POOL BOILING FROM HEATED MULTI-ROD

BY

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ABSTRACT:

The influence of both tube spacing (or pitch to diameter ratio) and length on surface temperature and heat transfer coefficient for a vertical bundle of heated tubes has been determined experimentally.

A stainless steel rod bundle was manufactured specially, to simulate the fuel cell in the reactor. This bundle had a 7-rods, each of them had a 21 cm. length, 10mm outer diameter and 8mm inside diameter. The bundle was inserted inside a stainless steel pool, and the bundle was connected in series and heated by conducting high electric D.C. current through it.

Although no analytical studies are presented, the experimental results are qualitatively explained from heat transfer principles. The parameters: mean heat transfer coefficient, mean temperature difference and pitch to diameter ratio are correlated with each other by using the least square method and a relation for calculation of heat transfer coefficient was obtained. The tube spacing (pitch to diameter ratio) was found to have a strong influence on the heat transfer coefficient, and the maximum rate of heat transfer occured at a pitch to diameter ratio equal to 1.8.

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1. INTRODUCTION:

In boiling water reactors, steam is generated in the core where direct contact of the coolant with the reactor fuel elements occurs. These reactors are designed to operate in nucleate boiling region. The high heat transfer coefficient in this region provides an excellent means, (as compared with pressurized water reactors), to dissipate the tremendous heat generated per unit volume of the fuel elements with relatively small temperature difference between the clad surface and coolant. The heat flux must be limited to the upper limit of this nucleate boiling regime in order to avoid what is called burnout or boiling crisis.

A thorough understanding of the process of heat transfer in pool boiling requires the investigation of the bubble formation (nucleation) process and the subsequent growth and motion of these bubbles. These processes were investigated by W.M. Rohsenow [16] , McAdams [11], Nukiyama[13] , Jhon G. Colliev[7], L.S.Tong[15], Forster and Zuber[3,4,5], cryder and Gilliland[6], Jackob and Linke[8], Insinger and Blise[19], K.K. Fung[20], Kruzhilin G.N.[9], saini, Gupta and Lal[13,14] and Cumo, Farello, Pezzilli and Pinchere[10] but the investigators did not take into account the effect of pitch to diameter ratio on heat transfer coefficient of the tube bundle in pool boiling. Therefore the present work investigates the effect of different parameters specially the pitch to diameter ratio on heat transfer coefficient in pool boiling heat transfer.

2. EXPERIMENTAL APPARATUS:

In nuclear reactors, large heat transfer areas in the core are required. This is acheived by arranging thin fuel rods in assembled bundles. Each bundle so-called a fuel cell, has the fuel rods laid out such that they permit the coolant to absorb certain heat transfer rates. For this reason we suggested the test apparatus which is shown schematically in Fig.(1). The experimental loop was constructed manufactured and mounted to investigate the effect of the heat transfer coefficient distribution. The test section (8), is fixed in the middle of the pool boiling tank (11). The level glass (3) indicates the saturated water level in the boiling tank. The steam is generated when the electric power supply is connected to the tube bundle. The condenser (1) is designed for the removal of the latent heat of the steam formed. The condensed vapour is collected in a reservoir (7), then returns back to the pool boiling tank. The compensating tank (2) is used to feed the saturated water to the closed loop by gravity across the compensating value (9). Feed tank heater (10) is used to keep the compensating water at saturation temperature. Fig.(2) shows the test section tube bundle and also, indicates the test section tube arrangement.

3. EXPERIMENTAL MEASUREMENTS AND ERROR ANALYSIS:

Twenty thermocouples previously calibrated were distributed on both periphey and middle rods. Fifteen thermocouples were located along the periphery rod while the other five thermocouples were located along the middle rod at X/L = 12%, 31%, 50%, 69%, and 88%.

The electric power is supplied by a welding rectifier unit, type MCRA 900, of maximum power 58 KW, maximum currunt 900 amps, and maximum voltage 65 volts. The bundle is connected to the rectifier by copper bus-bar. In order to avoid the voltage drop across the copper bus-bar and to know the exact voltage drop across the bundle, separate voltmeters are connected directly in parallel with the test section rods of the bundle.

The electric power is calculated by the formula.

$P_p = I\ V_p$ watt. (for periphery rod).

$P_m = I\ V_m$ watt. (for middle rod).

1-Condenser.
2-Compensating Tank.
3-Level Glass.
4-Condensing Tank.
5-Water Separator.
6-Feed Valve.
7-Condensate Reservoir.
8-Test Section Rods.
9-Compensating Valve.
10-Feed Tank Heater.
11-Boiling Tank.
12-Feed Tank Base.
13-Manometer.

