

EFFECT OF PERIPHERAL WALL CONDUCTION IN POOL BOILING

by

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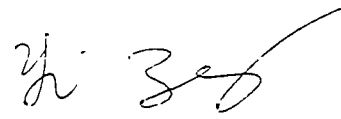
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ABSTRACT

With uniform heat generation within a heater placed in an asymmetrical boundary condition, as in pool boiling from a horizontally placed cylindrical heater, heat flows by conduction within the heater create a non-uniform surface temperature distribution because of the asymmetrical nature of the fluid flow around the perimeter of the cylinder. The variation of the surface temperature caused by peripheral wall conduction may affect the overall heat transfer rate significantly for geometrically similar surfaces.

In the present study, a non-dimensional conduction parameter $K^* = K_{1o} r_o / K_w b$ [1] is used to characterize the peripheral wall heat conduction. In the experimental investigation, seven test sections having different values of K^* (from 0.014 to 0.075) were studied in both nucleate and film boiling regions. A critical value of K^* is found for S. S. 304 material with freon 113 ($K^*_{cri} = 0.051$). For $K^* < K^*_{cri}$, the heat transfer coefficient decreases with K^* , while in the range of $K^* > K^*_{cri}$, the opposite seems to be true. The added asymmetry of the thermal boundary condition affects the average heat transfer rate up to a maximum of 100% for the ranges of K^* and heat flux studied in the nucleate boil-

ing region. However, the effect seems to be negligible in the film boiling region.

The effect of the material was also investigated in the study. It shows that the material influences the heat transfer significantly in nucleate pool boiling, but has little effect in film pool boiling in the ranges studied.

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NOMENCLATURES

b	Wall thickness of the test tube, mm
B	Constant in Mikic-Rohsenow's correlation [30]
Bi	Biot number, hD/K_w
B_1	Constant in Levy correlation's [31]
C	Specific heat, J/Kg °C
C_{sl}	Empirical constant in Rohsenow's correlation [26]
D	Diameter of the test tube, mm
g	Gravitational constant, 9.8 M/S^2
h	Local heat transfer coefficient, $\text{W/M}^2 \text{ }^\circ\text{C}$
h_{fg}	Latent heat, J/Kg
I	Current flow, Ampere
K	Thermal conductivity, $\text{W/M} \cdot ^\circ\text{C}$
K_s	Constant in Sakurai's correlation [37]
K^*	Dimensionless peripheral wall conduction parameter, $K_l r_o / K_w b$

L	Power measurement length, mm
Nu	Nusselt number, hD/K_1
P	Pressure, Pa
q	Heat flux, W/M^2
$\dot{q}$	Heat generation per unit volume, W/M^3
r	Radius, mm
r^+	Nondimensional radius, r/r_o
T	Temperature, °C
ΔT	Wall superheat, $\bar{T}_o - T_s$, °C
T^+	Dimensionless temperature, $(T - T_s)/(\bar{T}_o - T_s)$
V	Voltage drop within L, Volt
X	Axial coordinate, mm, origin at the middle of a test tube.

Greek Symbols

θ	Angle in degree
ρ	Density, Kg/M^3
α	Thermal diffusivity, M^2/S

ε	Emissivity
μ	Dynamic viscosity, Pa·S
σ	Surface tension, N/M
λ_c	Critical wave length, $2\pi \left[\sigma / g(\rho_1 - \rho_v) \right]^{\frac{1}{2}}$
σ_0	Stefan constant, $\sigma_0 = 5.67 \times 10^{-8} \text{ W/(M}^2 \cdot \text{K}^{-4})$

Superscript

- = Mean

Subscripts

w	Wall material
l	liquid
v	vapour
o	Outside surface
i	Inside surface
s	Saturation
st	Refers to Stephan's correlation [33]

sa Refers to Sakurai's correlation [37]

cri Refers to critical value

rad Refers to radiation

max Refers to maximum

min Refers to minimum

atm Refers to atmospheric pressure

CHAPTER 1 INTRODUCTION

Pool boiling heat transfer has been investigated extensively for many years because of its wide applications in engineering. Effects of fluid and thermal properties, of surface finish and coating, of dissolved non-condensable gases, of orientation of the heater, of agitation of the fluid, of the container geometry, of the gravitational field and other parameters were investigated and a large number of correlations were proposed and are being used. However, at the present time it is still difficult or even impossible to predict heat transfer coefficient with satisfactory accuracy in the nucleate boiling region. Many existing results on the phenomena are inconsistent with each other or differ widely. It is clear that to compare the experimental results obtained by different investigators all parameters governing the heat transfer process should be set equal. These parameters should include the surface roughness, heater material, diameter of the heater, pressure, etc.. However, most investigators seldom include the circumferential heat conduction, which is dependent on the thermal conductivity of the cylinder wall material, wall thickness, the heat generation rate, the cylinder diameter, and other factors.

An isothermal test section is usually assumed by many investigators. However, in reality this is not true for many of the experimental conditions. With constant heat generation, such as nuclear heating, electric resistance heating, radiant heating, etc., a problem arises in pool boiling in the case of a horizontal cylinder: because of the asymmetric nature of fluid flow around the periphery of the cylinder, temperature gradients are developed and cause heat flow by conduction in the peripheral direction. The non-uniform temperature distribution within a heater may affect both the local and overall heat transfer rate significantly since the type of heating boundary has a strong effect on heat transfer rate. This problem has been realized by a number of researchers in their experiments, such as Sauer et al. [2] and Jensen et al. [3]. Sauer et al. [2] pointed out that the maximum uncertainty in their experiment lay in the variation of the surface temperature along the periphery of the test cylinder, showing that circumferential wall conduction has a significant effect on both the local and average heat transfer coefficients in nucleate pool boiling. It seems that one of the reasons for the discrepancy by different investigators is the peripheral wall conduction. This has led to the study presented in this report.

Therefore, the objectives of the study were:

(1) to investigate the effect of peripheral wall conduction on wall temperature distribution, and on local and average heat transfer coefficients in both nucleate and film boiling regions; and

(2) to investigate the effect of surface material on boiling heat transfer.

An analysis may be possible for the local boiling heat transfer coefficient in the film boiling region, but in the regions of nucleate and transitional boiling, this is for the moment not feasible. Thus, an empirical approach to the problem seemed to be appropriate.

For the study of the effect of the peripheral wall conduction on boiling heat transfer, the non-dimensional parameter, K^* , should be varied by using different wall thicknesses or different diameters for the same material since the material also has a strong effect on boiling heat transfer.

Seven test sections made of stainless steel 304 with five different wall thicknesses (2.87 mm, 1.65 mm, 1.24 mm, 1.02 mm and 0.81 mm, respectively), one made of monel 400 ($b = 2.92$ mm) and the other inconel 600 ($b = 2.29$ mm), were used to vary the non-dimensional parameter K^* between 0.014 and 0.075. The working fluid was 99% pure commercial grade freon 113. All the test sections were electrically heated

to provide uniform heat generation throughout the test section. Experiments were conducted in both nucleate and film boiling regions at near atmospheric pressure.

CHAPTER 2 LITERATURE SURVEY

A great deal of work has been carried out on boiling phenomena in the last few decades. Many effects on pool boiling have been investigated, such as the effects of pressure [4-6], geometry of container [7], heater diameter [8-9], fouling [10], and others. However, there are many aspects of boiling that are still not clearly understood.

2.1 Boiling Curve

A typical pool boiling curve is shown in Fig. 2.1, which was first obtained by Nukiyama [11] in 1934. It can be seen from Fig. 2.1 that there are approximately four distinctive regimes in pool boiling, which are surface evaporation, nucleate boiling, transition boiling, and film boiling.

In the regime 1, heat transfer occurs at the free surface without the formation of bubbles when the heating surface T_o is only a few degree above saturation temperature T_s .

Natural convective current is the major mechanism of heat transfer. When the heating surface temperature is further increased, vapour bubbles form and agitate the liquid in the

vicinity of the heating surface. This type of boiling, or the regime 2, is known as "nucleate boiling". After the peak of the curve at the upper limit of the regime 2 is reached, an unstable situation develops. Large patches of vapour cover the surface and the heat transfer rate is reduced. This film is unstable and continually collapses and forms again. Additional increase in the surface temperature causes reduction in the heat transfer rate, as indicated in the regime 3, and called "transient boiling". When ΔT is large enough, the heating surface becomes completely "vapour blanketed", and a stable film of vapour is formed over the surface (regime 4). This results in a process called "film boiling". Since the present study concentrates on nucleate boiling and film boiling, the attention will be focused on these two regions.

2.2 Effect of Surface Condition

Many experiments show that the heating surface condition, including the surface roughness and material, is one of the most important aspects which affects nucleate boiling heat transfer. Because of the apparent importance of surface condition on boiling, it seems necessary thoroughly to discuss the effect of surface condition on boiling heat transfer.

The first aspect of the surface condition is the surface roughness. A rough surface, as compared to a smoother one, has a larger surface area, more adsorbed gas (which may affect the boiling heat transfer only at the beginning), and generally a greater number of active sites from which nucleation can begin. These factors usually combine to produce a higher heat transfer rate for a rough surface when compared to a smoother surface in the nucleate boiling region. This has been confirmed by many experiments, such as Jakob's and Fritty's experimental results [12]. It seems that roughness above 0.8 mm rms would not increase the heat transfer coefficient further, as shown by Kurihara and Myers [13].

Berenson [14] studied the effect of roughness on pool boiling, covering nucleate boiling, transition boiling, and film boiling, as shown in Fig. 2.2. It should be noted that the effect of roughness on film boiling is negligible since the heating surface is covered completely with vapour during film boiling. Only for a very coarse surface, is the flow of vapour on the heating surface disturbed, with a resulting change in heat transfer coefficient.

Another aspect of surface condition is the surface material. Even if the surface roughness is kept constant for different materials, the heat transfer rate could still be significantly different in the nucleate boiling region.

This has been shown by a number of experiments [14-19]. This may be due to the fact that the contact angle depends strongly on the material for a given fluid.

Berenson [14] found that the surface thermal properties affect nucleate boiling significantly. His experimental data showed that, for a given heat flux, the temperature difference ΔT increases with the decrease of conductivity, K_w . In other words, the heat transfer rate increases with the conductivity, K_w .

Sharp [19] argued that since experiments indicate a sudden drop in surface temperature when bubbles begin to grow, and since the micro-layer temperature remains constant during evaporation, this process can be approximated by the transient conduction process of a temperature pulse on a semi-infinite surface. Starting from this assumption, he showed that the heat transfer coefficient increases with $K_w/\sqrt{a}$. The results of Konig [20] and Magrini [18] seem to follow this trend. However, Agrawal and Hus [21] and Bliss [15] found their experimental results do not agree with this rule. The discrepancy among the results of different investigators shows that the parameter which should be used to characterize the materials is still unknown.

In the film boiling region, however, the effect of material seems negligible [22-24]. Again, this may be due to the fact that the heating surface is covered completely by

vapour, and therefore the heat transfer rate is governed by the behavior of vapour film. Only when surface temperature is very high, and radiation becomes important, can the effect of material be significant, since the emissivity depends on the material.

2.3 Correlations of Boiling Data

As can be found in the references [25-33], a large number of correlations have been proposed in the past for boiling heat transfer. Because of lack of a complete understanding of the nucleate mechanism and of the surface and geometric effects on nucleate boiling, the correlation which can be applied to any situation with reasonable accuracy has not yet been found. Many of the correlations differ widely one from another, and most of these correlations contain constants which must be determined experimentally for the particular surface-fluid combination under consideration.

Rohsenow's correlation [26], perhaps, is the best known and most widely used. Assuming a similarity between forced-convection turbulent flow without boiling and nucleate boiling, he finally reached the following equation:

$$\frac{C_1 \cdot \Delta T}{h_{fg}} = C_{s1} \cdot \left[\frac{\bar{q}}{\mu_1 h_{fg}} \cdot \sqrt{\frac{\delta}{g(\rho_1 - \rho_v)}} \right]^{\frac{1}{3}} \cdot \left[\frac{\mu_1 \cdot C_1}{K_1} \right]^{1.7} \quad (2.1)$$

Like Rohsenow's correlation, most of the existing correlations do not contain the thermal properties of the heating surface, the thickness of the heating wall, and the diameter of the heater. These quantities do affect nucleate boiling, as shown by Magrini et al. [18], and by Sharp [19]. Perhaps the empirical constant, such as C_{s1} in Rohsenow's correlation, could take account for the effect of material, but it obviously cannot include the effects of the heating wall thickness and the heater diameter which govern the temperature distribution of the heater surface in an asymmetrical flow condition.

Based on hydrodynamic considerations, Farber and Sco-rach [34] and others developed an equation for critical heat flux. However, their equation contains neither the surface temperatures nor any other surface properties. Kurihara and Myers [13] made a very interesting statement concerning nucleate boiling heat transfer correlations: "None of the correlations referred to by Westwater [35] contains terms which describe the nature of the heating surfaces, although many experimental investigations have shown that the condition of the heating surface has a major effect on boiling performance. The reason for this omission is due largely to the difficulty of describing a surface quantitatively. Until the time when the essential elements of a surface which affect boiling can be measured and related mathematically to boiling performance, it is unlikely that any truly reliable correlation will be developed."

In the film boiling region, a number of correlations also have been proposed [9, 22, 36-38]. Bromley [22], Pitschman and Grigg [39] and others developed the correlations based on a conduction model. This model assumes that heat transfer through the vapour film is of primary importance and is mainly by conduction. Another widely used model is the hydraulic instability model. In this model it is assumed that heat removal from the heating surface is governed by the behavior of the bubbles, which in turn should be related to the occurrence of hydrodynamic instabilities at the liquid-vapour interface. Zuber [40], Chang [41], Zuber and Tribus [42], Berenson [38], Breen and Westwater [9], and others have presented model theories for film boiling.

With the development of electronic computers, numerical solutions to film boiling appeared after 1958. The common assumption used in the numerical solution was that the vapour layer could be regarded as a boundary layer. The common technique employed to simplify the governing equations was the similarity transformation. Representative work concerning the numerical solution in film boiling can be found in the references [43-48]. However, the numerical solution results are still not comparable to experimental results. This could be due to using some non-realistic assumptions in the numerical solution, such as the smoothness of the vapour-liquid interface, or the assumption that the vapour flow

pattern is laminar. In addition, the diameter effect and curvature effect are not taken into consideration.

2.4 Effect of Peripheral Wall Conduction

To the author's knowledge, no one has investigated the effect of peripheral wall conduction in pool boiling. Due to the nature of the asymmetrical boundary condition for a horizontal heater, the surface temperature varies with the angle. Although a few studies on boiling heat transfer indirectly recognized the variation of the surface temperature on the surface heat transfer coefficient, most of the investigators did not consider the effect of the variation of the surface temperature, which depends on the heater material, wall thickness, heater diameter, and the specific heat generation rate of the heater.

Sauer et al. [2] and Jensen et al. [3], in their studies on the effect of oil concentration in nucleate pool boiling, have observed some significant variations of the circumferential wall temperature and have attempted to explain the uncertainty in their experimental results via this variation. They concluded that the circumferential wall conduction could have a significant effect on both the local and the average heat transfer coefficient in nucleate boiling.

Berenson [14], Kovlov et al. [16], Bliss et al. [15], Magrini et al. [18], Sharp [19], and others investigated the effects of the material and wall thickness, used for the wall surface coating of the test heaters, on the overall heat transfer coefficient in nucleate boiling. However, none of them has measured the circumferential variation of the wall surface temperature.

It seems that no studies on film boiling heat transfer which recognize the effect of this peripheral wall conduction on heat transfer exist. Perhaps only McFadden [48] in his Ph.D. thesis mentioned the non-isothermal wall effect on film boiling from a vertical plate in his approximate numerical solution.

Deissler and Taylor [49], Lee et al. [1, 50-52], Leung, Kays, Reynolds [53-54], and others were the early workers who recognized the peripheral conduction effect on heat transfer. Deissler and Lee suggested the wall conduction parameter as $K_l r_o / K_w b$. They studied the peripheral wall conduction effect on the heat transfer rate in laminar and turbulent flow in a circular horizontal tube and concluded that peripheral conduction has a significant effect on the heat transfer rate. However, whether this is true in the case of pool boiling should be verified by experiments or deduced from the governing equation.

Thus, the observed effects of heater wall thickness and surface material on pool boiling indicate that an investigation into the effect of the peripheral wall conduction on pool boiling is needed.

CHAPTER 3 THEORETICAL CONSIDERATIONS

It is well known that, when all other flow conditions are set equal, the overall heat transfer rate is strongly affected by the type of the heating boundary. For instance, the Nusselt number for the fully developed laminar flow in a circular duct for constant surface temperature is 3.658, whereas that for the constant heat flux 4.364, a 19% difference [55].

As long as there is an influence of the type of the heating boundary, the effect of the peripheral wall conduction can also be expected. The added asymmetrical boundary condition may be due to the gravitational force for a horizontally placed heater, and therefore the effect would be almost non-existent for the heaters placed vertically in a fluid.

The governing equation of the heater may be obtained from the energy equation with a source term:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\dot{q}}{k_w} = 0 \quad (3.1)$$

Here the radiation loss is assumed to be negligible.

Introducing parameters T^+ and r^+ as:

$$T^+ = (T - T_s) / (\bar{T}_o - T_s) \quad (3.2)$$

$$r^+ = r / r_o \quad (3.3)$$

where T_s is the saturation temperature.

$\bar{T}_o$ is the average temperature of the outside wall.

r_o is the outside radius of the test tube.

Therefore, Eq. (3.1) becomes:

$$\frac{\partial^2 T^+}{\partial r^{+2}} + \frac{1}{r^+} \frac{\partial T^+}{\partial r^+} + \frac{1}{r^{+2}} \frac{\partial^2 T^+}{\partial \theta^2} + \frac{r_o^2 \dot{q}}{K_w \Delta T} = 0 \quad (3.4)$$

Since

$$\dot{q} = \frac{2 \cdot r_o \cdot \bar{q}}{(r_o^2 - r_i^2)} = \frac{\bar{h}}{b} (\bar{T}_o - T_s) = \frac{\bar{h}}{b} \Delta T \quad (3.5)$$

Eq. (3.4) simplifies to:

$$\frac{\partial^2 T^+}{\partial r^{+2}} + \frac{1}{r^+} \frac{\partial T^+}{\partial r^+} + \frac{1}{r^{+2}} \frac{\partial^2 T^+}{\partial \theta^2} + \frac{1}{2} \cdot K^* \cdot Nu = 0 \quad (3.6)$$

where

$$K^* = K_l r_o / K_w b \quad (3.7)$$

Since the boundary condition at the outside wall of the test tube is unknown, it is impossible to solve Eq. (3.6) alone. To solve the problem completely, the governing equations in the fluid region should be considered so that the required boundary condition at the outside wall may be obtained.

In the nucleate boiling region, two separate processes are involved: the formation of bubbles (nucleation) and the subsequent growth and motion of these bubbles. As yet, there is no completely satisfactory theory of nucleation. Most of the proposed theories assume the existence of "nuclei" from which bubbles originate, but the exact nature and origin of these nuclei remains a mystery. As a result, an analytic study seems extremely difficult in the nucleate boiling region at the present time.

However, in the film boiling region, it seems that it might be possible to obtain a numerical solution. The governing equations may be written for solid (heater), vapour and liquid regions with proper boundary and matching conditions. Coupling the governing equations in the three regions, the problem might be solved by a numerical method. More information about the numerical solution may be found in the references [43-48].

Even in the film boiling region, the numerical solution would be very complicated and tedious, although an analytic study might be possible. Therefore, an empirical approach to the problem seems to be most appropriate.

In the present study, as suggested by Lee [1], a non-dimensional parameter $K^* = K_l r_o / K_w b$, which was derived from the energy differential equation, has been used to characterize the peripheral wall heat conduction.

CHAPTER 4 EXPERIMENTAL STUDY

4.1 Apparatus

The schematic diagram and a front view of the test apparatus used in the present study are shown in Fig. 4.1 and 4.2. The working fluid used in the experiments was 99% pure commercial grade freon 113 as supplied by the Air Product Company. The experimental apparatus consisted mainly of a vertical boiling vessel, test sections, a reservoir, and the power supply. Following are the detailed descriptions of each part.

4.1.1 Boiling Vessel

The dimensions of the boiling vessel were 430 mm by 280 mm by 380 mm. The vessel was made of stainless steel with double walls. Insulating fiber glass was installed between the walls. As shown in Fig. 4.1, a water-cooled condenser was situated on the top part of the boiling vessel to condense back the vapour produced during the experiments. The cover of the boiling vessel was made of pyrex (20 mm in thickness) so that the inside of the vessel could be seen from the top as well as from the sides through two glass

windows. Before the freon 113 entered the boiling vessel, a filter was provided so that impurities could be prevented from entering the vessel.

4.1.2 Test Sections

Seven test cylinders (electrical resistance heating) made of stainless steel 304, monel 400 and inconel 600 with different wall thicknesses were used. The details of the test sections are given in table 4.1 and shown in Fig. 4.3 and Fig. 4.4 (a). The outside diameters of the test cylinders were kept at approximately 25.4 mm to maintain an identical hydrodynamic part or fluid flow pattern around the test section for each test tube.

All test tubes were 177.8 mm (7 inches) in length. Nine chromel-alumel thermocouples (K type, 24 Gauge) were spot welded onto the inner wall periphery at the middle of the test cylinders. As shown in Fig. 4.4 (a), thermocouple junctions 1 to 7 measured the surface wall temperatures at 30 degree intervals in the right portion, and the junctions 8 and 9, located at 60 degree intervals in the left portion, were used to check the symmetry of the temperature distribution in the right and left portions of the cylinder. Several additional thermocouples were positioned on the inner wall 13 to 26 mm away from the middle of the test heaters to check the uniformity of the axial temperature distribution.

In this way, the end effect of the temperature readings could be checked. The voltage drop within about a 50 mm length in the central portion of test tube was measured with two alumel wires embedded in the cylinder wall 50 mm apart. The temperature and power input were acquired through a HP 3052 A data acquisition system controlled by a HP 9835 A computer.

To test the accuracy of the spot welded thermocouples, thermocouples were installed on three additional test tubes (test tube 2, 4, and 5) using the "split junction" method. Details of the split hot junction are shown in Fig. 4.4 (b). The comparison of typical temperature readings is shown in Fig. 4.4 (c). As shown in Fig. 4.4 (c), the temperature readings by the split junction method are between the inside and outside surface temperatures (the outside surface temperature was obtained from Eq. (4.1), as given in Appendix 4). This is obvious since the temperature measured by split junction method is a sort of "average wall temperature".

Great care was taken to maintain the same surface roughness for each test tube. The surfaces were finished in a lathe using different sizes of silicon-carbide papers. Finishing began with a medium paper, followed by 180 and 320 grit, in that order.

Two copper conductors were shrink fitted into the test tubes to heat them electrically. To lead thermocouple wires out from inside of the test tube, an elbow union was used to connect the copper conductor and a copper tube. The details are given in Fig. 4.5. One end of the electrodes was connected to the copper conductor, the other to an electrical source. The electrodes were fixed onto the cover of the boiling vessel by nuts.

4.1.3 Reservoir

The reservoir was made of stainless steel. Its dimensions were 305 mm in diameter and 610 mm in height. A 3 KW Watlow plug immersion heater (BCC16N1) was installed from the bottom of the reservoir so that the freon 113 could be heated up to the desired temperature. With a compressed air cylinder connected to the reservoir, freon 113 in the reservoir could be charged into the boiling vessel by the compressed air when necessary. For safety, a pressure relief valve was installed. The temperature in the reservoir was measured by a mercury thermometer and a K type gauge 24 thermocouple. The liquid level inside was indicated by a glass tube. Connecting the reservoir and boiling vessel was a half inch copper tube.

4.1.4 Power Supply

The test sections were heated electrically, with the power delivered to the test tube through a powerstat (a variable transformer of 13.4 KVA rating from Super Electric Co.) and a step down transformer (dry type 15 KVA Marcus Co.) to obtain a high current. The powerstat was connected to a 208V-30A electrical source. Double cables (size 4/o) were used because of the high current. The power supply circuit is shown in Fig. 4.6.

4.2 Instrumentation

4.2.1 Temperature Measurement

As stated above, the thermocouples were spot welded onto the inside wall of the test tubes (the test tubes with the thermocouples installed using the "split junction" method were used only for reference). The inside surface temperature around the circumference of the test tube was measured by K type 24 gauge thermocouples. A Hewlett Packard 9835 Desktop computer, a Hewlett Packard 3495A Scanner, and a 3455A Digital Voltmeter (shown in Fig. 4.7) were employed to measure the thermal emf and to convert the emf into temperature values by using a system subprogram Temp. The maximum error of the temperature measurement by this method was less than 1% of the temperature readings. Before each experimental run, temperature readings were checked. The dif-

ference of temperature readings was less than 0.1 °C. Typical temperature readings before an experiment are shown in Fig. 4.8. The common cold junction temperature used was the room temperature which was measured by a thermistor built into the Hewlett Packard thermocouple connector.

For temperature readings, it should be noted that the temperature indicated by the thermocouples was the inside surface temperature of the test cylinder. By solving the steady state conduction equation, the outside temperature may be obtained from:

$$T_o = T_i - \frac{\bar{q}}{2bk_w} \left[\frac{1}{2} (r_o^2 - r_i^2) + r_i^2 \cdot \ln \frac{r_i}{r_o} \right] \quad (4.1)$$

The derivation of Eq. (4.1) can be found in Appendix 4.

The liquid temperature in the boiling vessel was measured by two K type thermocouples. One was located 60 mm above and 60 mm to the right of the test tube, the other 60 mm below and 60 mm to the left of the test tube. The liquid temperature, averaged by the two thermocouple readings, was approximately 46 °C for all of the experiments (the normal boiling point is 47.5 °C [56]).

4.2.2 Power Measurement

The power supply and measurement circuit is shown in Fig. 4.6. The power dissipated in the test tube was deter-

mined by measuring the voltage drop across about 50 mm length along the test tube and the current through it. The voltage drops were measured by a Hewlett Packard 3455A Digital Voltmeter through two alumel wires welded on the inside surface of the test tube. The error of the digital voltmeter was 0.47% of the readings. The electrical current through the test tube was measured by a KEITHLEY multimeter in conjunction with a current transformer (General Electric Co. JP-1) because of a high current flow through the test tube. The error of the current measurement was estimated to be about 3.5%.

4.2.3 Pressure Measurement

The atmospheric pressure was read by a mercury barometer (Fisher Scientific Ld.). The pressure difference between the inside and outside of the boiling vessel was measured by a 220BH-2A1-B-1 type pressure transducer (MKS Instrument Inc.). During the experiments, due to the water cooling condenser, the pressure difference between inside and outside of the boiling vessel was less than 1 mm Hg.

4.3 Experimental Procedure

Experiments were conducted at atmospheric pressure. Pure freon 113 was preheated to saturation temperature in

the reservoir with a 3 KW electrical immersion heater. The temperature in the reservoir was measured by a mercury thermometer and a K type thermocouple. Upon reaching the desired temperature, the freon-113 was charged to the boiling vessel by compressed air.

For a typical nucleate boiling run, the boiling vessel was filled with the saturated freon-113 up to a level of 7 cm above the test section. The power supplied to the test section was then turned on and the test liquid was boiled vigorously for a half hour to purge the noncondensable gases from the system. The flow rate of the cooling water was adjusted to keep the pressure difference between the inside and outside of the test vessel less than 1 mm Hg. Then, the power was changed to a desired level to start the test. The power was increased for each succeeding data point until a maximum heat flux of about 80 KW/M^2 was reached. After that, the power was gradually decreased to replicate data obtained during the increasing sweep. For each level of power, the system was allowed to reach steady state. All the data were then recorded.

For a typical film boiling run, the power supplied to the test section was turned on and the test section was heated up to 300 C before freon-113 was charged to the boiling vessel from the storage tank. During this process, the temperature of the test section and the power input were

continuously monitored. The working fluid at the saturation temperature was then admitted into the test vessel so that a film boiling pattern could be obtained. Other procedures were similar to those in nucleate boiling runs.

At the completion of all the tests, the liquid level was checked to see if the amount of the test fluid had changed. Because of the water-cooled condenser, the test fluid loss was negligible.

4.4 Data Reduction

The surface area was measured from dimensional measurements of the test section. The average heat flux is given by:

$$\bar{q} = IV/\pi DL \quad (4.2)$$

The local heat transfer coefficient h should be calculated from:

$$h = \frac{\frac{d^2T}{d\theta^2} + \frac{r_o^2 \bar{q}}{bK_w}}{r_o^2(T_o - T_s)/bK_w} \quad (4.3)$$

Since the magnitude of $d^2T/d\theta^2$ (10^{-3} °C) is much smaller than that of $r_o^2 \bar{q}/bK_w$ (10^2 °C), the Eq. (4.3) can be reduced to:

$$h = \bar{q}/(T_o - T_s) \quad (4.4)$$

The seven outside surface temperatures at the middle of the test section were averaged and used to obtain the average heat transfer coefficient $\bar{h}$, as given below:

$$\bar{h} = \bar{q}/(\bar{T}_o - T_s) \quad (4.5)$$

The local and average Nusselt numbers are calculated from the definition:

$$Nu = hD/K_1 \quad (4.6)$$

$$\bar{Nu} = \bar{h}D/K_1 \quad (4.7)$$

where conductivity K_1 of freon 113 was evaluated at the saturation temperature T_s for nucleate boiling, and at the film temperature $\frac{1}{2} \cdot (T_o + T_s)$ for film boiling .

The radiation correction can be obtained from:

$$q_{\text{rad}} = \epsilon \cdot \sigma \cdot [T_o^4 - T_s^4] \quad (4.8)$$

In the nucleate boiling region, the difference between T_o and T_s was less than 20 °C. Therefore, the radiation correction is negligible. In the film boiling region, although the wall temperature was much higher than the liquid temperature, but the emissivity is very small ($\epsilon = 0.074$ [57] for polished stainless steel); consequently, the radiation correction is also very small. The maximum error due to neglecting the radiation was estimated to be less than 2%, as shown in Appendix 3.

Another correction which should be mentioned here is the "end effect". In the nucleate boiling region, the temperature distribution along the axis was quite uniform, as given in Fig. 4.9 (a). The end effect, therefore, is negligible. However, in the film boiling region, the axial temperature distribution was not so uniform, as given in Fig. 4.9 (b). Because of the heat loss from the two ends, the maximum error could be as much as 13% in the film boiling region, as illustrated in Appendix 2.

CHAPTER 5 RESULTS AND DISCUSSION

The experimental results of the present studies are presented in graphical and tabulated forms. Tables 5.1 (a) to (g) and 5.2 (a) to (g) contain the original experimental data. The experimental results are described in Tables 5.1 to 5.4 as well as in Figures 5.1 to 5.21.

5.1 Nucleate Boiling Region

5.1.1 Effect of K^* On Nucleate Boiling

Because the material of the heating surface has a strong effect on nucleate boiling, only the stainless steel 304 tubes with different wall thicknesses are discussed in this section.

For stainless steel tubes, the temperature distributions are depicted as T_o versus θ in Figs. 5.1 (a) to (d) at different heat fluxes, where T_o is the corrected outside surface temperature. From these diagrams, it can be seen that there is a large variation in the surface temperature, and the variation depends strongly on the value of K^* .

The distributions of the non-dimensional temperature T_o^+ in the nucleate boiling region are plotted in Figs. 5.2 (a) to (d). The definition of T^+ is given in Eq. (3.2), and the physical meaning of T_o^+ may be interpreted as the ratio of the average heat transfer coefficient to the local heat transfer coefficient. These diagrams clearly show that the variations of both the local surface temperature and the local heat transfer coefficient are significant. For instance, a 50% difference in T_o^+ is shown in Fig. 5.2 (a) for $K^*=0.051$.

From Figs. 5.1 to 5.3, it can also be seen that the T_o and T_o^+ on the bottom portion are lower than that on the top portion. This temperature pattern agrees with Bliss' experimental results, as reported in the reference [15]. In the case of natural convection without boundary layer separation, the temperature distribution has the same pattern, as shown in Fig. 5.4. Since the thermal boundary layer thickness on the bottom portion is smaller than that on the top portion, the resistance to heat transfer between the heating surface and the fluid on the bottom portion is then smaller. Therefore, the temperature on the bottom portion is lower than that on the top portion. In the case of nucleate boiling, the thermal boundary layer concept would not be applicable. The basic processes involved in nucleate boiling are the formation of bubbles and the subsequent growth and motion of these bubbles. The presence of convection currents

induced by the stirring action of the bubbles greatly facilitates this heat transfer process. According to this mechanism, it could be assumed that the departure frequency of bubbles on the bottom portion would be higher than that on the top portion. Therefore, the stirring action on the bottom portion would be stronger than that on the top portion. In other words, the wall surface temperature on the bottom portion would be lower than that on the top portion.

From Fig. 5.5, it is shown that the temperature variation, $T_{\max} - T_{\min}$, becomes smaller with an increase of heat flux, $\bar{q}$. This may be due to the fact that the bubble population increases with heat flux, $\bar{q}$. When the heat flux is large enough, the departure frequency of bubbles is very high, and the local condition would be almost the same for both the top and bottom of the cylinder. In other words, the variation of surface temperature seems to decrease with the increase of the heat flux.

The important characteristic apparent in Fig. 5.6 and also in Figs. 5.3 (a) to (d) is that there is a critical value for parameter K^* at which the maximum temperature variation occurs for a given heat flux. For $K^* < K^*_{\text{cri}}$, the temperature variation increases with K^* . However, when $K^* > K^*_{\text{cri}}$, the temperature variation decreases with K^* .

Referring to Figs. 5.7 (a) and (b), it is clearly shown that in the nucleate boiling region, when $K^* > K^*_{\text{cri}}$, the

overall heat transfer rate increases with K^* , or with the decreasing of wall thickness for stainless steel 304. But in the region of $K^* < K^*_{\text{cri}}$, the opposite seems to be true. It may be deduced that the present results agree with Sharp's [19] prediction in the $K^* < K^*_{\text{cri}}$ region, and with Magrini's [18] and Kovalev's [16] results in the $K^*_{\text{cri}} < K^*$ region.

The existence of critical K^* should be explained from the governing equation, Eq. (3.6). It should be noted that K^* is not the only parameter which governs the temperature distribution. The boundary condition at the outside wall and the average Nusselt number also play important roles in the surface temperature distribution. But the boundary condition is influenced by the K^* value, while Nu is dependent on K^* , the boundary condition and the temperature distribution. Thus, the temperature distribution, average Nusselt number, and boundary conditions are interrelated, and the dependence of temperature distribution on K^* would not be simply monotonic. As long as the relationship between temperature distribution and K^* is not monotonic, there would be a possibility of a critical K^* value existing, at which the the heat transfer rate would be the lowest. It could be deduced that the heat transfer rate increased with K^* from Sharp's study [19], and decreased with K^* from Magrini's et al. results [18]. This fact reveals that the effect of K^* on nucleate boiling is complicated and still not well under-

stood. A possible explanation of the existence of critical K^* might be the following.

An assumption made here is that a higher heat density $\dot{q}$ within the wall would be associated with a higher density of active sites. It seems that there is some experimental evidence to support the hypothesis. Bartolini and Fantini [58] in their photographic study* found a strong increase in the bubble population with decreasing wall thickness, as shown in Fig. 5.8 (a). For a thinner wall, the heat density $\dot{q}$ in the wall is larger than that in a thicker wall for a given heat flux since $\dot{q} = \bar{q}/b$. Therefore, the experimental phenomena could be interpreted as the assumption made above.

If conditions other than the heater wall thickness are set equal (the present study was near this condition), the effect of K^* on nucleate boiling is equivalent to that of wall thickness on nucleate boiling. Because the heat density $\dot{q}$ in a thinner wall is larger than that in a thicker wall for a given heat flux, according to the above assumption, a thinner wall would be associated with a larger bubble population. A higher bubble population may produce a strong stirring current near the wall, and therefore, a lower surface temperature results at the same heat flux. A lower value of wall thickness makes a higher value of K^* , therefore the heat transfer rate increases with K^* in the range of $K^* > K^*_{\text{cri}}$.

On the other hand, however, when the wall thickness is very large, the transverse heat flux directed to the base of the bubble by the surrounding area would be large because of low thermal resistance to the transverse flux, as shown in Fig. 5.8 (b). In this case, the bubble extracts heat from not only the wall beneath the bubble base but also from the surrounding area of the bubble. Consequently, the bubble on the thicker wall could extract more heat than that on the thinner wall. Therefore, the total heat transfer rate would be higher. A larger wall thickness produces a lower value of K^* . Hence, the heat transfer rate increases with the decreasing of K^* , or, the heat transfer rate decreases with K^* , in the ranges of $K^* < K^*_{\text{cri}}$.

From the above discussions, it could be easy to explain the existence of K^*_{cri} . If the wall thickness happens to be the value at which both the effects mentioned above are not strong, then the lowest heat transfer rate would result. This critical wall thickness should correspond to the critical K^* .

From the temperature distribution, the local heat transfer coefficient is calculated, as plotted in Figs. 5.9 (a) to (d). It is clear that the heat transfer rate is more efficient in the bottom portion than in the top portion. This is because the temperature on the bottom portion is lower than that on the top portion, as discussed previously.

Figs. 5.10 (a) to (d) show the effect of K^* on the local heat transfer coefficient.

Some typical experimental boiling curves are shown in Figs. 5.11 (a) to (e) in the nucleate boiling region. As can be seen in the figures, the reproducibility of the test results is excellent. Least square regression analysis was employed to correlate the experimental data, as given in Fig. 5.12 (a).

The present results are partly contrary to that which may be seen in forced convection heat transfer from a horizontal cylindrical heater in a single phase fluid flow case. [1]. This may be because the heat transfer process involved would not be the same since there is a boundary layer separation in the forced convection cross flow case, and since the ranges of K^* covered in ref. [1] were not as wide as the present study. It is, therefore, unknown whether there is a critical value of K^* for the single phase fluid cross flow case.

The correlations of Stephan [33], Borishanskiy [28], McNeilly [25], Levy [31], and Yilmaz [27], are plotted in Fig. 5.12 (b) and given in table 5.5. These correlations differ widely. The Stephan's correlation seems to fit the present results best. None of the correlations recognizes the effect of the peripheral conduction.

To demonstrate the effect of K^* on the nucleate boiling region, the results in the nucleate boiling were normalized using Stephan's correlation as the reference in Fig. 5.13. The added asymmetry of the thermal boundary condition, due to the value of K^* , affects the average heat transfer rate up to a maximum of about 100% for the ranges of K^* and the heat flux studied in the nucleate boiling region, as shown in Fig. 5.13.

5.1.2 Effect of Material On Nucleate Boiling

There is strong evidence that the material of the heating surface affects nucleate boiling heat transfer greatly. Many correlations of nucleate boiling heat transfer data contain constants which must be determined experimentally for the particular surface-fluid combination under consideration. The present results also show that the materials influence the nucleate boiling heat transfer significantly. As shown in Fig. 5.14, there is a large difference between the heat transfer rate of the test heater made of s. s. 304 and that of inconel 600, even though the values of K^* are about the same.

Berenson [14] found that the heat transfer rate increased with wall conductivity K_w from his experimental data. Magrini et al. [18], Sharp [19], and Kong [20] showed that the heat transfer coefficient increased with the param-

eter $K_w/\sqrt{a}$, or $\sqrt{K_w \rho C}$ was the characteristic parameter of the heater material. Grigriev et al. [17] observed an increase in the heat transfer coefficient with an increase in the thermal diffusivity of the heater material for a cryogenic liquid. But present results do not follow the above rules. The result of Bliss [15] also seems not to follow any of the above rules. Even the results of Bliss were contrary to Magrini's results to a certain extent (their experimental methods were about the same). Magrini et al. found that the heat transfer coefficient of zinc coating was higher than that of tin coating, while Bliss found the opposite result. All these results show that the mechanism of the material effect on nucleate boiling is still not well understood.

The effect of material should be explained from the bubble formation and growth, in terms of contact angles, or the dispersion energy of vapors from a given solid surface [59]. Fowkes [60] measured the dispersion energies between heptane and copper, silver, and tin. He found that the dispersion energy of copper was the smallest, that of silver next, and that of tin the largest. Probably, this information might explain why the heat transfer coefficient of a copper coating is higher than that of a silver coating, as demonstrated by Magrini et al. [18], although the conductivity of silver is higher than that of copper. Since the dispersion energy was not measured in the present study, it

might be deduced that the dispersion energy between stainless steel 304 and freon 113 might be smaller than that between inconel 600 or monel 400 and freon 113, for other factors being equal.

5.2 Film Boiling

The non-dimensional temperature T_0^+ is plotted in Figs. 5.15 (a) to (d). Compared with nucleate boiling, the experimental results in film boiling region have the following features:

(1) The relative temperature variation is very small compared with the nucleate boiling region, as shown in Figs. 5.15 (a) to (d). Because of this feature, one may conclude that the effect of parameter K^* in the film boiling region would be very small, or even negligible. From a physical point of view, this phenomena could be explained in terms of the Biot number. In the film boiling region, the heat transfer coefficient h is on the order of 10^2 , therefore, the Biot number is on the order of 10^{-1} ($Bi = hD/K = 10^{-3} \cdot h$ for the present experimental condition). Since the Biot number is small, the thermal resistance within the heater is relatively small; consequently the temperature variation within the heater is small.

(2) The local heat transfer coefficient h varies little with angle, as shown in Figs. 5.16 (a) to (d). This is mainly due to the fact that the relative temperature variation is very small.

Figs. 5.17 (a) to (e) show that a satisfactory reproducibility of the experimental data in the film boiling region was obtained. The regressive lines of the experimental data are plotted in Fig. 5.18. The correlations of Sakurai et al. [37], Breen and Westwater [9], Bromley [22] and Berenson [38] are plotted in Fig. 5.19, and also given in table 5.6.

In Fig. 5.20, the results were normalized using Sakurai's correlation as the reference in the film boiling region, because the empirical correlation proposed by Sakurai et al. seems to correlate the present results best. It can be seen from this figure that the difference is less than 10%, which is within the experimental error, as discussed in Appendix 2.

Because of the strong end effect in the film boiling region (see Appendix 2), it was difficult to reach steady state except at very high heat flux. Therefore, a relatively large error was involved in the film boiling region compared with that in nucleate boiling region.

From Fig. 5.21, it can be seen that the effect of the material on film boiling is very small. This finding is

consistent with other experimental results [22-24], and of course, differs markedly from the case of nucleate boiling. Since the hot surface is covered completely with vapour during film boiling, and nucleation occurs at the vapour-liquid interface, the type of heating material should be of little importance. Westwater [24] pointed out that there are two conditions in which the surface could play an important role in film boiling. These are a very rough surface or very high temperature. This was not the case for the present experiment.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

From present study, it may be concluded that:

1. The peripheral wall conduction, or parameter K^* , very definitely has an effect on the heat transfer coefficient during nucleate boiling of freon 113 from horizontal tubes. This effect can increase or decrease the heat transfer rate depending on the range of K^* .

2. There is a critical value of K^* in the nucleate boiling region. For stainless steel 304 with freon 113, $K^* = 0.051$. When $K^* < K^*_{\text{cri}}$, the heat transfer coefficient decreases with K^* , while in the range of $K^* > K^*_{\text{cri}}$, the opposite seems to be true.

3. The added asymmetry of the thermal boundary conditions, due to the value of the parameter K^* , affects the average heat transfer rate up to a maximum of 100% for the ranges of K^* and heat flux studied in the nucleate boiling region.

4. The heater material influences the heat transfer coefficient significantly in nucleate boiling, and it is still not clear what parameter should be used to characterize a material.

5. However, in the film boiling region, the effects of both peripheral conduction and material are very small.

The results of this work suggest other avenues of investigations.

