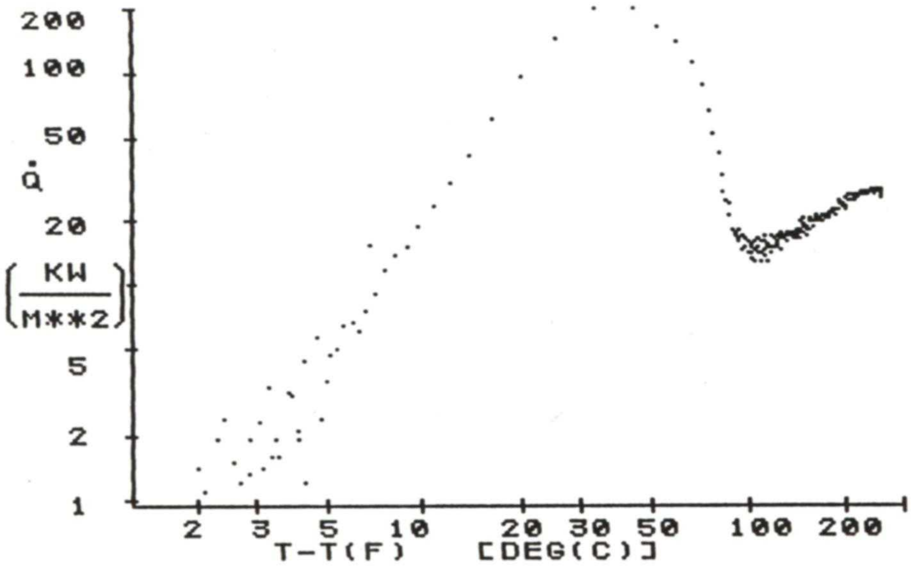


Fig. 4. The Boiling Curve for Refrigerant 11

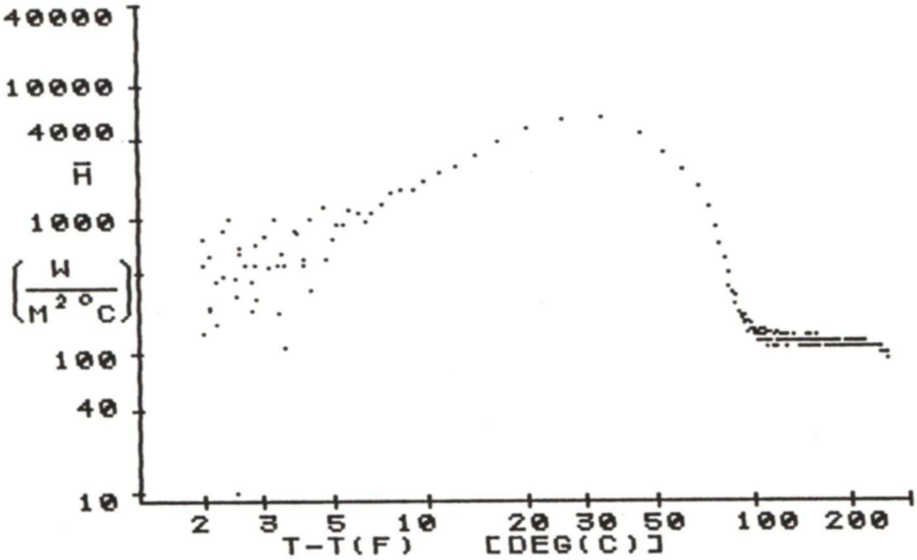
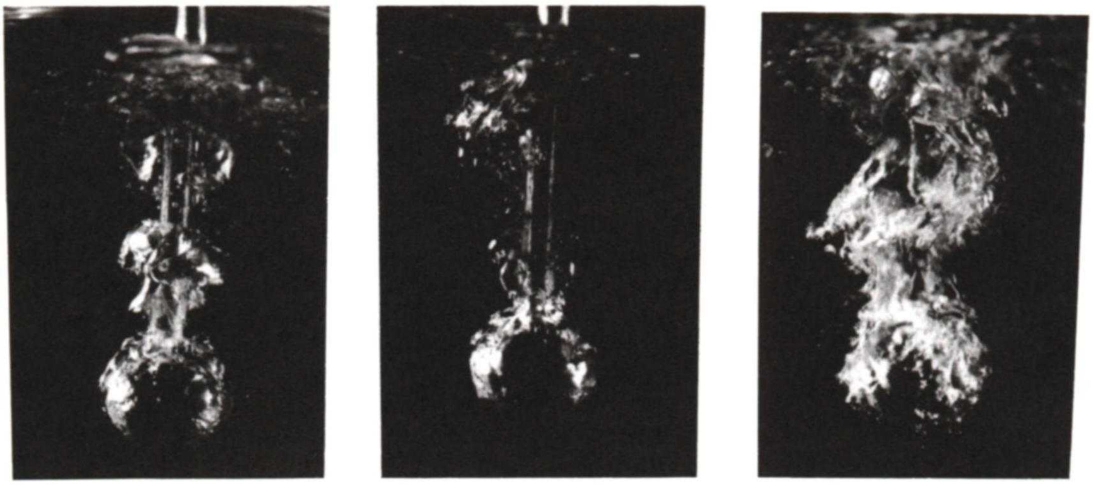