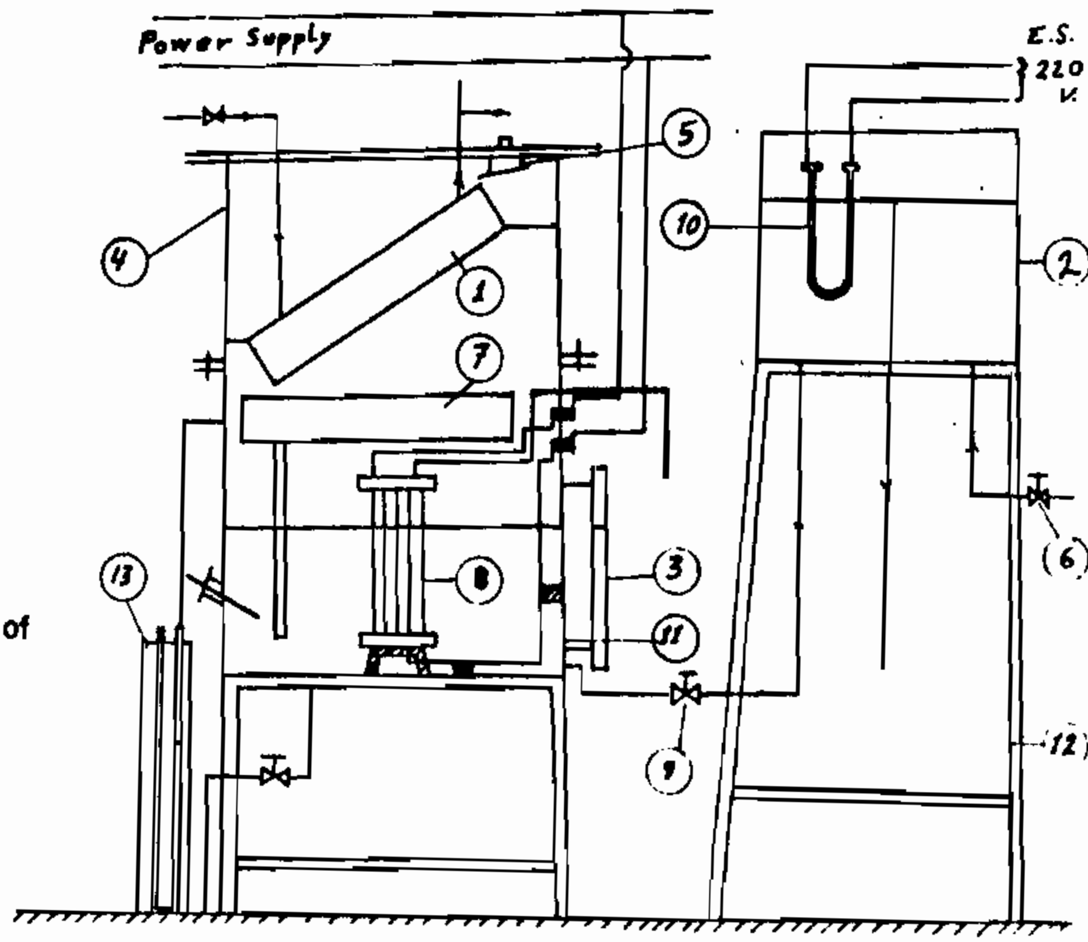

Fig:(1): Line Diagram of the Test Loop.

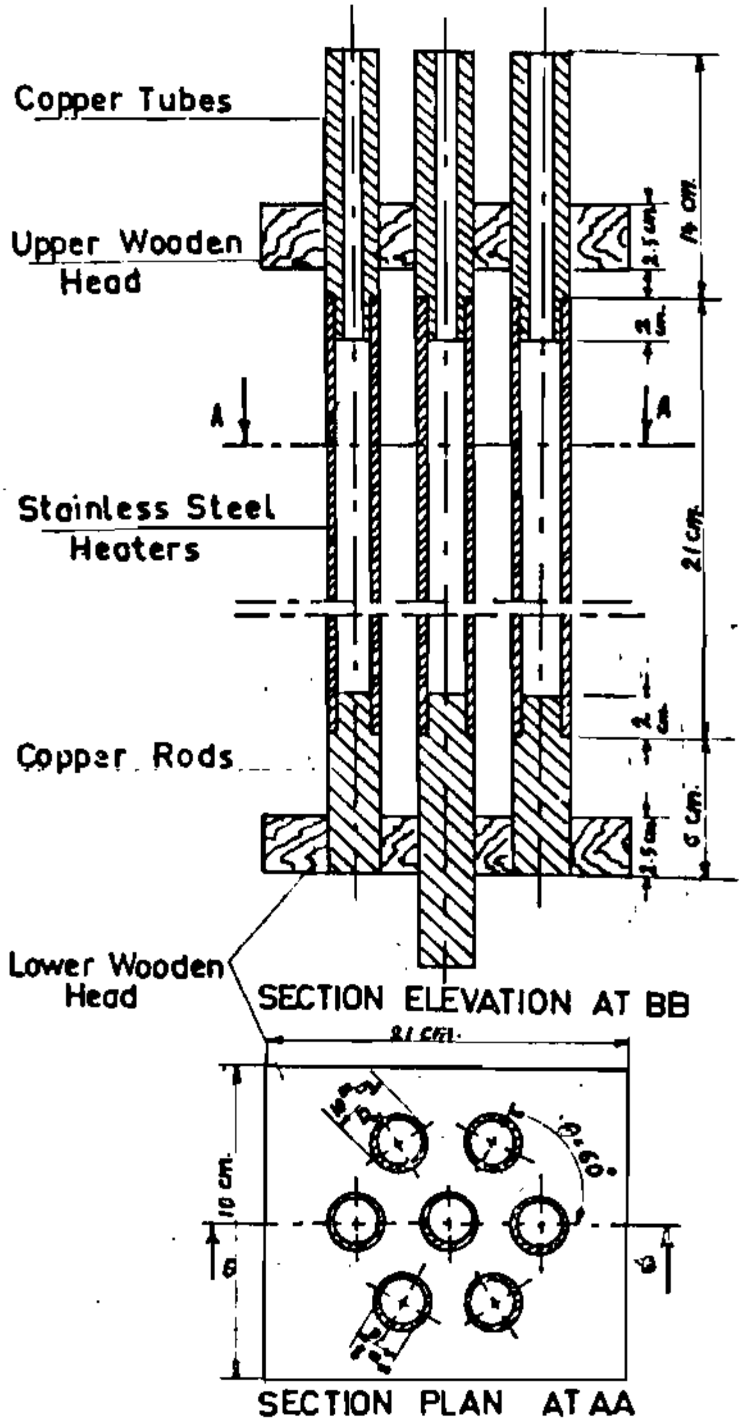

Fig.(2).Test Section Tube Bundle.

From the above - mentioned formula heat transfer coefficient is calculated as shown in the following relations.

$$q_p = P_p \text{ (watt) } \& \ q_m = P_m \text{ (watt).}$$

$$\dot{q}_p = \frac{q_p}{A} \text{ (w/cm}^2\text{.) } \& \ \dot{q}_m = \frac{q_m}{A} \text{ (w/cm}^2\text{.)}$$

$$h_p = \dot{q}_p \,/(Q)_p \qquad \text{(w/cm}^2\text{. °C).}$$

$$h_m = \dot{q}_m \,/(Q)_m \qquad \text{(w/cm}^2\text{. °C).}$$

The maximum percentage relative error in calculating the heat transfer coefficient is about 5%.