First of all, although some work has been done on the effect of heater diameters, the diameter range covered was very small and the results do not quantitatively correlate the diameter effect. The effect of diameter would appear in two aspects: changing the parameter K^* and the flow condition. An investigation of this type seems needed.

Another fertile field for investigation is in the determination of contact angles between the bubbles and the surface on which they form since the data on contact angles is presently scarce and spotty.

It is obvious that an analytical solution or numerical solution to the problem would be desirable. To do that, some reasonable assumption should be proposed, since the nature of nucleate boiling has not been well understood.

Appendix 1: Estimation Of Experimental Errors

The experimental uncertainty can be estimated by using the standard method of uncertainty analysis [61], which finds the total uncertainty by taking the square root of the sum of the squares of the individual uncertainties affecting the result. In mathematic form, this method is as follows:

Let the result Y be a function of M independent variables, $X_1, X_2, \dots, X_m$,

$$Y = Y(X_1, X_2, \dots, X_m) \quad (A1-1)$$

Then the uncertainty of the result Y is given by :

$$\Delta Y = \left[\left(\frac{\partial Y}{\partial X_1} \Delta X_1 \right)^2 + \left(\frac{\partial Y}{\partial X_2} \Delta X_2 \right)^2 + \dots + \left(\frac{\partial Y}{\partial X_m} \Delta X_m \right)^2 \right]^{\frac{1}{2}} \quad (A1-2)$$

Where ΔY is the uncertainty in the result, $\Delta X_1, \Delta X_2, \dots, \Delta X_m$ are the uncertainty in the independent variables. If Y is of the form of $Y = A \cdot X_1^{N_1} \cdot X_2^{N_2} \dots X_m^{N_m}$, where A is a constant, and $N_1, N_2, \dots$ and N_m are either 1 or -1, then the uncertainty of Y can be expressed as:

$$\frac{\Delta Y}{Y} = \left[\left(\frac{\Delta X_1}{X_1} \right)^2 + \left(\frac{\Delta X_2}{X_2} \right)^2 + \dots + \left(\frac{\Delta X_m}{X_m} \right)^2 \right]^{\frac{1}{2}} \quad (A1-3)$$

The uncertainties in heat transfer $\bar{h}$ and Nusselt number Nu are evaluated by using Eq. (A1-3).

(1) the uncertainty of heat transfer coefficient $\bar{h}$:

$$\bar{h} = \bar{q}/\Delta T = IV/\pi D L \Delta T \quad (A1-4)$$

The estimated uncertainties in each term are:

$$\frac{\Delta V}{V} = 0.47 \% \quad , \quad \frac{\Delta I}{I} = 3.5 \% \quad , \quad \frac{\Delta D}{D} = 0.5 \%$$

$$\frac{\Delta L}{L} = 0.5 \% \quad , \quad \frac{(\Delta T)}{\Delta T} = 1 \%$$

Then:

$$\frac{\Delta \bar{h}}{\bar{h}} = [(0.47\%)^2 + (3.5\%)^2 + (0.5\%)^2 + (0.5\%)^2 + (1\%)^2]^{\frac{1}{2}} = 3.74\%$$

(2) the uncertainty of Nusselt number Nu:

$$\bar{Nu} = \bar{h}D/K_1$$

$$\frac{\Delta \bar{Nu}}{\bar{Nu}} = [(3.74\%)^2 + (0.5\%)^2]^{\frac{1}{2}} = 3.77\%$$

It should be pointed out that above estimations do not include the end effect and the radiation effect. The estimation of the error due to end effect can be found in Appendix 2, and that of the error due to neglecting radiation can be found in Appendix 3.

Appendix 2: Estimation Of The End Effects

The end effect in the test heaters can be produced by heat being conducted away by the bus bars since the internal heat generation in them is negligible. Because of the end effect, the unsteady state effect is also brought about in the film boiling region.

From Fig. 4.9 (a), it is clear that the axial temperature distribution is quite uniform in the nucleate boiling region, so that the end effect would be negligible in this region. However, in the film boiling region the axial temperature distribution is not uniform, as can be seen from Fig. 4.9 (b). By a graphical method, the temperature gradient can be obtained from:

$$dT/dx = \delta T / \delta x \quad (\text{referring to Fig. 4.9 (b)})$$

Thus, the heat conducted away from the ends could be estimated by:

$$Q = \pi D b K_w dT/dx \quad (A2-1)$$

The maximum error due to the end effect would belong to the test tube which has the largest wall thickness for a given material. For s. s. 304, it is found that the maximum

error due to the end effect is up to 13% for test tube 1 which had the greatest wall thickness.

Appendix 3: Estimation Of Radiation Effect

The heat loss due to radiation may be calculated by:

$$q_{\text{rad}} = \epsilon \cdot \sigma_0 \cdot [T_o^4 - T_s^4] \quad (\text{A3-1})$$

where ϵ is the emissivity of the heater material, for stainless steel $\epsilon = 0.074$ [57].

In the nucleate boiling region, the maximum wall temperature was about 65 °C. The maximum heat loss due to radiation would then be:

$$q_{\text{rad}} = 0.074 \times 5.67 \times 10^{-8} \times [(65+273)^4 - (46+273)^4] = 10 \text{ W/M}^2$$

Since the total heat flux $\bar{q}$ was larger than 10^4 W/M^2 , then:

$$q_{\text{rad}} / \bar{q} = 0.1\% \text{ , Which is very negligible.}$$

In the film boiling region, the maximum wall temperature was about 400 °C. Therefore,

$$q_{\text{rad}} = 0.074 \times 5.67 \times 10^{-8} \times [(400+273)^4 - (46+273)^4] = 816 \text{ W/M}^2$$

When wall temperature was about 400 °C, the total heat flux was about $5 \times 10^4 \text{ W/M}^2$. Then:

$$q_{\text{rad}} / \bar{q} = 1.6\% \text{ , which is also relatively small.}$$

Therefore, it may be stated that the error due to neglecting radiation is negligibly small in both the nucleate and film boiling regions.

APPENDIX 4: Derivation of Outside Surface Temperature

(Eq. (4.1))

Considering a general case, a two dimensional conduction equation can be written as:

$$r \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial \theta^2} + \frac{r^2 \dot{q}}{K_w} = 0 \quad (\text{A4-1})$$

Experimental results show that, $d^2T/d\theta^2$ is on the order of 10^{-3} , while $r \frac{\partial}{\partial r} (r \frac{\partial T}{\partial r})$ on the order of 10^2 , thus:

$$r \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \gg \frac{\partial^2 T}{\partial \theta^2} \quad (\text{A4-2})$$

This means that the net heat flow in a radial direction is much higher than that in a circumferential direction. Therefore, Eq. (A4-1) can be further reduced to:

$$\frac{d^2 T}{dr^2} + \frac{1}{r} \frac{dT}{dr} + \frac{\dot{q}}{K_w} = 0 \quad (\text{A4-3})$$

Eq. (A4-3) is a typical Euler equation.

Let $r=e^y$, $y=\ln r$

$$\frac{dT}{dr} = \frac{dT}{dy} \frac{dy}{dr} = \frac{1}{r} \frac{dT}{dy} \quad (\text{A4-4})$$

$$\frac{d^2 T}{dr^2} = \frac{d}{dy} \left(\frac{1}{r} \frac{dT}{dy} \right) \cdot \frac{dy}{dr} = \frac{1}{r^2} \frac{d^2 T}{dy^2} - \frac{1}{r^2} \frac{dT}{dy} \quad (\text{A4-5})$$

Substituting Eqs. (A4-4) and (A4-5) into Eq. (A4-3),

$$\frac{1}{r^2} \frac{dT}{dy^2} + \frac{\dot{q}}{K_w} = 0$$

$$\frac{d^2T}{dy^2} + \frac{\dot{q}}{K_w} e^{2y} = 0 \quad (A4-6)$$

The general solution of Eq. (A4-6) is :

$$T = B_0 + B_1 \cdot y - \frac{\dot{q}}{4K_w} e^{2y} \quad (A4-7)$$

If assuming boundary condition at the inner wall is :

$$\left. \frac{dT}{dr} \right|_{r_1} = 0 \text{ then :}$$

$$B_1 = \frac{\dot{q}}{2K_w} r_1^2$$

$$T_o = T_1 - \frac{\dot{q}}{2K_w} \left[\frac{1}{2} \cdot (r_o^2 - r_i^2) + r_i^2 \cdot \ln \frac{r_1}{r_o} \right]$$

$$T_o = T_1 - \frac{\bar{q}}{2bK_w} \left[r_i^2 \cdot \ln \frac{r_1}{r_o} + \frac{1}{2} (r_o^2 - r_i^2) \right]$$

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Table 4.1 Characteristics Of Test Tubes

NO.	Material	O.D. (mm)	Thickness (mm)	Conductivity K_w^+ W/(M-°C)	K^{*++}
1	S. S. 304	23.55	2.87	13.98	0.0206
2	S. S. 304	25.15	1.65	13.98	0.0383
3	S. S. 304	25.40	1.24	13.98	0.0513
4	S. S. 304	24.33	1.02	13.98	0.0602
5	S. S. 304	23.52	0.81	13.98	0.0746
6	Monel 400	26.04	2.92	21.80	0.0143
7	Inconel 600	26.67	2.29	14.85	0.0275

+ Taken from Mark's Standard Handbook For Mechanical Engineers, Eight Edition, 1978.

++ The conductivity of freon 113 was 0.0702 W/M-C which was taken from ASHRAE HANDBOOK & Product Directory, 1977 Fundamentals.

Table 5.1 (a) Experimental Data In Nucleate Boiling

Test Tube #1, Material S. S. 304, $K^*=0.0206$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	60111	61.7	61.9	62.3	61.6	61.7	61.8	61.9	61.8	14.3	4203	1408
2	50526	60.6	60.6	61.1	60.6	60.8	61	61.3	60.8	13.3	3798	1272
3	43712	60.2	60.1	60.7	60.1	60.5	60.9	61.4	60.5	13	3362	1126
4	36763	59.7	59.6	60.1	59.6	60.3	61	61.5	60.2	12.7	2894	969
5	30421	59	59.1	59.3	59	59.8	60.5	61.1	59.6	12.1	2514	842
6	26681	59.3	59.8	59.9	59.6	60.4	61.2	61.9	60.3	12.8	2084	698
7	22975	58.1	58.5	58.6	58.4	59.3	60.2	60.7	59.1	11.6	1980	663
8	18621	57.6	58	58.1	57.5	58.6	59.7	60.1	58.5	11	1692	567
9	15144	56.9	57.4	57.7	57.1	58.2	59.3	59.5	58	10.5	1442	483
10	12446	56.5	56.7	56.6	56.1	57.4	58.6	58.8	57.2	9.7	1283	430
11	12299	56.2	56.7	56.5	56.1	57.4	58.7	59.1	57.2	9.7	1267	424
12	15389	56.6	57.4	57.3	56.7	57.9	59.2	59.5	57.8	10.3	1494	500
13	18812	57.3	57.8	57.9	57.5	58.6	59.7	60.2	58.4	10.9	1725	578
14	22143	57.6	58.1	58.2	57.9	58.9	59.9	60.4	58.7	11.2	1977	662
15	25924	58	58.5	58.6	58.4	59.2	60.1	60.7	59	11.5	2254	755
16	29424	58.5	58.8	59	58.7	59.5	60.3	61	59.4	11.9	2472	828

Table 5.1 (a) Experimental Data In Nucleate Boiling

Test Tube #1. Material S.S.304. $K^*=0.0206$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	33228	59.6	59.9	60.1	59.8	60.5	61.2	61.9	60.4	12.9	2575	863
18	39296	60.3	60.6	61	60.6	61.1	61.6	62.2	61	13.5	2910	975
19	46303	60	60.4	60.7	60.2	60.5	60.9	61.3	60.5	13	3561	1193
20	54142	60.3	60.9	61.1	60.6	60.7	60.8	61.1	60.7	13.2	4101	1374
21	64040	60.8	61.3	61.6	60.9	61	61.1	61	61.1	13.6	4708	1577
22	64464	61.5	62	62	61.3	61.9	62.5	62.5	61.9	14.4	4476	1500
23	53571	60.7	61.2	61.4	60.8	61.4	62.1	62.4	61.4	13.9	3854	1291
24	46935	61.1	61.6	61.7	61.3	62	62.8	63.3	61.9	14.4	3259	1092
25	41956	59.8	60.4	60.5	60.2	61	61.9	62.6	60.9	13.4	3131	1049
26	37474	59.2	59.9	60.1	59.8	60.8	61.7	62.4	60.5	13	2882	965
27	32385	58.8	59.3	59.6	59.5	60.6	61.8	62.4	60.2	12.7	2550	854
28	27532	58.1	58.9	59.1	58.9	60.1	61.3	62.1	59.7	12.2	2256	756
29	22542	57.7	58.2	58.3	58.3	59.6	60.8	61.5	59.2	11.7	1926	645
30	18840	57.4	57.9	58	58	59.2	60.4	61.2	58.8	11.3	1667	558
31	14606	57.7	58.3	58.3	58.2	59.5	60.9	61.6	59.2	11.7	1248	418
32	11991	57.3	57.5	57.8	57.7	59	60.2	61	58.6	11.1	1080	361

Table 5.1 (a) Experimental Data In Nucleate Boiling

Test Tube #1, Material S.S. 304, $K^*=0.0206$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
33	70711	62.2	62.7	63	62.2	62.7	63.3	63.1	62.7	15.2	4652	1559
34	64416	60.9	61.6	61.7	60.9	61.5	62	62	61.5	14	4601	1542
35	53772	60.4	60.8	61.2	60.6	61.2	61.9	62.2	61.1	13.6	3953	1324
36	45818	59.9	60.5	60.6	60.3	61	61.8	62.4	60.9	13.4	3419	1145
37	38824	59	59.6	59.8	59.6	60.5	61.4	62.1	60.2	12.7	3057	1024
38	32189	58.4	59	59.2	59	60.1	61.2	62	59.8	12.3	2616	876
39	27040	57.8	58.3	58.6	58.6	59.8	61	61.7	59.4	11.9	2272	761
40	21920	57	57.7	57.8	57.9	59	60.2	60.7	58.6	11.1	1974	661
41	17281	56.8	57.5	57.5	57.3	58.6	60	60.6	58.3	10.8	1600	536
42	13050	56.3	56.5	56.5	56.6	58	59.4	59.8	57.5	10	1305	437
43	63886	60.6	60.7	60.7	60	61	62	61.9	60.9	13.4	4767	1597
44	54861	60.2	60.4	60.3	59.7	60.7	61.8	61.9	60.7	13.2	4156	1392
45	48498	59.7	59.7	59.8	59.4	60.5	61.6	61.9	60.3	12.8	3788	1269
46	41222	59.1	59.2	59.3	59	60.1	61.3	61.9	59.9	12.4	3324	1114
47	34838	58.5	58.7	58.8	58.6	59.8	61.1	61.8	59.6	12.1	2879	964
48	28972	58.9	59.1	59.1	59	60.4	61.8	62.5	60.1	12.6	2299	770

Table 5.1 (a) Experimental Data In Nucleate Boiling

Test Tube #1, Material S.S.304, $K^*=0.0206$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
49	23356	57.8	57.6	57.7	57.6	59.1	60.6	61.3	58.8	11.3	2066	692
50	18309	57.4	57.4	57.2	57.2	58.7	60.2	61	58.4	10.9	1679	562
51	14073	56.9	57	56.9	56.9	58.4	59.8	60.4	58	10.5	1340	449

Note:

1. Run 1: NO.1 to NO.21, $T_1=45.9$ (°C), $P_{atm}=764$ mm Hg, performed on Feb. 17, 1985.
2. Run 2: NO.22 to NO.32, $T_1=46.0$ (°C), $P_{atm}=762$ mm Hg, performed on Feb. 18, 1985.
3. Run 3: NO.33 to NO.51, $T_1=45.5$ (°C), $P_{atm}=757$ mm Hg, performed on Feb. 26, 1985.

Table 5.1 (b) Experimental Data In Nucleate Boiling

Test Tube #2, Material S.S. 304, $K^*=0.0383$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	24844	59.2	59.6	60.2	60.4	60.4	61.7	62.7	60.6	13.1	1896	678
2	19888	57.7	58.1	59	59.1	59.2	60.7	61.8	59.3	11.8	1685	603
3	15911	57.4	57.8	58.2	58.5	59	60.6	61.9	59	11.5	1383	495
4	12880	56.4	56.8	57.4	58.1	58.4	60	61.3	58.3	10.8	1192	426
5	9044	55.9	56.5	56.8	57.4	57.5	58.9	59.9	57.5	10	904	323
6	28510	58.8	59.1	59.8	60.1	59.9	61.2	62.3	60.1	12.6	2262	809
7	33384	59.9	60	60.6	60.8	60.5	61.6	62.6	60.8	13.3	2510	898
8	39038	60.5	60.7	61.2	61.3	60.9	61.9	62.8	61.3	13.8	2828	1012
9	44234	61.2	61.5	61.9	62	61.3	62.2	63	61.8	14.3	3093	1107
10	64250	62.7	62.7	63.2	63.4	63.4	62.8	63.4	63	15.5	4145	1483
11	12215	54.7	54.7	55.8	57.5	59	61.2	62.7	57.9	10.4	1174	420
12	21191	57	56.9	58.4	60.1	60.5	61.3	62.7	59.5	12	1765	631
13	33158	59.5	59.2	60.3	60.4	60.9	61.8	62.9	60.7	13.2	2511	898
14	45837	61.9	61	61.5	61	61.4	62.2	63.1	61.7	14.2	3227	1155
15	65572	64.5	62.7	62.6	61.9	62.2	62.7	63.5	62.8	15.3	4285	1533
16	82577	65.8	63.5	63.2	62.4	62.7	63.3	64.2	63.5	16	5161	1847

Table 5.1 (b) Experimental Data In Nucleate Boiling

Test Tube #2, Material S.S. 304, $K^*=0.0383$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	15919	56	55.6	57.1	59	60	61.5	62.1	58.7	11.2	1421	508
18	20002	57.2	56.8	58.6	60.4	61	61.9	62.5	59.7	12.2	1639	586
19	25285	59.1	58.6	60.2	61.4	62	63.1	63.6	61.1	13.6	1859	665
20	30544	59.4	58.9	60.4	61.3	61.5	62.4	62.8	60.9	13.4	2279	815
21	38195	60.9	60.1	61.2	61.7	62	62.6	63	61.6	14.1	2708	969
22	46214	62.4	61.4	62.1	62.1	62.5	63.1	63.2	62.4	14.9	3101	1110
23	57890	64.1	62.7	63.2	62.6	63.1	63.6	63.5	63.2	15.7	3687	1319
24	64831	64.8	63.3	63.7	63	63.4	63.9	63.9	63.7	16.2	4001	1432
25	74236	65.6	63.9	64.2	63.4	63.9	64.5	64.4	64.2	16.7	4445	1591

Note:

1. Run 1: NO. 1 to NO. 10, $T_1=46.1$ (°C), $P_{atm}=765$ mm Hg, performed on Nov. 26, 1984.
2. Run 2: NO. 11 to NO. 16, $T_1=45.3$ (°C), $P_{atm}=757$ mm Hg, performed on Nov. 28, 1984.
3. Run 3: NO. 17 to NO. 25, $T_1=45.5$ (°C), $P_{atm}=758$ mm Hg, performed on Nov. 29, 1984.

Table 5.1 (c) Experimental Data In Nucleate Boiling

Test Tube #3, Material S.S. 304, $K^*=0.0513$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	89380	63.9	63.9	63.8	63.9	68.4	67.2	67.5	65.5	18	4965	1795
2	77535	62.5	62.5	62.5	62.5	66.6	65.2	65.8	63.9	16.4	4727	1709
3	64212	61.5	61.6	61.7	61.7	65.4	64.1	64.9	62.9	15.4	4169	1507
4	51665	61.6	61.7	61.8	62	65.4	64.4	65.7	63.2	15.7	3290	1189
5	45944	60.3	60.4	60.6	60.9	64.1	63.4	64.9	62	14.5	3168	1145
6	38053	59.4	59.6	59.7	60.2	63	62.9	64.6	61.3	13.8	2757	996
7	35805	58.9	59.2	59.4	60.1	62.9	63	64.5	61.1	13.6	2632	951
8	29909	58.2	58.5	58.8	59.3	61.9	62.8	64.1	60.5	13	2300	831
9	17603	57.3	57.8	58.4	59	61.2	62.9	63.6	60	12.5	1408	509
10	71356	63.6	63.9	64.3	63.5	65.9	66.1	67	64.9	17.4	4100	1482
11	60623	62.5	62.8	63.1	62.5	64.8	65	65.8	63.7	16.2	3742	1352
12	51758	61.7	62.1	62.5	61.8	64.4	64.5	65.6	63.2	15.7	3296	1191
13	45724	61.3	61.7	62	61.3	63.8	64.2	65.4	62.8	15.3	2988	1080
14	40001	61	61.3	61.6	61	63.5	64	65.5	62.5	15	2666	963
15	34422	59.8	60.3	60.9	60.3	62.8	63.6	65	61.8	14.3	2407	870
16	30420	59.7	60.3	60.9	60.6	62.9	64	65.5	61.9	14.4	2112	763

Table 5.1 (c) Experimental Data In Nucleate Boiling

Test Tube #3, Material S.S. 304, $K^*=0.0513$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	25633	58.3	58.9	59.4	59.1	61.4	62.9	64.2	60.6	13.1	1956	707
18	21564	57.8	58.2	58.7	58.4	60.8	62.6	63.9	60	12.5	1725	623
19	18109	57.1	57.5	58	57.9	60.6	62.4	63.6	59.5	12	1509	545
20	14076	56.1	56.5	57	57.5	60.1	61.9	62.8	58.8	11.3	1245	450
21	83860	63.4	63.4	63.4	63.1	67.2	65.9	66.3	64.6	17.1	4904	1773
22	70609	62.7	62.7	62.6	62.2	66	64.7	65.5	63.7	16.2	4358	1575
23	57516	61.8	61.9	62	61.5	65	64	65.1	63	15.5	3710	1341
24	51404	61.2	61.5	61.8	61.2	64.6	63.8	64.9	62.7	15.2	3381	1222
25	45557	60.9	61.1	61.3	60.8	64	63.5	65	62.3	14.8	3078	1112
26	40775	60.4	60.7	60.9	60.5	63.5	63.4	65	62	14.5	2812	1016
27	35004	59.6	59.9	60.3	60	62.6	63.1	64.6	61.4	13.9	2518	910
28	29906	59.1	59.5	59.8	59.8	62.1	62.9	64.4	61	13.5	2215	800
29	25288	58.3	58.8	59.4	59.5	61.5	62.6	63.8	60.5	13	1945	703
30	21505	57.5	58	58.6	58.9	61	62.6	63.3	59.9	12.4	1734	626

Note:

- Run 1: NO. 1 to NO. 9, $T_1=45.5$ (°C), $P_{atm}=753$ mm Hg, performed on Feb. 15, 1985.
- Run 2: NO. 10 to NO. 20, $T_1=45.8$ (°C), $P_{atm}=755$ mm Hg, performed on Feb. 15, 1985.
- Run 3: NO. 21 to NO. 30, $T_1=45.4$ (°C), $P_{atm}=754$ mm Hg, performed on Feb. 16, 1985.

Table 5.1 (d) Experimental Data In Nucleate Boiling

Test Tube #4, Material S. S. 304, $K^*=0.0602$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	18457	57.6	58.2	58.2	58.7	57.5	59.9	60.6	58.6	11.1	1662	575
2	25980	58.4	59	58.9	59.3	58.5	60.2	61.1	59.3	11.8	2201	762
3	32580	59.3	59.6	59.6	59.9	59.4	60.7	61.4	59.9	12.4	2627	909
4	41350	60.2	60.8	60.5	60.8	60.5	61.3	61.8	60.8	13.3	3109	1076
5	51634	60.8	61.7	61	61.2	61.5	62	62.1	61.4	13.9	3714	1286
6	63071	61.6	62.6	62	62.3	62.4	62.7	62.7	62.3	14.8	4261	1475
7	76195	62.4	63.5	62.8	63.1	63.5	63.7	63.5	63.2	15.7	4853	1680
8	92150	63	64.4	63.6	64.1	64.4	64.5	64.3	64	16.5	5584	1934
9	18790	57.4	58.4	58	58.5	57.5	59.8	60.8	58.6	11.1	1692	586
10	25979	58.2	58.9	58.7	59.2	58.6	60.2	61.3	59.3	11.8	2201	762
11	34640	59.5	60.1	59.9	60.3	59.9	60.9	61.7	60.3	12.8	2706	937
12	41753	60.1	60.6	60.4	60.7	60.6	61.1	61.8	60.7	13.2	3163	1095
13	54394	60.8	61.6	61.1	61.3	61.5	61.8	62	61.4	13.9	3913	1355
14	66922	61.6	62.6	61.9	62.2	62.4	62.6	62.5	62.2	14.7	4552	1576
15	80281	62.3	63.4	62.7	63.1	63.5	63.5	63.3	63.1	15.6	5146	1782
16	92171	62.8	64.1	63.2	63.7	64.2	64.4	63.9	63.7	16.2	5689	1970

Table 5.1 (d) Experimental Data In Nucleate Boiling

Test Tube #4, Material S.S. 304, $K^*=0.0602$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	75264	62.1	63.2	62.5	62.9	63.2	63.3	63.1	62.9	15.4	4887	1692
18	61856	61.3	62.2	61.7	62.1	62.1	62.3	62.4	62	14.5	4265	1477
19	50255	60.6	61.4	61	61.4	61.1	61.5	62.1	61.3	13.8	3641	1261
20	40753	59.8	60.5	60.2	60.6	60.2	60.9	61.8	60.5	13	3134	1085
21	31035	58.8	59.6	59.3	59.9	59.3	60.6	61.5	59.8	12.3	2523	873
22	19380	57.8	58.7	58.8	59.9	58.5	60.6	61.4	59.3	11.8	1642	568
23	26695	58.7	59.4	59.3	59.9	59.1	60.8	61.8	59.8	12.3	2170	751
24	31833	58.8	59.2	59.2	59.7	59.2	60.4	61.3	59.6	12.1	2630	910
25	42880	59.8	60.5	60.1	60.4	60.2	60.8	61.4	60.4	12.9	3324	1151
26	54256	60.7	61.5	61	61.3	61.3	61.6	61.9	61.3	13.8	3931	1361
27	65513	61.3	62.3	61.6	61.8	62.1	62.3	62.3	61.9	14.4	4549	1575
28	76010	61.9	62.9	62.3	62.7	63	63.1	62.9	62.6	15.1	5033	1743
29	90932	62.5	63.8	63	63.5	64.1	64.3	63.7	63.5	16	5683	1968
30	72885	61.7	62.7	62.1	62.5	62.7	62.8	62.7	62.4	14.9	4891	1694
31	59645	61	61.9	61.3	61.6	61.7	62.1	62.1	61.6	14.1	4230	1465
32	50373	60.3	61	60.6	60.9	60.8	61.3	61.6	60.9	13.4	3759	1302

Table 5.1 (d) Experimental Data In Nucleate Boiling

Test Tube #4, Material S.S. 304, $K^*=0.0602$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
33	40409	59.9	60.4	60.2	60.5	60	60.9	61.5	60.4	12.9	3132	1084
34	31901	58.9	59.5	59.4	59.8	59.2	60.4	61.2	59.7	12.2	2614	905

Note:

1. Run 1: NO. 1 to NO. 8, $T_1=45.6$ (°C), $P_{atm}=758$ mm Hg, performed on Apr. 22, 1985.
2. Run 2: NO. 9 to NO. 21, $T_1=45.3$ (°C), $P_{atm}=757$ mm Hg, performed on Apr. 30, 1985.
3. Run 3: NO. 22 to NO. 34, $T_1=45.3$ (°C), $P_{atm}=757$ mm Hg, performed on Apr. 30, 1985.

Table 5.1 (e) Experimental Data In Nucleate Boiling

Test Tube #5, Material S.S. 304, $K^*=0.0746$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	24575	58.1	58	58.1	58.7	59.4	60.2	60.8	59	11.5	2136	715
2	32556	57.8	58.3	58.3	58.7	59.2	59.8	60.6	58.9	11.4	2855	955
3	40671	58.9	59.2	59.5	59.6	59.8	59.9	60.9	59.6	12.1	3361	1125
4	49429	59.7	59.8	60	60	59.9	59.8	60.8	60	12.5	3954	1323
5	58372	60.7	60.9	60.9	60.8	60.6	60.5	61.3	60.8	13.3	4388	1469
6	68005	60.9	61.3	61.3	61.1	60.9	60.5	61.4	61	13.5	5037	1686
7	79036	61.7	62.1	62.2	61.7	61.3	61.1	61.9	61.7	14.2	5565	1863
8	68200	60.9	61.6	61.5	61.2	60.9	60.8	61.6	61.2	13.7	4978	1666
9	87454	61.9	62.4	62.5	62.1	61.7	61.4	62.1	62	14.5	6031	2019
10	76146	61.3	61.8	61.9	61.5	61.1	60.9	61.6	61.4	13.9	5478	1834
11	65512	60.6	61	61.1	60.8	60.5	60.4	61.2	60.8	13.3	4925	1648
12	54377	59.7	60	60.1	60	59.8	59.9	60.7	60	12.5	4350	1456
13	44966	60	60.4	60.6	60.5	60.4	60.9	61.7	60.6	13.1	3432	1149
14	37653	58.3	58.8	58.7	58.9	59.2	59.8	60.4	59.1	11.6	3245	1086
15	29930	58.1	58.2	57.7	58.2	58.7	59.6	60.2	58.6	11.1	2696	902
16	23901	58.5	58.5	57.7	58.4	59.2	60.3	60.6	59	11.5	2078	695

Table 5.1 (e) Experimental Data In Nucleate Boiling

Test Tube #5, Material S.S. 304, $K^*=0.0746$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	19160	57.3	57.2	56.5	57.3	58	59.3	59.3	57.8	10.3	1860	622
18	15362	56.2	56.1	55.4	56.6	57.7	59.1	59.3	57.2	9.7	1583	530
19	16897	56.8	55.6	56.3	57.2	58.2	59.4	59.6	57.5	10	1689	565
20	23398	56.8	56.8	57.6	58	58.4	59.6	59.9	58.1	10.6	2207	738
21	29452	57.6	58.1	58.3	58.7	59	60	60.5	58.8	11.3	2606	872
22	32953	58.2	58.6	58.5	58.9	59.3	60	60.5	59.1	11.6	2840	950
23	37902	59.5	60.1	60.1	60.2	60.4	61	61.7	60.4	12.9	2938	983
24	43781	59.1	59.6	59.8	59.8	59.8	60.2	60.9	59.8	12.3	3559	1191
25	49360	59.2	59.9	60.1	59.9	59.8	60	60.8	59.9	12.4	3980	1332
26	53928	59.9	60.4	60.4	60.3	60.1	60.3	61.1	60.3	12.8	4213	1410
27	59551	60.2	60.7	60.7	60.5	60.2	60.4	61.2	60.5	13	4580	1533
28	65108	60.4	61	61.1	60.8	60.6	60.6	61.4	60.8	13.3	4895	1638
29	77233	61.1	61.9	61.8	61.5	61.2	61	61.8	61.4	13.9	5556	1860
30	88378	61.7	62.5	62.6	62.2	61.8	61.6	62.2	62	14.5	6095	2040
31	78459	62.4	62.9	63	62.6	62.3	62	62.8	62.5	15	5230	1751
32	67672	60.6	61.2	61.3	61	60.7	60.6	61.3	60.9	13.4	5050	1690

Table 5.1 (e) Experimental Data In Nucleate Boiling

Test Tube #5, Material S.S. 304, $K^*=0.0746$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
33	61661	60.4	61	61.1	60.8	60.6	60.6	61.4	60.8	13.3	4636	1552
34	56774	59.9	60.6	60.7	60.4	60.2	60.5	61.2	60.5	13	4367	1462
35	52690	59.5	60.3	60.4	60.2	60	60.4	61.1	60.2	12.7	4148	1388
36	47924	59.5	60.2	60.2	60.1	60	60.5	61.1	60.2	12.7	3773	1263
37	43413	59.1	59.9	60	59.9	59.8	60.4	61.1	60	12.5	3473	1162
38	39816	59	59.5	59.7	59.7	59.7	60.4	61	59.8	12.3	3237	1083
39	35825	58.6	59.2	59.4	59.5	59.6	60.4	60.9	59.6	12.1	2960	991
40	32298	59.2	59.6	59.8	60	60.2	61	61.5	60.1	12.6	2563	858
41	28823	58.5	58.2	58.5	58.9	59.2	60.2	60.6	59.1	11.6	2484	831
42	25427	58.4	58	58.4	58.8	59.1	60.3	60.5	59	11.5	2211	740
43	21587	57.8	57.2	57.6	58.2	58.9	60	60.2	58.5	11	1962	656

Note:

1. Run 1: NO. 1 to NO. 18, $T_1=45.6$ (°C), $P_{atm}=759$ mm Hg, performed on Feb. 27, 1985.
2. Run 2: NO. 19 to NO. 30, $T_1=45.7$ (°C), $P_{atm}=764$ mm Hg, performed on Feb. 28, 1985.
3. Run 3: NO. 31 to NO. 43, $T_1=45.8$ (°C), $P_{atm}=764$ mm Hg, performed on Feb. 28, 1985.

Table 5.1 (f) Experimental Data In Nucleate Boiling

Test Tube #6. Material Monel 400. $K^*=0.0383$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	59852	66.1	66	65.9	67	66.9	67.3	67	66.6	19.1	3133	1161
2	53280	65.4	65.4	65.3	66.4	66.3	66.7	66.4	65.9	18.4	2895	1072
3	47667	65.5	65.5	65.6	66.5	66.5	66.9	66.7	66.1	18.6	2562	949
4	41116	63.9	64	64.1	65.1	65.1	65.6	65.4	64.7	17.2	2390	885
5	35869	63.9	64	64.1	65.1	65.2	65.7	65.6	64.8	17.3	2073	768
6	31038	62.3	62.4	62.5	63.5	63.8	64.5	64.5	63.3	15.8	1964	727
7	24363	61.1	60.9	60.8	61.8	62.5	63.6	63.7	62	14.5	1680	622
8	20053	60.3	59.8	59.3	60.3	61.2	62.6	63.1	60.9	13.4	1496	554
9	16619	59.8	59	58.2	59.3	60.4	62	62.5	60.1	12.6	1318	488
10	12246	59.3	58.5	57.7	58.6	59.8	61.4	61.7	59.5	12	1020	378
11	53169	65.3	65.3	65.4	65.9	65.2	65.6	65.4	65.4	17.9	2970	1100
12	47657	64.5	64.6	64.7	65.2	64.6	65	64.8	64.7	17.2	2770	1026
13	43304	63.9	64	64.1	64.6	64	64.4	64.3	64.1	16.6	2608	966
14	39512	63.4	63.6	63.8	64.3	63.8	64.1	64.1	63.8	16.3	2424	898
15	35580	62.8	63	63.2	63.8	63.3	63.7	63.8	63.3	15.8	2251	834
16	32596	62.4	62.6	62.8	63.5	63	63.5	63.6	63	15.5	2102	779

Table 5.1 (f) Experimental Data In Nucleate Boiling

Test Tube #6. Material Monel 400, $K^*=0.0383$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	27068	61.5	61.5	61.5	62.4	62.3	62.9	63.1	62.1	14.6	1853	686
18	24257	60.9	60.6	60.3	61.2	61.4	62.4	62.7	61.3	13.8	1757	651
19	20464	60.2	59.6	58.9	60.1	60.4	61.8	62.2	60.4	12.9	1586	587
20	17621	59.8	59	58.2	59.2	59.8	61.3	61.8	59.8	12.3	1432	530
21	14968	59.1	58.2	57.3	58.1	58.7	60.5	61.1	59	11.5	1301	482
22	13007	58.3	57.8	57.2	58.6	59.6	60.7	60.9	59	11.5	1131	419
23	15129	58.9	58.4	57.9	59.3	60.3	61.3	61.6	59.6	12.1	1250	463
24	18193	59.7	59.3	59	60.5	61.3	61.8	62.1	60.5	13	1399	518
25	20985	60.2	60.1	59.9	61.3	61.5	62.1	62.3	61	13.5	1554	575
26	23833	60.5	60.6	60.7	61.9	61.8	62.3	62.5	61.4	13.9	1714	635
27	27448	61.5	61.7	61.8	62.8	62.5	62.9	63.2	62.3	14.8	1854	687
28	30461	62	62.2	62.3	63.2	62.7	63.2	63.4	62.7	15.2	2004	742
29	34974	62.7	62.9	63.1	63.7	63.3	63.6	63.7	63.2	15.7	2227	825
30	39270	63.3	63.4	63.5	64.1	63.5	63.9	64	63.6	16.1	2439	903
31	43747	64.1	64.1	64.2	64.7	64.2	64.6	64.5	64.3	16.8	2603	964
32	48747	64.7	64.8	64.8	65.4	64.7	65.1	65	64.9	17.4	2801	1038

Table 5.1 (f) Experimental Data In Nucleate Boiling

Test Tube #6, Material Monel 400. $K^*=0.0383$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
33	52067	65.2	65.2	65.2	65.7	65.1	65.5	65.4	65.3	17.8	2925	1084
34	57180	65.7	65.7	65.7	66.3	65.6	66	65.8	65.8	18.3	3124	1157
35	63479	66.6	66.5	66.5	67.1	66.3	66.8	66.5	66.6	19.1	3323	1231
36	52521	65.2	65.3	65.3	66.1	65.1	65.6	65.6	65.4	17.9	2934	1087
37	47172	64.7	64.7	64.7	65.5	64.6	65.1	65.2	64.9	17.4	2711	1004
38	42923	63.4	63.4	63.3	64.1	63.3	63.9	64.1	63.6	16.1	2666	988
39	38061	63.3	63.2	63.2	63.9	63.3	64	64.3	63.6	16.1	2364	876
40	34215	61.8	61.8	61.8	62.5	62	62.7	63.1	62.2	14.7	2327	862
41	30616	61.1	61	61	61.6	61.2	62.1	62.6	61.5	14	2186	810
42	26755	60.3	60.3	60.2	60.7	60.6	61.6	62.2	60.8	13.3	2011	745
43	22984	59.8	59.5	59.3	59.8	59.9	61.1	61.6	60.1	12.6	1824	675
44	18933	59.2	58.8	58.4	58.9	59.2	60.5	61	59.4	11.9	1591	589

Note:

1. Run 1: NO.1 to NO.10, $T_1=45.9$ (°C), $P_{atm}=751$ mm Hg, performed on Jan. 15, 1985.
2. Run 2: NO.11 to NO.35, $T_1=45.6$ (°C), $P_{atm}=753$ mm Hg, performed on Jan. 15, 1985.
3. Run 3: NO.36 to NO.44, $T_1=46.2$ (°C), $P_{atm}=763$ mm Hg, performed on Jan. 16, 1985.

Table 5.1 (g) Experimental Data In Nucleate Boiling

Test Tube #7, Material Inconel 600, $K^*=0.0275$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	51125	62.6	62.5	62.2	62.9	63.4	62.8	63.1	62.7	15.2	3363	1276
2	43977	61.3	61	60.9	61.6	62.1	61.4	61.7	61.4	13.9	3163	1200
3	36514	60.1	59.9	59.8	60.4	61	60.8	61.1	60.4	12.9	2830	1074
4	31009	59.2	59	58.9	59.4	60	60.2	60.6	59.6	12.1	2562	972
5	26490	58.7	58.4	58.5	59	59.6	60	60.3	59.2	11.7	2264	859
6	23124	58.4	58.1	58.2	58.5	59.2	59.5	59.8	58.8	11.3	2046	776
7	18201	57.8	57.2	57.3	57.5	58	58.9	59.1	57.9	10.4	1750	664
8	16394	57.3	56.9	56.8	57.3	57.6	58.9	59	57.6	10.1	1623	616
9	19369	57.5	57.2	57.3	57.8	58.3	59.2	59.4	58.1	10.6	1827	693
10	23218	58.8	58.6	58.8	59.4	59.8	60.4	60.8	59.5	12	1934	734
11	26977	58.8	58.7	58.9	59.4	59.9	60.2	60.5	59.4	11.9	2266	860
12	32558	60.2	60.2	60.2	60.7	61.4	61.4	61.8	60.8	13.3	2447	928
13	37627	60.1	60.1	60	60.6	61.2	61.1	61.4	60.6	13.1	2872	1090
14	43210	60.8	60.6	60.6	61.2	61.7	61.4	61.7	61.1	13.6	3177	1206
15	49085	62.3	62.2	62.1	62.8	63.2	62.8	63	62.6	15.1	3250	1233
16	21104	57.9	57.8	58.5	59.2	59.6	60.5	60.6	59.1	11.6	1819	690

Table 5.1 (g) Experimental Data In Nucleate Boiling

Test Tube #7, Material Inconel 600, $K^*=0.0275$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	25969	58.1	58.4	58.9	59.5	60.1	60.8	61	59.5	12	2164	821
18	30252	58.8	59.1	59.5	60.1	60.7	61	61.4	60	12.5	2420	918
19	35568	59.5	59.9	60.1	60.8	61.4	61.5	61.8	60.7	13.2	2694	1022
20	41784	60.3	60.5	60.7	61.5	62	61.8	62.2	61.2	13.7	3049	1157
21	47612	60.9	61.1	61.3	62	62.6	62.2	62.5	61.8	14.3	3329	1263
22	56380	61.7	61.9	61.9	62.8	63.4	62.8	63	62.5	15	3758	1426
23	21346	57.3	57.4	58.4	59.2	59.4	60.3	60.6	58.9	11.4	1872	710
24	26068	58.4	58.7	59.6	60.1	60.5	61.1	61.3	59.9	12.4	2102	798
25	31022	58.9	59.1	59.8	60.4	60.9	61.2	61.5	60.2	12.7	2442	927
26	36422	59.6	59.8	60.3	61	61.4	61.5	61.8	60.7	13.2	2759	1047
27	42601	61.4	61.4	61.7	62.3	62.9	62.7	63	62.2	14.7	2898	1100
28	47845	61.3	61.2	61.3	62.1	62.5	62.2	62.5	61.8	14.3	3345	1269
29	54660	62	61.9	62	62.8	63.3	62.8	63.1	62.5	15	3644	1383
30	14912	57.9	57.1	57.7	58.2	57.9	59.3	59.6	58.2	10.7	1393	528
31	17715	58.3	57.7	58.3	58.6	58.5	59.7	60	58.7	11.2	1581	600
32	19966	58.4	58	58.6	58.9	58.7	59.9	60.2	58.9	11.4	1751	664

Table 5.1 (g) Experimental Data In Nucleate Boiling

Test Tube #7, Material Inconel 600, $K^*=0.0275$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
33	23427	58.8	58.6	59.2	59.4	59.3	60.1	60.4	59.4	11.9	1968	747
34	26030	59.2	59.3	59.7	59.9	59.7	60.4	60.7	59.8	12.3	2116	803
35	29339	59.6	59.5	59.8	60.1	60	60.5	60.8	60	12.5	2347	891
36	32700	60.2	60.1	60.3	60.7	60.5	60.9	61.2	60.5	13	2515	954
37	36318	60.5	60.4	60.5	61	60.7	61	61.2	60.7	13.2	2751	1044
38	41194	61.3	61.2	61.2	61.7	61.4	61.6	61.8	61.4	13.9	2963	1124
39	44135	61.6	61.4	61.4	61.9	61.6	61.7	61.9	61.6	14.1	3130	1188
40	48944	62	61.9	61.9	62.4	62	62.1	62.2	62	14.5	3375	1281
41	54112	62.5	62.5	62.3	62.9	62.6	62.5	62.6	62.5	15	3607	1369

Note:

1. Run 1: NO. 1 to NO. 15, $T_1=45.3$ (°C), $P_{atm}=742$ mm Hg, performed on Jan. 19, 1985.
2. Run 2: NO. 16 to NO. 29, $T_1=45.5$ (°C), $P_{atm}=745$ mm Hg, performed on Jan. 20, 1985.
3. Run 3: NO. 30 to NO. 41, $T_1=45.7$ (°C), $P_{atm}=760$ mm Hg, performed on Jan. 29, 1985.