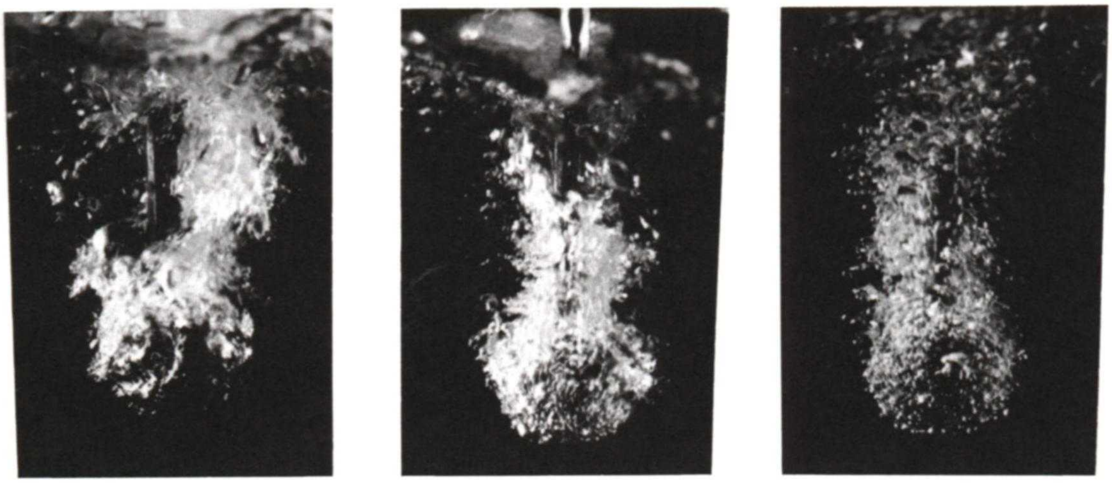
Fig. 5. Boiling Heat Transfer coefficient for Refrigerant 11



t=10s, ΔT = 235°C
Film Boiling

t=85, ΔT = 102°C
Min. Heat Flux

t=101, ΔT = 53°C
Transition Boiling



t=102, ΔT = 37°C
Critical Heat Flux

t=103, ΔT = 20°C
Nucleate Boiling

t=105, ΔT = 12°C
Nucleate Boiling

Fig. 6. Photographs Showing Different Boiling Regimes (Refrigerant 11)

photographs correspond to the different regimes in Fig. 3.

Boiling heat flux calculations are usually performed using different empirical correlations relevant to the particular boiling regime of interest [7]. A comparison of the experimental results with the empirical correlations predictions are given in Fig. 7. The boiling curves plotted here represent the range of data obtained from several experiments. Considering the uncertainty of correlations as well as experimental errors, the agreement is good. Once the experimental data is obtained and plotted, comparisons with the predictions of empirical correlations can be performed by students as an exercise.

In design calculations related to boiling heat transfer, one of the important parameters is the critical heat flux. Its value depends on the degree of liquid subcooling (saturation and bulk fluid temperature difference) and increases linearly with increasing subcooling [7]. To demonstrate this effect, a number of experiments were performed using water with different degrees of subcooling. The results are presented in Fig. 8. It can be seen that the results compare well with the predictions from an empirical correlation [12].