4. EXPERIMENTAL RESULTS AND DISCUSSION:

The number of the pool boiling heat transfer analytical studies are limited. Most of the pool boiling heat transfer correlations are of imperical nature. These correlations depend mainly on the experimental results. Thus the effect of the tube spacing (pitch), and longitudinal position (X/L), in the nucleate boiling region, on the surface temperature and the heat transfer coefficient is presented experimentally, and the experimental results are qualitatively explained from the heat transfer principles.

The experimental results are registered at $s/d = 1.5$, 1.8, 2.2 and 2.5.

Figure (3) illustrates the surface temperature distribution along the test section for the middle and periphery rods at I = 775 ampers. It is clear that the temperature increases with the increase of X/L, as X measured from the apper end. This means that the heat transfer coefficient value is higher at the upper end of the test section than that at the lower end. This is due to the bubble nucleation, growth and its detachement results in current streams of bubbles with high velocity at the upper end of the test section more than those at the lower end. This current streams increase tbe turbulence

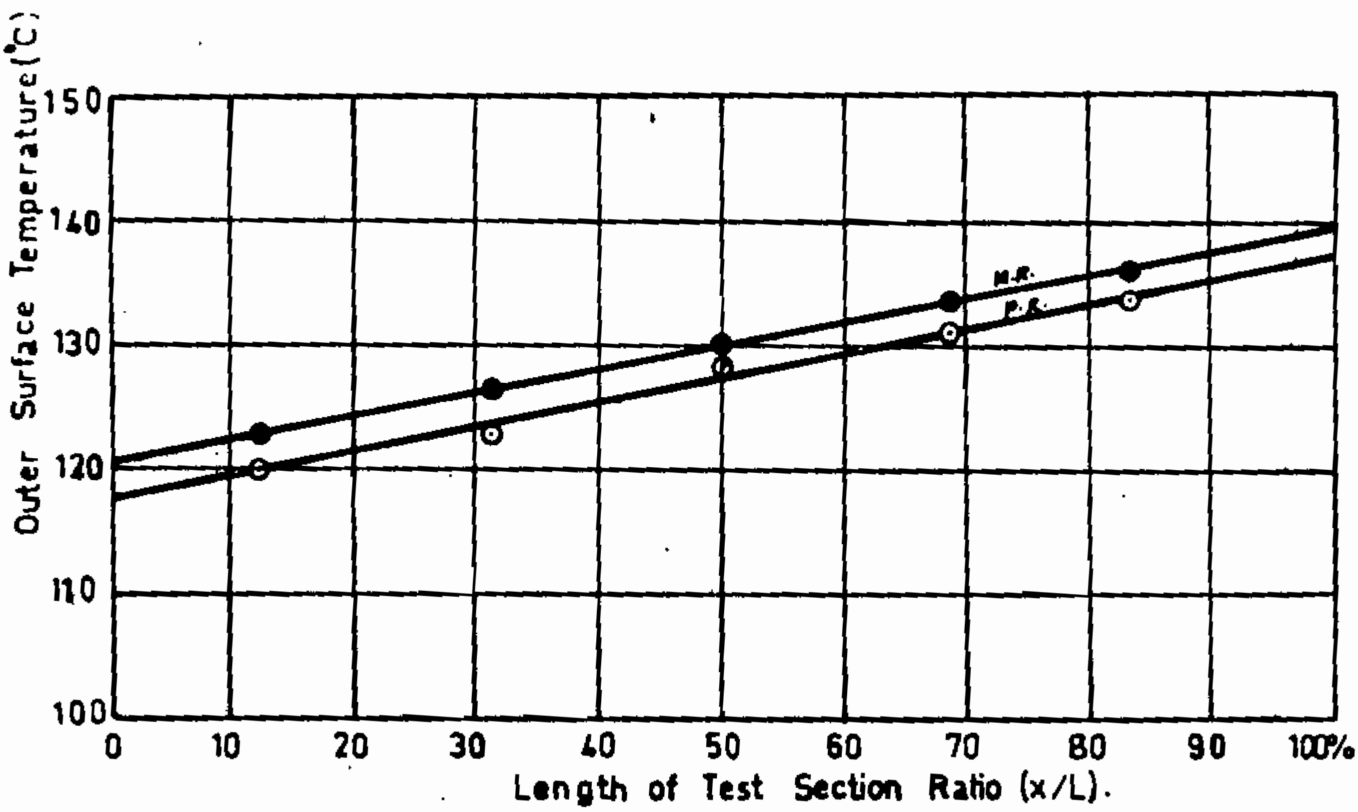

Fig.(3): Outer Surface Temperature Versus (X/L) for (L=21cm., S/d=1.5, I=775 cmp.)

and agitation. Consequantly the heat transfer coefficient increases.

The frgure indicates that the surface temperature along the middle rod is higher than the corresponding of the periphery rod. This is due to the large number of bubble current streams created from the periphery rods and at the same time from the middle one. The bubble current streams result in unstable nucleate boiling and unstable film boiling on the middle rod. This means that there is a semi-transition boiling region that occurs before the actual transition boiling one.

The surface temperature increases with the decreases of pitch to diameter ratio. This is due to the rods effect on each other. But the surface temperature along the middle rod is still higher than its corresponding on the periphery rod at (I = 775 amp.) as shown in Fig. (4).

Figure (5) illustrates the variation of surface temperature with heat flux for the middleand periphery rods. It is noticed that at a certain location, the heat flux of the middle rod is higher than its corresponding for periphery rod. Also, the illustration shows that the surface temperature of the middle rod is higher than that for the periphery rod. But this increase in heat flux and surface temperature is relatively small.

Figure (6) shows the boiling curves for periphery rods at different locations. The illustrations indicate that the surface temperature varies with the variation of (X/L), i.e. increases with increase of (X/L) as (X) measured from the upper end of the test section. But the surface temperature of the middle rod at a certain position is still higher than its corresponding value for the periphery rod. Also, it is noticed that this phenomena is acceptable for different pitch-diameter ratio (s/d) values.