Table 5.2 (a) Experimental Data In Film Boiling

Test Tube #1, Material S. S. 304, $K^*=0.0206$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	56223	396	396	397	398	401	404	403	399	351	160	53
2	44970	354	353	354	355	358	361	360	357	309	145	48
3	39966	320	319	319	320	323	326	325	322	274	145	48
4	34113	290	290	289	291	293	296	295	292	244	139	46
5	29263	257	256	256	258	260	262	261	258	210	139	46
6	25132	235	234	233	236	238	240	239	236	188	133	44
7	21703	212	211	210	214	216	218	216	214	166	130	43
8	60280	421	420	422	423	426	430	429	424	376	160	53
9	52519	386	386	387	388	391	394	393	389	341	154	51
10	42806	344	344	344	346	348	351	351	347	299	143	47
11	36016	304	304	304	305	307	310	309	306	258	139	46
12	32530	276	276	276	277	279	281	281	278	230	141	47
13	27295	250	250	250	251	253	255	255	252	204	133	44
14	23021	223	223	221	224	226	228	227	225	177	130	43
15	19743	198	197	194	199	201	203	201	199	151	130	43
16	56206	400	400	400	401	404	407	407	403	355	158	52

Table 5.2 (a) Experimental Data In Film Boiling

Test Tube #1, Material S. S. 304, $K^*=0.0206$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	49172	369	369	369	370	373	375	375	371	323	152	50
18	40118	326	326	326	327	330	332	332	328	280	143	47
19	32126	284	284	284	285	287	289	289	286	238	134	44
20	27143	255	254	254	255	257	259	259	256	208	130	43
21	22668	226	226	225	227	229	231	230	228	180	125	41
22	18949	207	206	205	208	210	212	211	208	160	118	39
23	55355	395	395	395	396	399	403	402	398	350	158	52
24	46978	364	364	364	365	368	371	371	367	319	147	49
25	40404	323	323	323	323	326	328	328	325	277	145	48
26	34321	290	289	289	290	292	294	295	291	243	141	47
27	27390	251	251	251	253	254	256	256	253	205	133	44
28	23084	227	227	226	229	230	232	231	229	181	127	42
29	19433	203	202	200	205	207	209	206	205	157	123	41

Note:

1. Run 1: NO. 1 to NO. 7. $T_1=45.9$ (°C), $P_{atm}=764$ mm Hg, performed on Feb. 18, 1985.
2. Run 2: NO. 8 to NO. 22. $T_1=45.5$ (°C), $P_{atm}=758$ mm Hg, performed on Feb. 26, 1985.
3. Run 3: NO. 23 to NO. 29. $T_1=45.6$ (°C), $P_{atm}=753$ mm Hg, performed on Feb. 27, 1985.

Table 5.2 (b) Experimental Data In Film Boiling

Test Tube #2. Material S.S. 304, $K^*=0.0383$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	50802	411	425	409	408	410	411	409	412	364	139	49
2	45992	387	395	386	385	387	388	386	388	340	135	48
3	41713	358	361	357	357	359	360	359	359	311	134	47
4	37601	334	332	332	332	334	335	334	333	285	131	46
5	34342	307	302	307	307	309	310	310	307	259	132	47
6	54890	427	423	425	425	427	429	426	426	378	145	51
7	48438	401	399	399	399	401	403	400	400	352	137	49
8	43769	375	374	373	373	375	377	375	375	327	133	47
9	39290	345	346	345	345	347	348	346	346	298	131	46
10	35159	321	321	319	319	321	323	322	321	273	128	45
11	31810	296	296	295	295	297	299	298	296	248	128	45
12	28377	267	264	267	268	270	272	271	268	220	128	45
13	56801	415	399	412	413	414	417	417	412	364	156	55
14	49385	387	380	384	384	386	389	388	385	337	146	52
15	43939	358	354	355	356	357	360	359	357	309	142	50
16	39330	333	329	330	330	332	335	334	332	284	138	49

Table 5.2 (b) Experimental Data In Film Boiling

Test Tube #2, Material S. S. 304, $K^*=0.0383$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	33992	305	303	303	303	305	308	307	305	257	132	47
18	29265	273	272	271	273	274	277	277	274	226	129	46

Note:

1. Run 1: NO. 1 to NO. 5, $T_1=45.4$ (°C), $P_{atm}=757$ mm Hg, performed on Nov. 28, 1984.
2. Run 2: NO. 6 to NO. 12, $T_1=45.4$ (°C), $P_{atm}=749$ mm Hg, performed on Nov. 29, 1984.
3. Run 3: NO. 13 to NO. 18, $T_1=45.5$ (°C), $P_{atm}=749$ mm Hg, performed on Nov. 29, 1984.

Table 5.2 (c) Experimental Data In Film Boiling

Test Tube #3, Material S.S. 304, $K^*=0.0513$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	53881	403	399	402	404	410	414	407	406	358	150	54
2	46356	377	375	376	379	384	388	381	380	332	139	50
3	38355	330	328	329	332	336	341	335	333	285	134	48
4	29263	277	276	277	280	283	287	282	280	232	126	45
5	22136	228	225	228	231	235	239	235	232	184	120	43
6	48234	376	373	374	376	382	386	380	378	330	146	52
7	42872	348	346	347	350	355	359	354	351	303	141	50
8	37982	324	322	323	326	331	336	330	327	279	136	49
9	31216	289	287	288	291	295	300	295	292	244	127	45
10	27671	259	256	258	262	266	271	266	263	215	128	46
11	24018	231	227	230	234	239	244	240	235	187	128	46
12	20310	206	200	203	207	212	218	215	209	161	126	45
13	57397	428	424	422	421	425	431	426	425	377	152	54
14	52125	400	396	394	395	398	404	399	398	350	148	53
15	42441	355	352	350	351	354	359	354	354	306	138	49

Table 5.2 (c) Experimental Data In Film Boiling

Test Tube #3. Material S.S. 304, $K^*=0.0513$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
16	36806	316	312	311	312	315	321	317	315	267	137	49
17	32361	286	282	281	284	287	293	290	286	238	135	48
18	27883	253	247	249	251	255	261	259	254	206	135	48
19	23857	229	223	224	227	232	238	236	230	182	131	47
20	59972	444	441	441	442	447	452	445	444	396	151	54
21	54576	418	415	416	418	424	428	422	420	372	146	52
22	46924	381	380	380	382	387	392	385	384	336	139	50
23	39354	342	341	341	343	348	352	347	345	297	132	47
24	31683	288	286	287	289	293	298	294	291	243	130	47
25	27548	259	256	258	260	264	269	265	262	214	128	46
26	20847	221	217	219	223	227	231	229	224	176	118	42
27	50441	401	399	400	402	408	413	406	404	356	141	50
28	43463	361	360	360	363	368	373	366	365	317	137	49
29	35513	314	312	312	315	319	324	318	316	268	132	47
30	28507	272	270	271	274	278	282	278	275	227	125	45

Table 5.2 (c) Experimental Data In Film Boiling

Test Tube #3, Material S. S. 304, $K^*=0.0513$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
31	23885	232	229	231	234	238	243	239	235	187	127	45
32	19194	204	199	202	205	210	215	213	207	159	120	43

Note:

1. Run 1: NO. 1 to NO. 12, $T_1=45.6$ (°C), $P_{atm}=759$ mm Hg, performed on Dec. 24, 1984.
2. Run 2: NO. 13 to NO. 19, $T_1=45.0$ (°C), $P_{atm}=756$ mm Hg, performed on Dec. 24, 1984.
3. Run 3: NO. 20 to NO. 32, $T_1=46.2$ (°C), $P_{atm}=768$ mm Hg, performed on Dec. 30, 1984.

Table 5.2 (d) Experimental Data In Film Boiling

Test Tube #4, Material S. S. 304, $K^*=0.0602$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	56687	424	425	425	423	438	445	438	431	383	148	51
2	47583	378	377	379	382	389	395	391	384	336	141	48
3	38910	326	326	330	329	335	340	335	332	284	137	47
4	32556	289	290	299	296	299	303	298	296	248	131	45
5	25261	246	246	256	250	254	258	255	252	204	123	42
6	55808	421	422	422	420	435	442	434	428	380	146	50
7	47661	382	384	384	387	394	399	392	389	341	139	48
8	40082	334	334	334	339	342	348	344	339	291	137	47
9	33339	290	291	292	293	299	304	299	295	247	134	46
10	27210	254	255	257	253	262	267	263	258	210	129	44
11	56949	425	427	427	423	439	446	438	432	384	148	51
12	48664	385	387	387	390	398	403	397	392	344	141	48
13	41447	341	341	342	347	351	357	352	347	299	138	47
14	35795	304	305	305	307	314	319	313	310	262	136	47
15	27246	255	256	256	258	263	268	264	260	212	128	44
16	62019	443	442	442	439	453	458	452	447	399	155	53

Table 5.2 (d) Experimental Data In Film Boiling

Test Tube #4, Material S.S. 304, $K^*=0.0602$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	51035	384	383	384	386	392	396	390	388	340	150	51
18	41835	336	336	339	342	343	347	342	341	293	142	49
19	35099	294	293	296	298	301	305	301	298	250	140	48
20	27320	255	256	253	251	263	267	264	259	211	129	44
21	59752	414	413	412	412	424	429	423	418	370	161	55
22	50012	368	368	368	369	377	381	375	372	324	154	53
23	42302	326	326	324	323	334	339	335	330	282	150	51
24	35138	290	289	285	280	300	305	301	293	245	143	49
25	25490	238	236	231	225	252	256	254	242	194	131	45

Note:

1. Run 1: NO. 1 to NO. 10, $T_1=46.0$ (°C), $P_{atm}=757$ mm Hg, performed on Apr. 30, 1985.
2. Run 2: NO. 11 to NO. 15, $T_1=45.7$ (°C), $P_{atm}=757$ mm Hg, performed on Apr. 30, 1985.
3. Run 3: NO. 16 to NO. 25, $T_1=45.3$ (°C), $P_{atm}=752$ mm Hg, performed on May 1, 1985.

Table 5.2 (a) Experimental Data In Film Boiling

Test Tube #5, Material S. S. 304, $K^*=0.0746$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	62570	442	440	446	453	459	449	438	447	399	156	52
2	49658	377	374	379	384	390	384	378	381	333	149	49
3	43148	338	336	341	346	351	346	341	343	295	146	48
4	38175	307	305	310	315	320	315	310	312	264	144	48
5	32621	268	268	273	279	285	281	278	276	228	143	47
6	60041	430	429	434	439	444	436	428	434	386	155	51
7	49578	376	373	377	381	385	383	381	379	331	149	49
8	44375	345	343	347	351	353	350	346	348	300	147	49
9	37392	295	294	299	304	306	300	293	299	251	148	49
10	32153	256	254	260	266	269	263	257	261	213	150	50
11	60159	436	435	441	447	452	446	441	443	395	152	50
12	50829	388	387	392	397	401	397	393	394	346	146	48
13	43633	344	342	346	351	355	353	351	349	301	144	48
14	37868	302	300	304	309	313	310	307	307	259	146	48
15	30907	258	258	263	269	274	274	275	267	219	141	47
16	58558	424	422	428	433	439	434	430	430	382	153	51

Table 5.2 (e) Experimental Data In Film Boiling

Test Tube #5, Material S. S. 304, $K^*=0.0746$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	49020	374	372	378	383	387	385	383	380	332	147	49
18	43621	339	337	342	346	350	348	346	344	296	147	49
19	40277	313	313	318	323	327	324	321	320	272	148	49
20	33235	268	268	274	279	284	284	284	277	229	145	48
21	57650	422	420	426	431	435	431	428	428	380	151	50
22	45151	356	355	359	363	368	369	371	363	315	143	47
23	38842	312	310	314	318	322	322	321	317	269	144	48
24	33416	272	272	277	282	286	284	281	279	231	144	48
25	27940	247	248	252	257	261	265	269	257	209	133	44

Note:

1. Run 1: NO. 1 to NO. 10, $T_1=45.3$ (°C), $P_{atm}=744$ mm Hg. performed on Mar. 12, 1985.
2. Run 2: NO. 11 to NO. 15, $T_1=46.0$ (°C), $P_{atm}=753$ mm Hg. performed on Mar. 13, 1985.
3. Run 3: NO. 16 to NO. 25, $T_1=45.3$ (°C), $P_{atm}=753$ mm Hg. performed on Mar. 13, 1985.

Table 5.2 (f) Experimental Data In Film Boiling

Test Tube #6, Material Monel 400, $K^*=0.0143$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
1	55389	402	402	402	404	407	409	407	405	357	155	57
2	48888	382	383	383	385	388	391	387	386	338	144	53
3	44315	361	362	362	365	368	370	367	365	317	139	51
4	38837	331	331	331	334	336	339	336	334	286	135	50
5	34818	304	305	305	307	310	312	310	308	260	133	49
6	30227	279	279	279	281	283	286	284	282	234	129	47
7	26121	256	256	256	258	260	263	260	258	210	124	45
8	22727	236	236	236	238	240	243	241	239	191	118	43
9	19169	213	213	213	215	217	220	217	215	167	114	42
10	15950	191	191	191	193	194	197	194	193	145	110	40
11	58801	415	416	417	421	425	429	426	421	373	157	58
12	52915	394	395	396	400	404	408	405	400	352	150	55
13	45671	367	368	369	373	377	381	377	373	325	140	51
14	39444	337	338	339	343	347	350	347	343	295	133	49
15	33995	303	304	305	309	312	315	312	308	260	130	48
16	30486	282	283	283	287	289	292	290	287	239	127	47

Table 5.2 (f) Experimental Data In Film Boiling

Test Tube #6, Material Monel 400, $K^*=0.0143$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{Nu}$
		0	30	60	90	120	150	180				
17	26556	249	250	250	253	256	259	257	253	205	129	47
18	20978	225	225	225	229	231	234	232	229	181	115	42
19	16743	200	200	201	204	206	209	206	204	156	107	39
20	56464	403	405	406	409	414	417	413	409	361	156	57
21	47145	374	375	376	380	384	387	383	380	332	142	52
22	39748	330	331	332	335	339	342	338	335	287	138	51
23	32862	302	303	303	306	309	312	309	306	258	127	47
24	27164	270	270	270	273	276	278	276	273	225	120	44
25	24112	243	244	244	246	248	250	248	246	198	121	44
26	20753	225	226	226	228	230	232	230	228	180	115	42
27	17914	206	206	207	209	211	213	211	209	161	111	41

Note:

1. Run 1: NO.1 to NO.10, $T_1=45.9$ (°C), $P_{atm}=760$ mm Hg, performed on Jan. 15, 1985.
2. Run 2: NO.11 to NO.19, $T_1=46.3$ (°C), $P_{atm}=765$ mm Hg, performed on Jan. 16, 1985.
3. Run 3: NO.20 to NO.27, $T_1=45.5$ (°C), $P_{atm}=763$ mm Hg, performed on Feb. 16, 1985.

Table 5.2 (g) Experimental Data In Film Boiling

Test Tube #7, Material Inconel 600, $K^*=0.0275$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{N}_U$
		0	30	60	90	120	150	180				
1	44662	375	375	375	376	384	383	384	379	331	134	50
2	38766	341	341	341	343	349	349	350	345	297	130	49
3	33739	313	313	313	315	321	321	322	317	269	125	47
4	28260	278	279	279	280	285	286	286	282	234	120	45
5	23234	248	249	249	250	254	256	256	252	204	113	42
6	19144	225	225	226	227	230	232	233	229	181	105	39
7	15158	197	198	198	200	203	205	206	201	153	99	37
8	54644	422	422	421	423	431	429	430	426	378	144	54
9	47501	389	389	389	391	398	397	398	393	345	137	52
10	41745	360	361	361	363	369	368	369	364	316	132	50
11	36389	336	336	336	338	344	344	345	340	292	124	47
12	30082	292	293	293	295	299	300	301	296	248	121	45
13	24843	256	256	257	258	262	263	264	259	211	117	44
14	20746	232	233	233	235	238	240	240	236	188	110	41
15	16296	199	200	200	202	205	208	208	203	155	105	39

Table 5.2 (g) Experimental Data In Film Boiling

Test Tube #7, Material Inconel 600, $K^*=0.0275$

NO.	$\bar{q}$ W/M ²	T_o (°C)							$\bar{T}_o$ (°C)	$\bar{T}_o - T_s$ (°C)	$\bar{h}$ W/M ² -°C	$\bar{N}_U$
		0	30	60	90	120	150	180				
16	45909	380	380	381	383	390	390	391	385	337	136	51
17	38073	335	335	336	338	343	344	345	339	291	130	49
18	32281	297	297	298	300	305	306	307	301	253	127	48
19	26189	259	259	259	261	266	267	268	263	215	121	45
20	22853	233	232	232	234	239	240	241	236	188	121	45
21	20212	212	213	212	214	220	221	222	216	168	120	45
22	16866	187	189	189	191	196	198	199	193	145	116	44
23	53406	413	413	413	415	423	422	423	418	370	144	54
24	46411	377	377	377	379	387	386	387	381	333	139	52
25	37329	339	339	340	342	348	349	350	344	296	126	47
26	31193	290	291	292	293	299	300	300	295	247	126	47
27	24635	253	253	253	255	259	261	262	257	209	117	44
28	21128	221	222	222	224	228	230	230	225	177	119	45

Note:

1. Run 1: NO.1 to NO.7, $T_1=45.2$ (°C), $P_{atm}=745$ mm Hg, performed on Jan. 20, 1985.
2. Run 2: NO.8 to NO.15, $T_1=45.3$ (°C), $P_{atm}=745$ mm Hg, performed on Jan. 20, 1985.
3. Run 3: NO.16 to NO.28, $T_1=45.9$ (°C), $P_{atm}=765$ mm Hg, performed on Feb. 5, 1985.

Table 5.3 (a) Correlations of Experimental Results In Nucleate Boiling

$$\bar{q} = a(\bar{T}_o - T_s)^m \quad (\text{S. I. unit})$$

	a	m	s
Test Tube #1	.375	4.505	.176
Test Tube #2	.556	4.215	.113
Test Tube #3	.602	4.144	.115
Test Tube #4	.699	4.245	.088
Test Tube #5	.512	4.489	.135
Test Tube #6	12.041	2.886	.11
Test Tube #7	8.286	3.229	.085

Note:

1. Stephan's correlation is given in [33].
2. s is the standard deviation.

Table 5.3 (b) Correlations of Experimental
Results In Film Boiling

$$\bar{q} = a(\bar{T}_o - T_s)^m \quad (\text{S.I. unit})$$

	a	m	s
Test Tube #1	30.59	1.276	.026
Test Tube #2	33.32	1.246	.035
Test Tube #3	38.1	1.226	.03
Test Tube #4	34.06	1.25	.037
Test Tube #5	73.89	1.121	.023
Test Tube #6	16.58	1.373	.026
Test Tube #7	24.27	1.296	.041

Note:

1. Sakurai's correlation is given in [37].
2. s is the standard deviation.

Table 5.4 (a) Comparisons of Experimental
Results In Nucleate Boiling

$$(Nu - Nu_{st}) / Nu_{st} \quad 100\%$$

$\bar{T}_o - T_s \text{ (}^\circ\text{C)}$	10	11	12	13	14	15	16	17
Test Tube #1	-1	5	10	15	20	25	30	35
Test Tube #2	-25	-23	-21	-19	-17	-15	-14	-12
Test Tube #3	-31	-29	-28	-27	-25	-24	-23	-22
Test Tube #4	2	5	8	11	13	16	18	21
Test Tube #5	30	38	45	51	58	64	70	76
Test Tube #6	-24	-31	-37	-42	-46	-50	-53	-56
Test Tube #7	16	9	2	-3	-8	-12	-16	-20

Table 5.4 (b) Comparisons of Experimental
Results In Film Boiling

	$(Nu - Nu_{sa}) / Nu_{sa} \text{ 100\%}$			
$\bar{T}_o - T_s \text{ (}^\circ\text{C)}$	175	200	225	250
Test Tube #1	-4	-2	-1	-1
Test Tube #2	-10	-9	-8	-9
Test Tube #3	-7	-7	-6	-7
Test Tube #4	-6	-5	-4	-5
Test Tube #5	4	4	3	1
Test Tube #6	-14	-11	-9	-8
Test Tube #7	-15	-14	-13	-12

Table 5.5 Different Correlations In Nucleate Boiling

A. Stephan-Abdelsalam [33]:

$$\bar{h} = C_4 \cdot \bar{q}^{0.745}, \text{ where } C_4 \doteq 1.1 \text{ for freon 113 at 1 atm.}$$

B. Yilmaz-Westwater [27]:

$$\bar{q} = 0.0532 \cdot \Delta T^{3.72} \quad (\text{for freon 113 only})$$

C. McNeilly [25]:

$$\frac{\bar{h}}{K_1} \frac{D}{D} = 0.225 \left(\frac{D \cdot \bar{q}}{h_{fg} \mu_1} \right)^{0.69} \left(\frac{P D}{\sigma} \right)^{0.31} \left(\frac{\rho_l - \rho_v}{\rho_v} \right)^{0.33} \left(\frac{\mu_1 \cdot C_1}{K_1} \right)^{0.69}$$

D. Rohsenow [26]:

$$\frac{C_1 \cdot \Delta T}{h_{fg}} = C_{s1} \left(\frac{\bar{q}}{\mu_1 h_{fg}} \cdot \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \right)^{0.33} \left(\frac{\mu_1 \cdot C_1}{K_1} \right)^{1.7}$$

E. Borishanskiy-Minchenko [28]:

$$\begin{aligned} \frac{h}{K_1} \left(\frac{\sigma}{g(\rho_l - \rho_v)} \right)^{0.5} &= 8.7 \times 10^{-4} \cdot \left(\frac{\bar{q}}{a_1 \rho_v h_{fg}} \cdot \left(\frac{\sigma}{g(\rho_l - \rho_v)} \right)^{0.5} \right)^{0.7} \\ &\times \left(\frac{P}{\sigma} \left(\frac{\sigma}{g(\rho_l - \rho_v)} \right)^{0.5} \right)^{0.7} \end{aligned}$$

Table 5.5 Different Correlations In Nucleate Boiling

F. Forster-Zuber [29]:

$$\frac{\bar{q}}{\Delta T \cdot K_1} \cdot \left(\frac{\Delta T \cdot C_1 \cdot \rho_1 \sqrt{\pi a_1}}{h_{fg} \cdot \rho_v} \right) \cdot \left(\frac{2\sigma}{\Delta P} \right)^{0.5} \cdot \left(\frac{\rho_1}{\Delta P} \right)^{0.25}$$

$$= 0.0015 \cdot \left(\frac{\rho_1}{\mu_1} \cdot \left(\frac{\Delta T \cdot C_1 \cdot \rho_1 \sqrt{\pi a_1}}{h_{fg} \cdot \rho_v} \right)^2 \right)^{0.62} \cdot \left(\frac{\mu_1 \cdot C_1}{K_1} \right)^{0.33}$$

G. Mikic-Rohsenow [30]:

$$\frac{\bar{q}}{\mu_1 h_{fg}} \left(\frac{\sigma}{g(\rho_1 - \rho_v)} \right)^{0.5} = B \cdot (\phi \cdot \Delta T)^{m+1}$$

Where:

$$\phi^{m+1} = \frac{K_1^{0.5} \cdot \rho_1^{2.13} \cdot C_1^{2.38} \cdot h_{fg}^{(m-2.88)} \cdot \rho_v^{(m-1.87)}}{\mu_1 \cdot (\rho_1 - \rho_v)^{1.13} \cdot \sigma^{(m-1.38)} \cdot T_1^{(m-1.88)}}$$

H. Levy [31]:

$$\bar{q} = \frac{K_1 C_1 \rho_1^2}{\sigma T_s (\rho_1 - \rho_v)} \cdot \frac{1}{B_1} \cdot (\Delta T)^3$$

I. Forster-Grief [32]:

$$\bar{q} = 4.3 \times 10^{-5} \frac{a_1 \cdot C_1 \cdot \rho_1 \cdot T_s}{\sigma^{0.5} (h_{fg} \cdot \rho_v)^{1.5}} \cdot (C_1 \cdot T_s \cdot a_1^{0.5})^{0.25} \cdot \left(\frac{\rho_1}{\mu_1} \right)^{0.625} \cdot \left(\frac{\mu_1 \cdot C_1}{K_1} \right)^{0.33} \cdot \Delta P^2$$

Table 5.6 Different Correlations In Film Boiling

A. Sakurai-Shiotsu-Hata [37]:

$$\frac{hD}{K_v} = K_s \left(\frac{g(\rho_l - \rho_v) D^3}{\rho_v \nu_v^2} \frac{C_v \mu_v}{K_v} \frac{h_{fg} (1 + 0.4 C_v \Delta T / h_{fg})^2}{C_v \Delta T} \right)^{0.228}$$

where:

$$K_s = 0.897 - 0.542 \log \left(\frac{\lambda_c}{D} \right) + 0.439 \left(\log \left(\frac{\lambda_c}{D} \right) \right)^2$$

B. Breen-Westwater [9]:

$$h \cdot (\lambda_c)^{0.25} = (0.59 + 0.069 \lambda_c / D) \cdot \left[\frac{K_v^3 \rho_v (\rho_l - \rho_v) g \cdot h_{fg} (1 + 0.4 C_v \Delta T / h_{fg})^2}{\mu_v \Delta T} \right]^{1/4}$$

C. Bromley [36]:

$$h = 0.425 \left(\frac{K_v^3 \rho_v (\rho_l - \rho_v) g \cdot h_{fg} (1 + 0.4 C_v \Delta T / h_{fg})^2}{\mu_v \Delta T \lambda_c} \right)^{0.25}$$

D. Berenson [38]:

$$h = 0.62 \left(\frac{K_v^3 \rho_v (\rho_l - \rho_v) g h_{fg} (1 + 0.4 C_v \Delta T / h_{fg})^2}{D \Delta T \mu_v} \right)^{0.25}$$

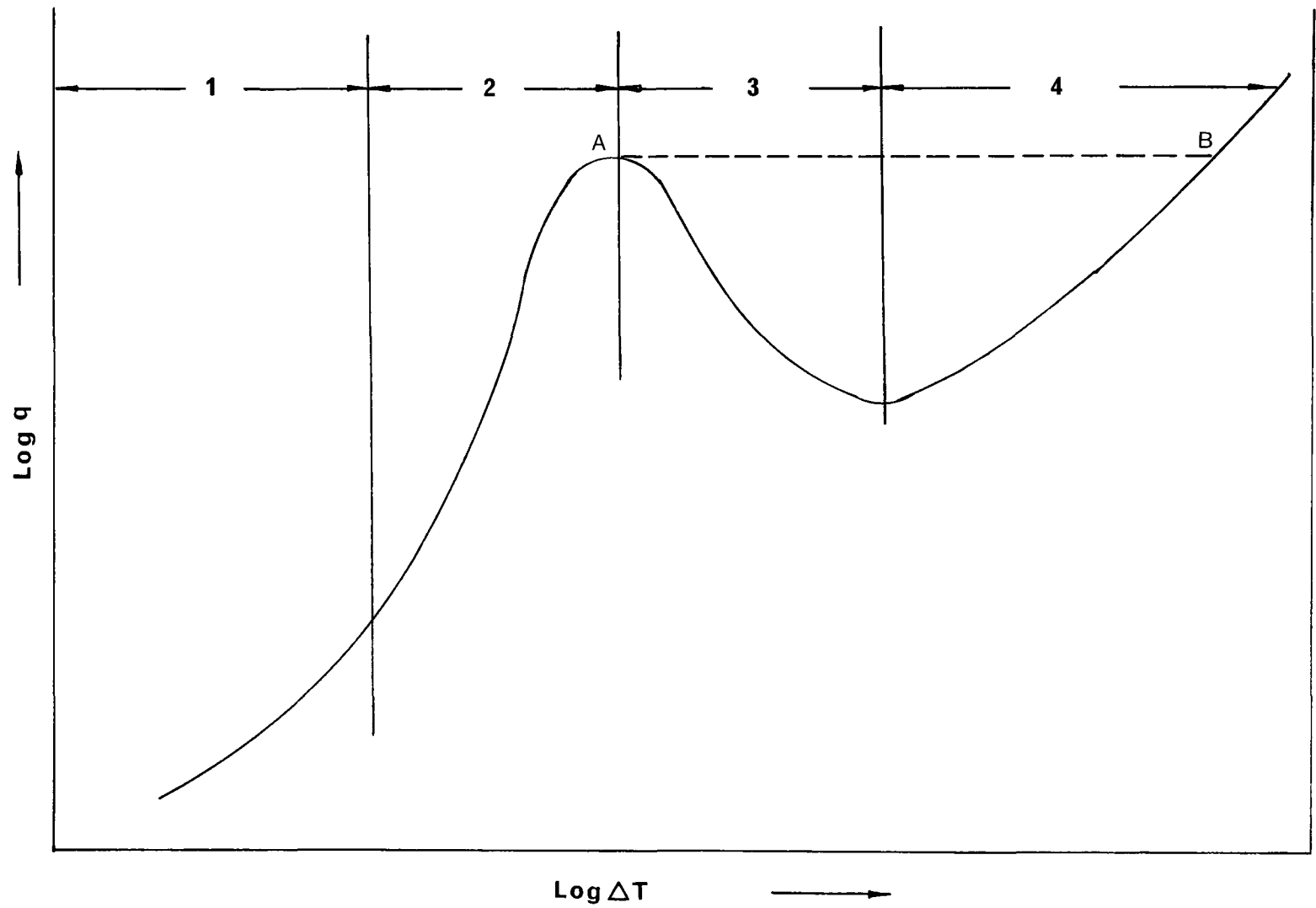


Figure 2.1 Typical Pool Boiling Curve

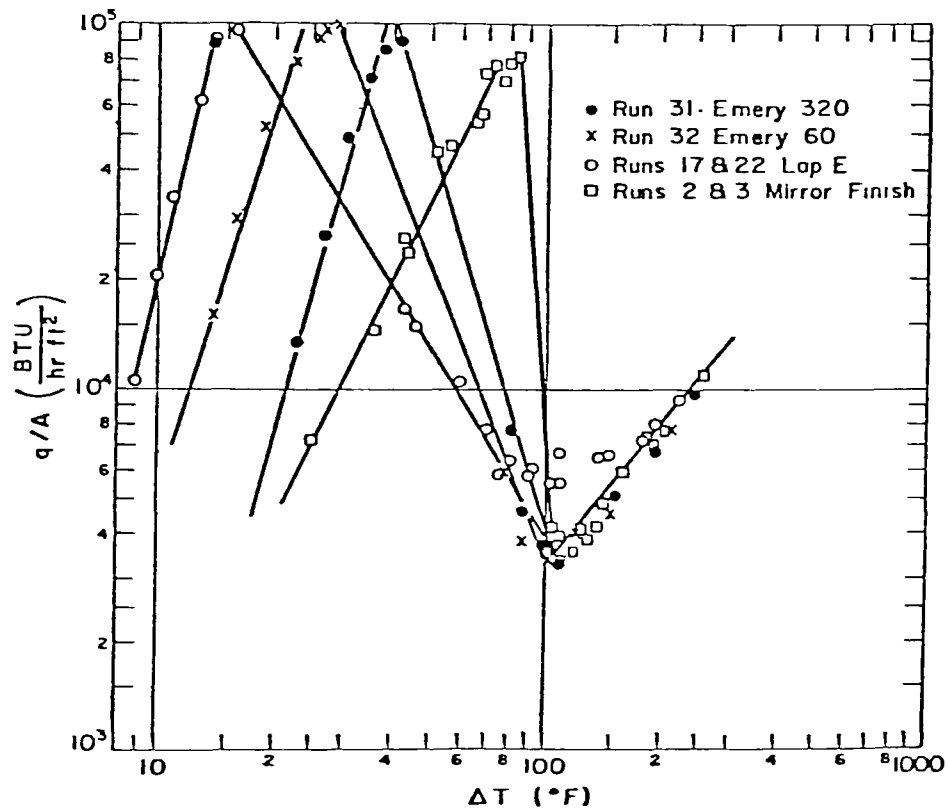


Figure 2.2 Copper Pentane Test Results:
Effect Of Roughness [14]