CONCLUSIONS

Experimental apparatus and software has been developed for demonstration of boiling phenomenon. The experimental method allows for transient temperature measurements to be made during quenching of a sphere in a pool of liquid. Different boiling regimes can be visually observed

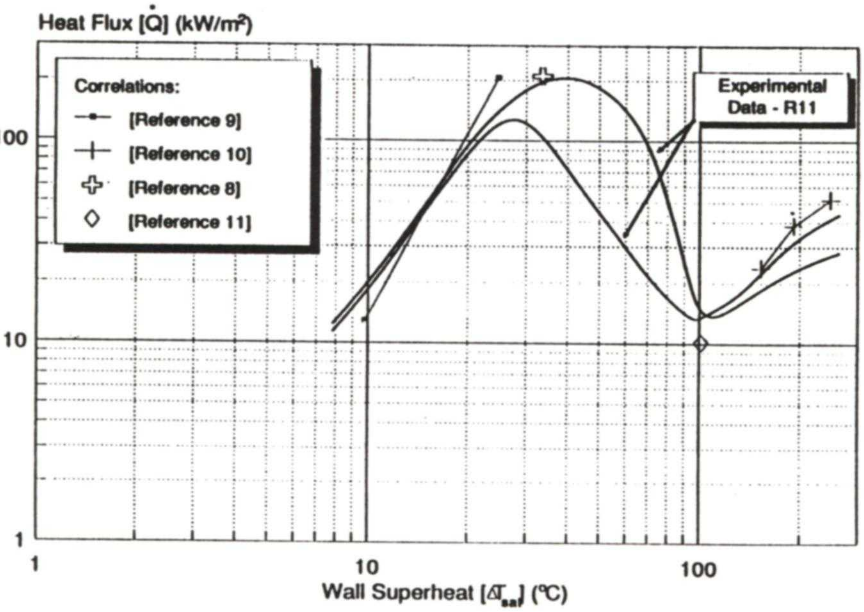


Fig. 7. Comparison with Empirical Correlations

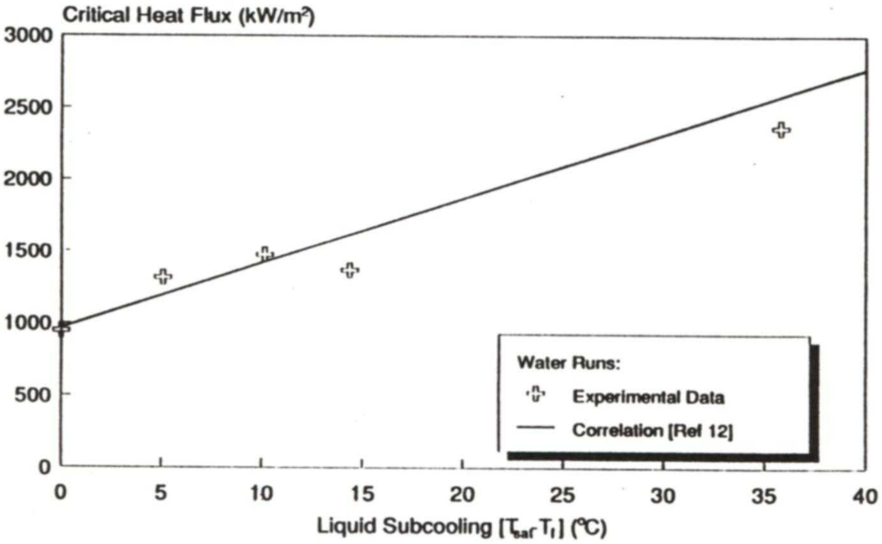


Fig. 8. Effect of Liquid Subcooling on Critical Heat Flux

and graphically presented. A personal computer is successfully used for data acquisition, analysis of the data, as well as plotting and listing the results.

The measured heat flux compares favourably with the predictions of available empirical correlations. The rig provides a useful tool for obtaining the boiling curve in a fast and cost effective manner. It can be used as an ideal experiment for classroom or laboratory teaching of two-phase flow and heat transfer subjects. It also demonstrates the application and advantages of personal computers for data acquisition and performing on-line analysis.

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