Figure (7) shows that the heat transfer coefficient decreases with increase of (X/L) at a certain value of pitch to

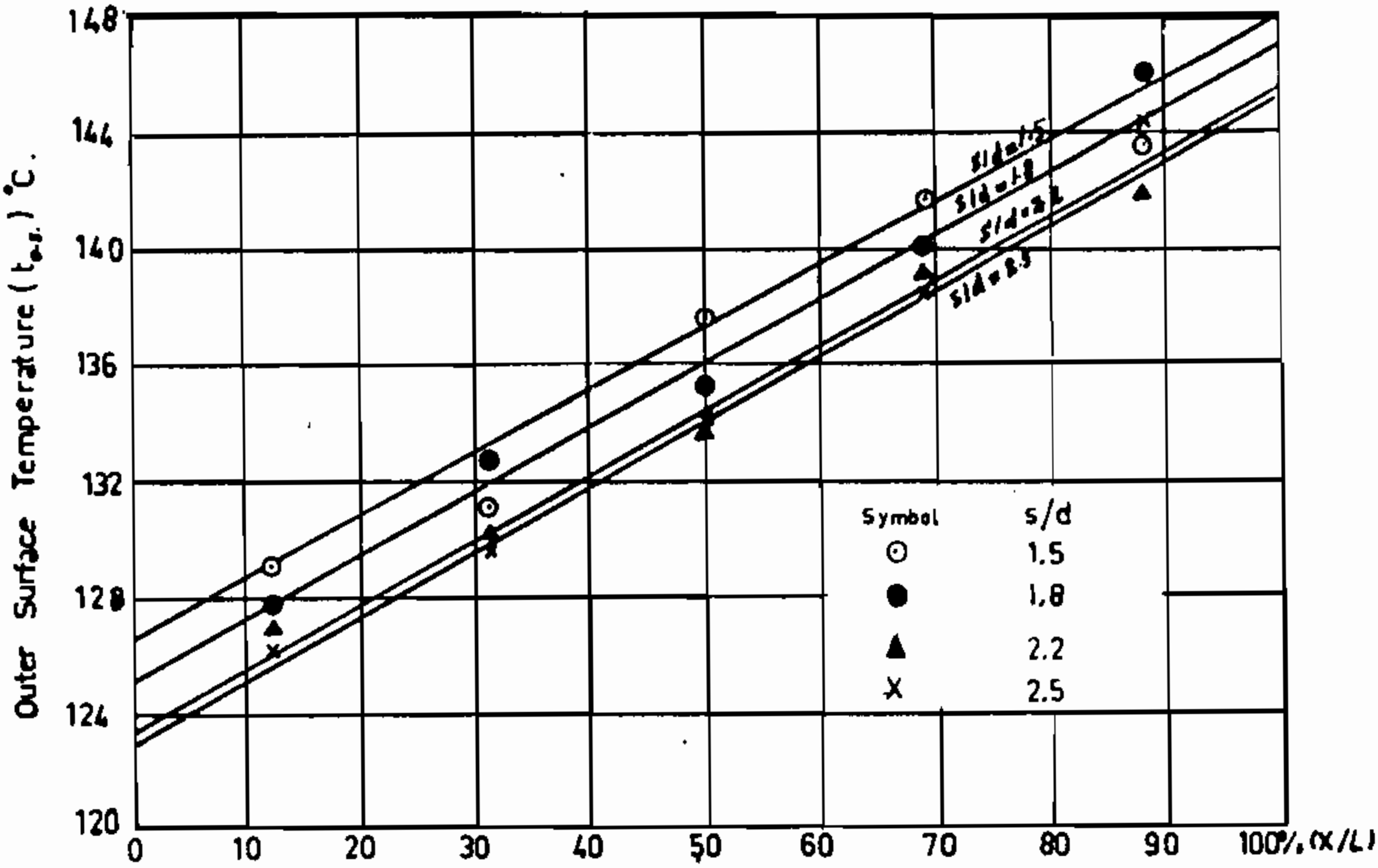

Fig.(4): Outer Surface Temperature Versus X/L for (L=21 cm., I=775amp., Periphery Rod).