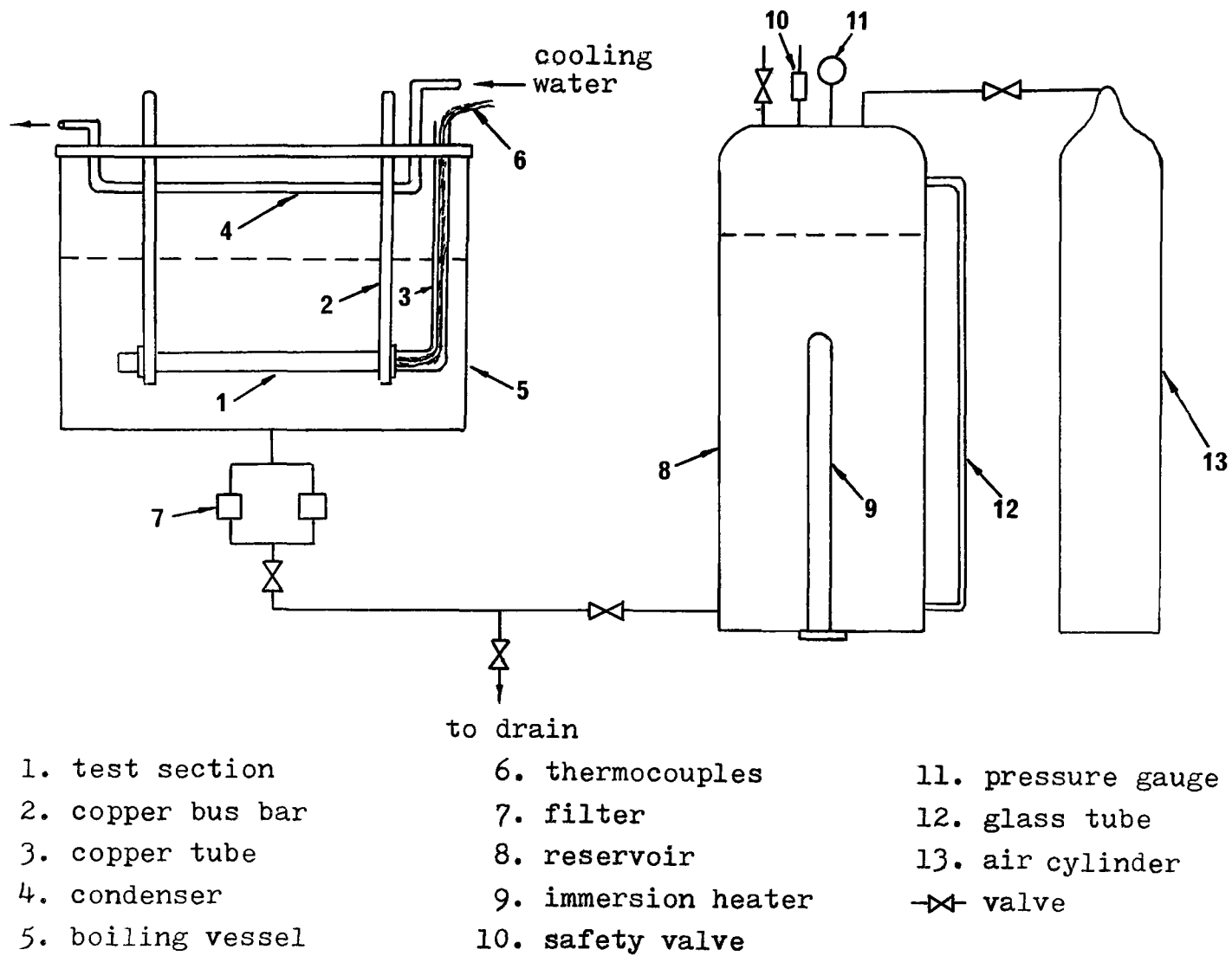


Figure 4.1 Schematic Of The Experimental Apparatus

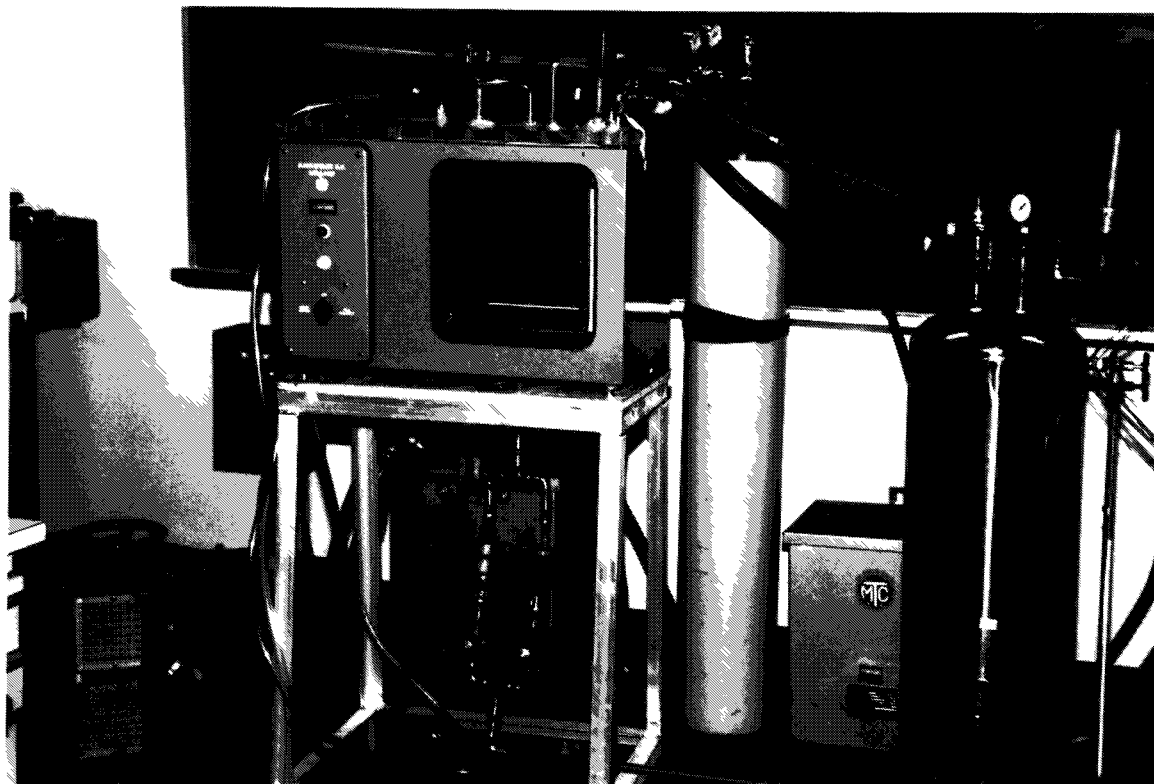


Figure 4.2 Front View Of The Experimental Set-Up

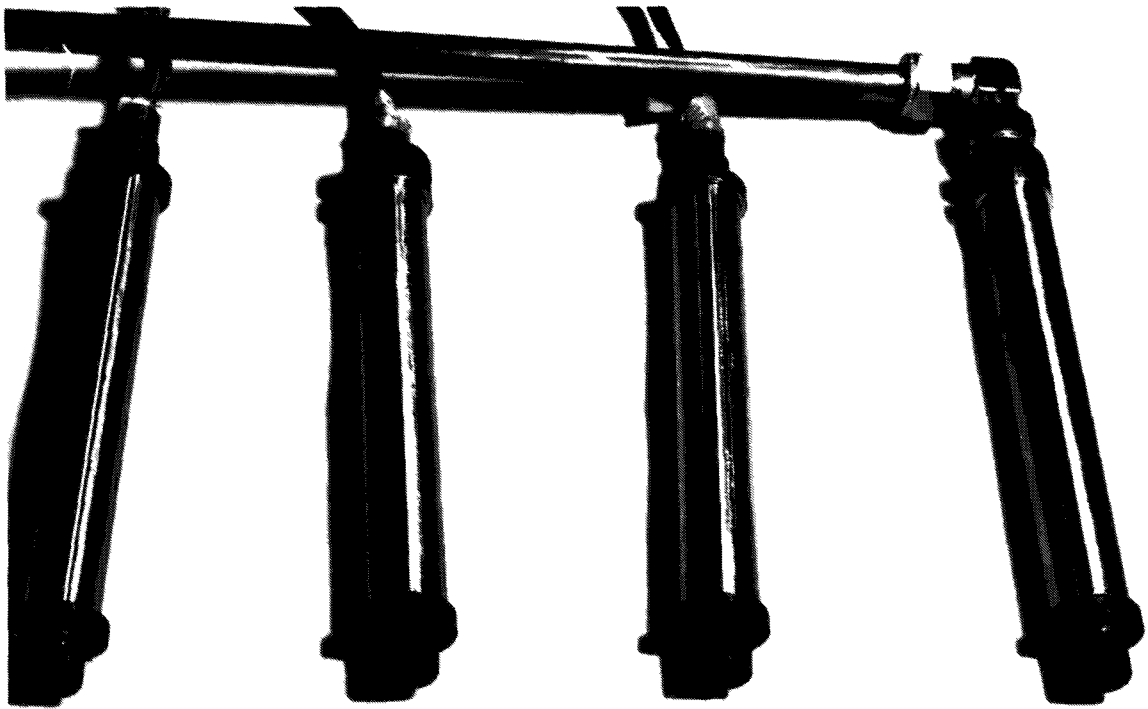


Figure 4.3 Test Sections

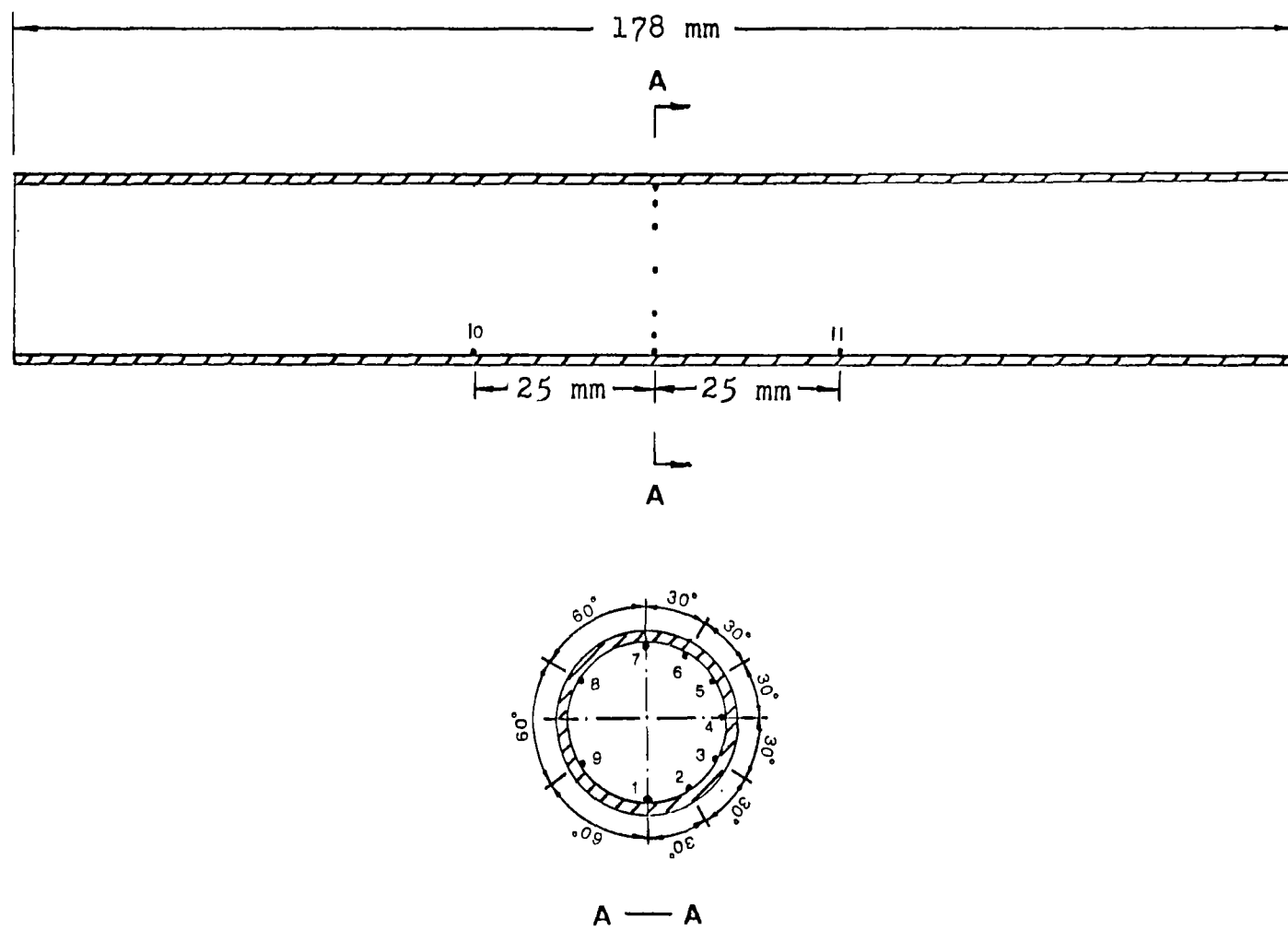


Figure 4.4 (a) Location Of Thermocouples

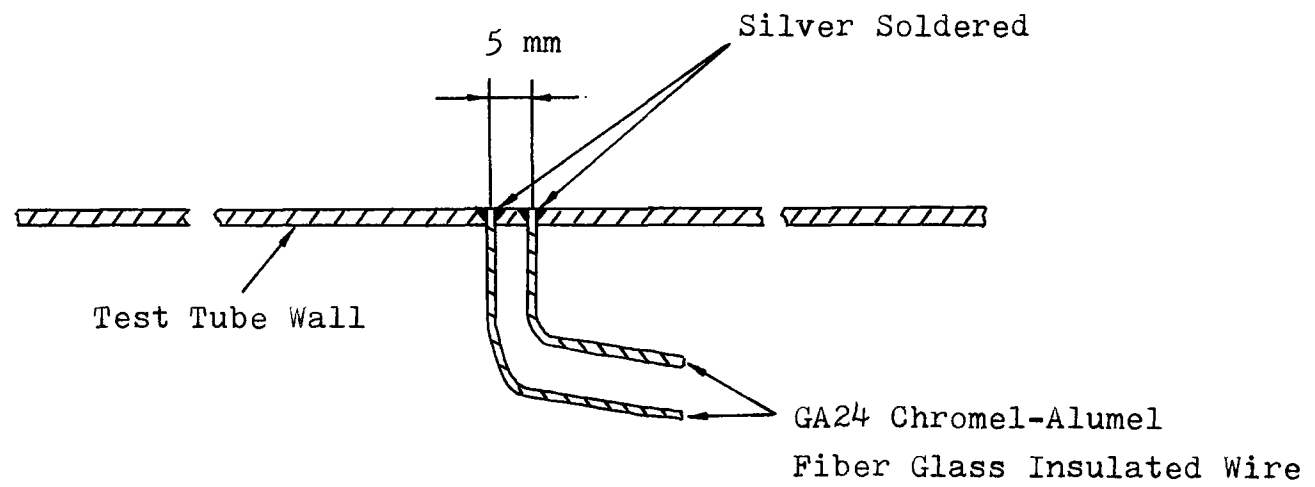


Figure 4.4 (b) Details Of Split Hot Junction

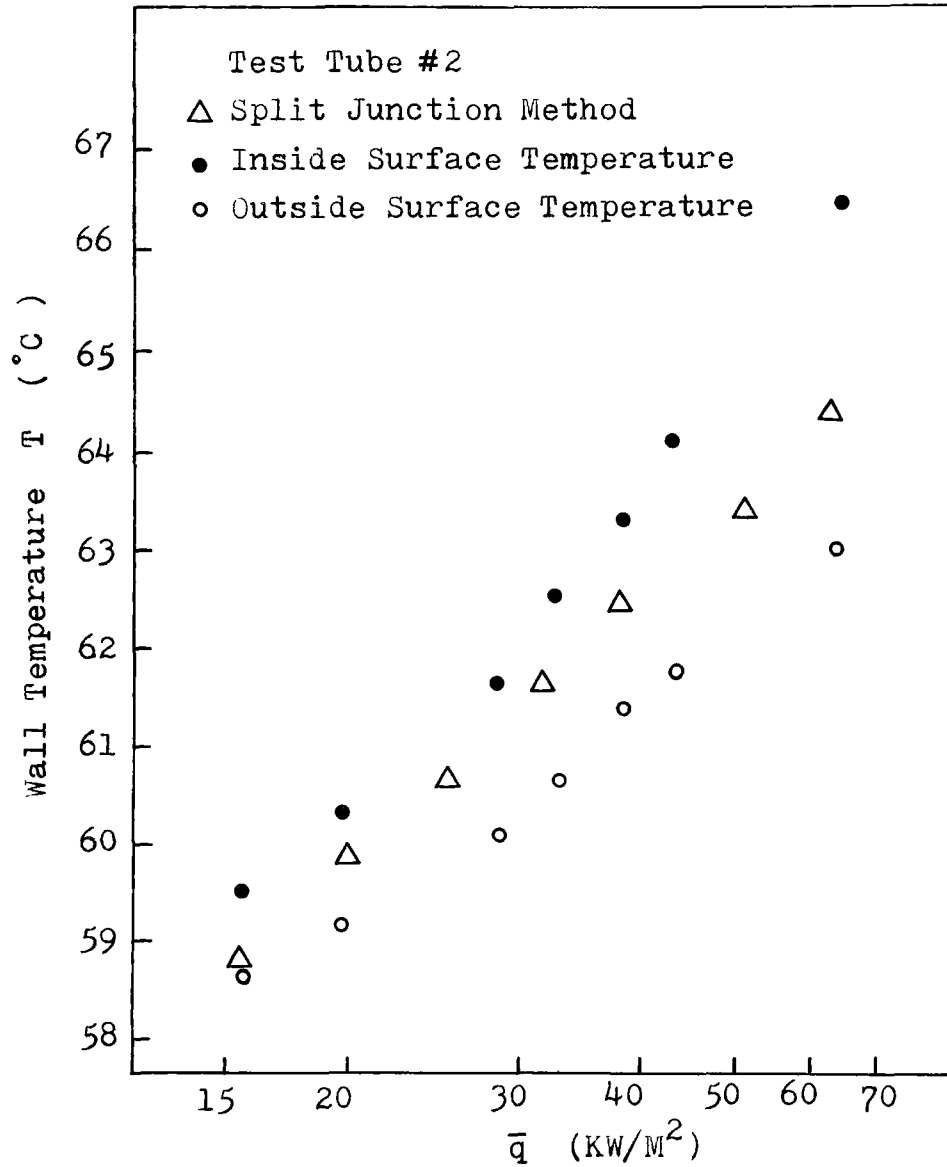


Figure 4.4 (c) Comparison Of Typical Wall Temperature Readings By Two Methods

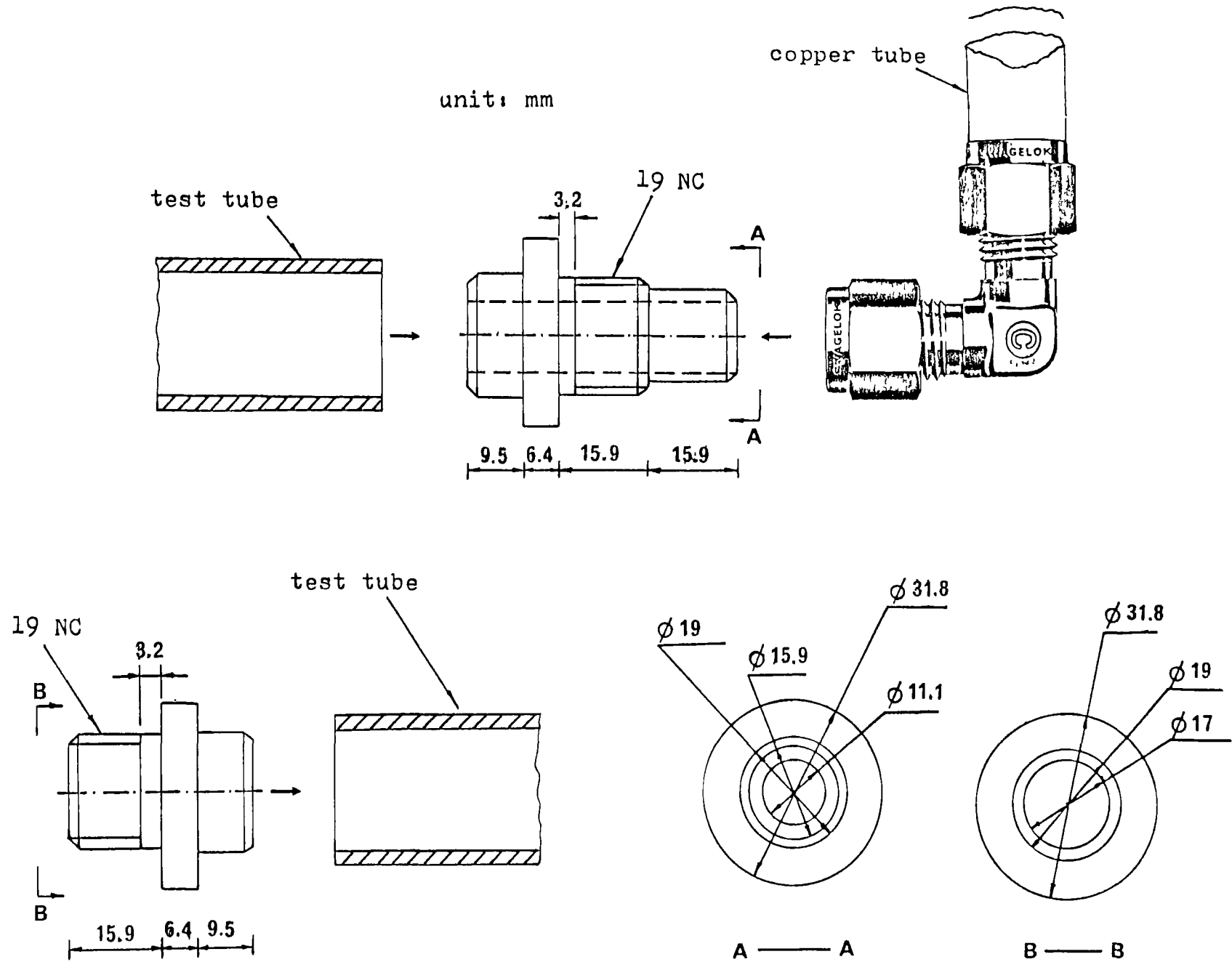


Figure 4.5 Details Of Test Tube Conductors

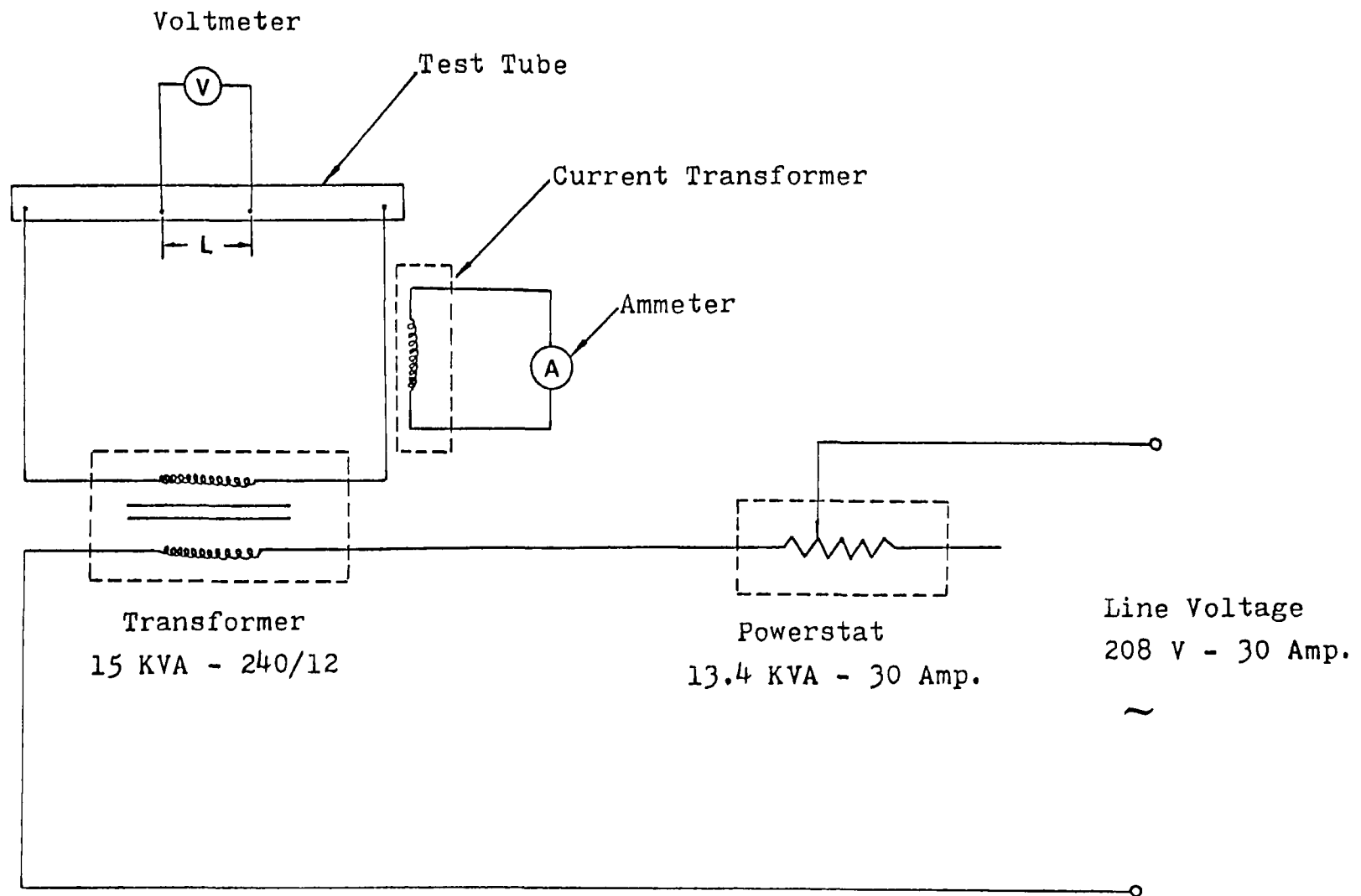


Figure 4.6 Power Supply and Measurement Circuit

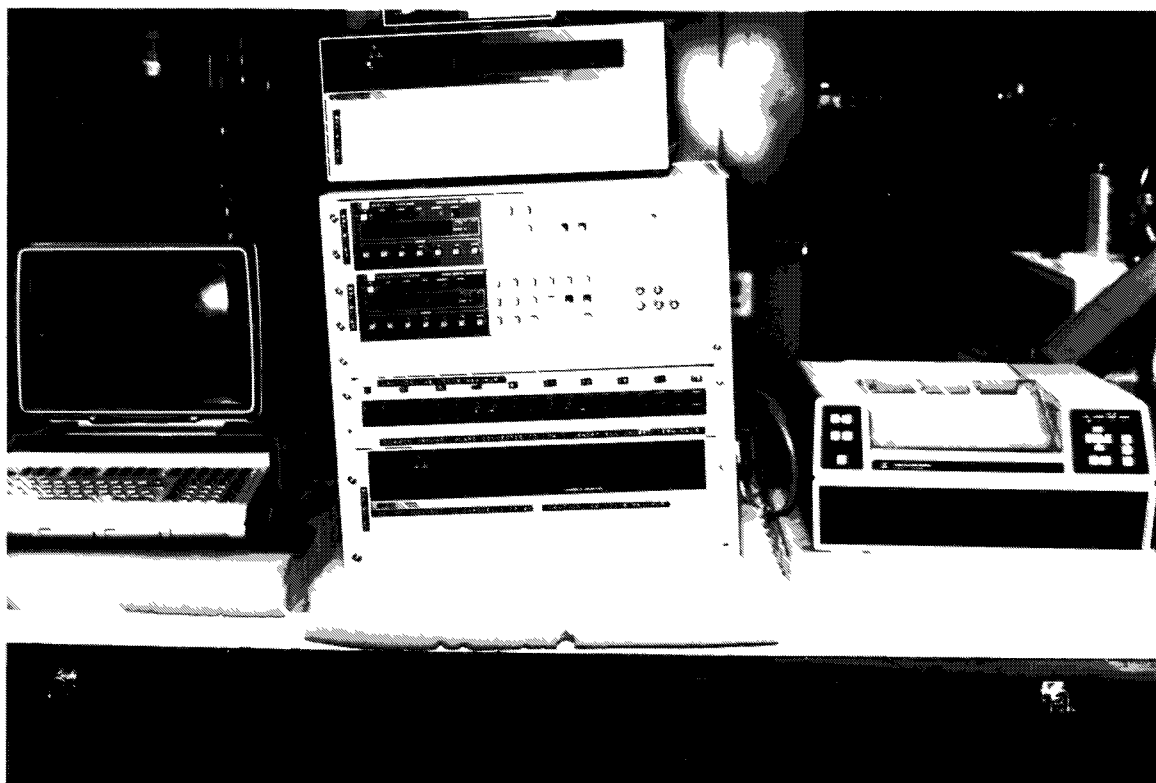


Figure 4.7 Data Acquisition System

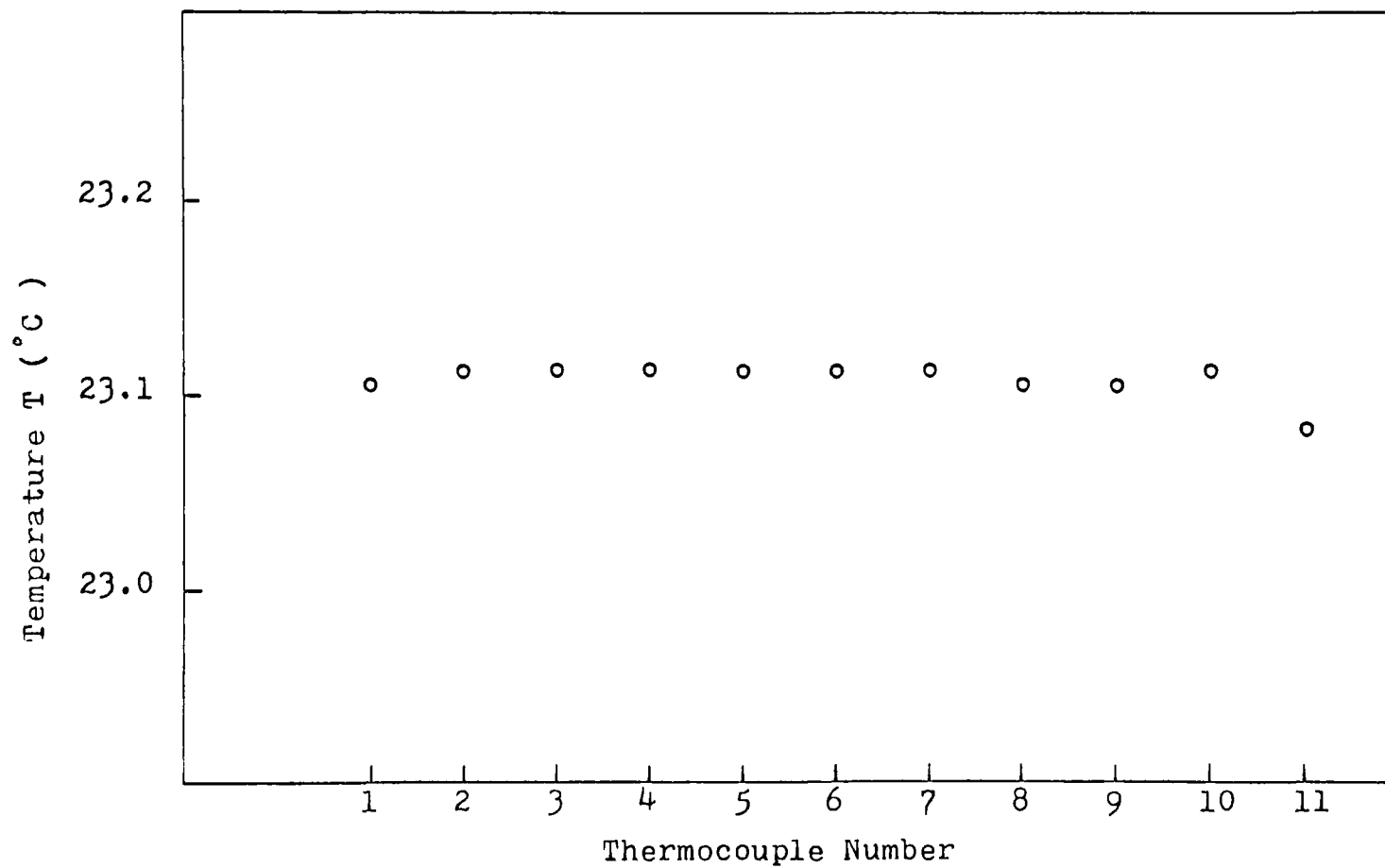


Figure 4.8 Typical Temperature Readings Before Experiment

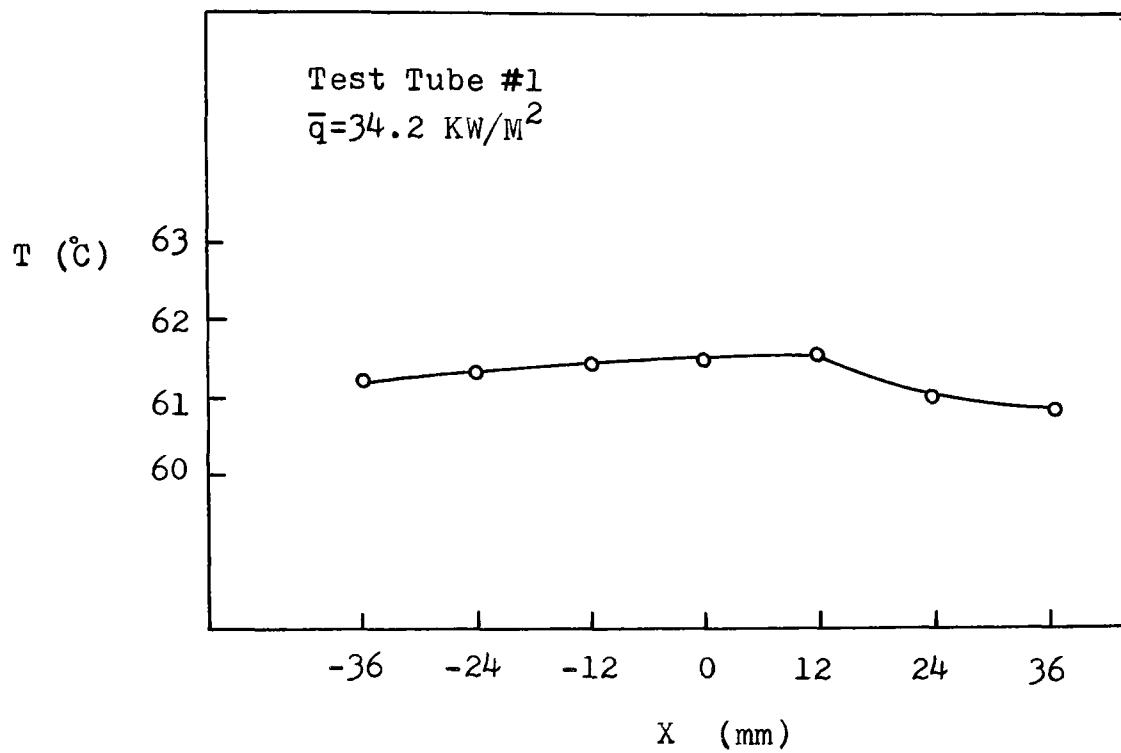


Figure 4.9 (a) Typical Axial Temperature Distribution In Nucleate Boiling

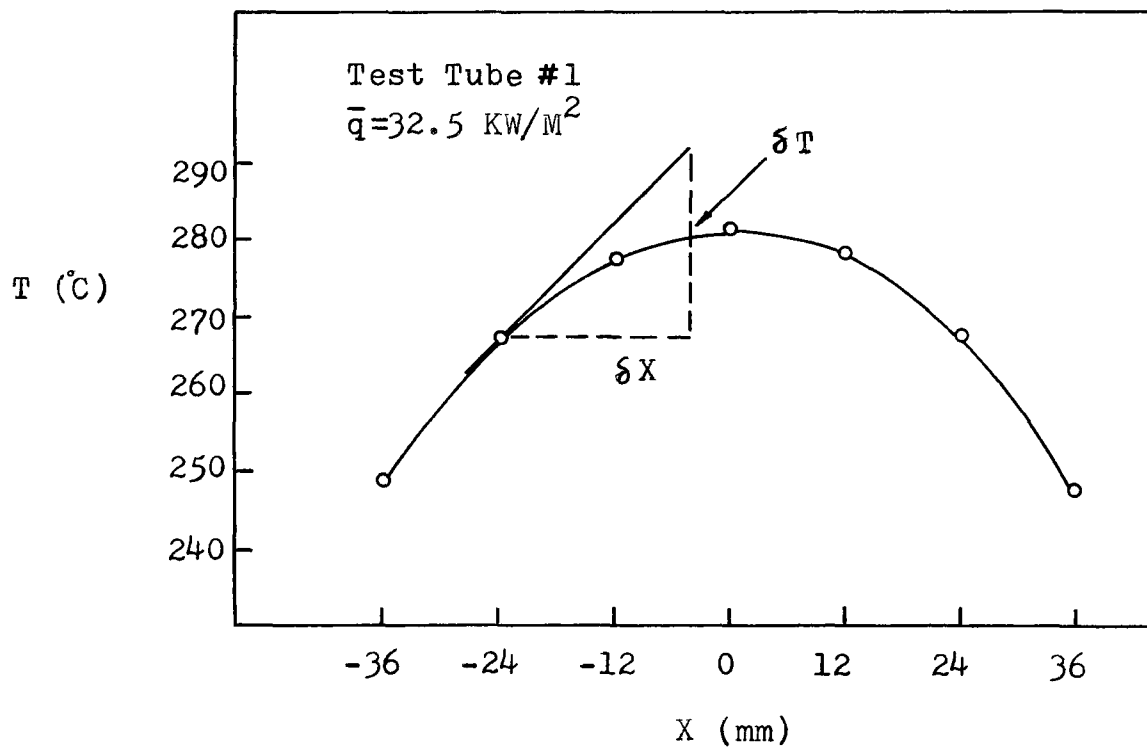


Figure 4.9 (b) Typical Axial Temperature Distribution In Film Boiling

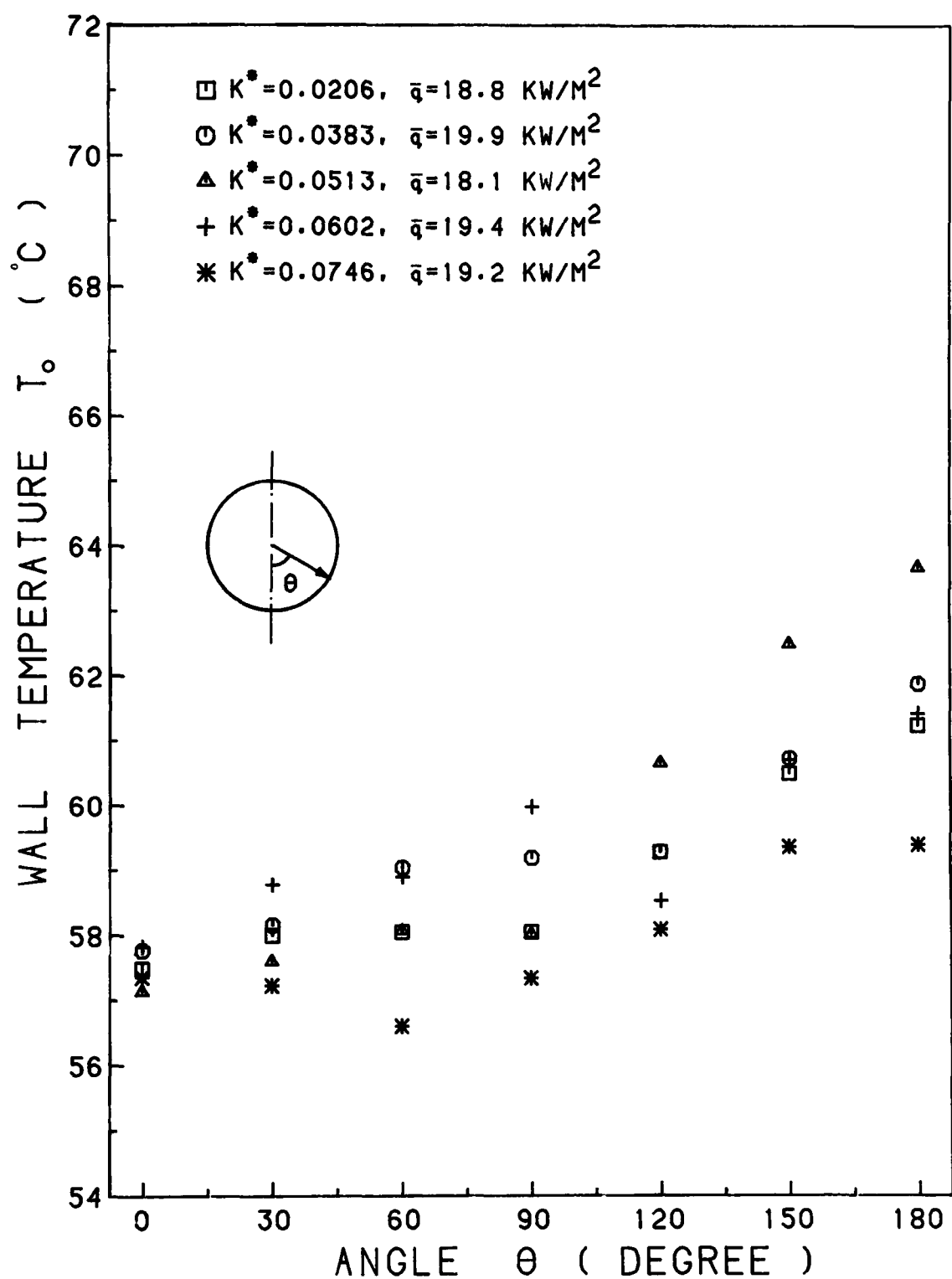


FIGURE 5.1 (a) WALL TEMPERATURE DISTRIBUTION IN NUCLEATE BOILING

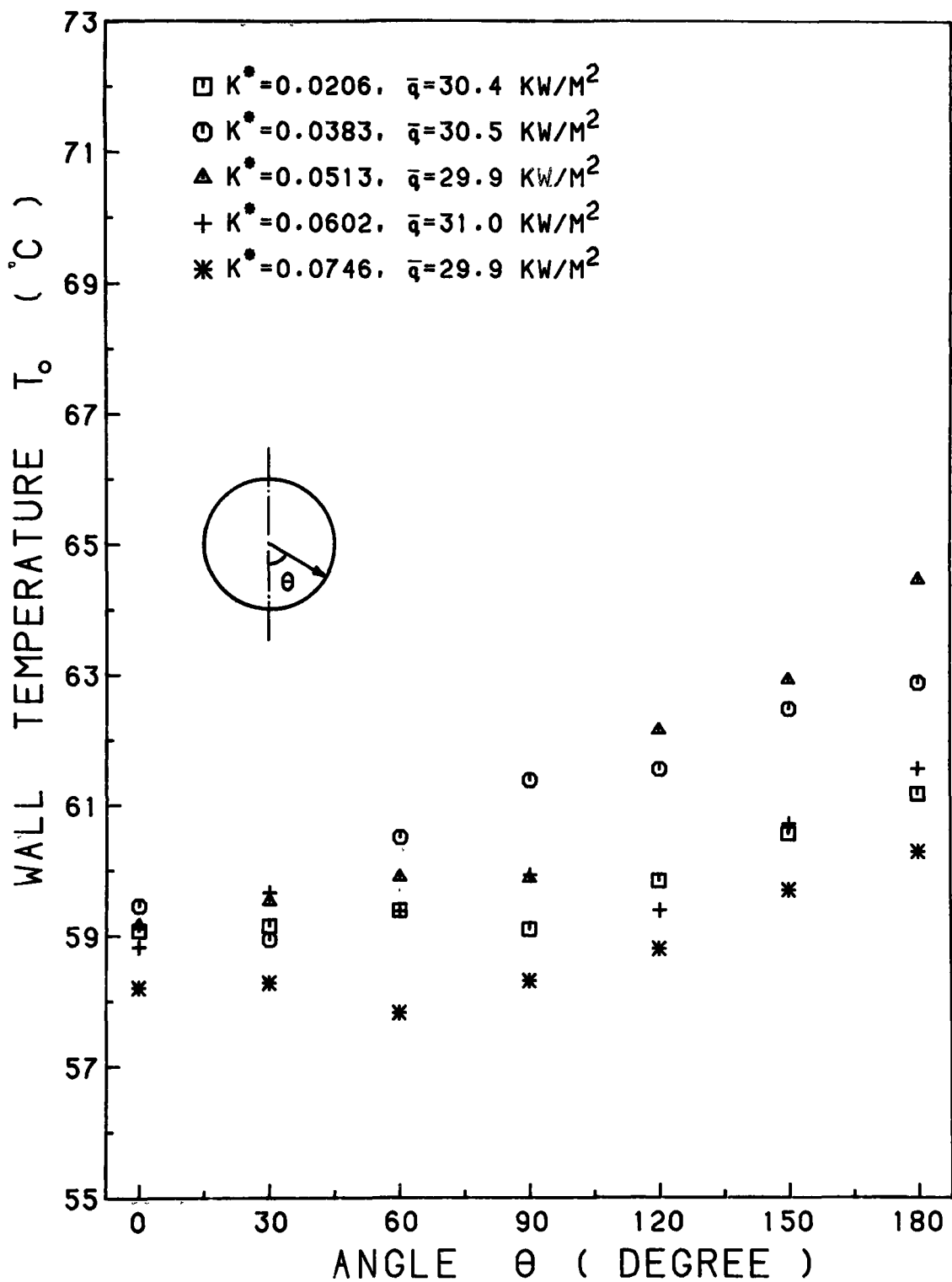


FIGURE 5.1 (b) WALL TEMPERATURE DISTRIBUTION IN NUCLEATE BOILING

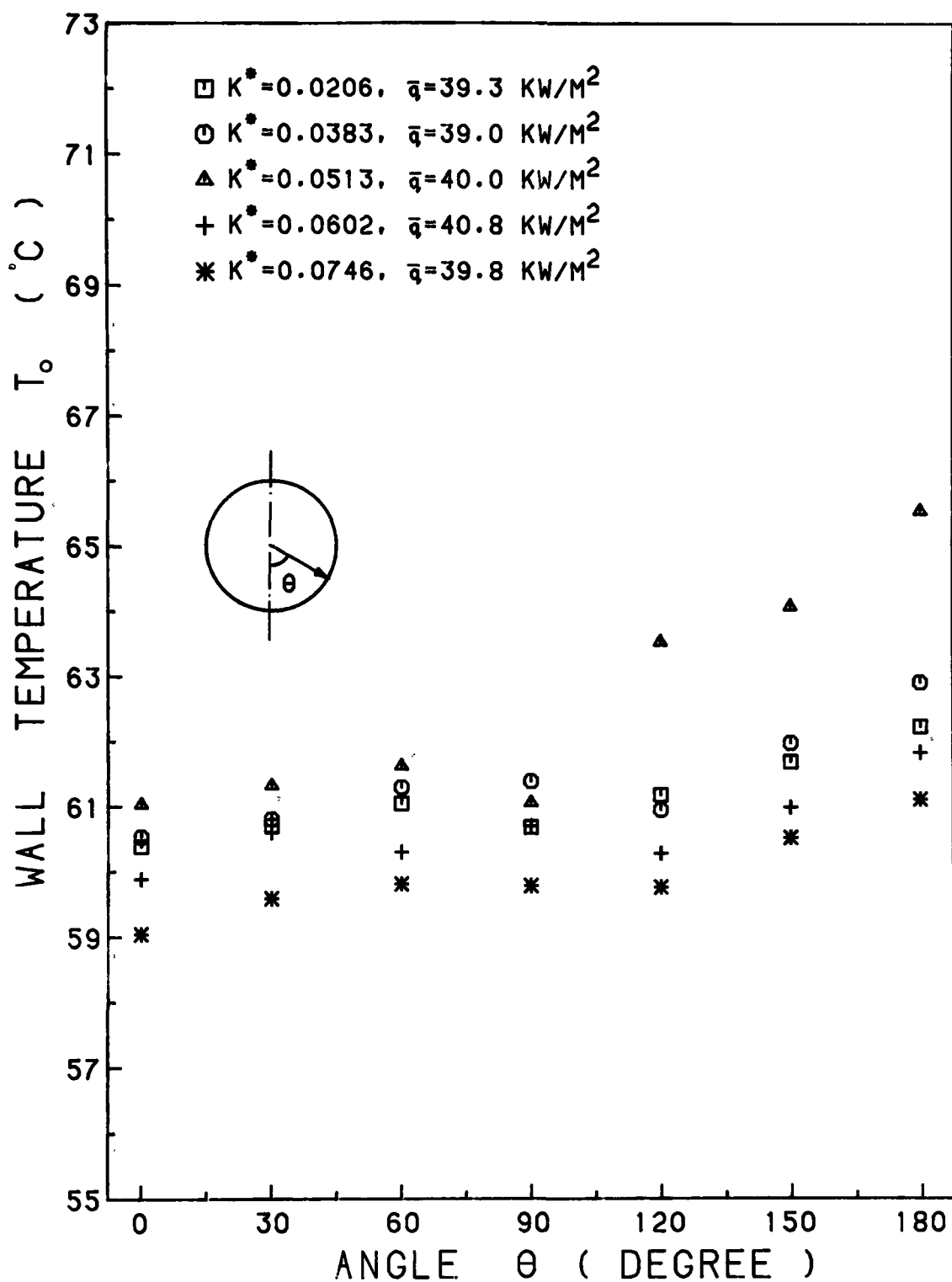


FIGURE 5.1 (c) WALL TEMPERATURE DISTRIBUTION IN NUCLEATE BOILING

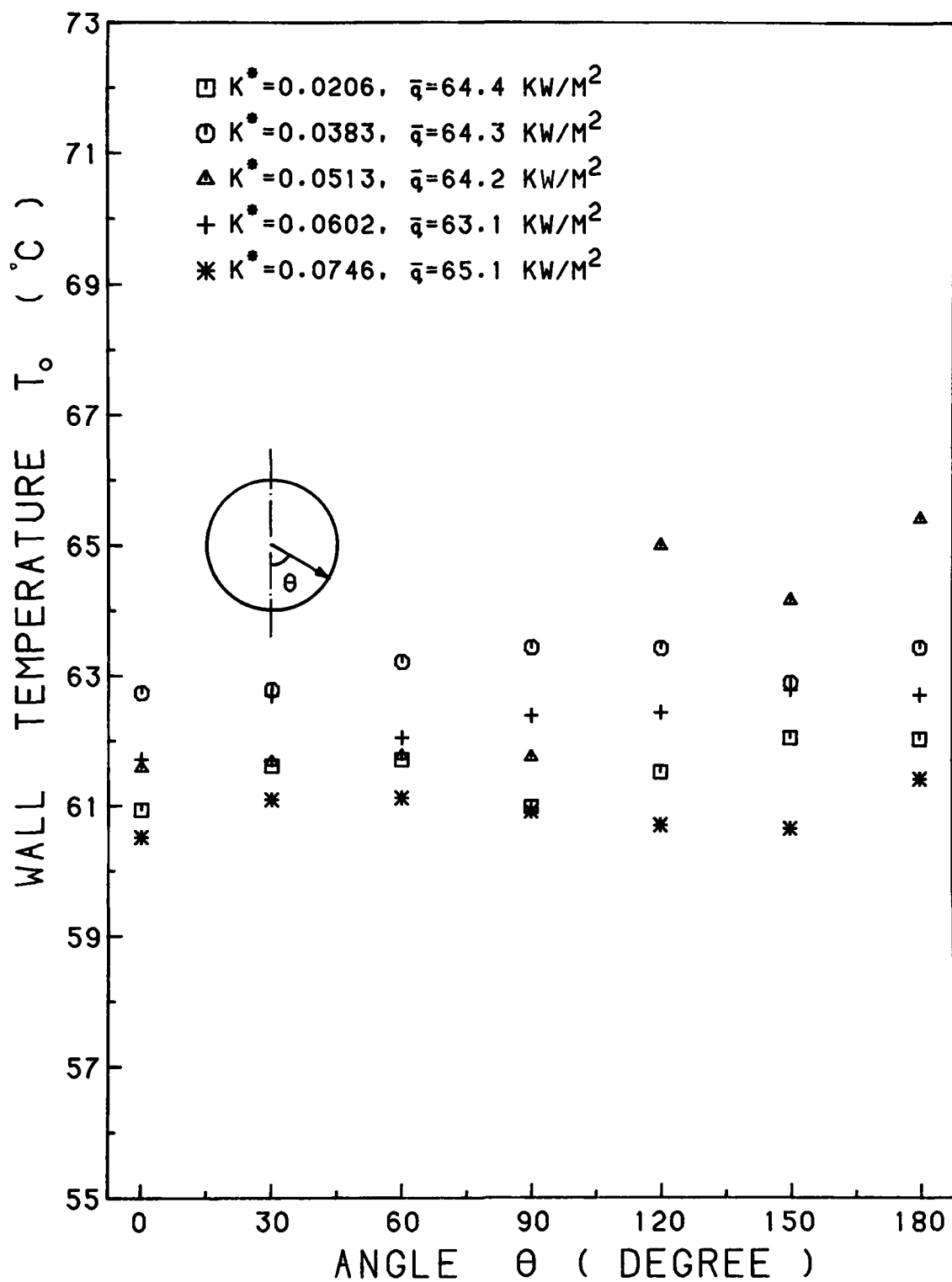


FIGURE 5.1 (d) WALL TEMPERATURE DISTRIBUTION IN NUCLEATE BOILING

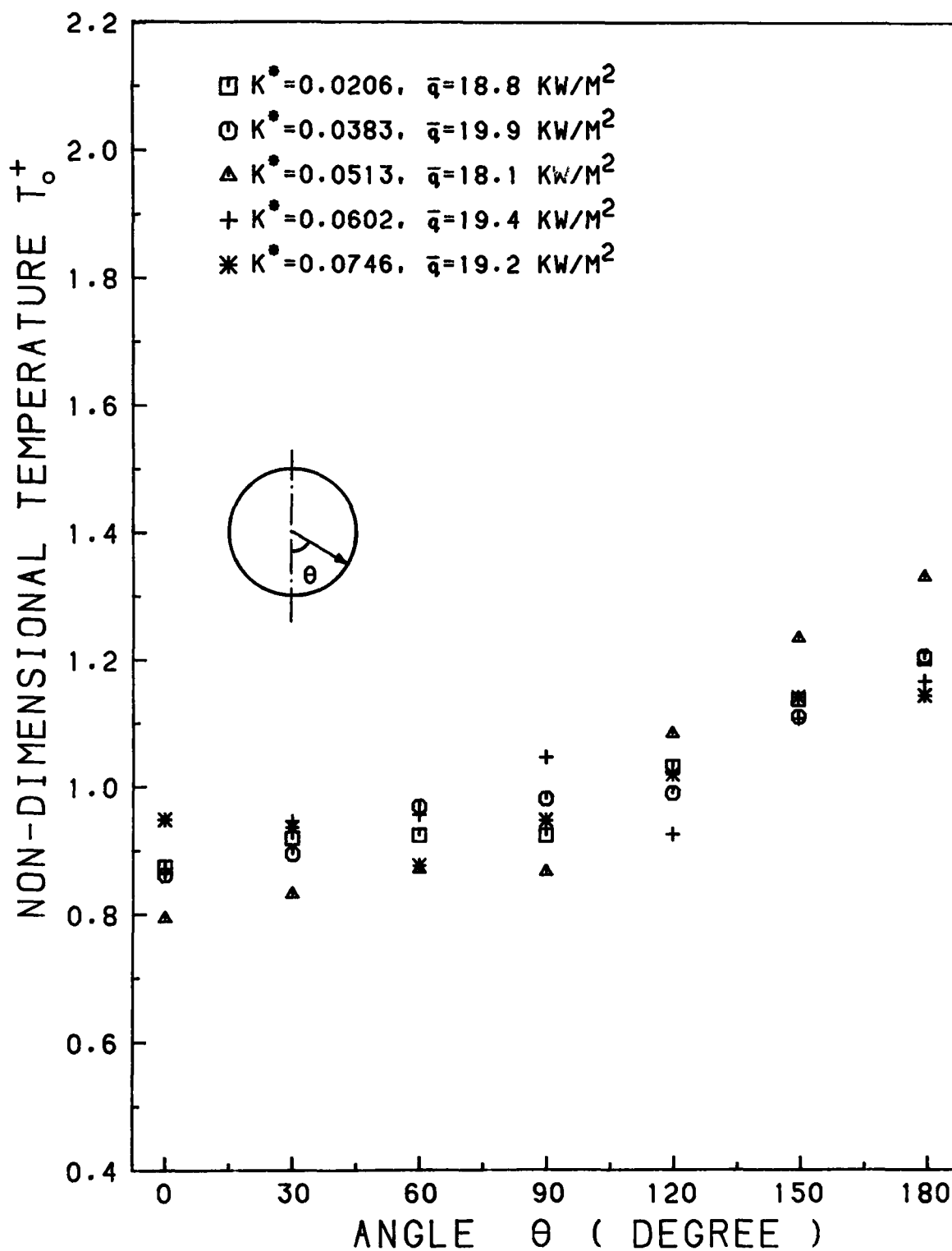


FIGURE 5.2 (a) NON-DIMENSIONAL TEMPERATURE IN NUCLEATE BOILING

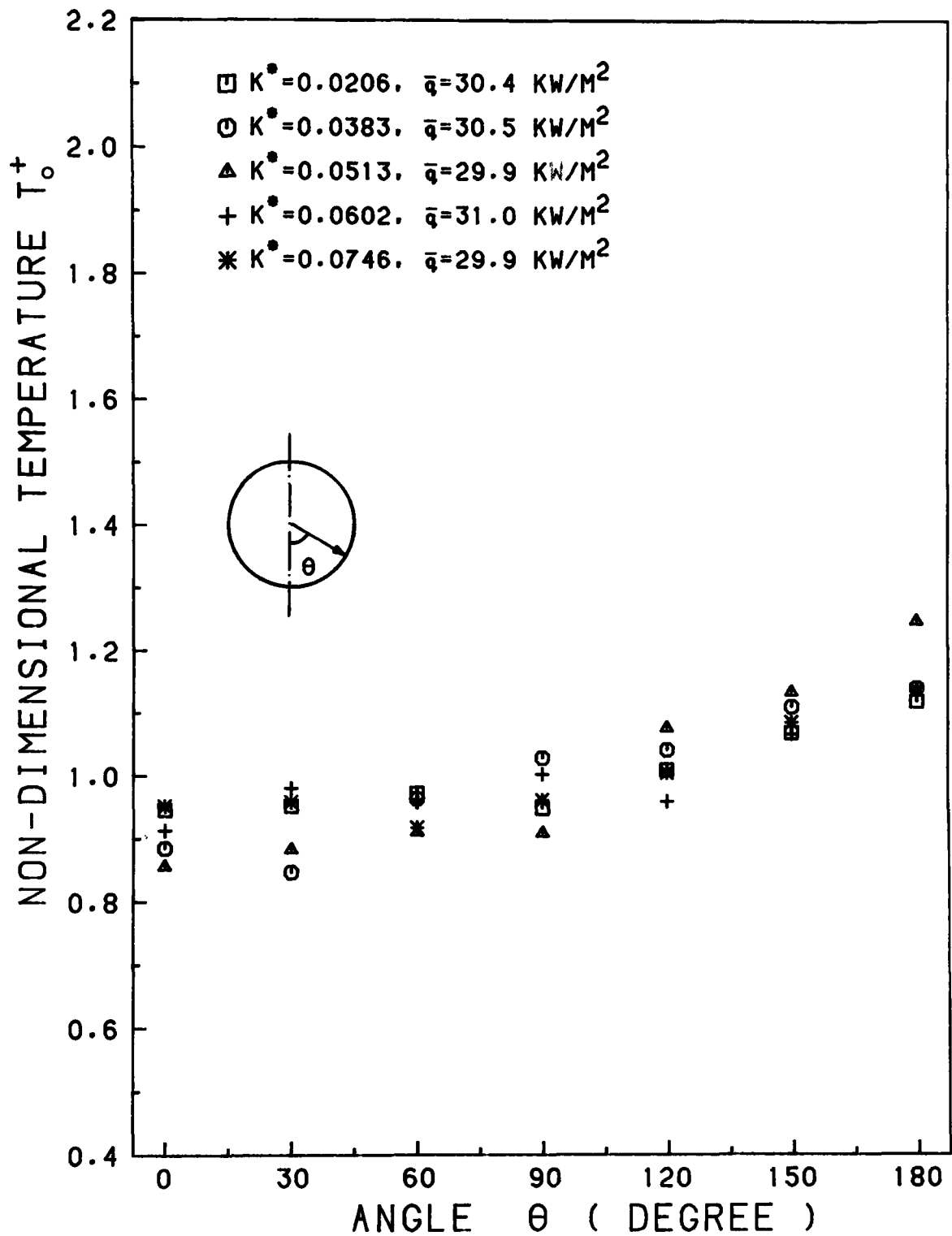