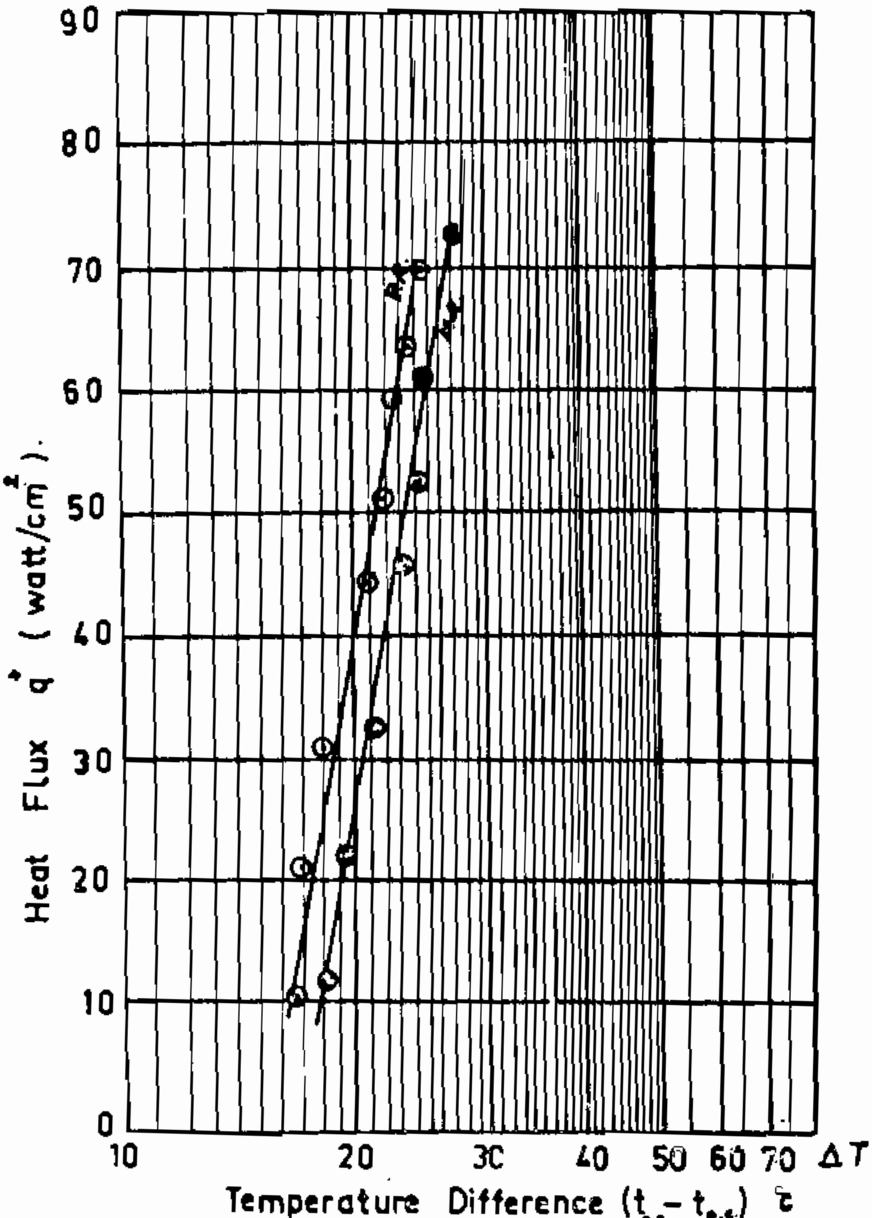

Fig. (5): Heat Flux Versus Temperature Difference for (L=21cm., X/L=12%, S/d=1.5).

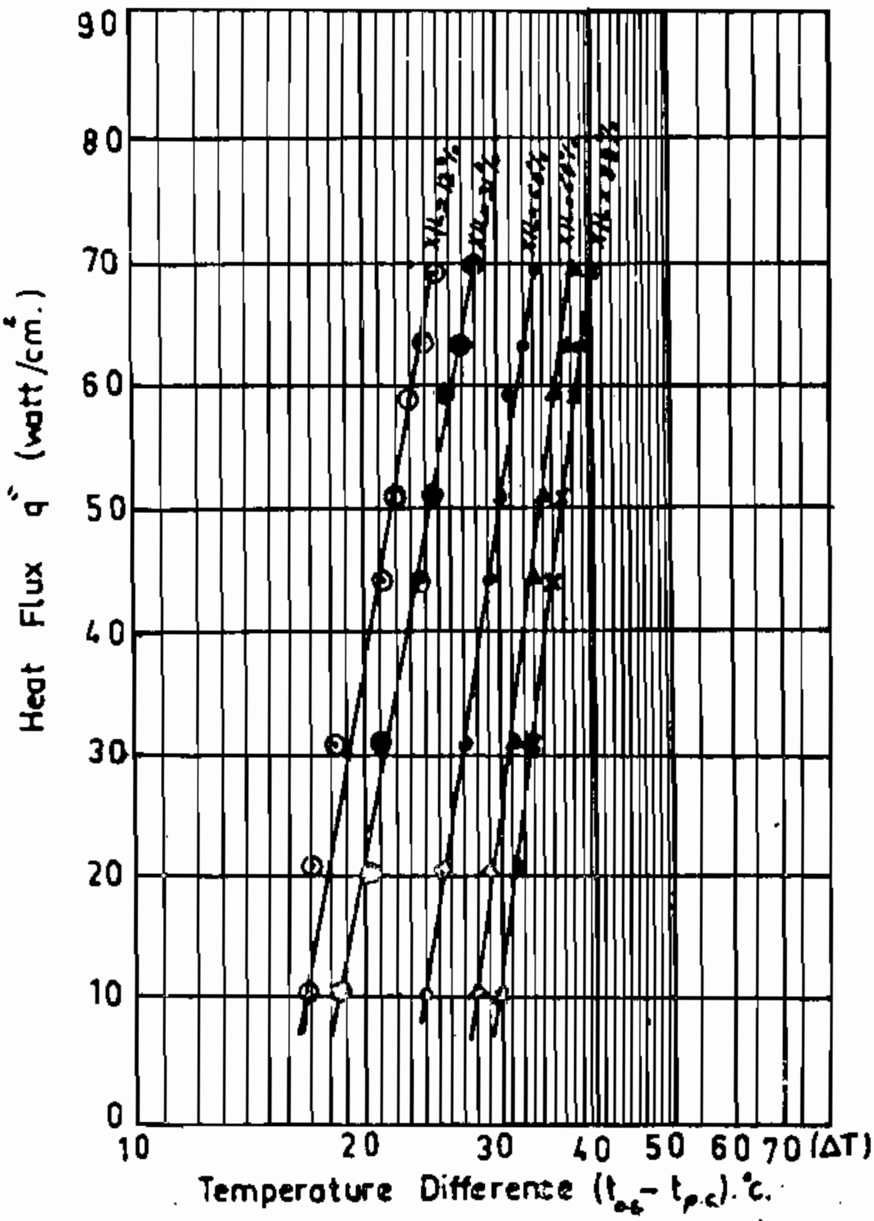

Fig. (6): Heat Flux Versus Temperature Difference for (L=31cm., S/d=1.5, Periphery Rod).

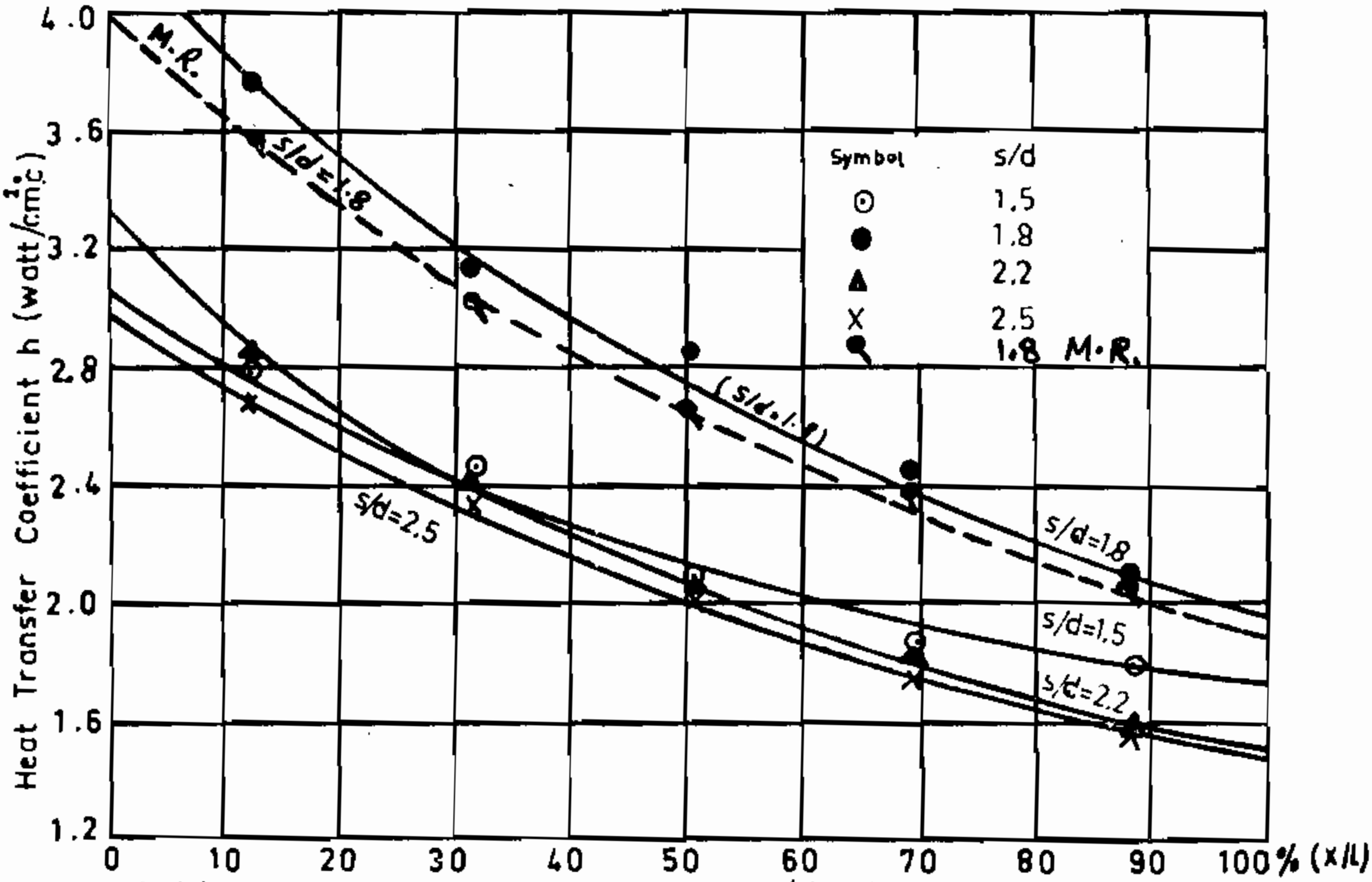

Fig.(7): Heat Transfer Coefficient Versus (x/L)for(L=21cm,I=775amp., Periphery Rod).

diameter ratio and constant current (I = 775 amp.). This phenomena is due to the increase of surface temperature at the lower end than at the upper end.

It is observed that the heat transfer coefficient along the middle rod has a lower value than those for the periphery rod. This phenomena is valid for all values of (s/d). This is due to the higher surface temperature along the middle rod.

Also, Fig. (7) shows that at constant current (I = 775 amp.) the heat transfer coefficient in the case of pitch to diameter ratio (s/d) equals (1.8) is higher than its value in the cases of 1.5, 2.2 and 2.5 respectively. It is observed that the values of the heat transfer coefficient are approximately equal for pitch to diameter ratios 1.5, 2.2 and 2.5 respectively.

Figure (8) illustrates the variation of teat transfer coefficient with pitch to diameter ratio at (I = 775 amp.). It is clear from the figure that the heat transfer coefficient increases with the decrease of (s/d) until a certain value of (s/d = 1.8) where it reaches its maximum value, then it starts to decrease. This phenomena occurs at a certain value of(X/L).

The illustration indicates that the heat transfer coefficient values along the periphery rod are higher than their corresponding values along the middle rod. This is due to the lower surface temperature on the periphery rod as mentioned before.

It is interesting to notice that at (X/L = 0.88) i.e. near the lower end of the test section, the heat transfer coefficient values along the periphery rod and the middle rod are the same. This is due to the stagnant region existing at the lower end i.e. the stream current velocity tends to zero, as shown in Fig. (8). Also, it is obvious, that at a certain current value (I = 775 amp.) and different values of (X/L), the heat transfer coefficient increases with the decrease of (X/L). But the values of the heat transfer coefficient along