FIGURE 5.2 (b) NON-DIMENSIONAL TEMPERATURE IN NUCLEATE BOILING

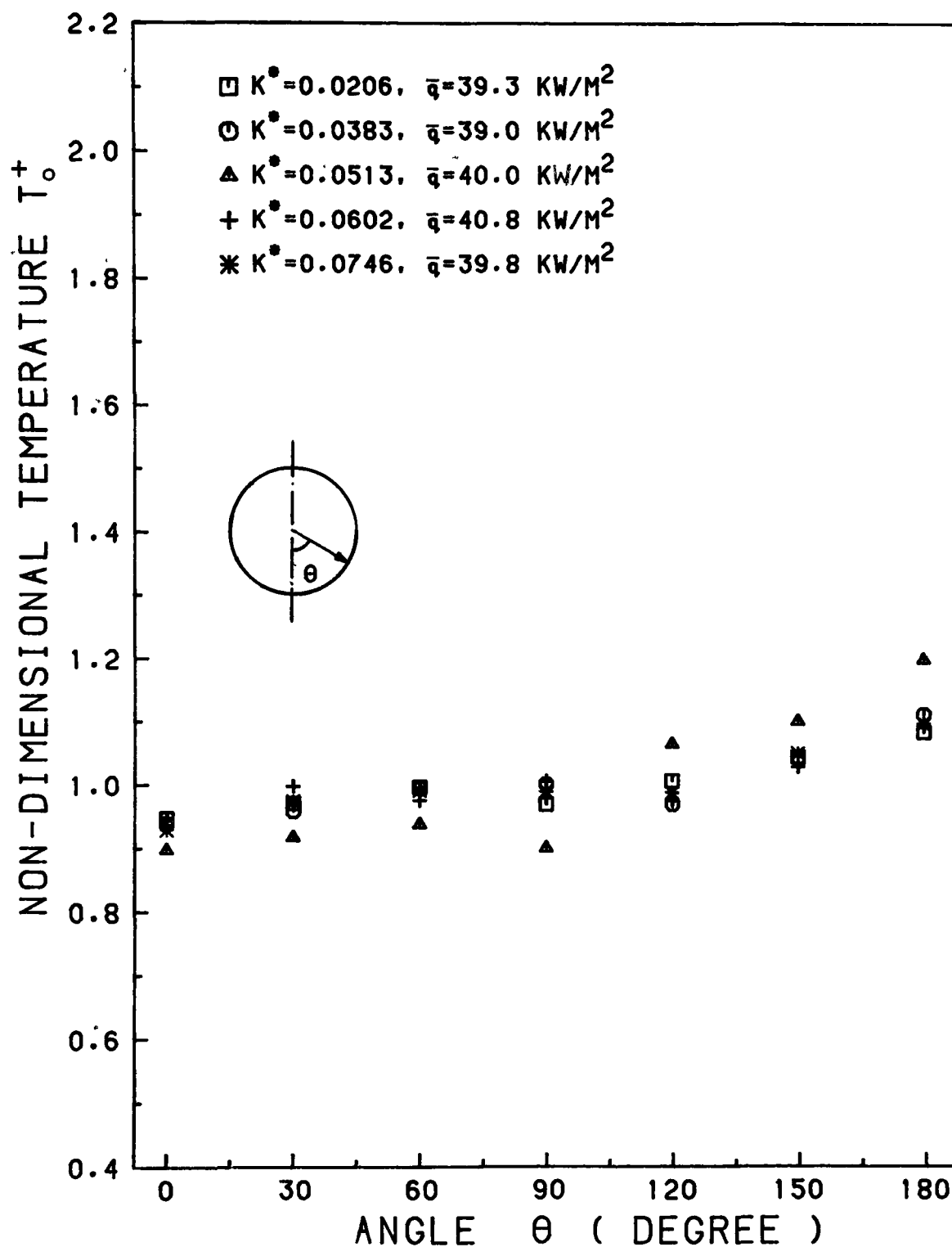


FIGURE 5.2 (c) NON-DIMENSIONAL TEMPERATURE IN NUCLEATE BOILING

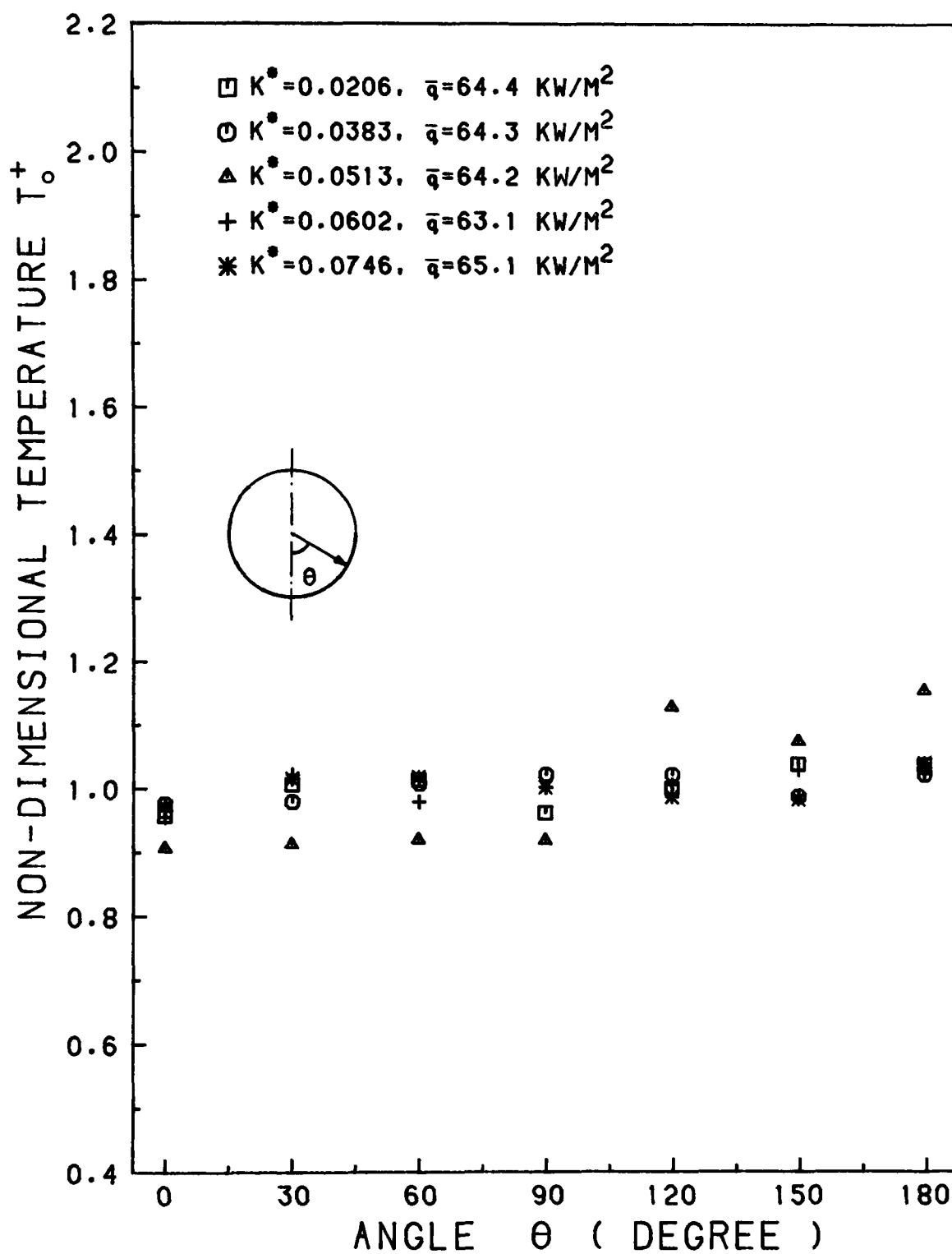


FIGURE 5.2 (d) NON-DIMENSIONAL TEMPERATURE IN NUCLEATE BOILING

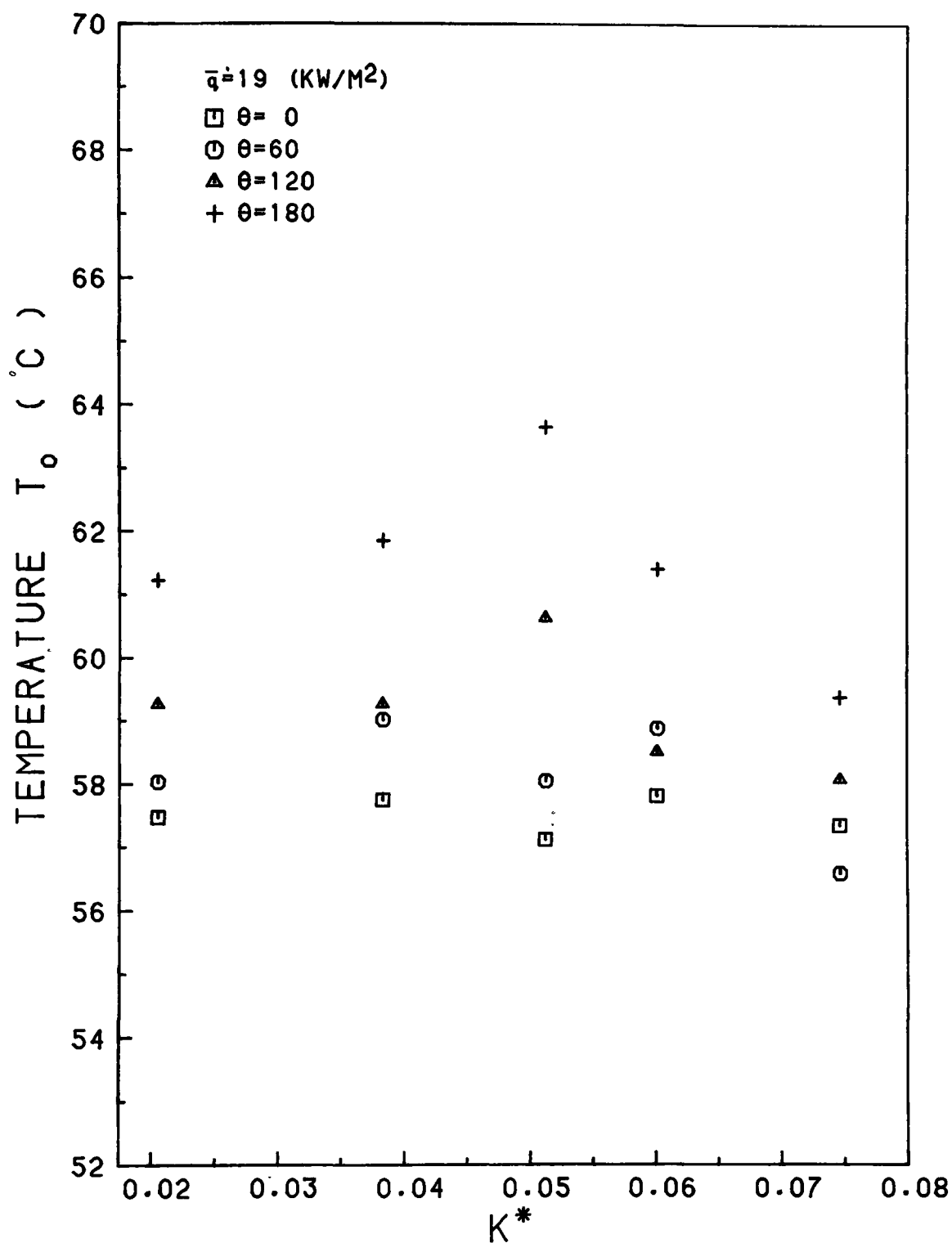


FIGURE 5.3 (a) VARIATION OF
LOCAL TEMPERATURE WITH K^*
IN NUCLEATE BOILING

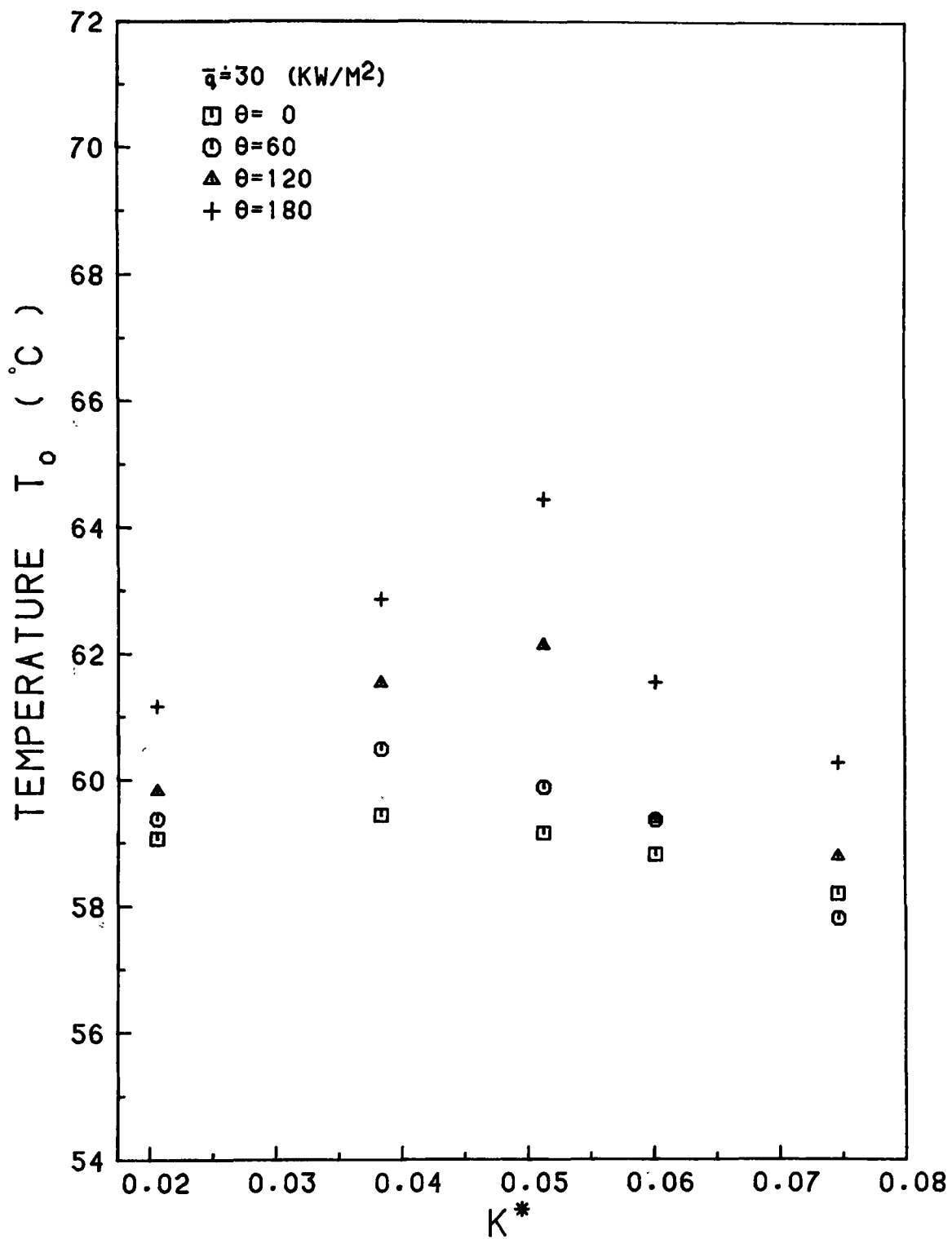


FIGURE 5.3 (b) VARIATION OF
LOCAL TEMPERATURE WITH K^*
IN NUCLEATE BOILING

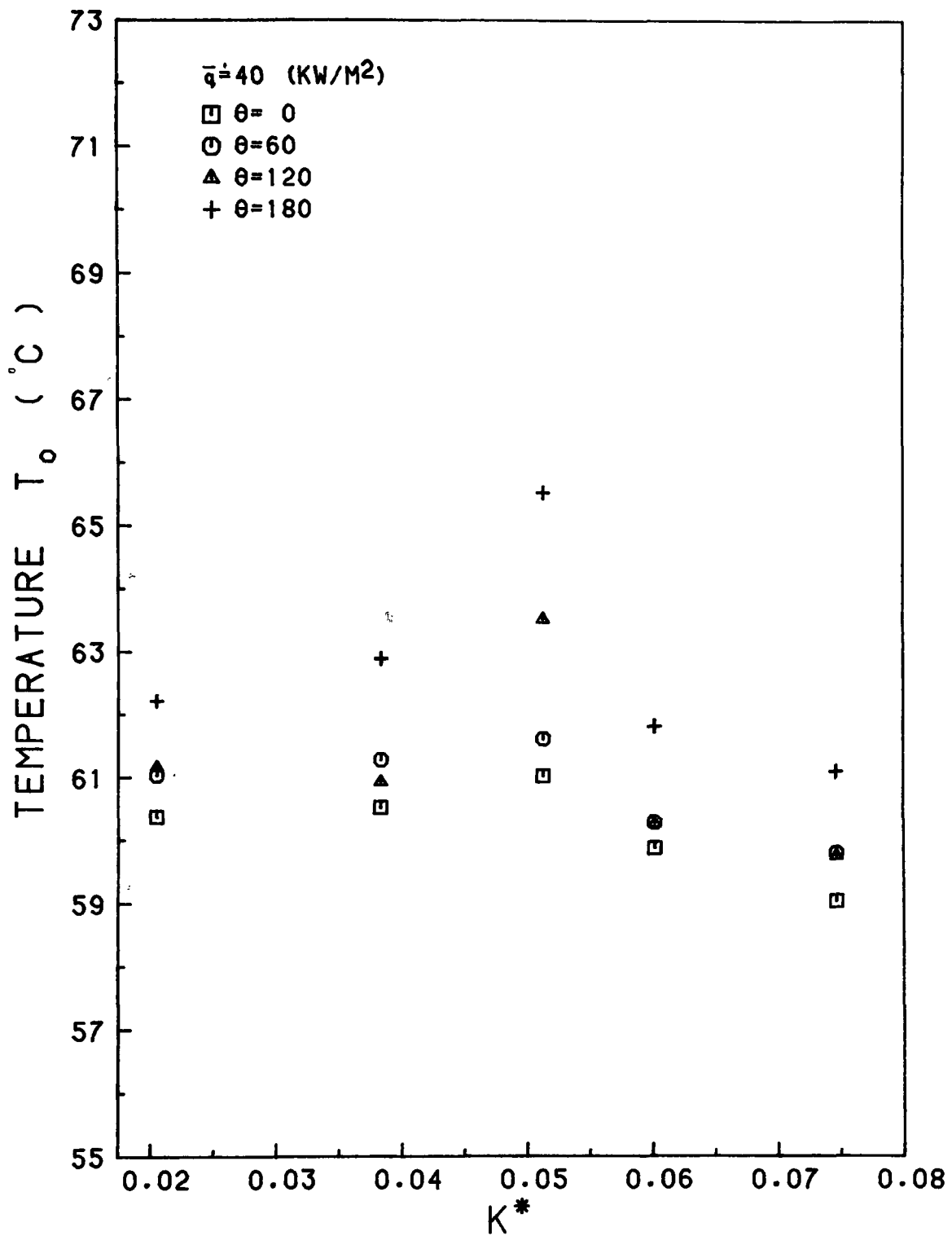


FIGURE 5.3 (c) VARIATION OF
LOCAL TEMPERATURE WITH K^*
IN NUCLEATE BOILING

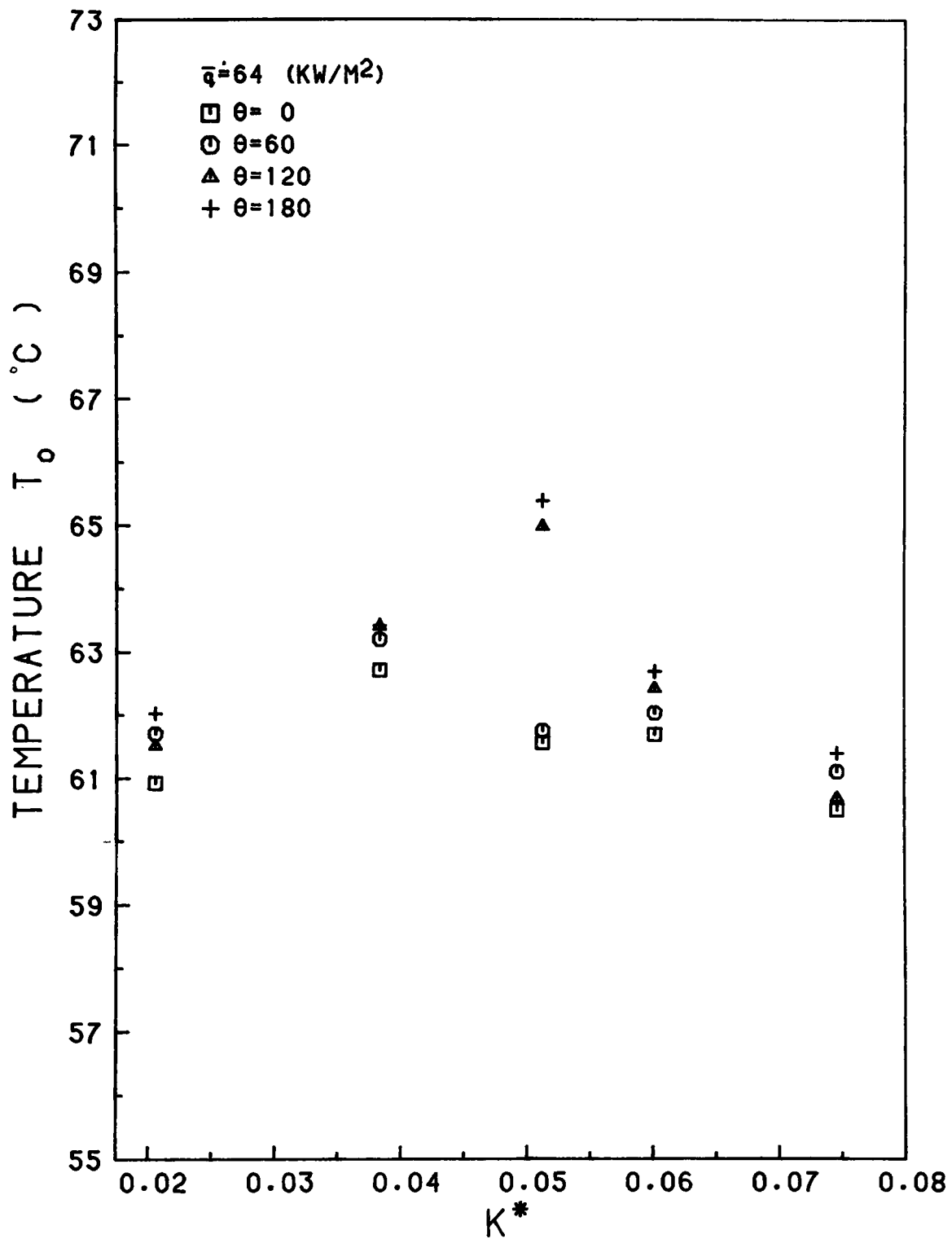


FIGURE 5.3 (d) VARIATION OF
 LOCAL TEMPERATURE WITH K^*
 IN NUCLEATE BOILING

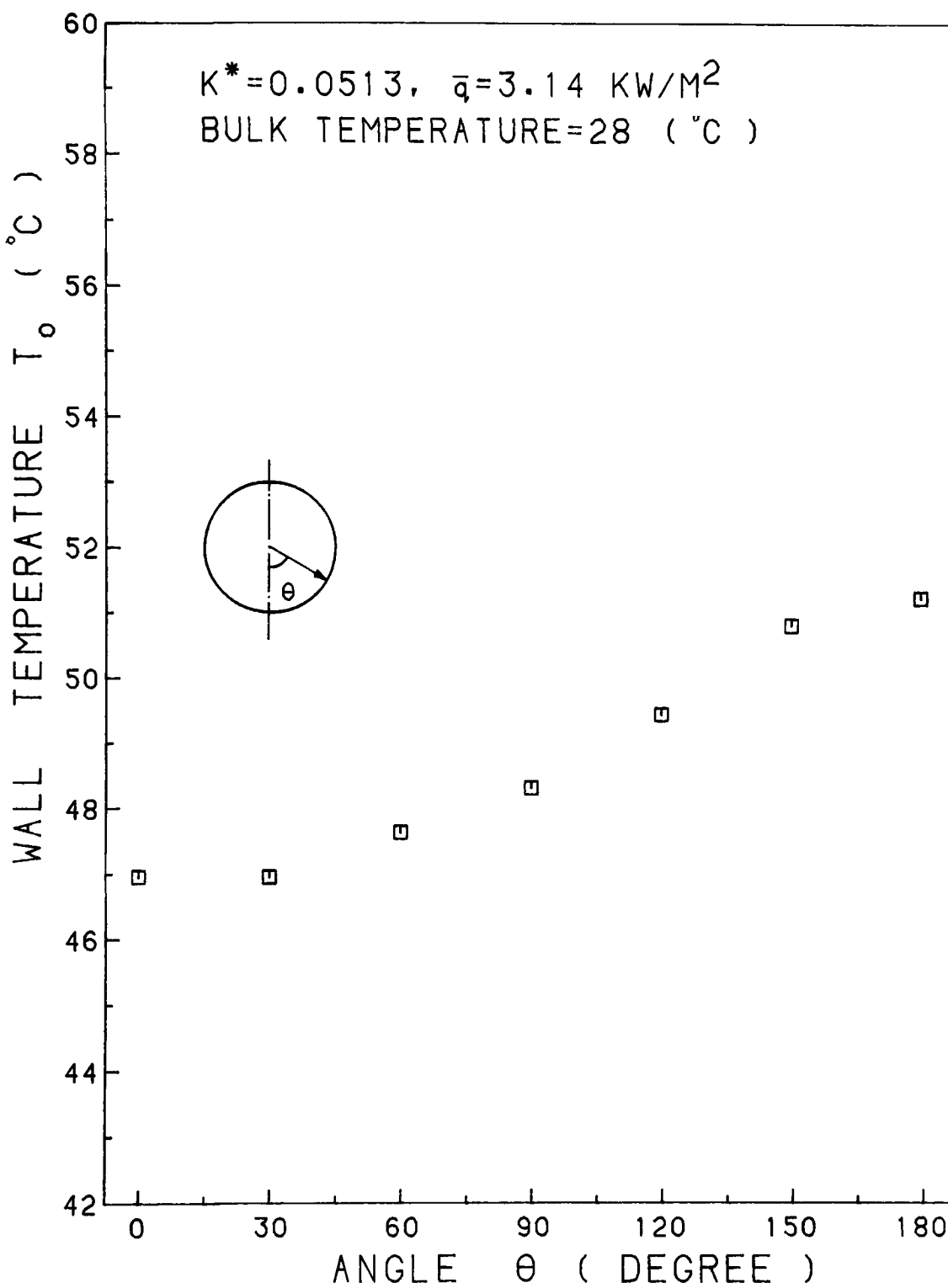


FIGURE 5.4 WALL TEMPERATURE DISTRIBUTION IN NATURAL CONVECTION

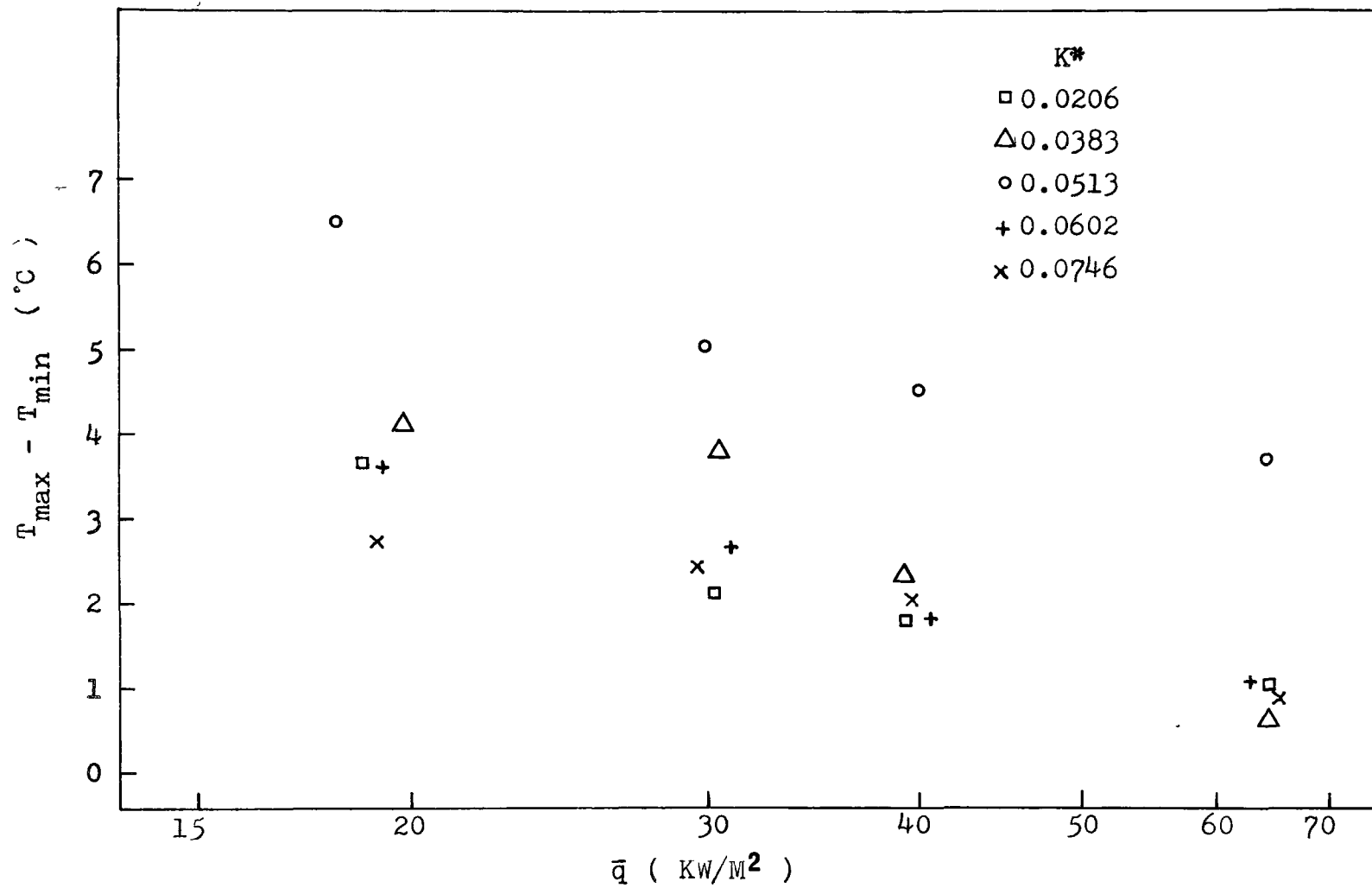


Figure 5.5 Maximum Wall Temperature Variations
With Power In Nucleate Boiling

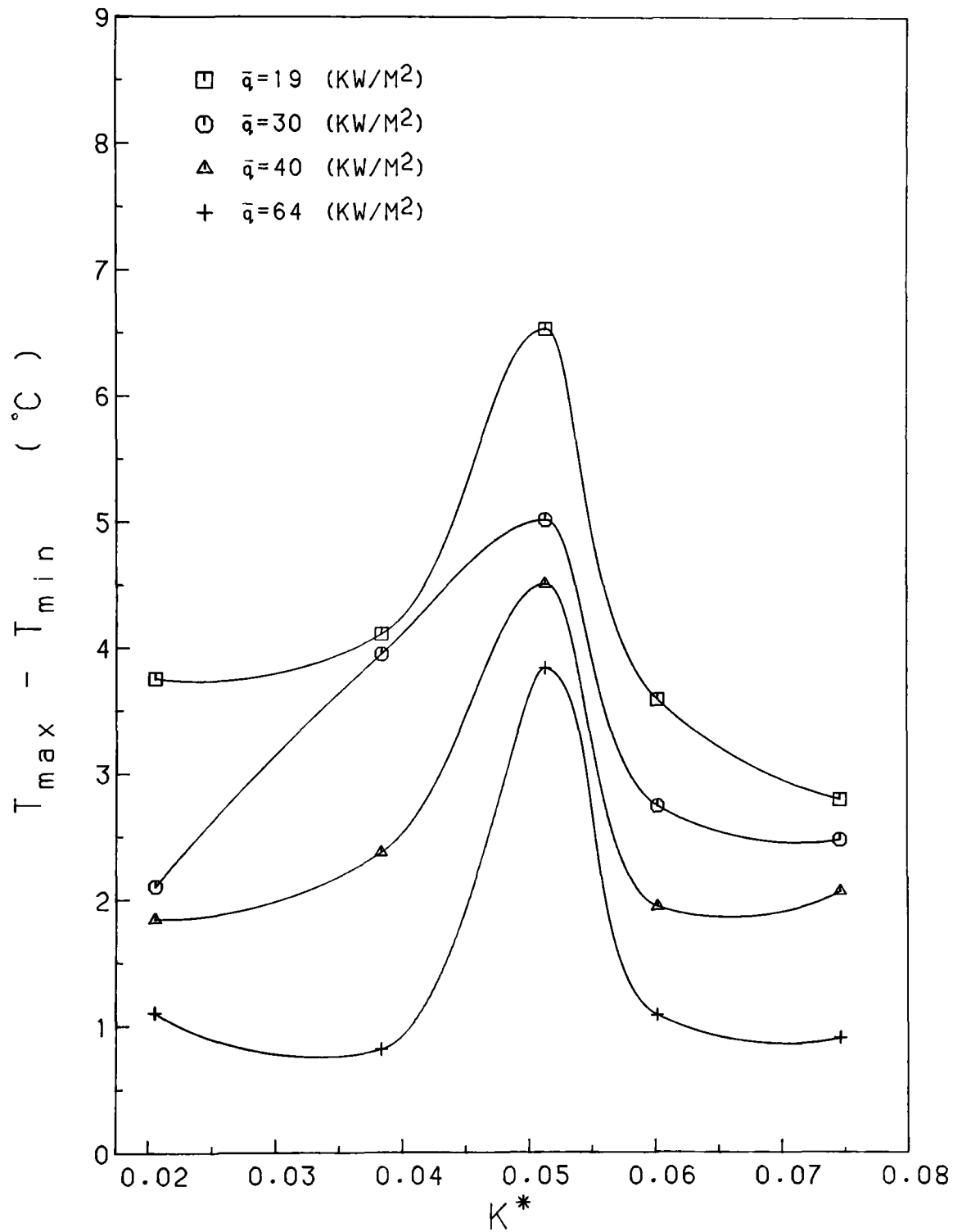


FIGURE 5.6 MAXIMUM WALL TEMPERATURE VARIATIONS WITH K^* IN NUCLEATE BOILING

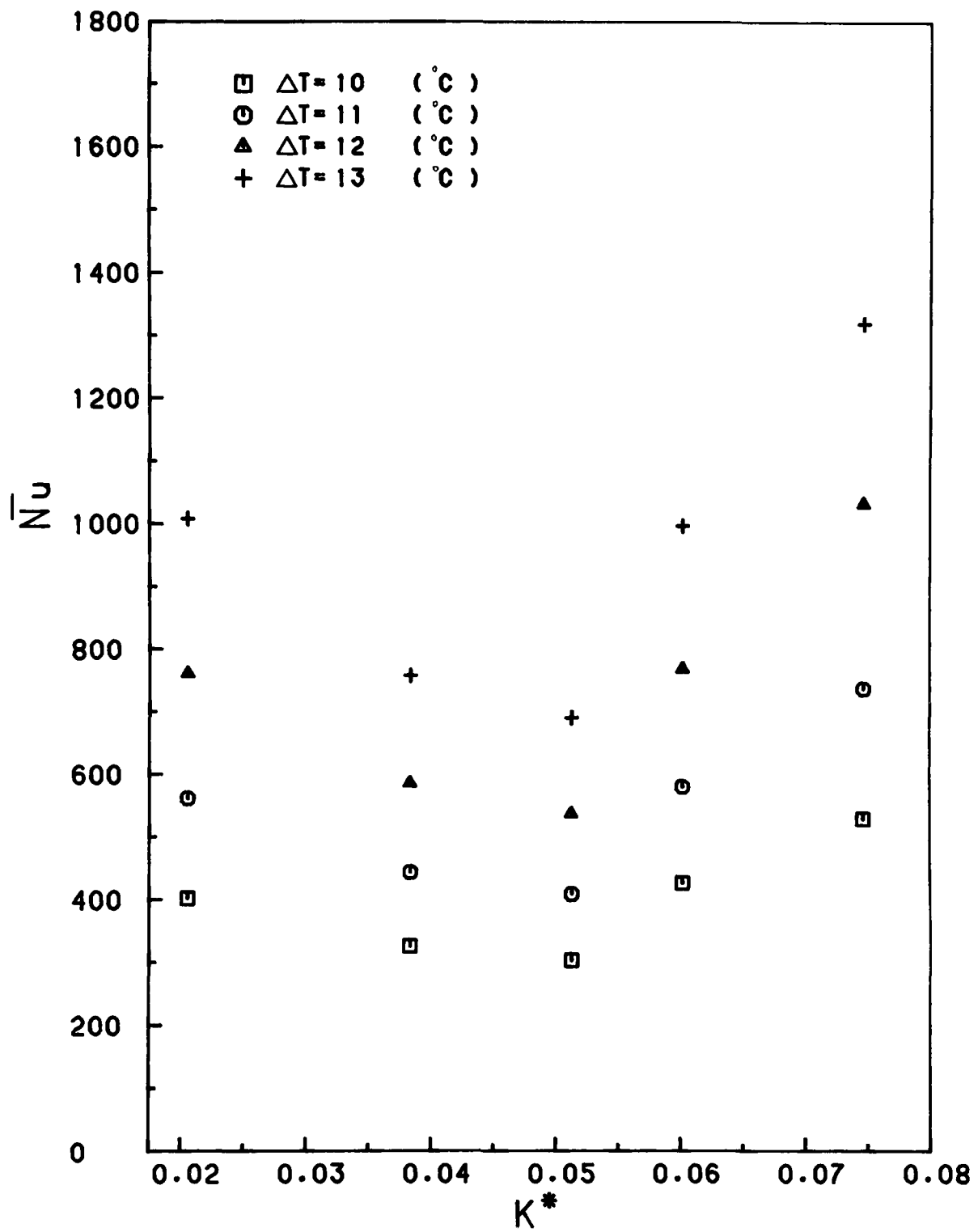


FIGURE 5.7 (a) EFFECT OF K^* ON AVERAGE Nu IN NUCLEATE BOILING

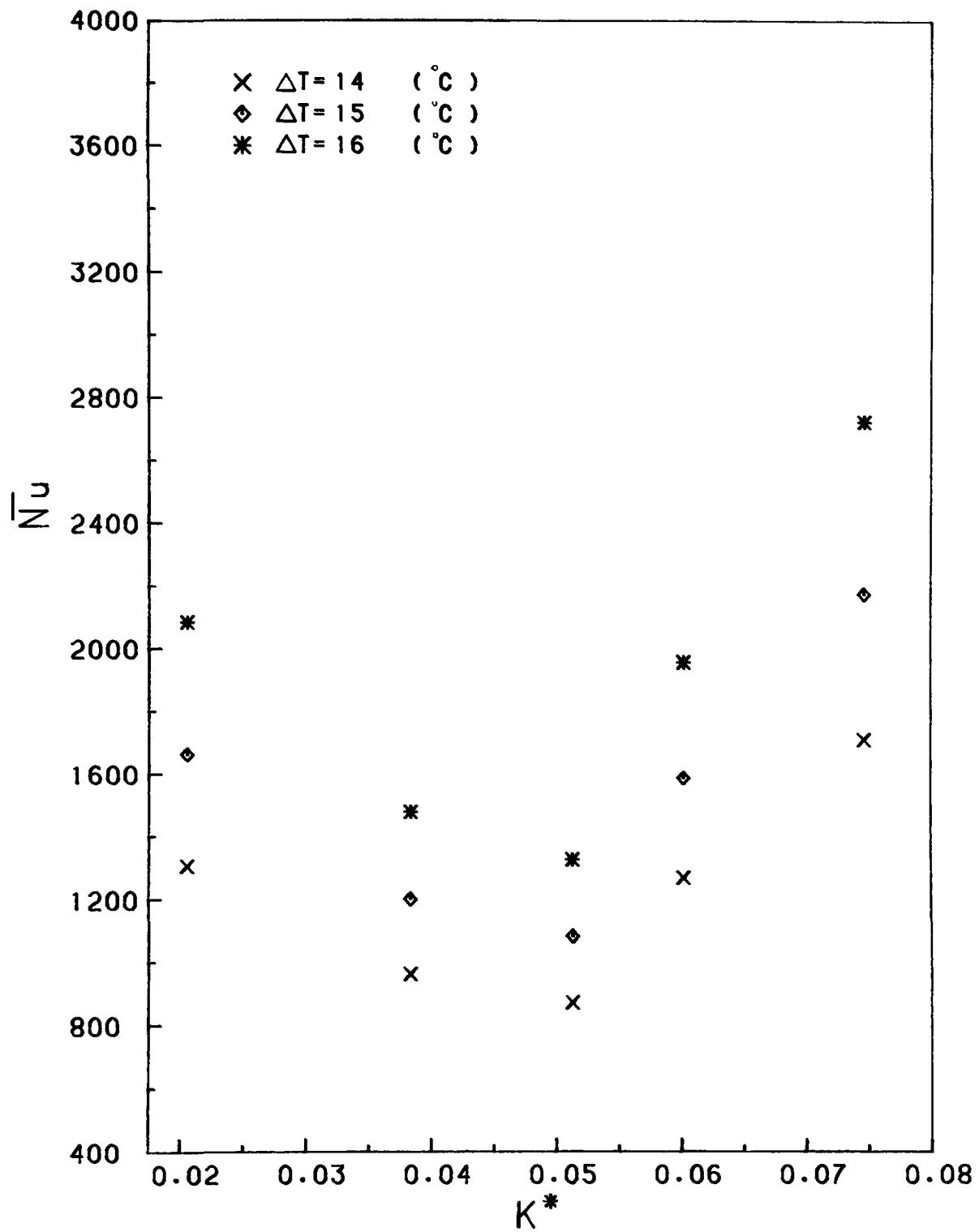


FIGURE 5.7 (b) EFFECT OF K^* ON AVERAGE Nu IN NUCLEATE BOILING

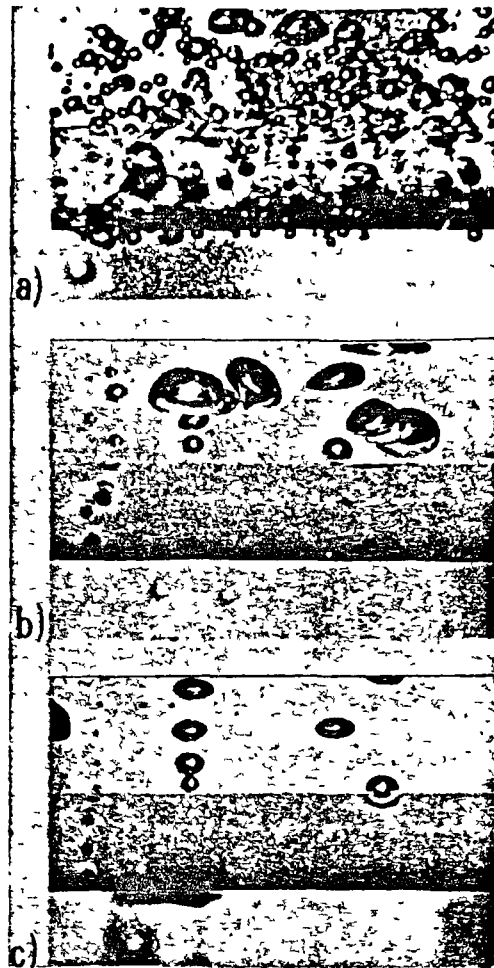


Figure 5.8 (a) Influence Of Nickel Thickness On Bubble Population: [58]
 (a) $b = 5 \mu\text{m}$, $\bar{q} = 24 \text{ KW/M}^2$, $\Delta T = 4^\circ\text{C}$
 (b) $b = 50 \mu\text{m}$, $\bar{q} = 24 \text{ KW/M}^2$, $\Delta T = 8^\circ\text{C}$
 (c) $b = 50 \mu\text{m}$, $\bar{q} = 10 \text{ KW/M}^2$, $\Delta T = 4^\circ\text{C}$

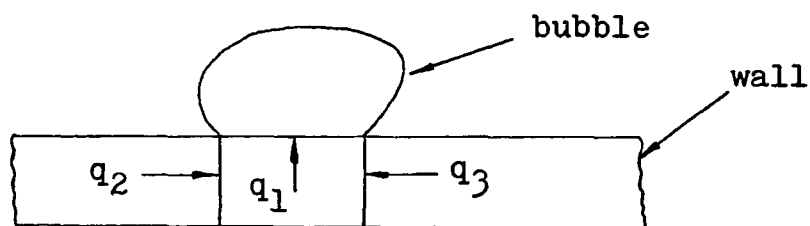


Figure 5.8 (b) Heat Transfer On The Thick Wall

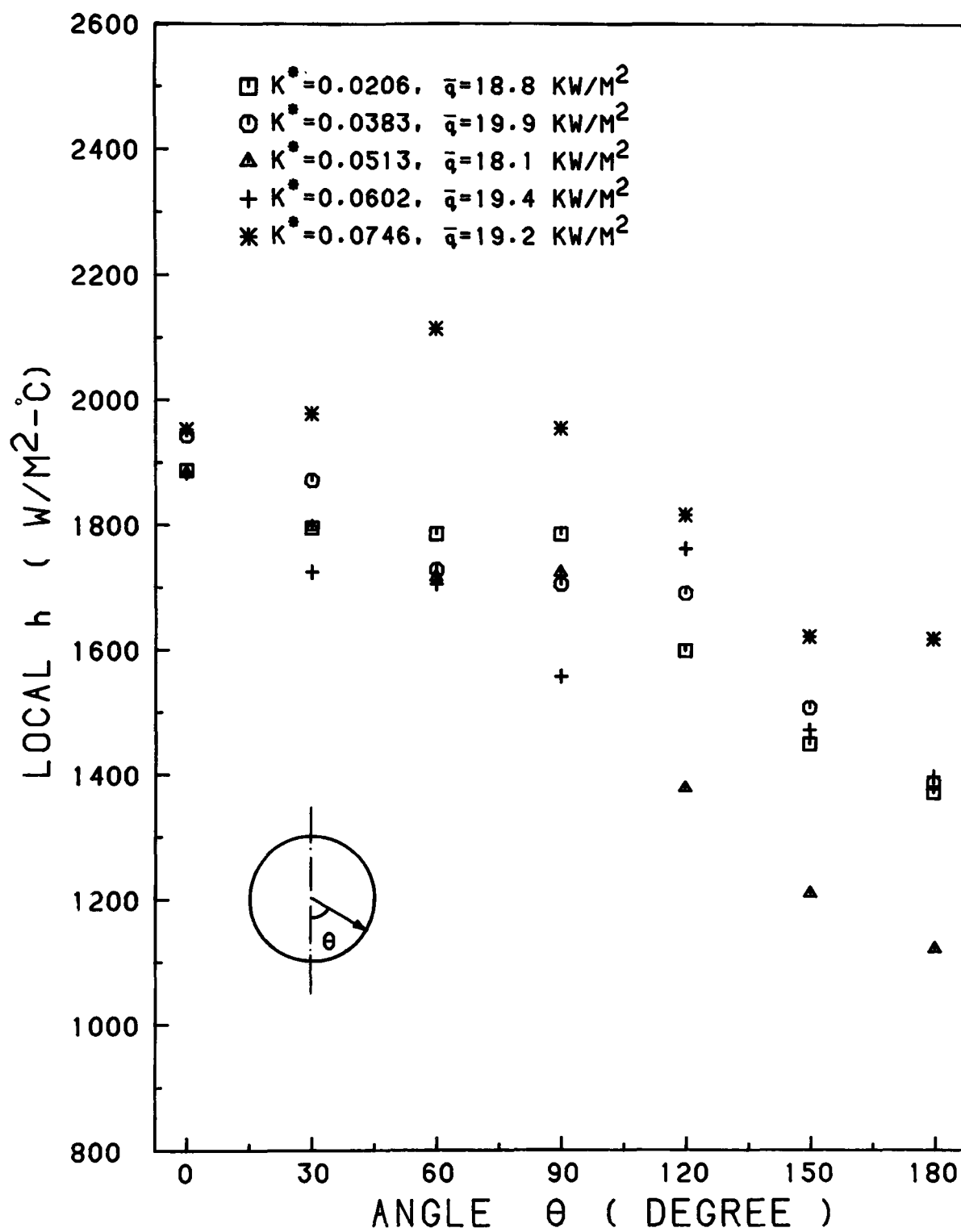


FIGURE 5.9 (a) DISTRIBUTION OF LOCAL h IN NUCLEATE BOILING

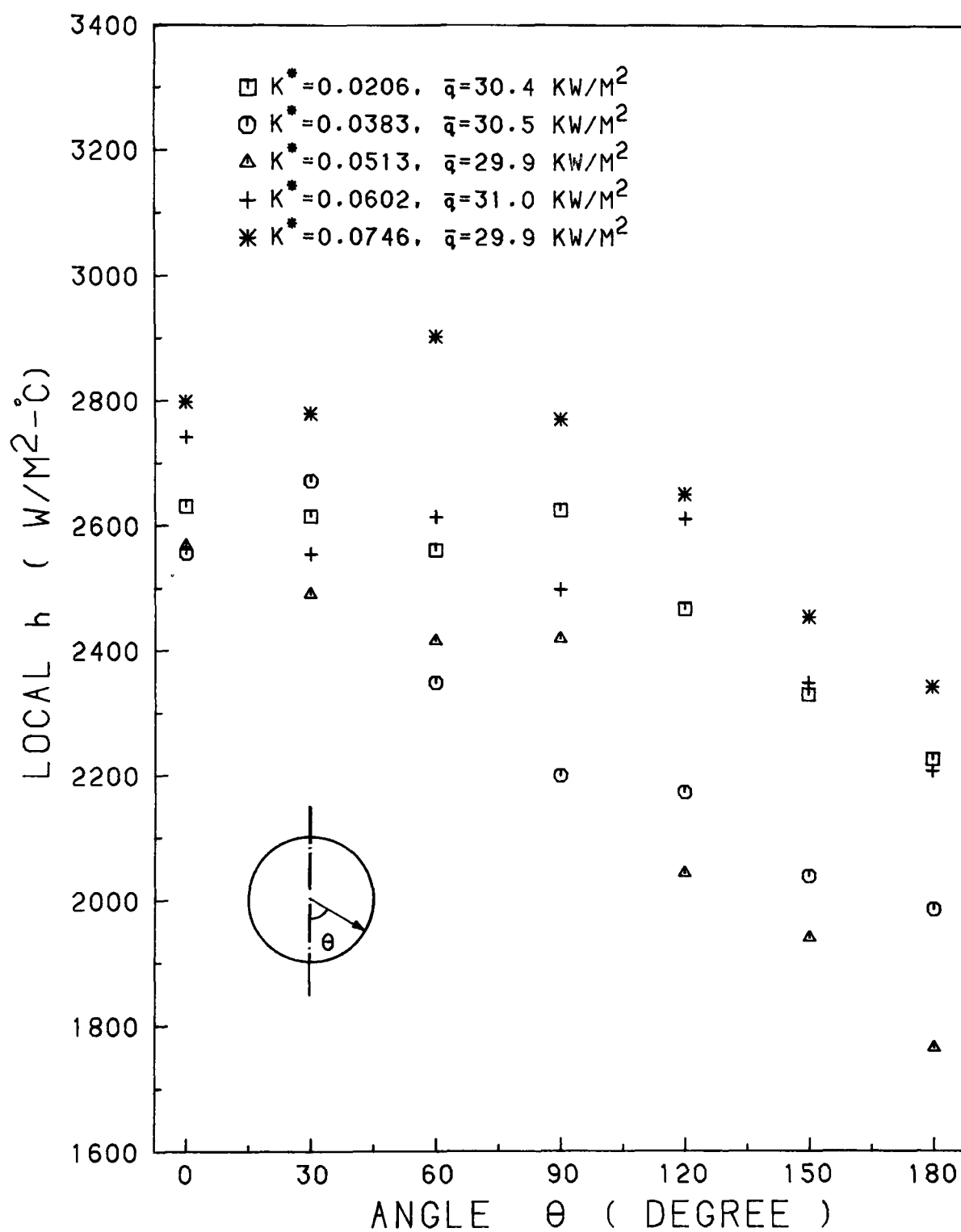


FIGURE 5.9 (b) DISTRIBUTION OF LOCAL h IN NUCLEATE BOILING

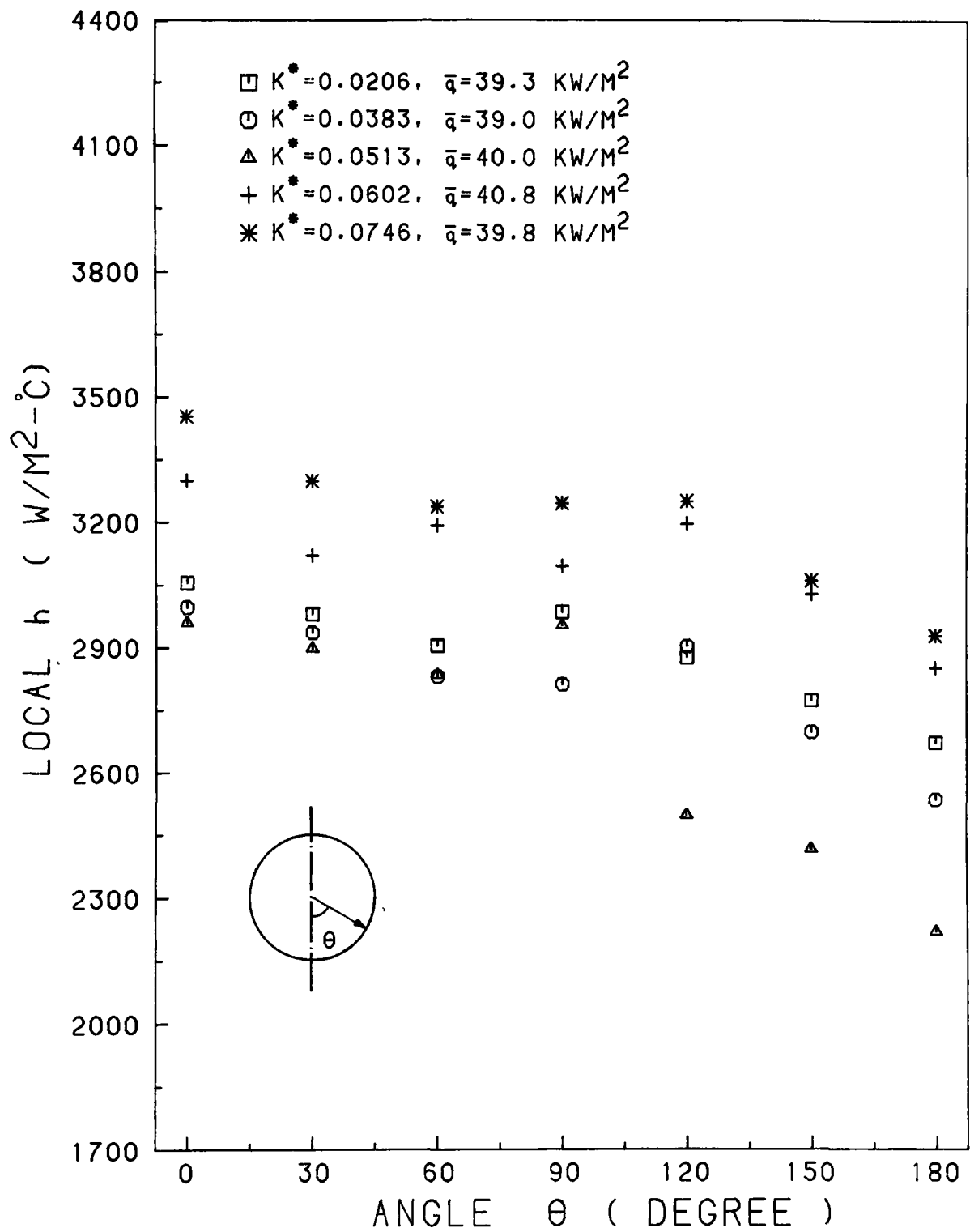


FIGURE 5.9 (c) DISTRIBUTION OF LOCAL h IN NUCLEATE BOILING

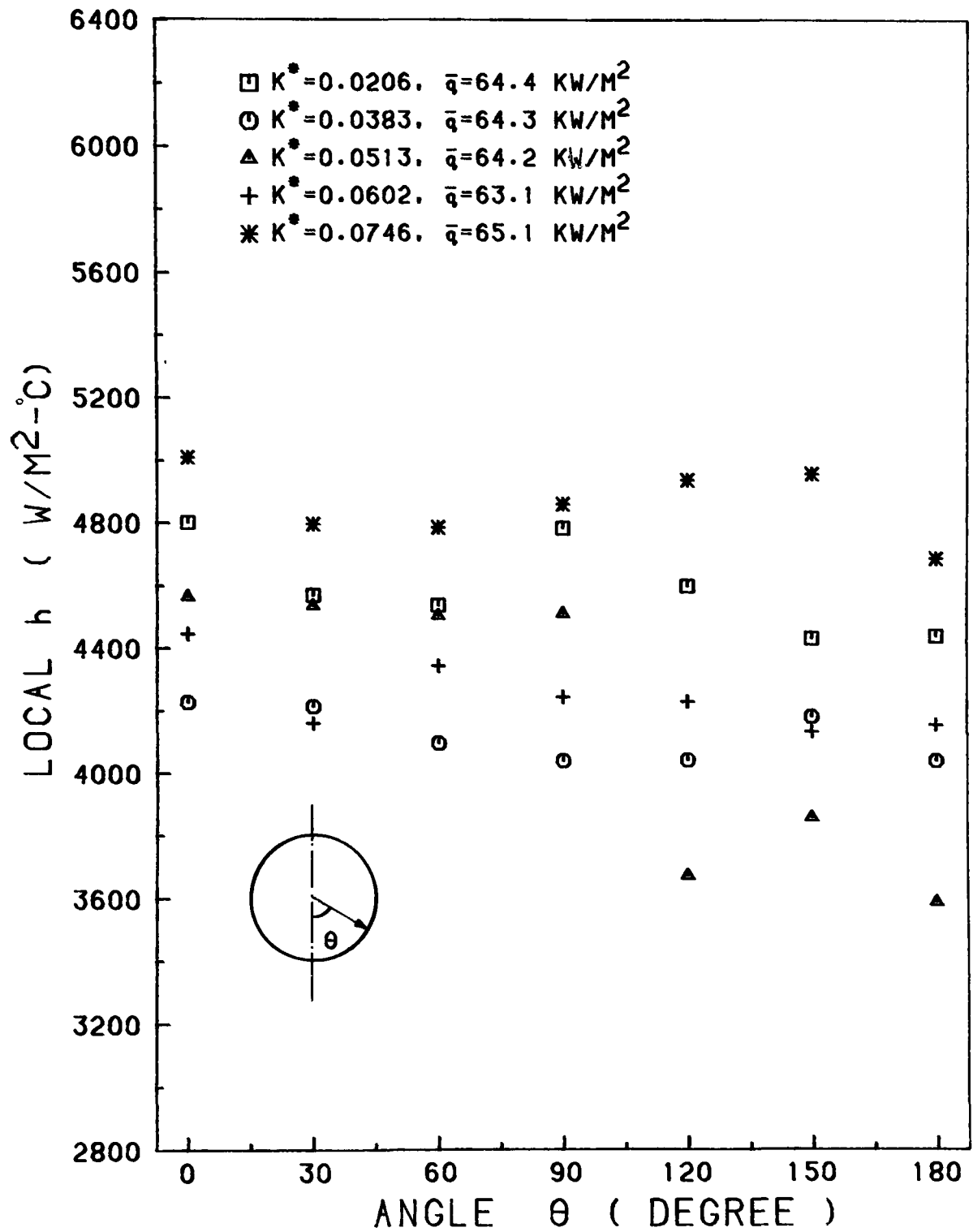


FIGURE 5.9 (d) DISTRIBUTION OF LOCAL h IN NUCLEATE BOILING

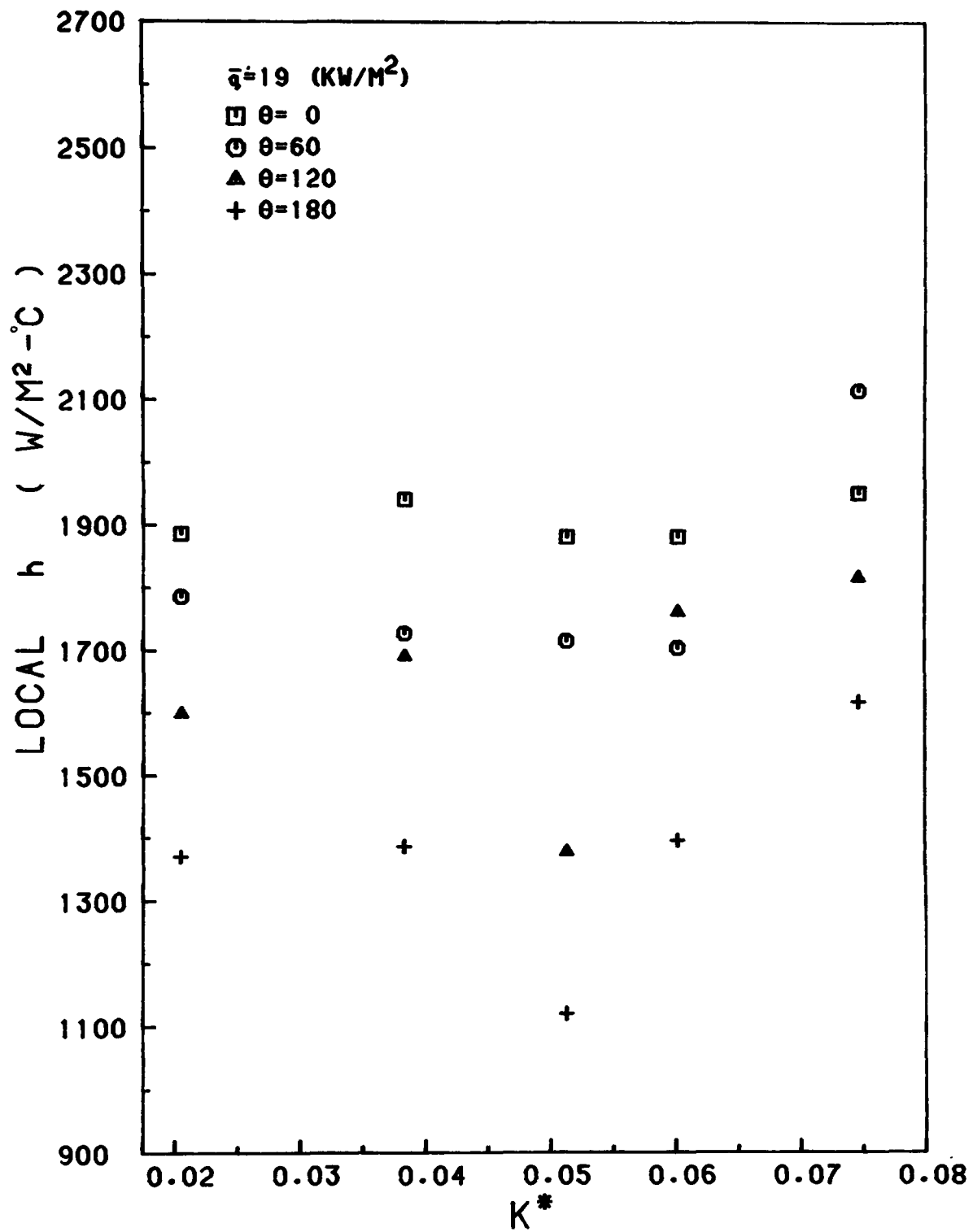


FIGURE 5.10 (a) EFFECT OF K^* ON
LOCAL HEAT TRANSFER COEFFICIENT
IN NUCLEATE BOILING REGION

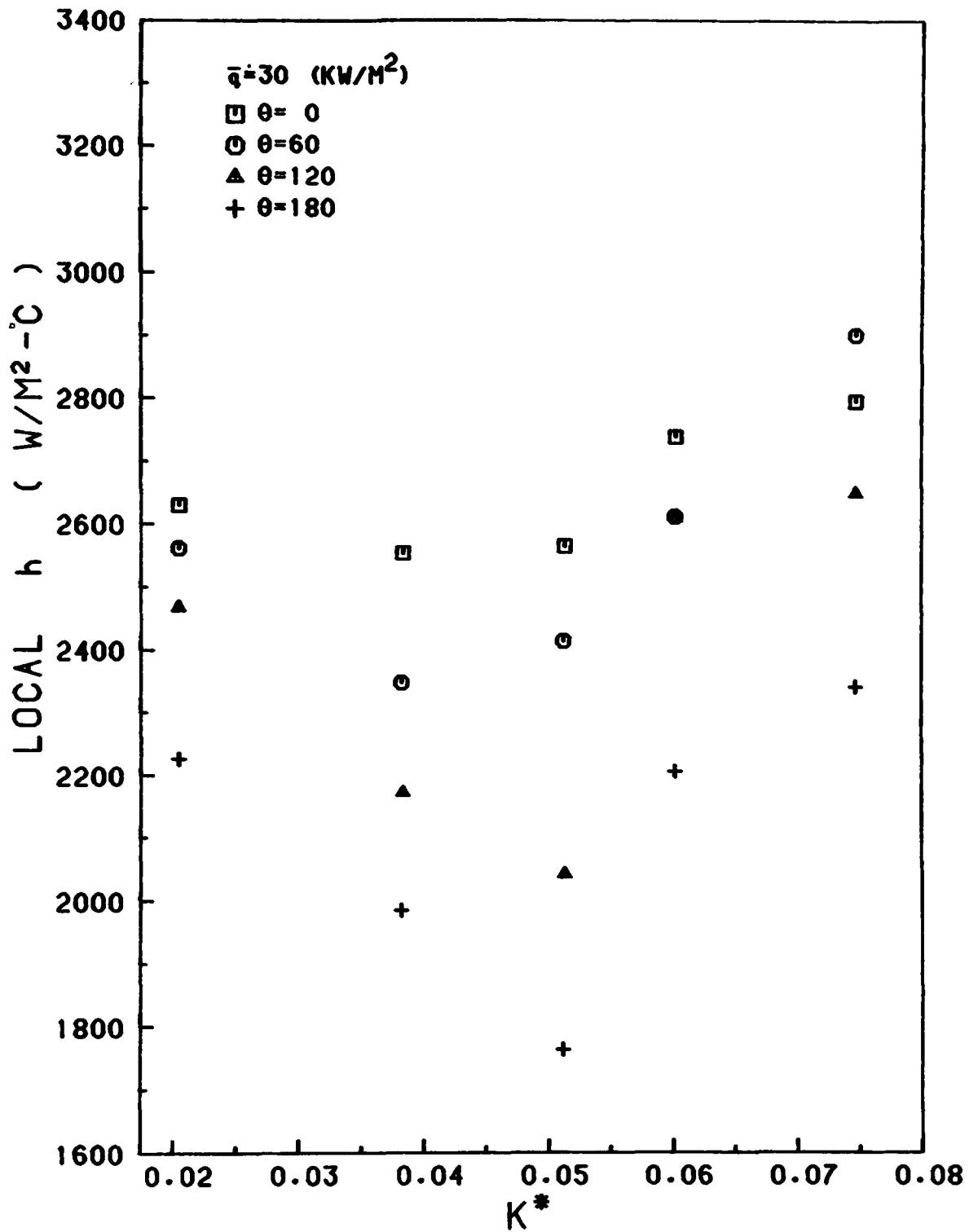


FIGURE 5.10 (b) EFFECT OF K^* ON LOCAL HEAT TRANSFER COEFFICIENT IN NUCLEATE BOILING REGION

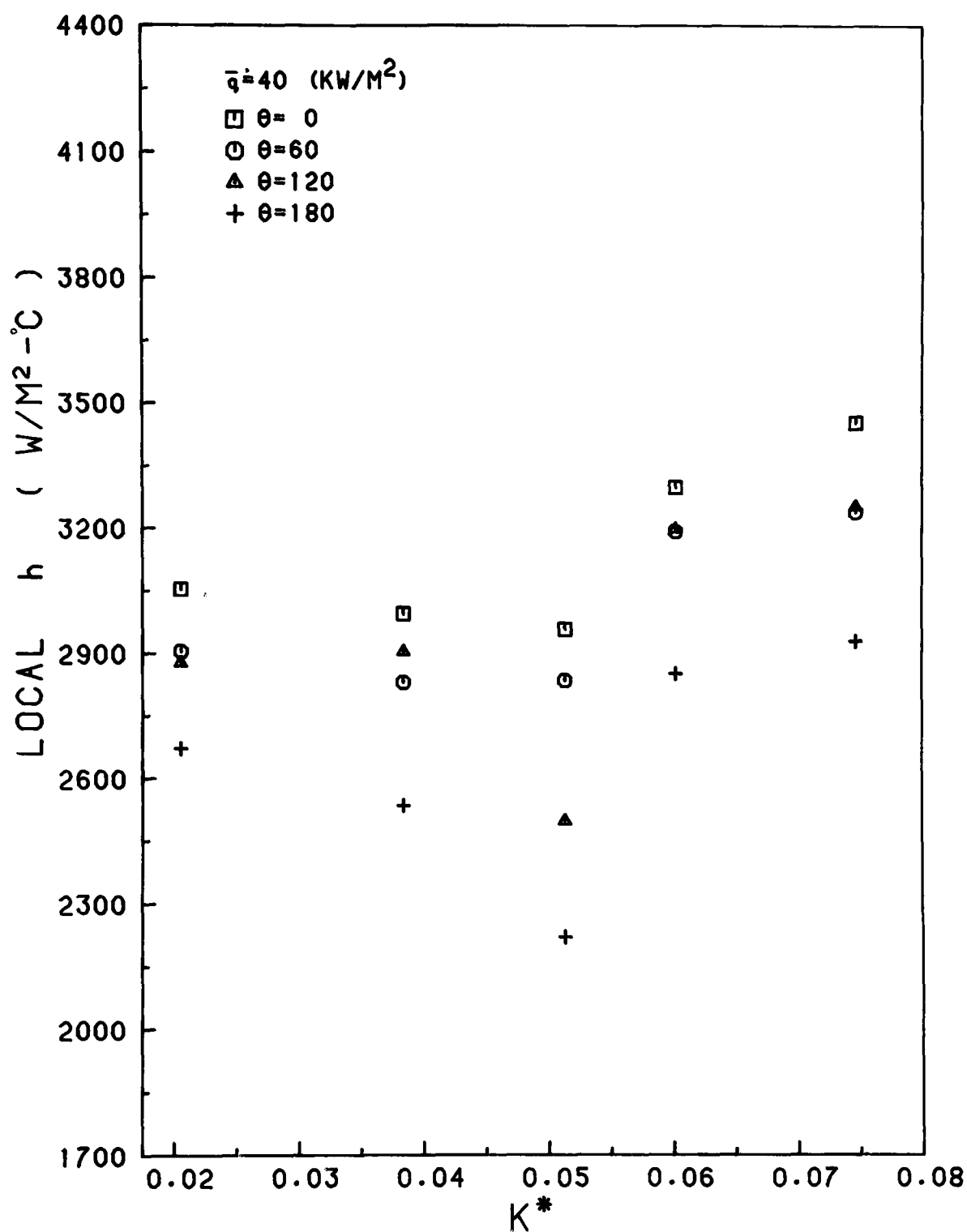


FIGURE 5.10 (c) EFFECT OF K^* ON
LOCAL HEAT TRANSFER COEFFICIENT
IN NUCLEATE BOILING REGION

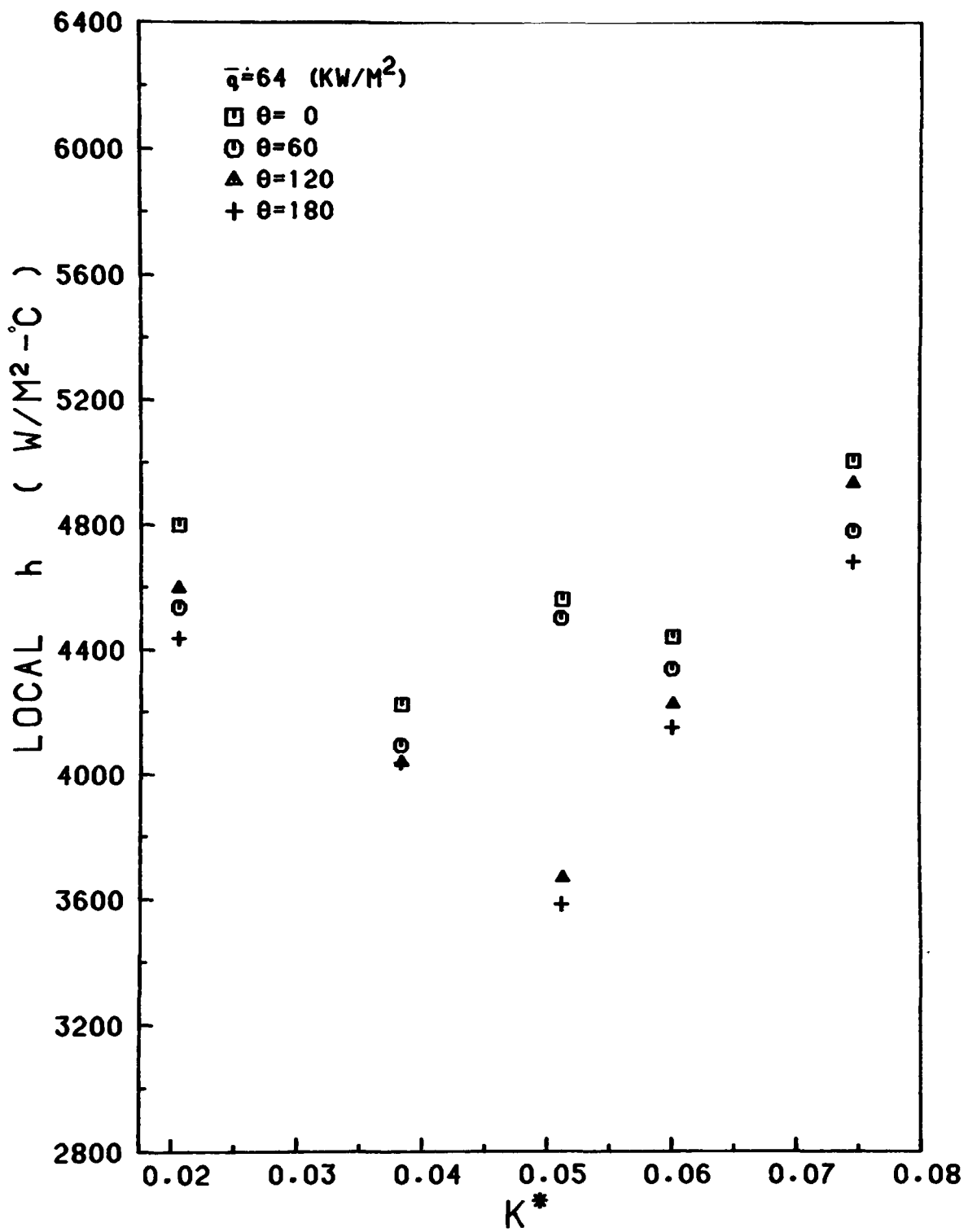


FIGURE 5.10 (d) EFFECT OF K^* ON
LOCAL HEAT TRANSFER COEFFICIENT
IN NUCLEATE BOILING REGION

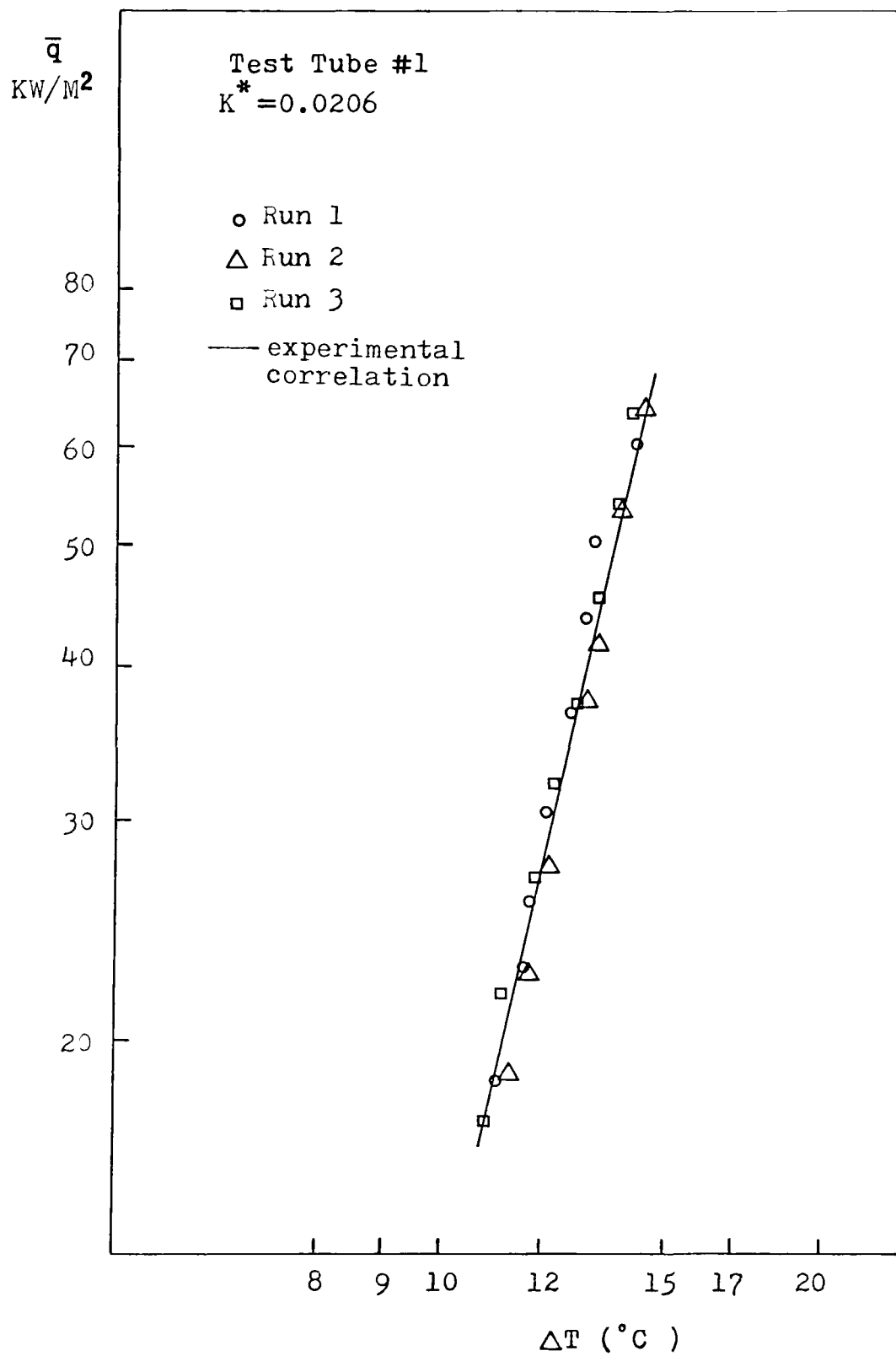


Figure 5.11 (a) Reproducibility Of Data
In Nucleate Boiling

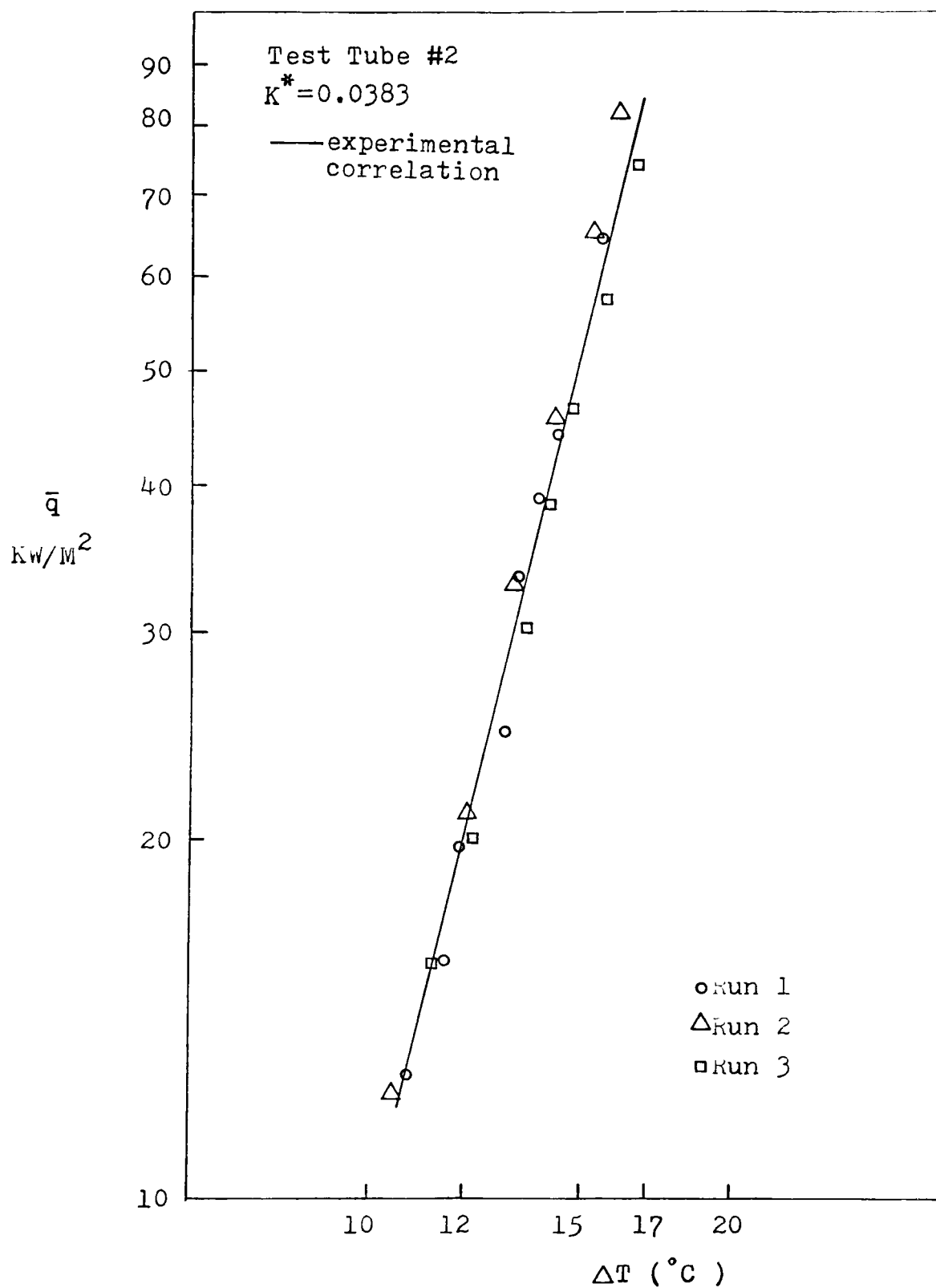


Figure 5.11 (b) Reproducibility Of Data
In Nucleate Boiling

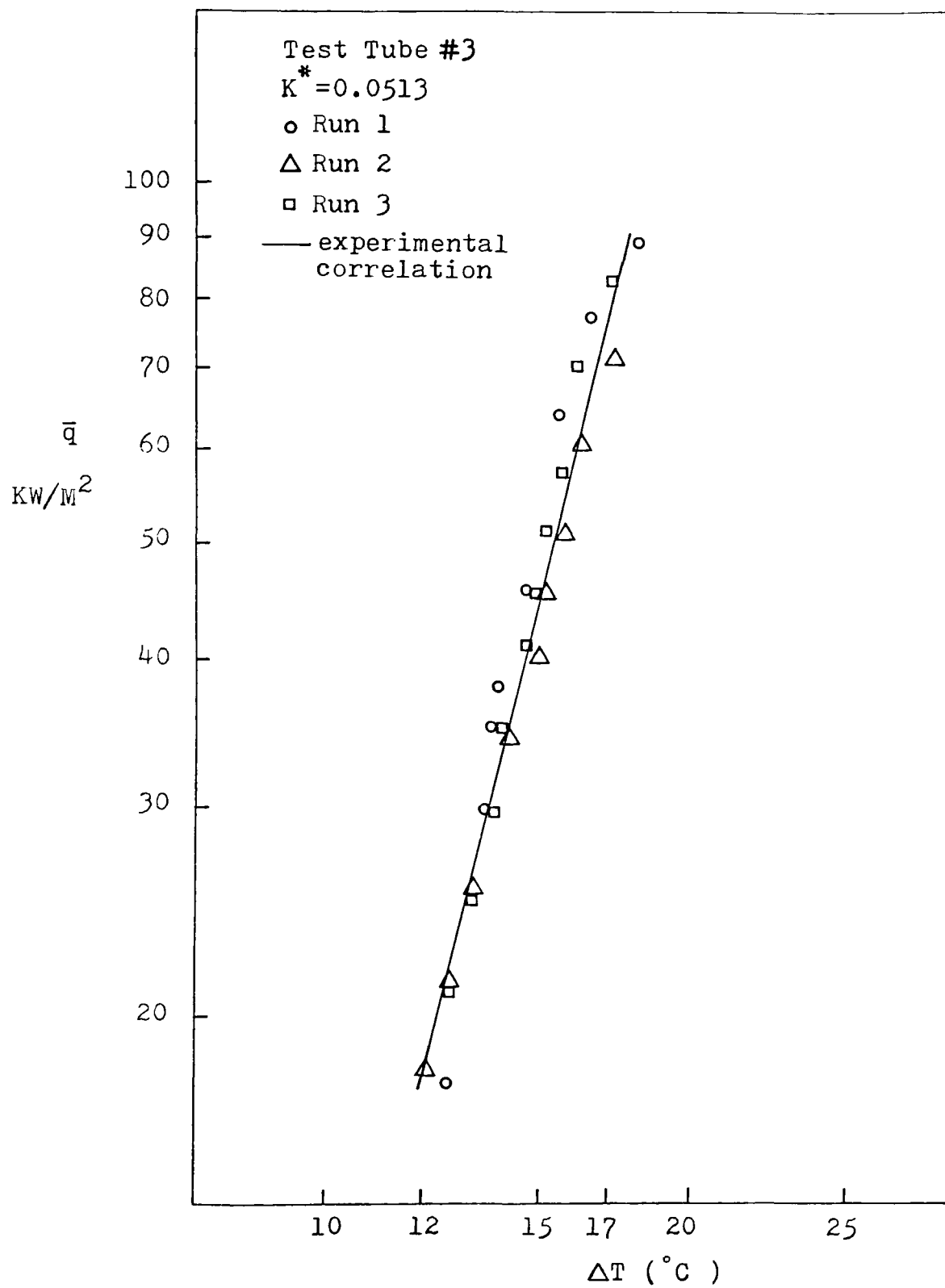


Figure 5.11 (c) Reproducibility Of Data
In Nucleate Boiling

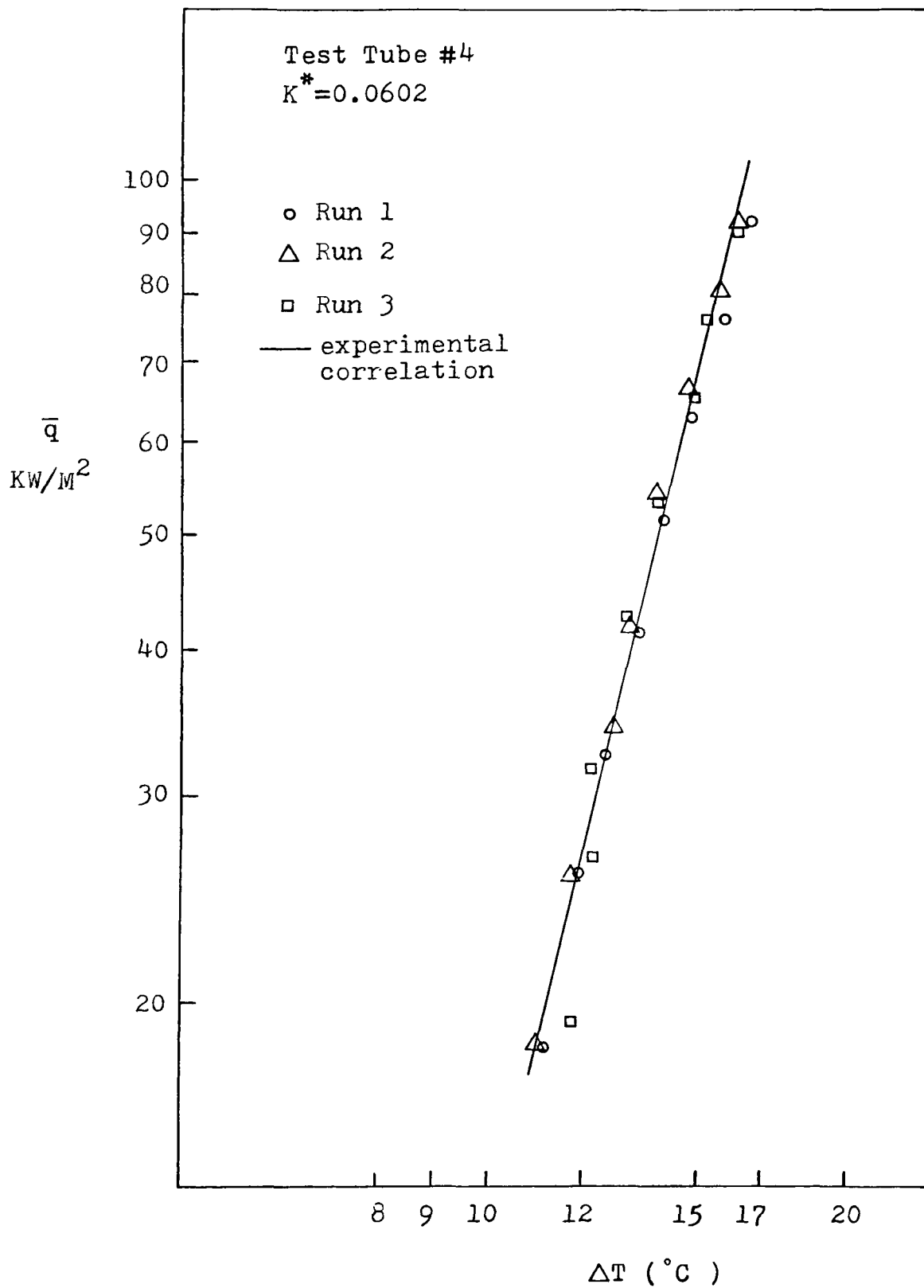


Figure 5.11 (d) Reproducibility Of Data
In Nucleate Boiling

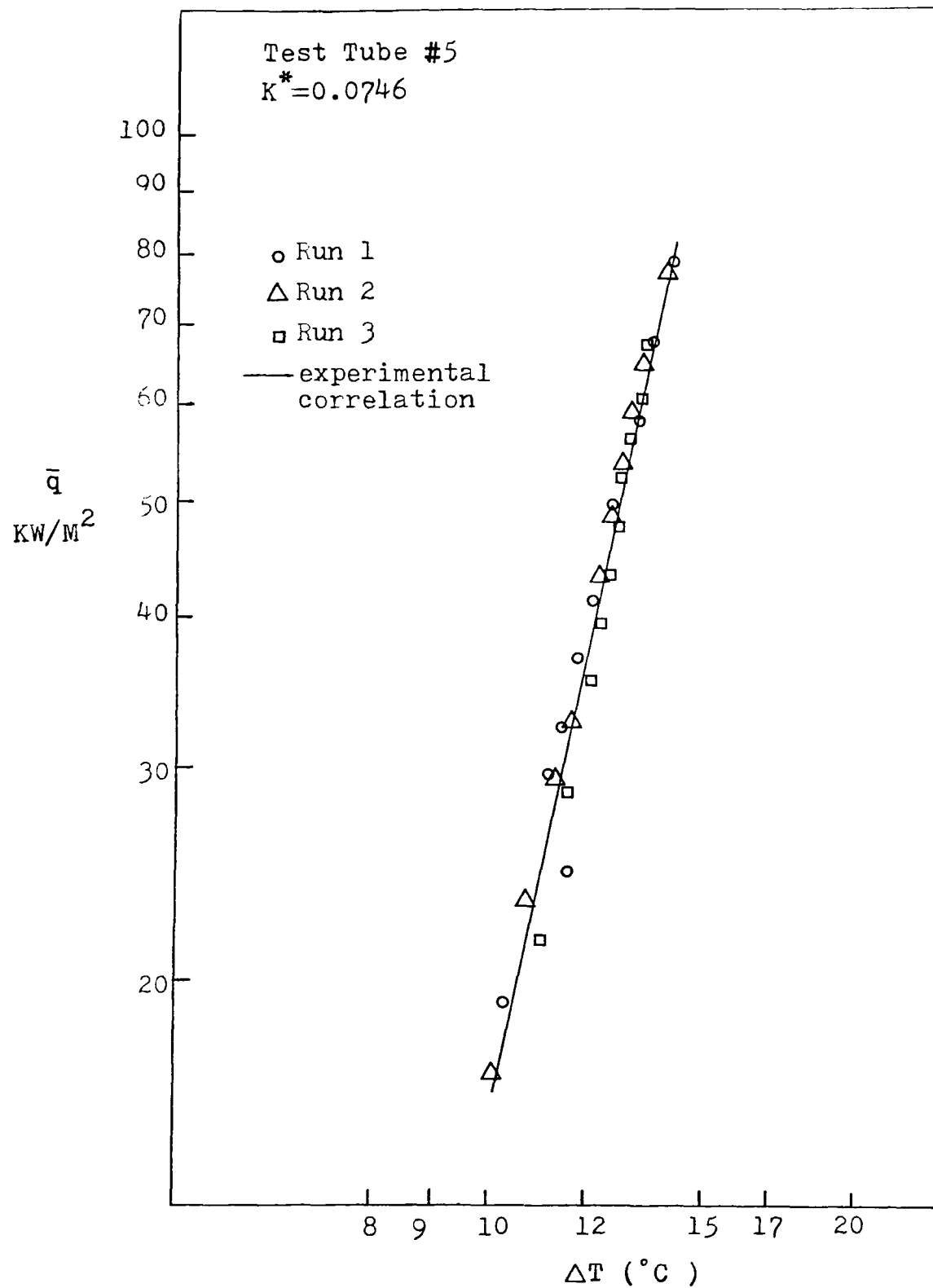


Figure 5.11 (e) Reproducibility of Data
In Nucleate Boiling

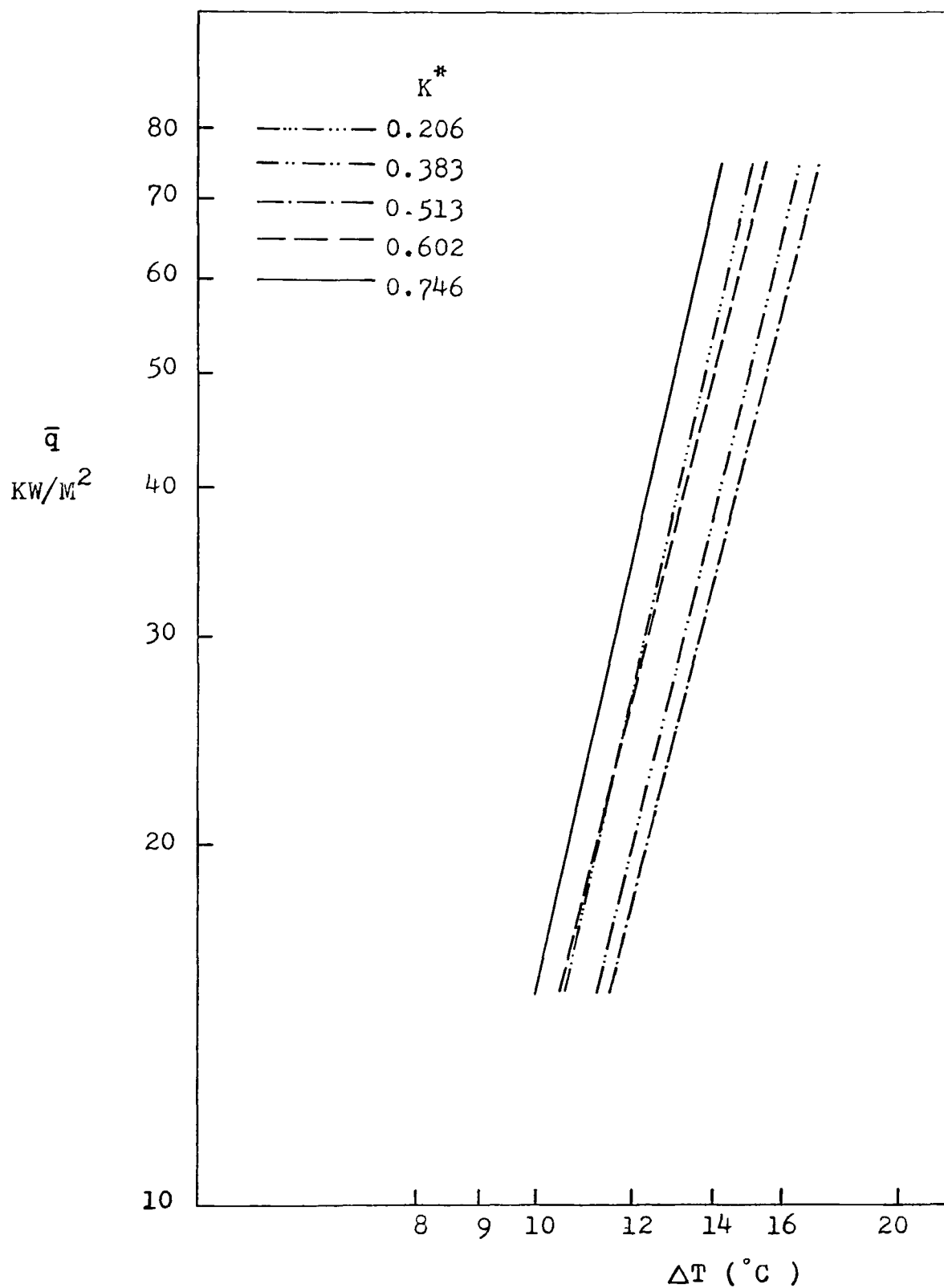


Figure 5.12 (a) Correlations Of Experimental Data In Nucleate Boiling

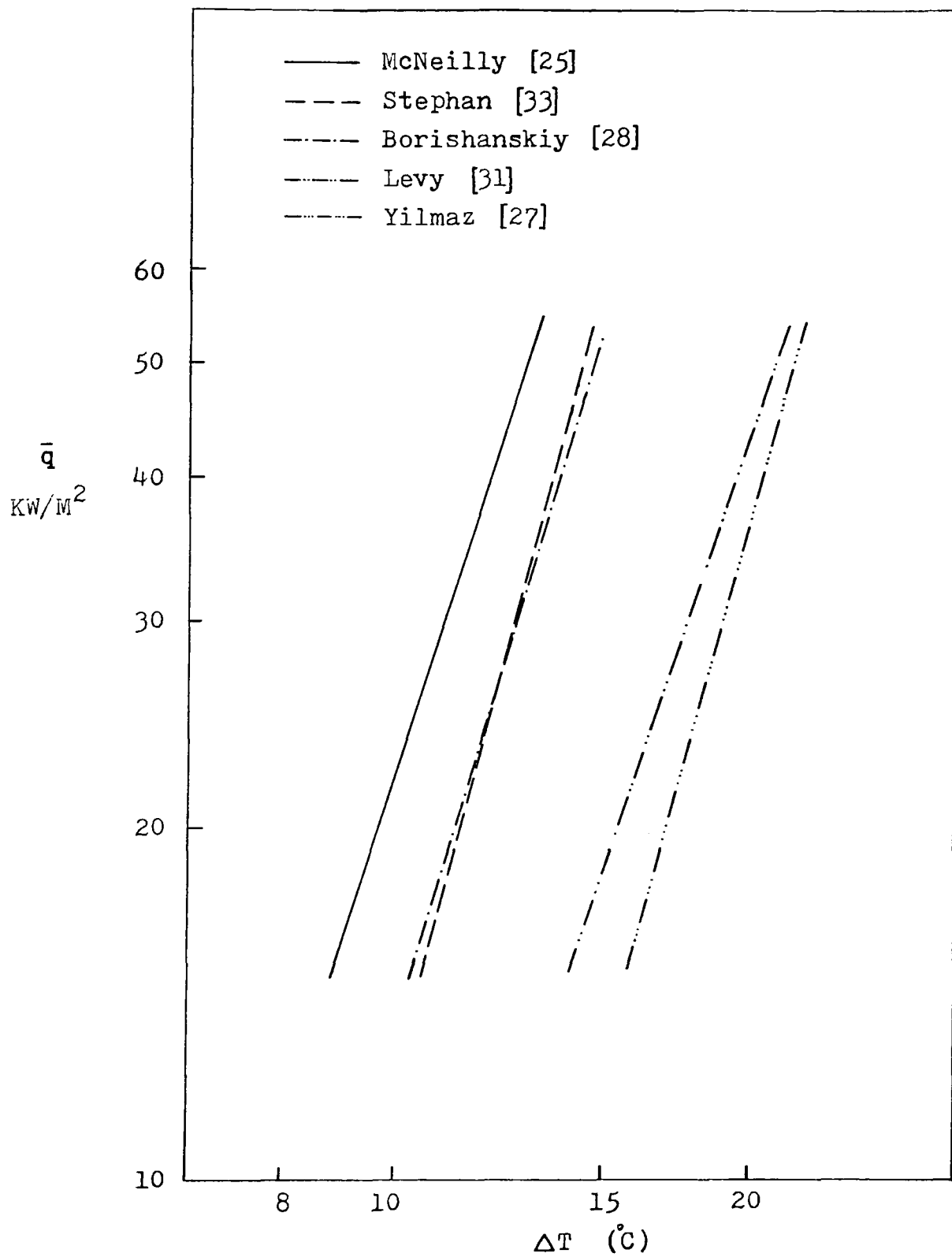


Figure 5.12 (b) Different Correlations In Nucleate Boiling

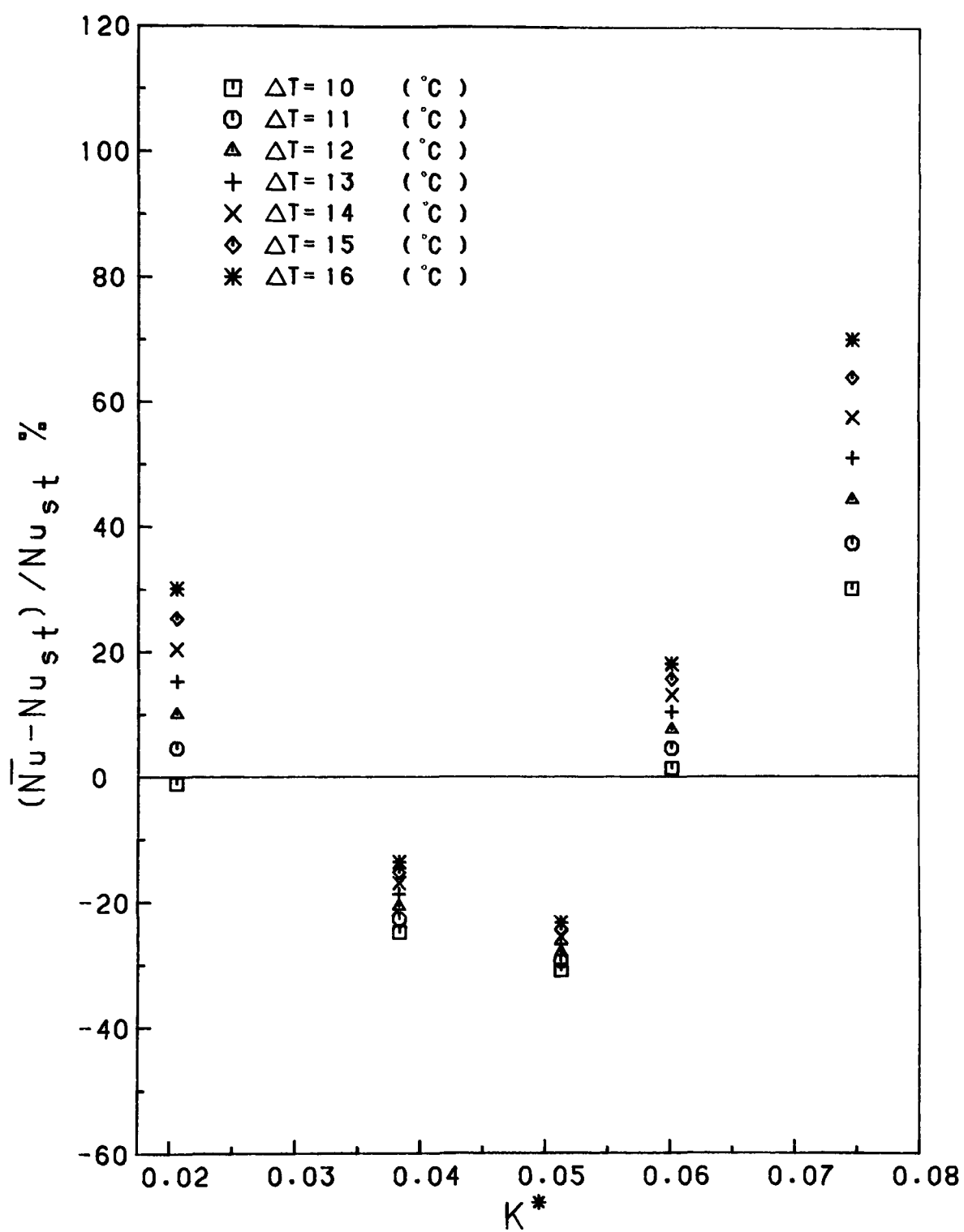


FIGURE 5.13 EFFECT OF K^* ON
OVERALL HEAT TRANSFER
IN NUCLEATE BOILING

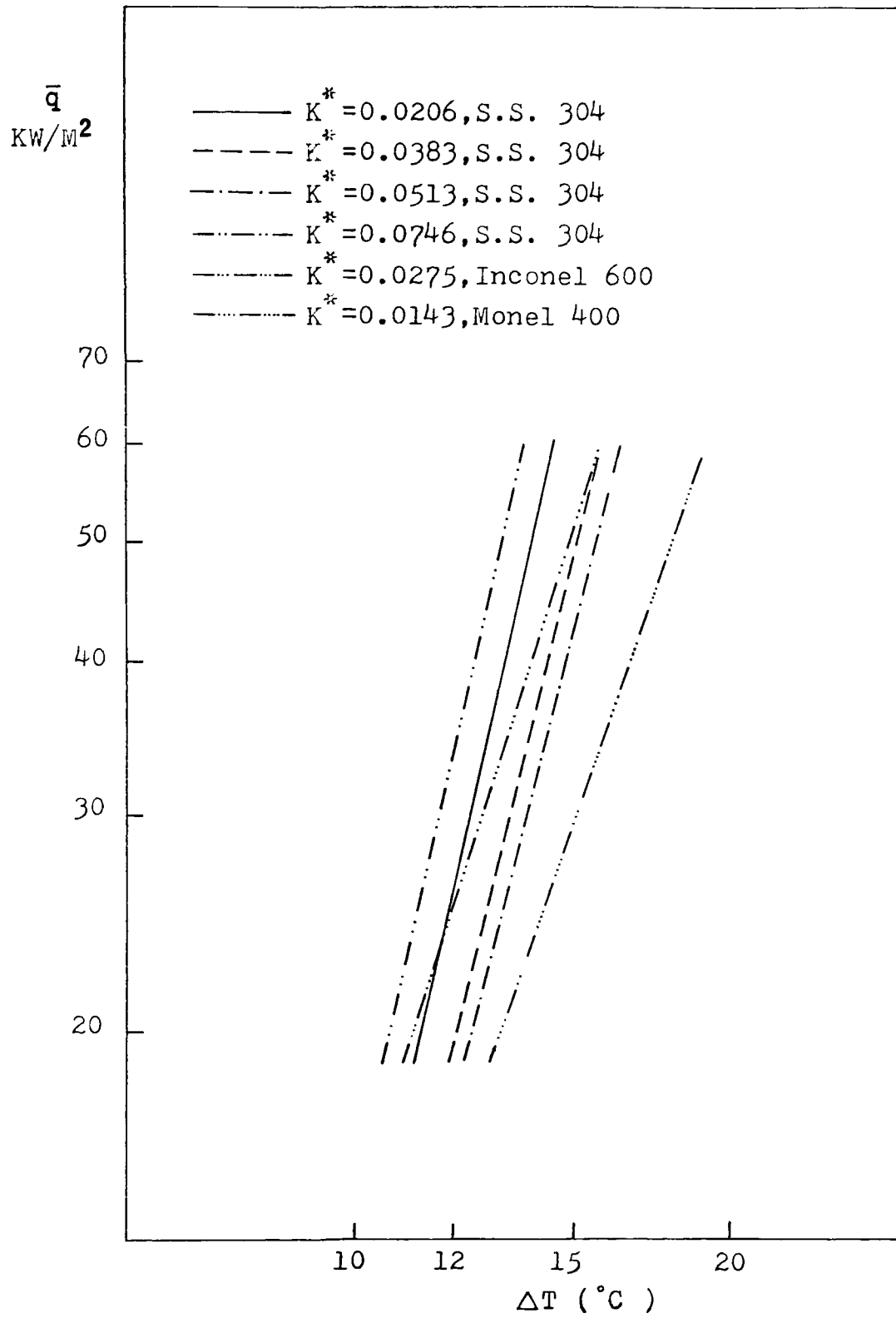


Figure 5.14 Effect Of Material On Nucleate Boiling

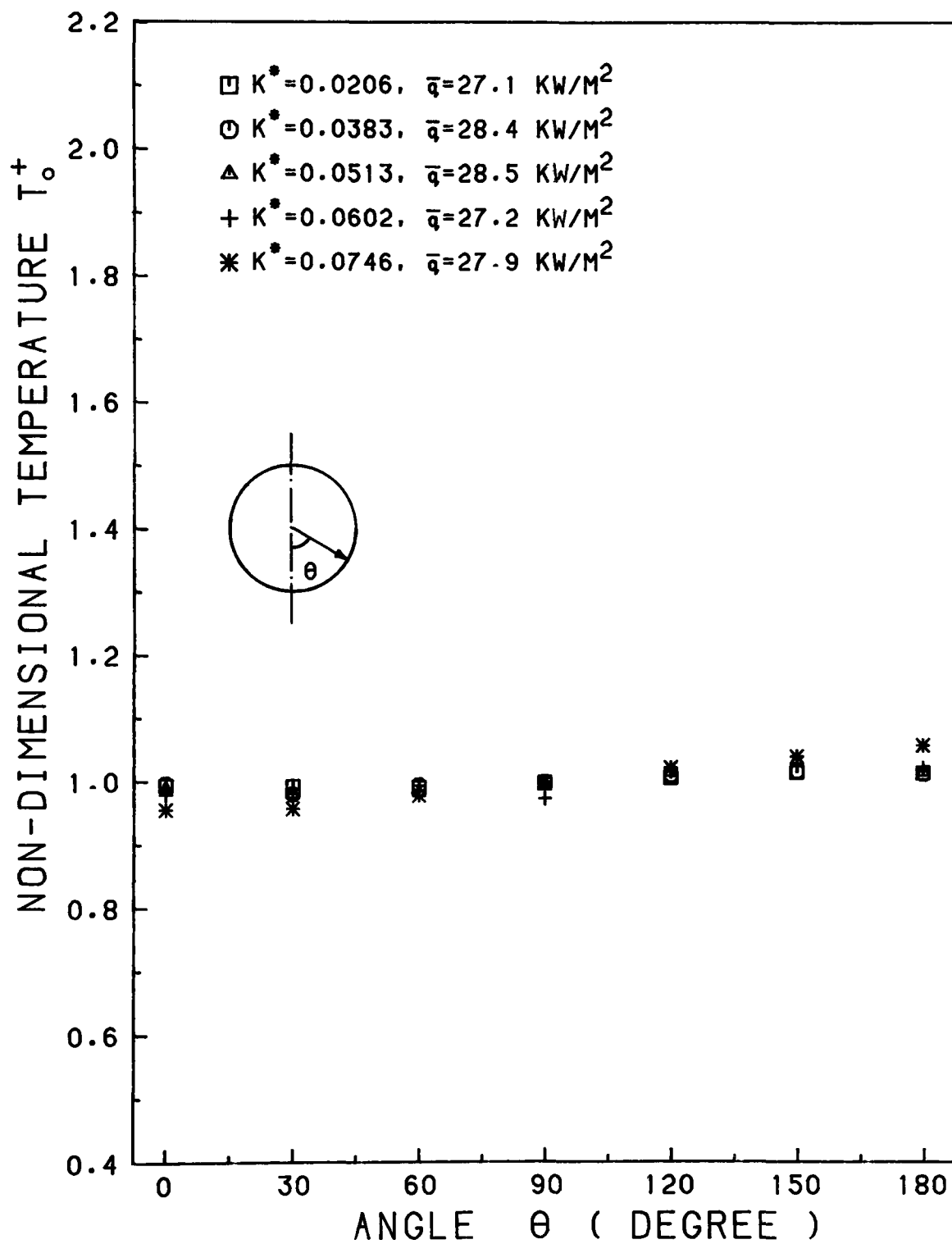


FIGURE 5.15 (a) NON-DIMENSIONAL TEMPERATURE IN FILM BOILING

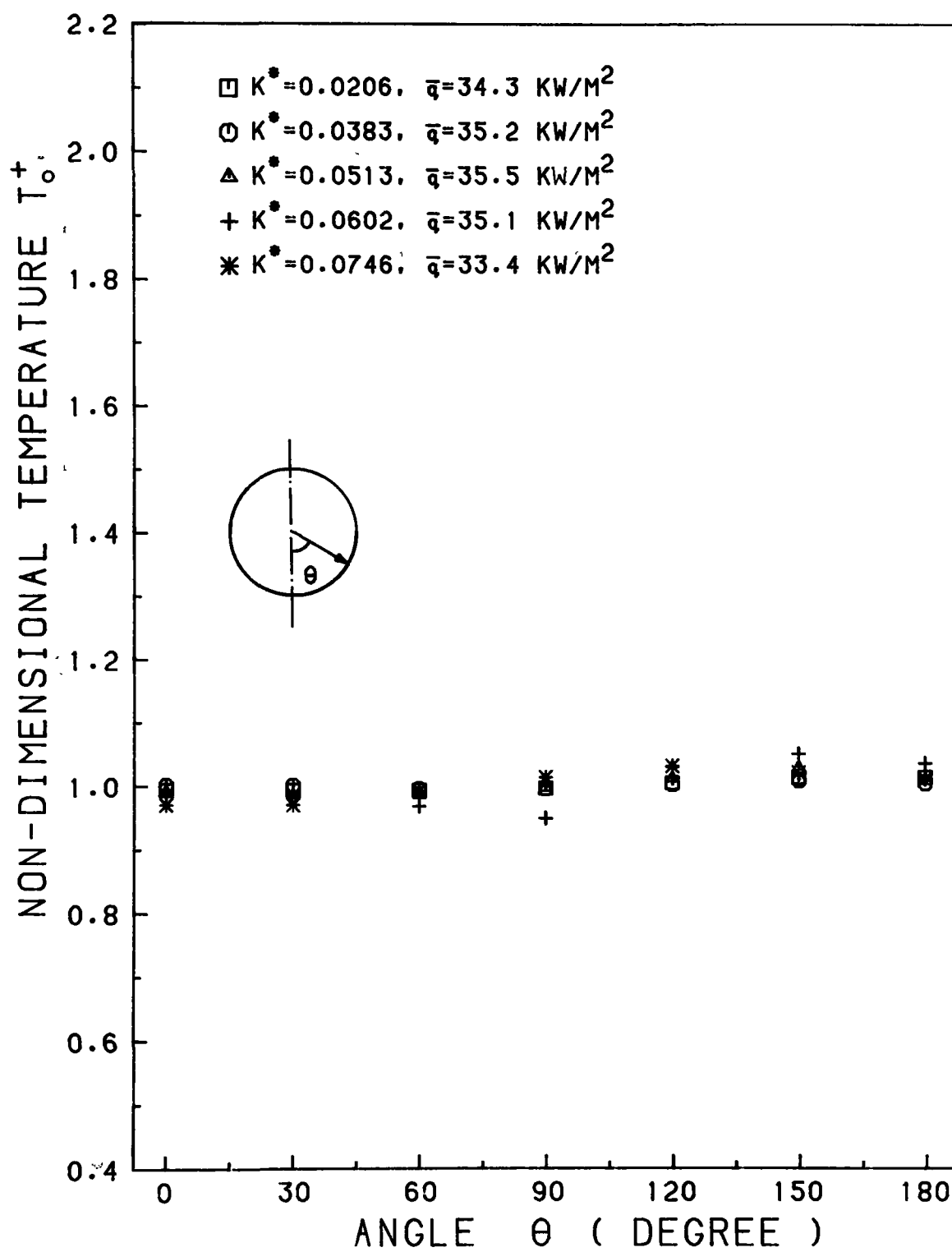


FIGURE 5.15 (b) NON-DIMENSIONAL TEMPERATURE IN FILM BOILING

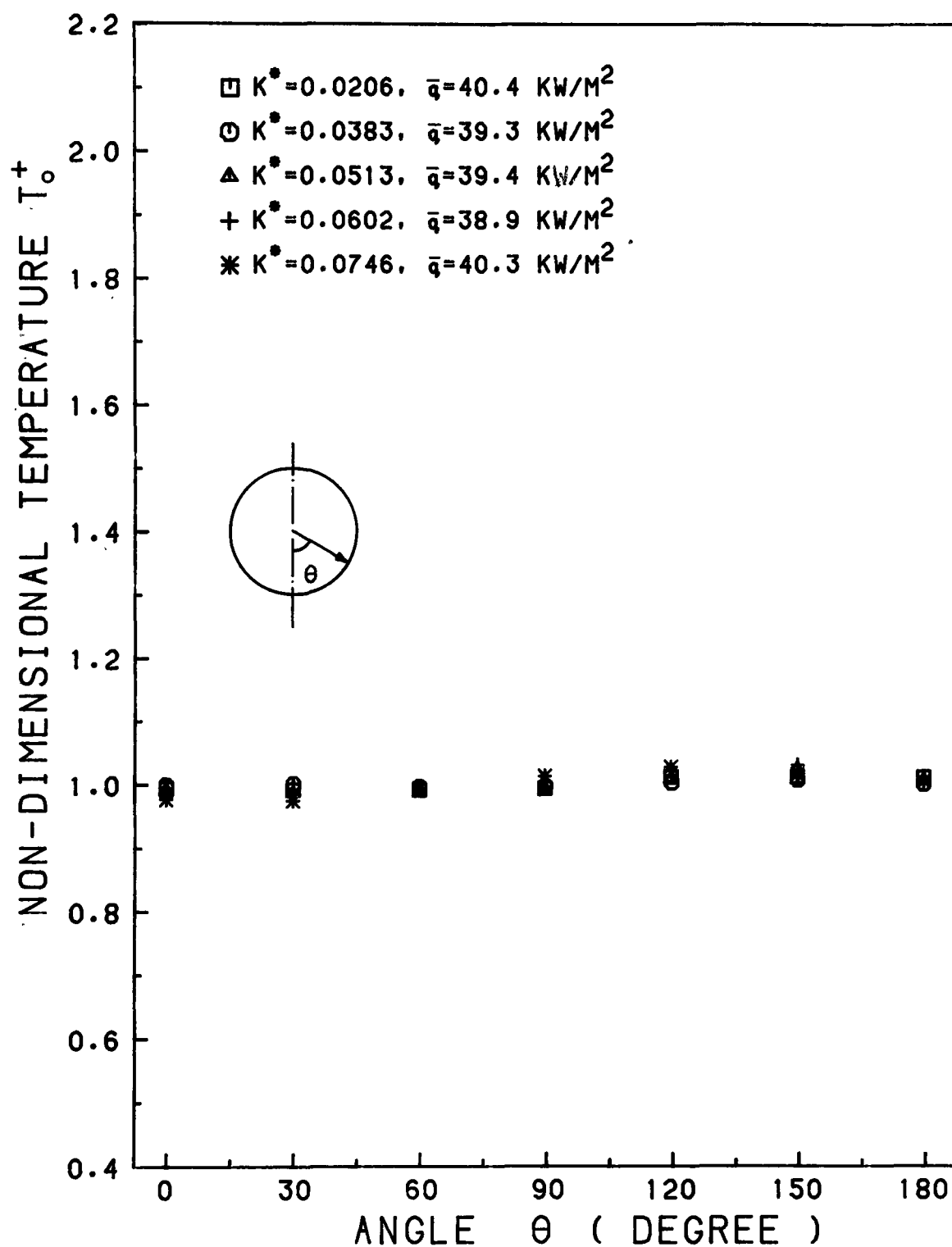


FIGURE 5.15 (c) NON-DIMENSIONAL TEMPERATURE IN FILM BOILING

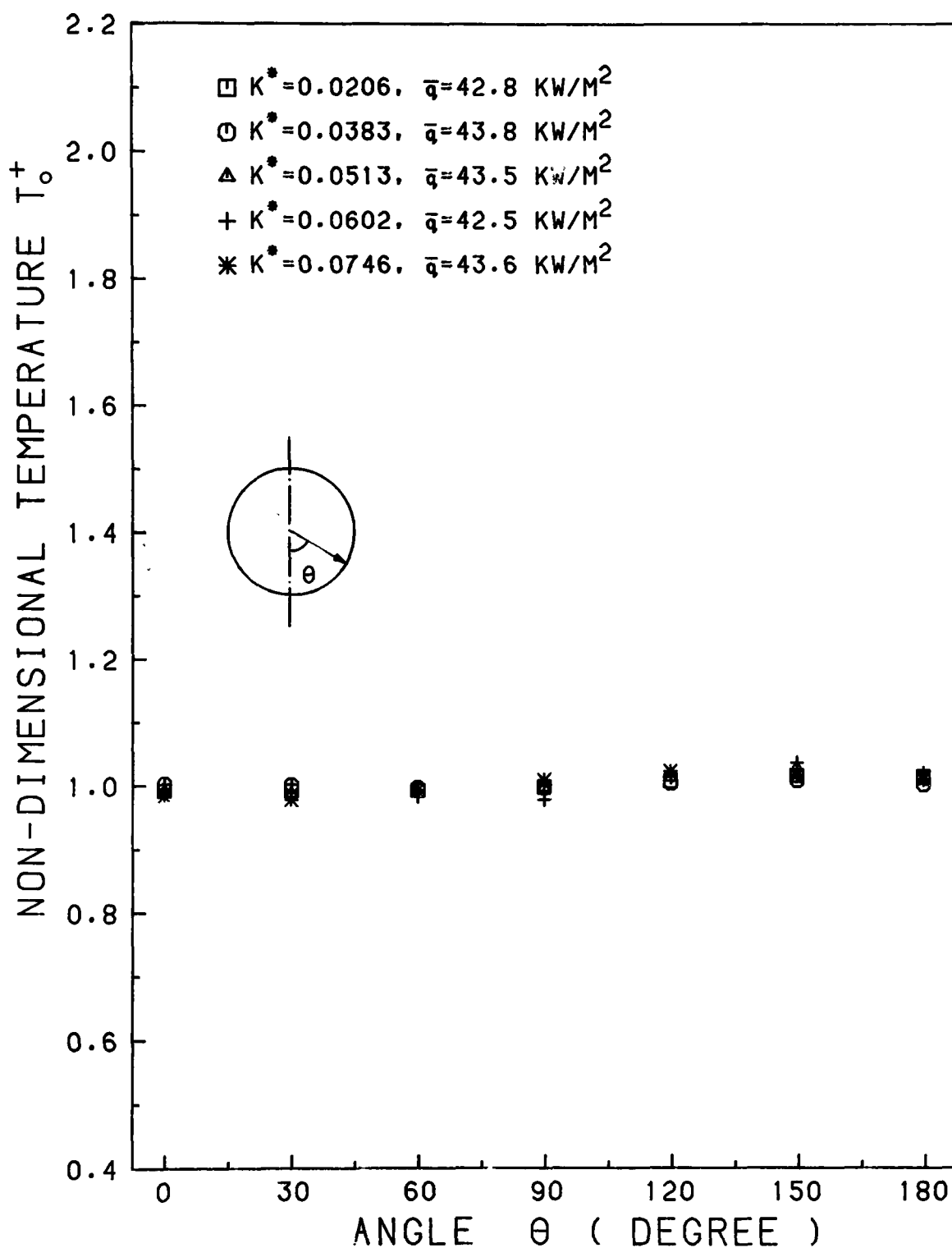


FIGURE 5.15 (d) NON-DIMENSIONAL TEMPERATURE IN FILM BOILING

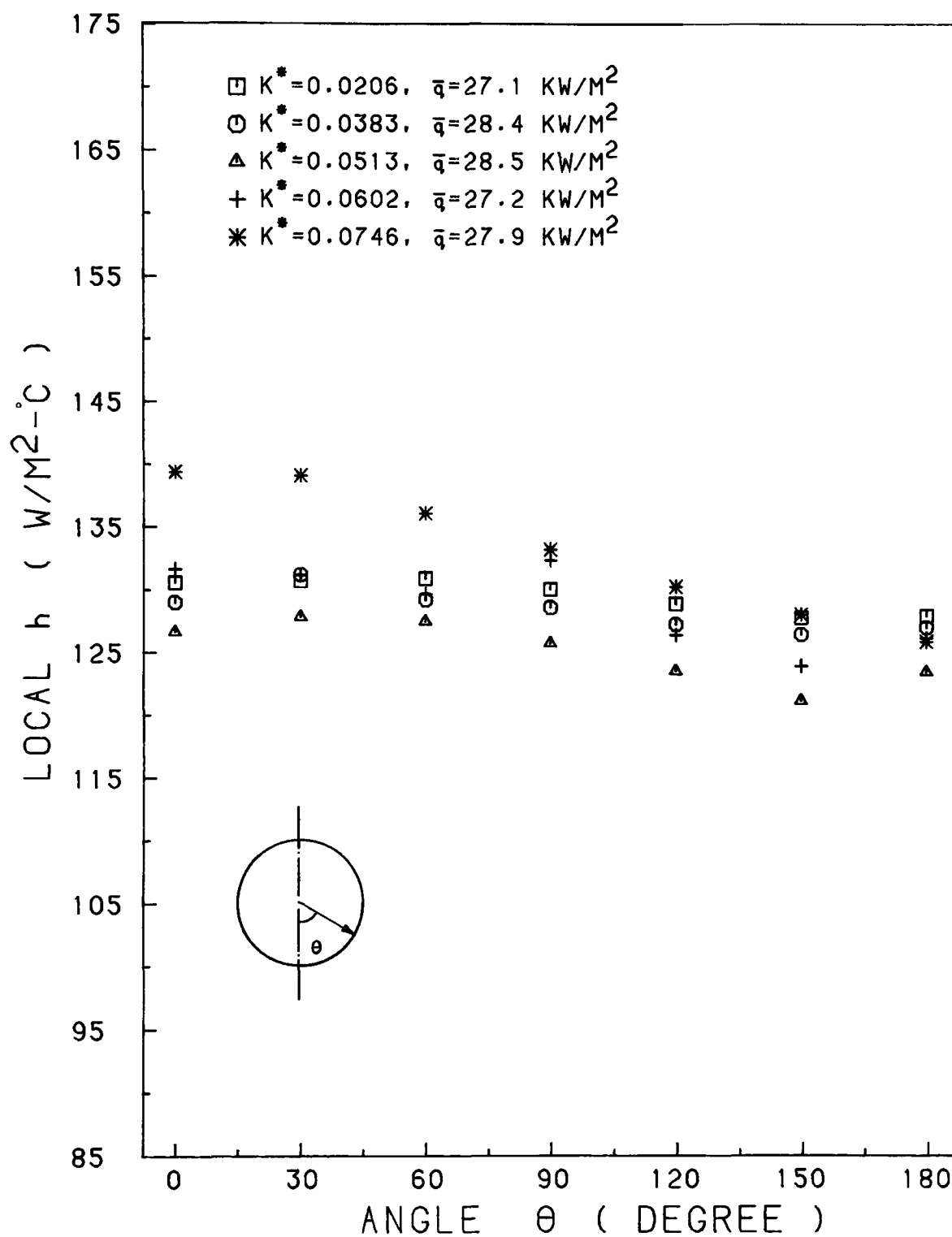


FIGURE 5.16 (a) DISTRIBUTION OF LOCAL h IN FILM BOILING

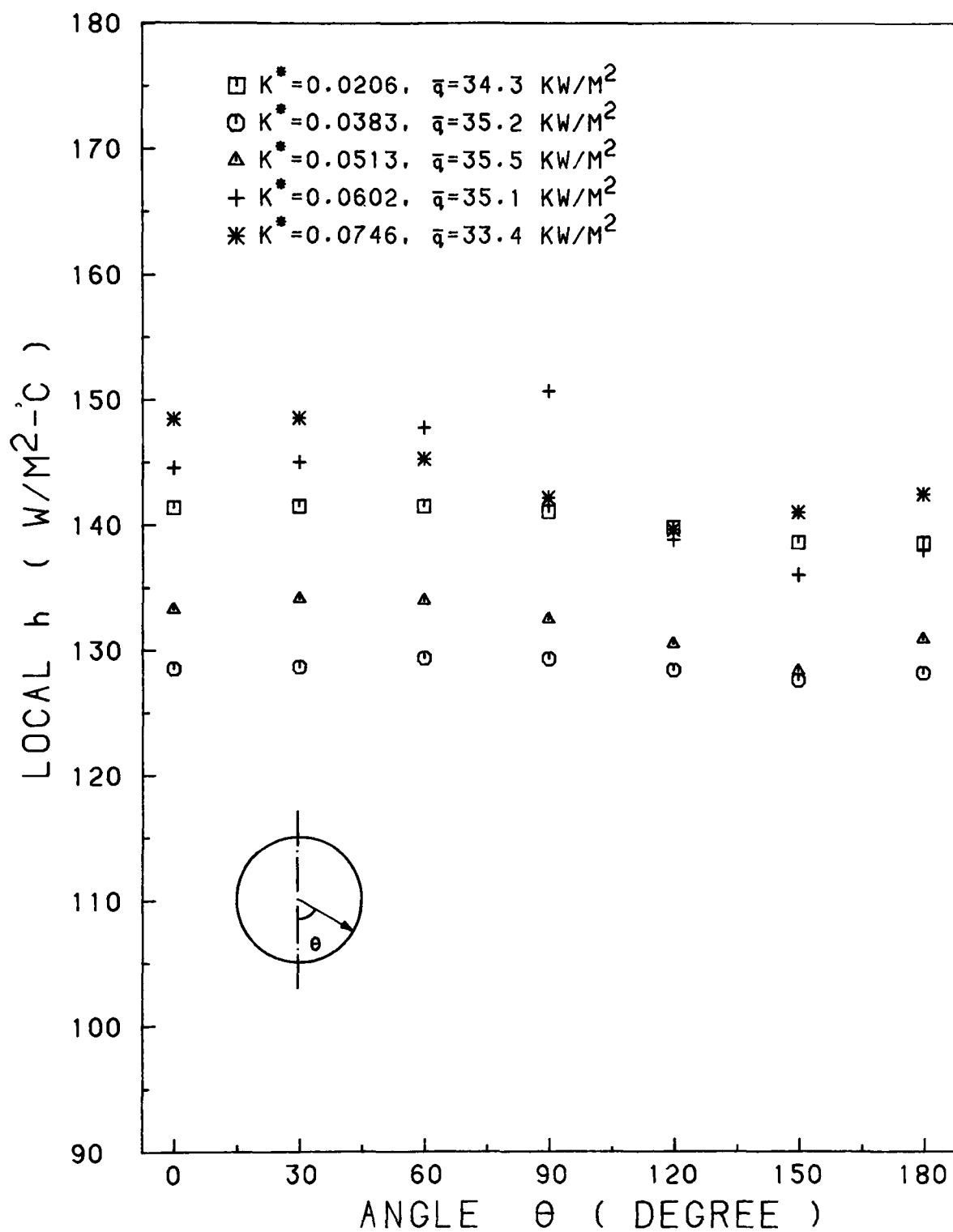


FIGURE 5.16 (b) DISTRIBUTION OF LOCAL h IN FILM BOILING

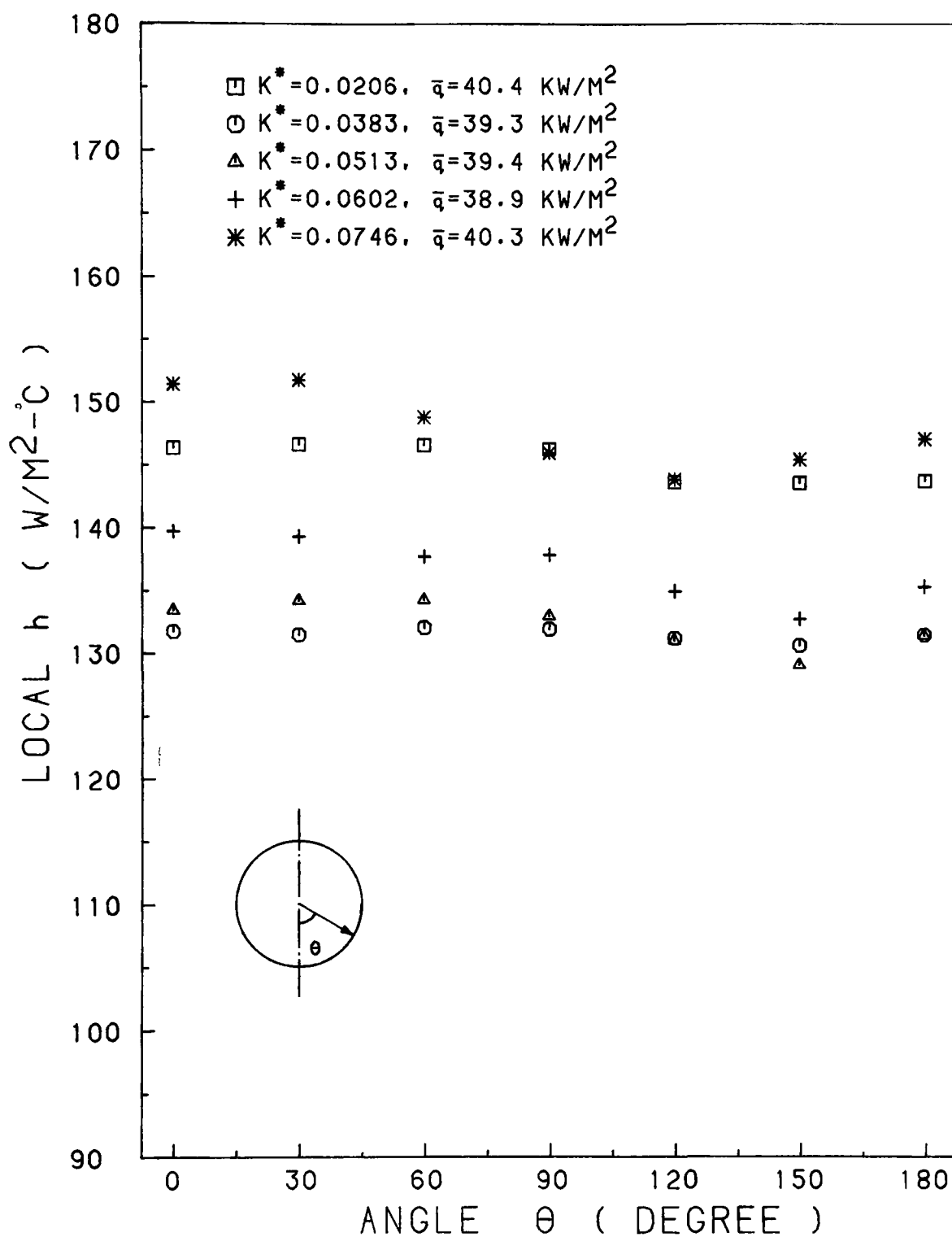


FIGURE 5.16 (c) DISTRIBUTION OF LOCAL h IN FILM BOILING

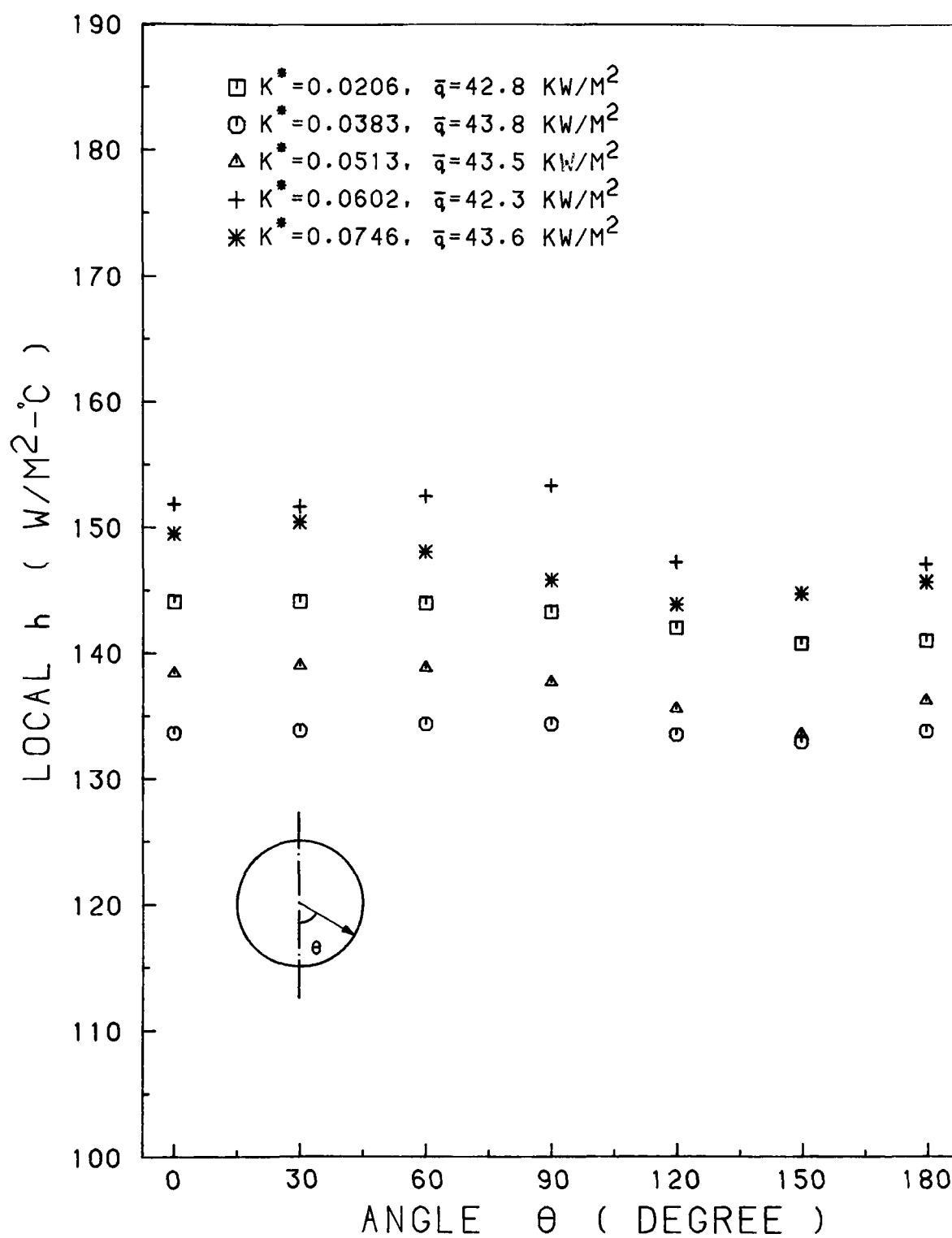


FIGURE 5.16 (d) DISTRIBUTION OF LOCAL h IN FILM BOILING

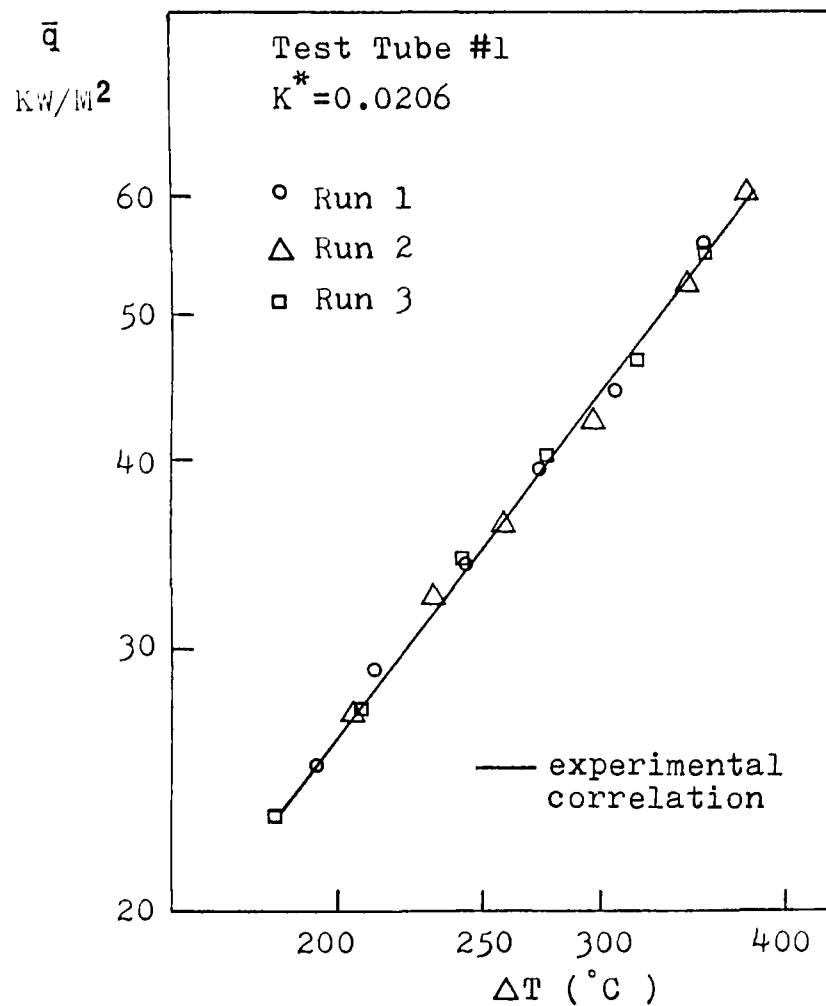


Figure 5.17 (a) Reproducibility
 Of Data In Film Boiling

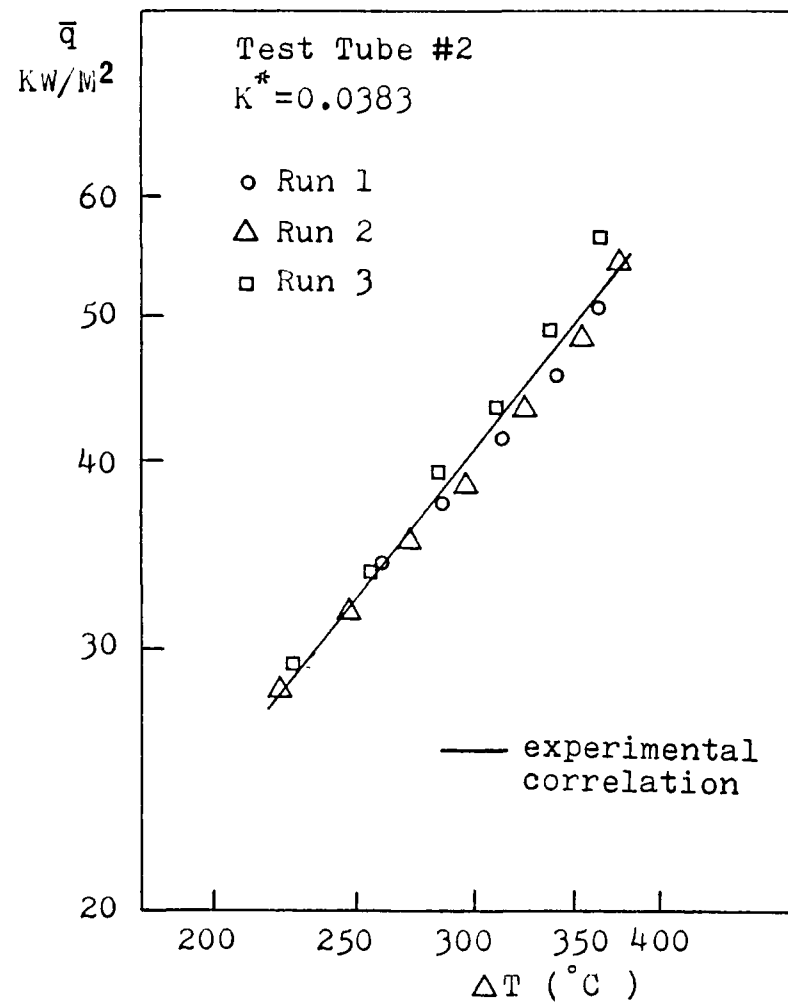


Figure 5.17 (b) Reproducibility
 Of Data In Film Boiling

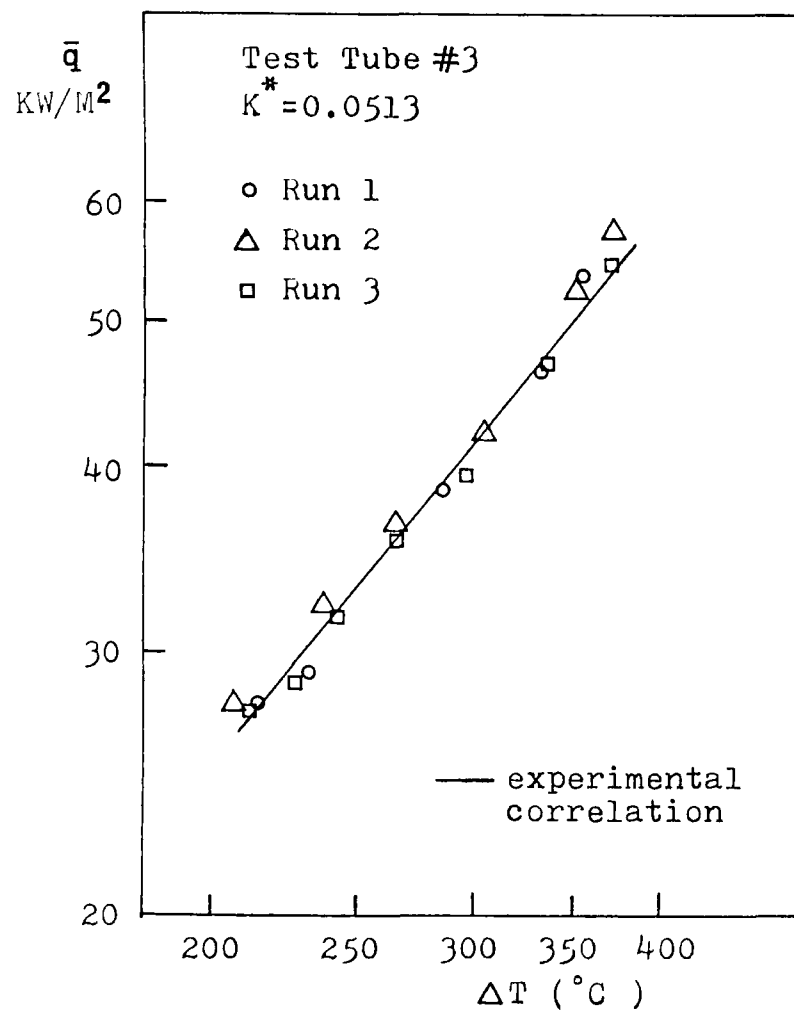


Figure 5.17 (c) Reproducibility
 Of Data In Film Boiling

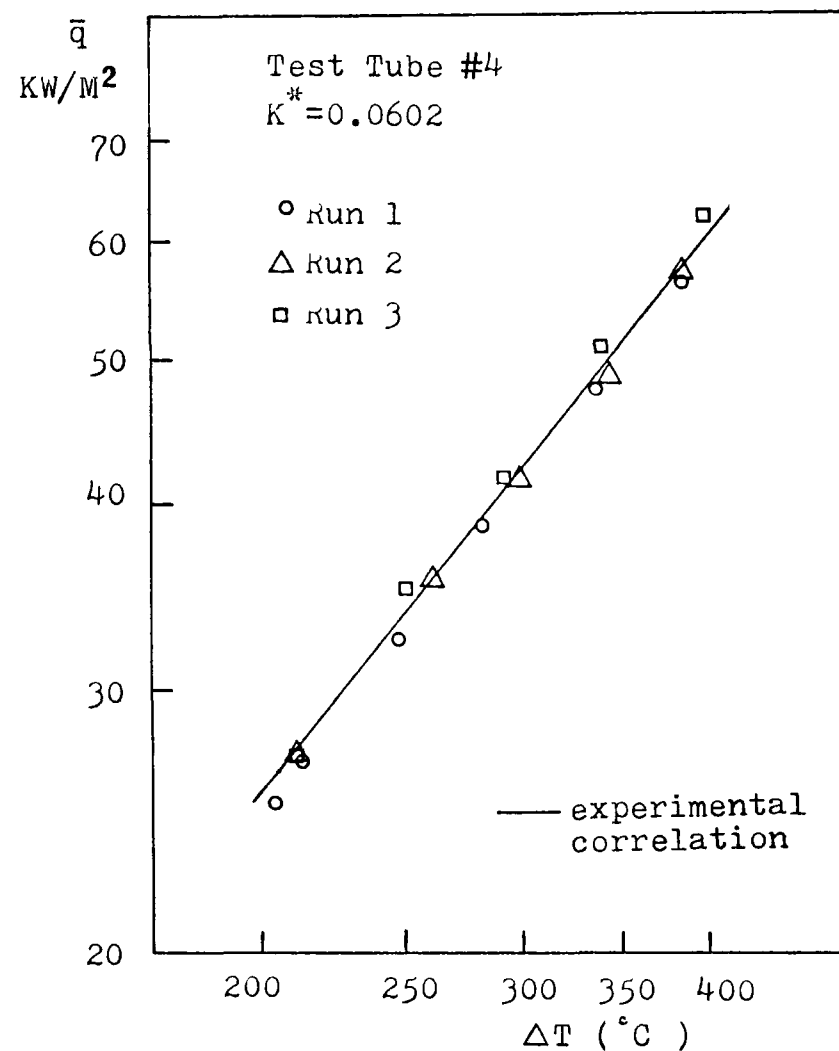


Figure 5.17 (d) Reproducibility
 Of Data In Film Boiling

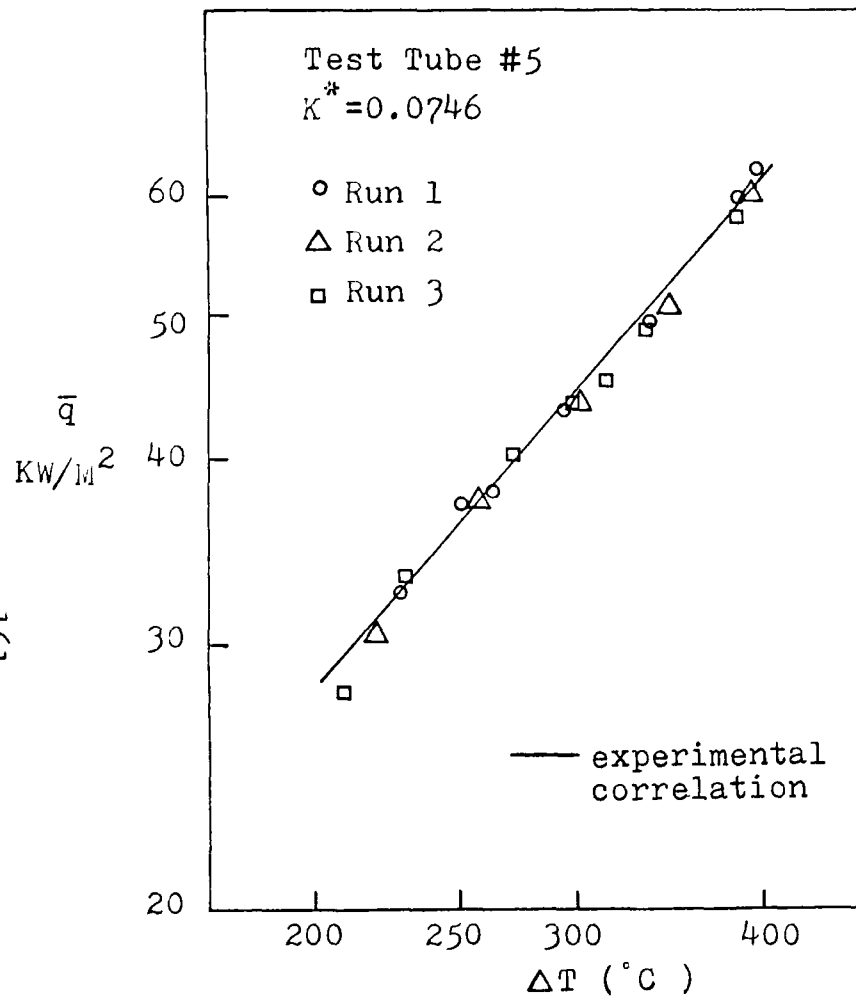


Figure 5.17 (e) Reproducibility
 Of Data In Film Boiling

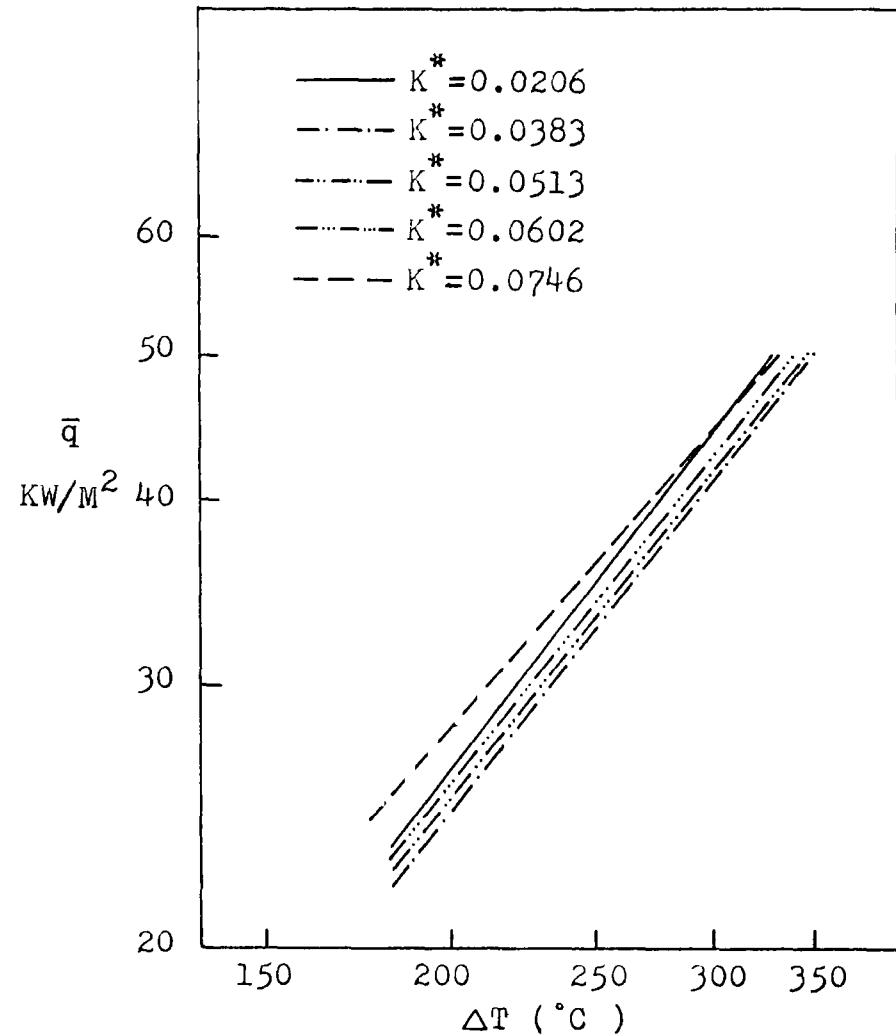


Figure 5.18 Correlations Of Experimental
 Data In Film Boiling

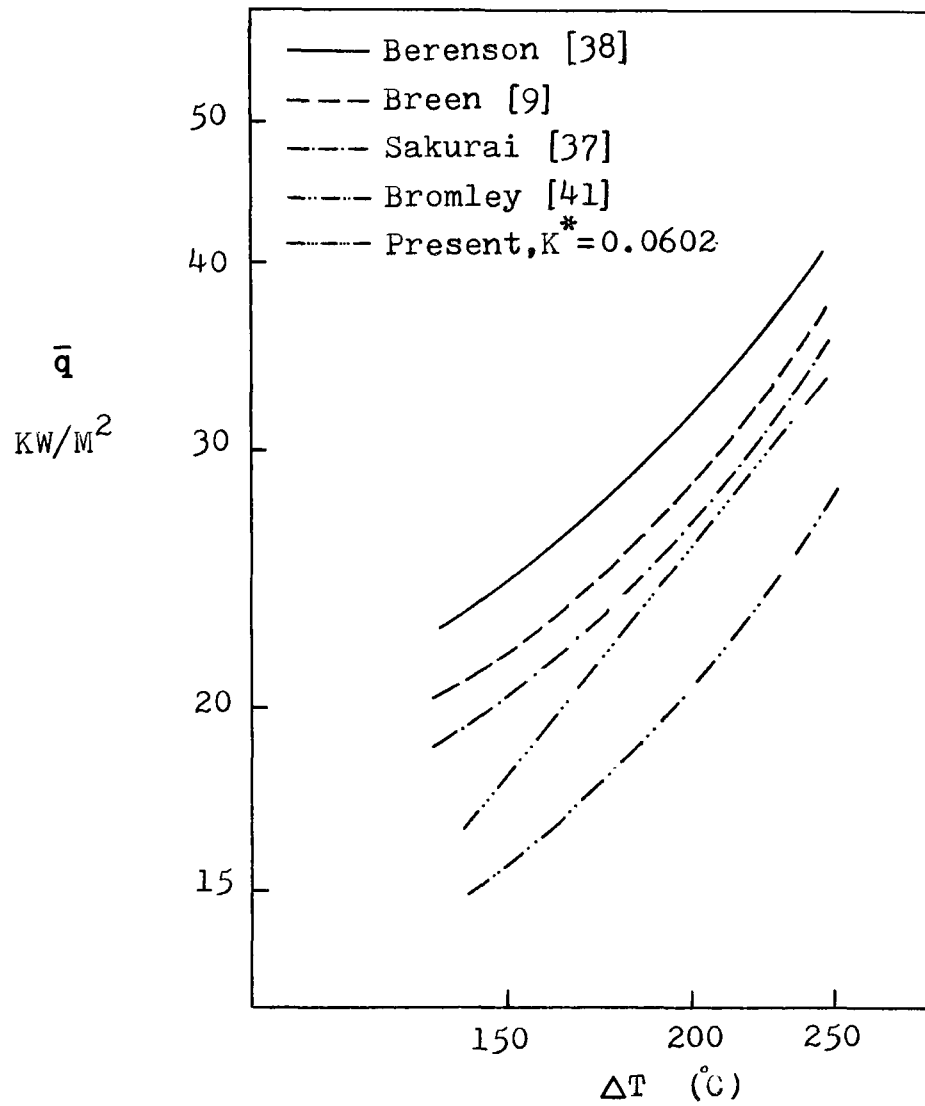


Figure 5.19 Different Correlations
In Film Boiling

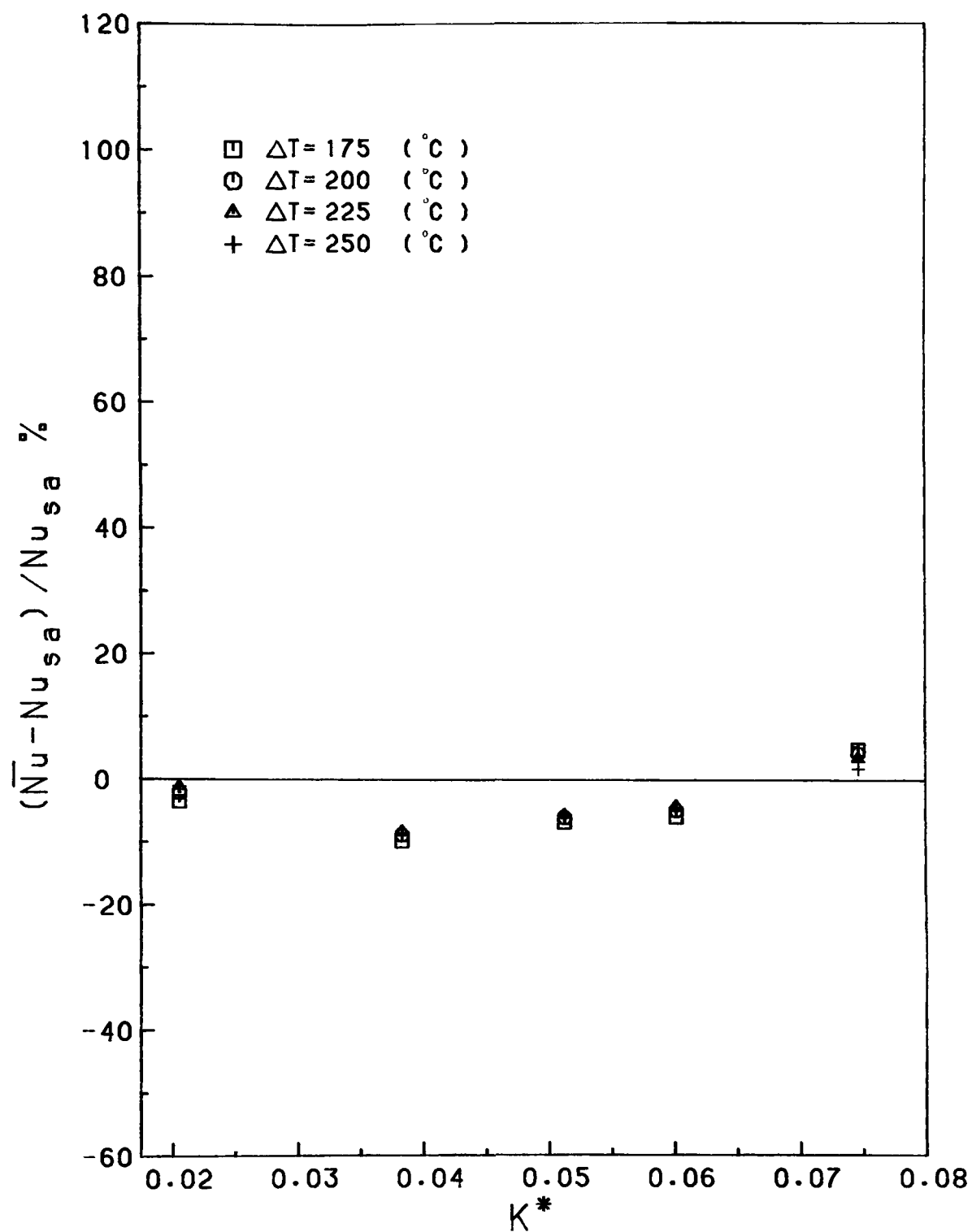


FIGURE 5.20 EFFECT OF K^* ON OVER HEAT TRANSFER IN FILM BOILING

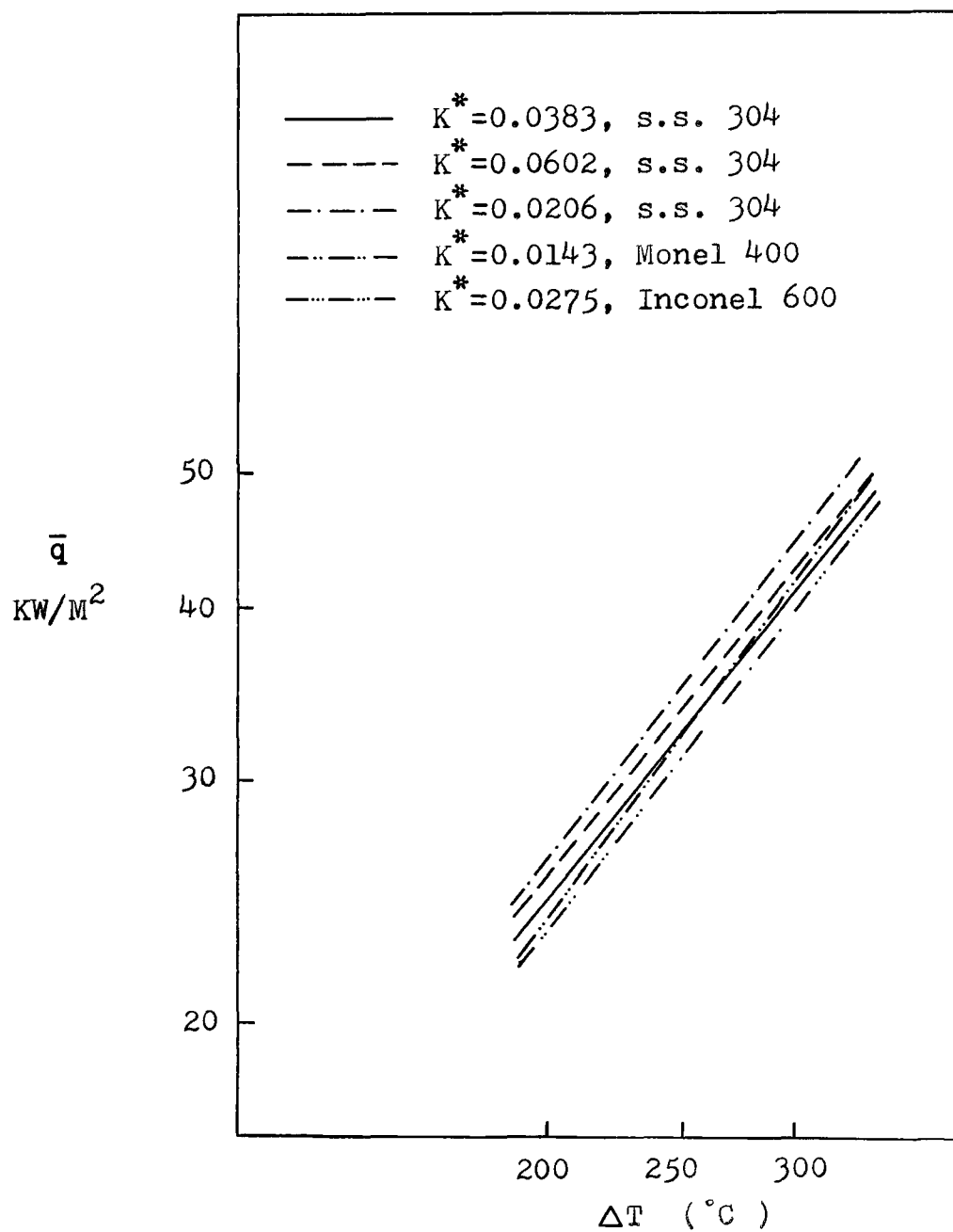


Figure 5.21 Effect Of Material On Film Boiling