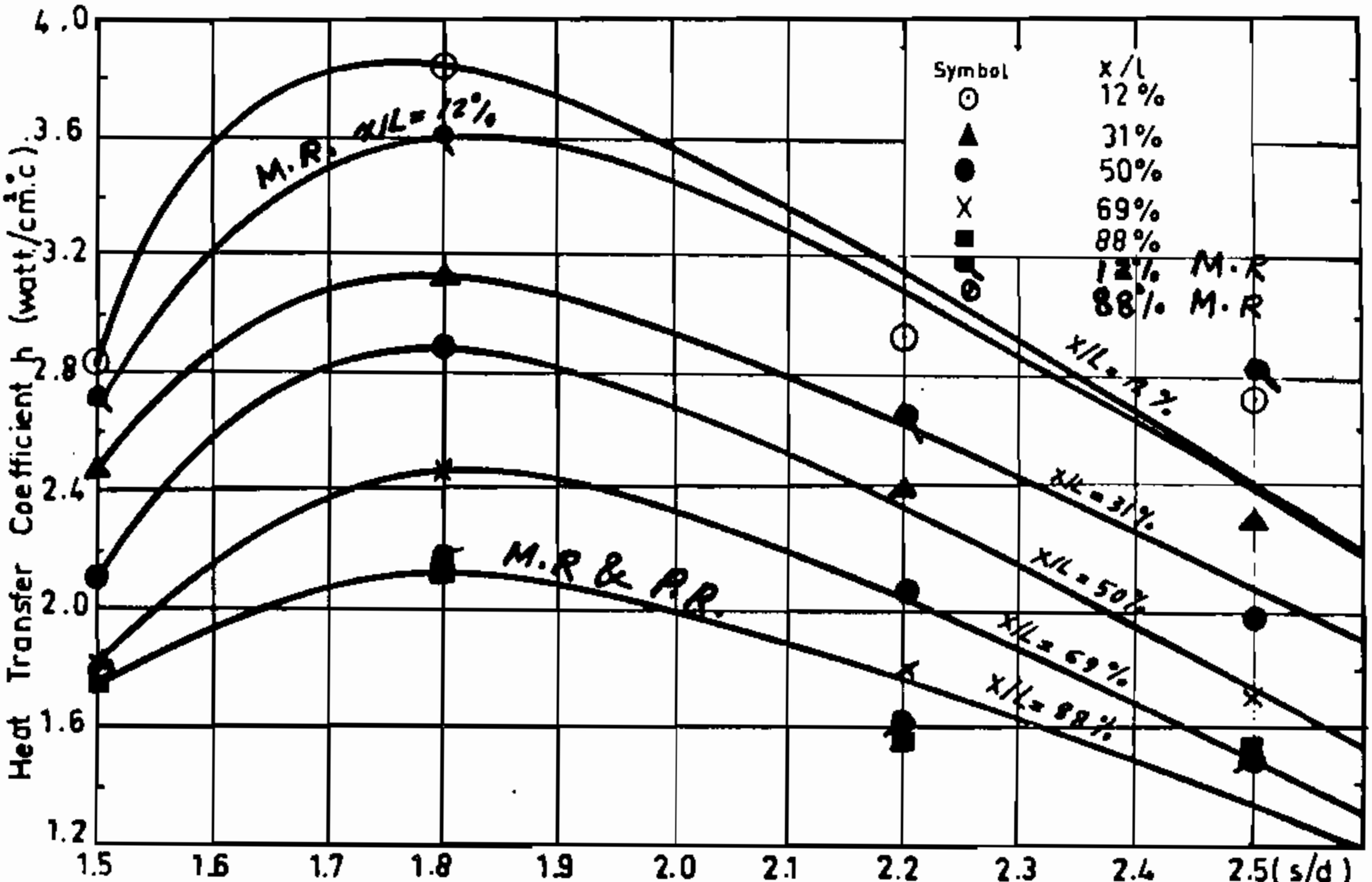

Fig.(8): Heat Tronsfer Coefficient Versus Pitch Diameter Ratio for(l=21cm,I=775 amp., Periphery Rod).

the periphery rod are still higher than those for the middle rod.

Figures (9) to (13) show the heat transfer coefficient variation with temperature difference for pitch to diameter ratios s/d = 1.5, 1.8, 2.2 and 2.5 respectively. The curves show that the heat transfer coefficient increases rapidly with relatively small increase in surface temperature. This means that there is good cooling resulting from bubble streams. At maximum current, (I = 775 amp.) it is clear that the heat transfer coefficient value on periphery rod ie higher than those on the middle rod at different locations.

Figures (10) and (13) show the heat transfer coefficient on the periphery rod and middlerod (at s/d - 1.8) respectively at different locations (X/L). These illustrations indicate, that the heat transfer coefficient decreases with the increase of (X/L) for both periphery and middle rods. However, the heat transfer coefficient on the periphery rod is still higher than its corresponding on the middle rod. Also, it is clear that increasing (X/L) increases the surface temperature as mentioned before.

Figure (14) shows that at maximum current (I = 775 amp.) the heat transfer coefficient for the value of pitch to diameter ratio (s/d = 1.8) is higher than all the values of other pitches for the periphery and middle rods respectively. In case of large pitches (2.2 and 2.5) the effect of rod to rod spacing decreases. But in case of small pitch (1.5), the effect of rod to rod spacing increases, i.e. the surface temperature highly increases and consequently the heat transfer cecreases.

From the experimental results, the mean heat transfer coefference (θ_m) are calculated at every run nsing the following formulas:

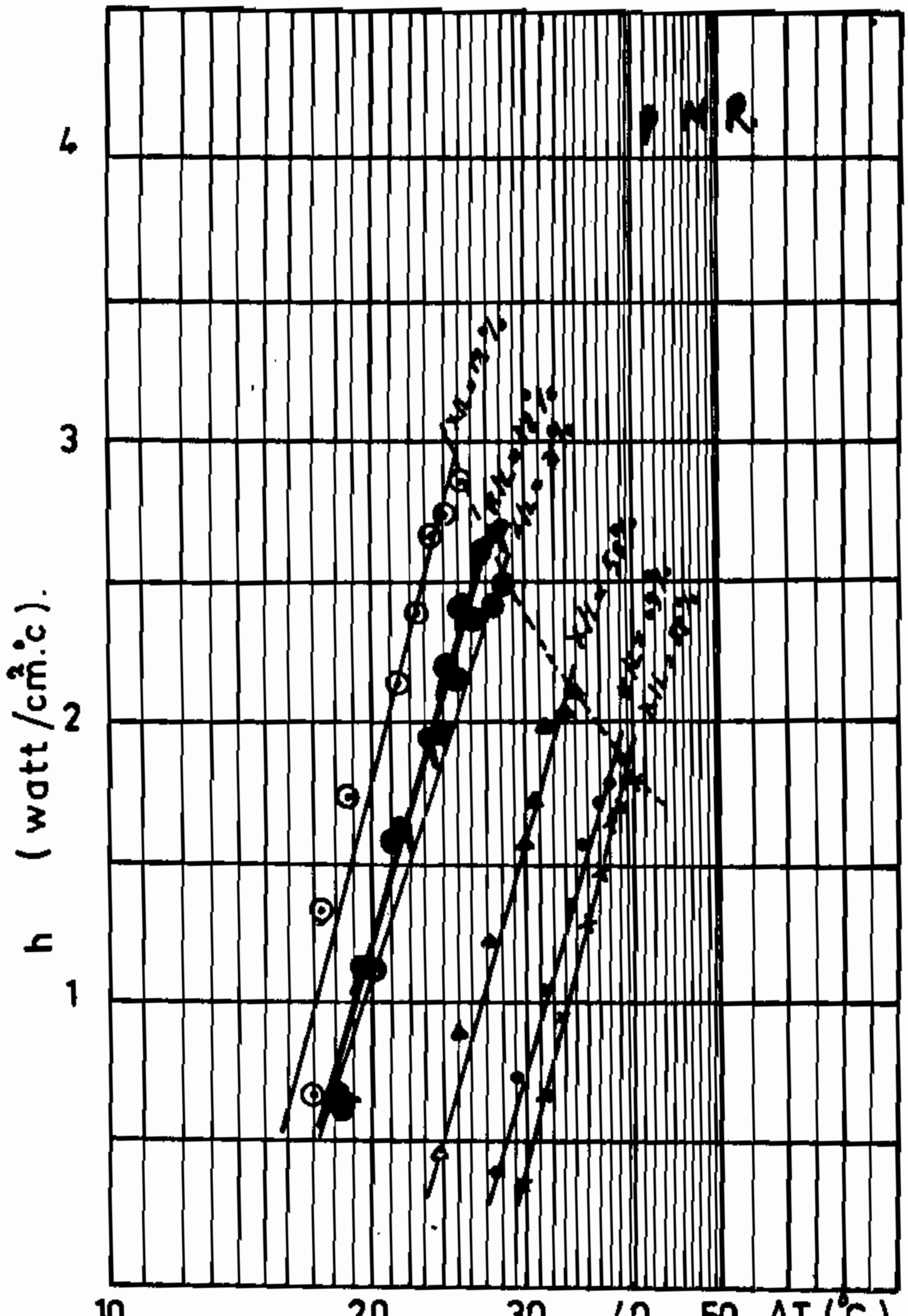

Fig.(9):Heat Transfer Coefficient (h) Versus Temperature Difference (ΔT) for (L=21cm., s/d=1.5, Periphery Rod).

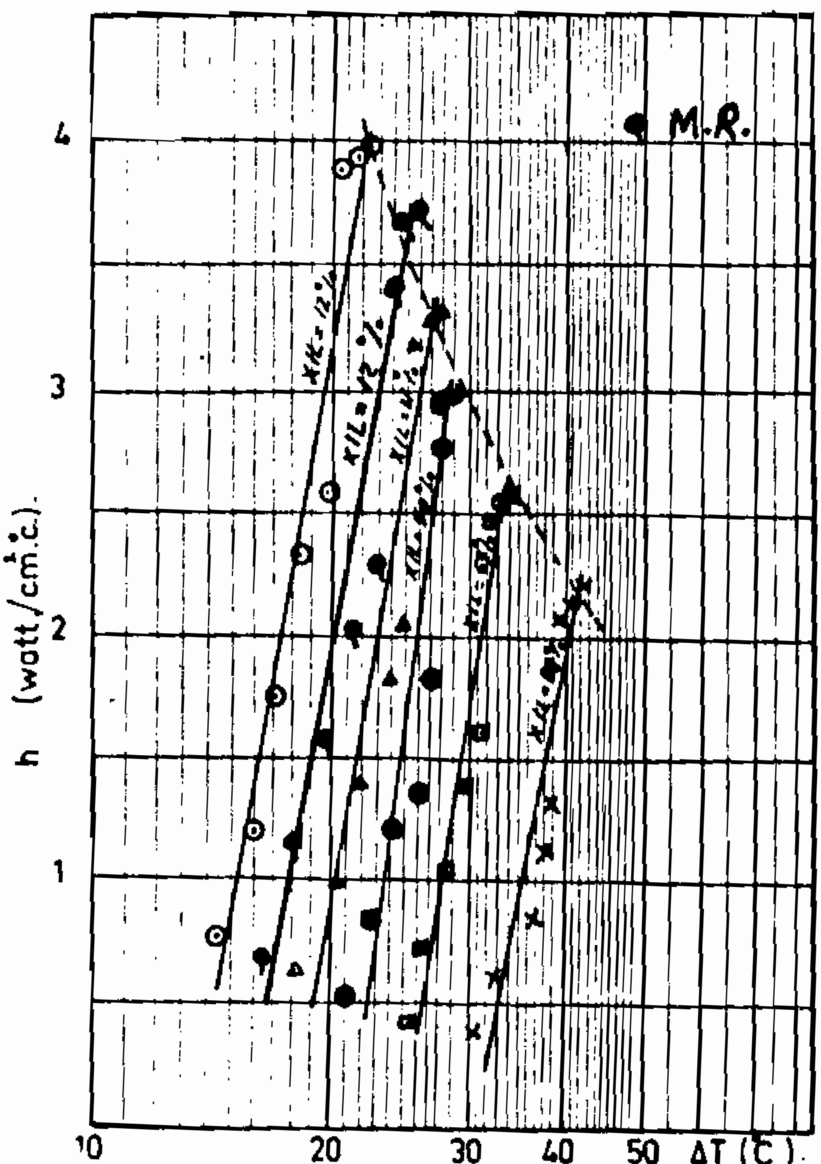

Fig.(10): Heat Transfer Coefficient h Versus Temperature Difference ΔT for (l=21cm., s/d=1.8, Periphery Rod).

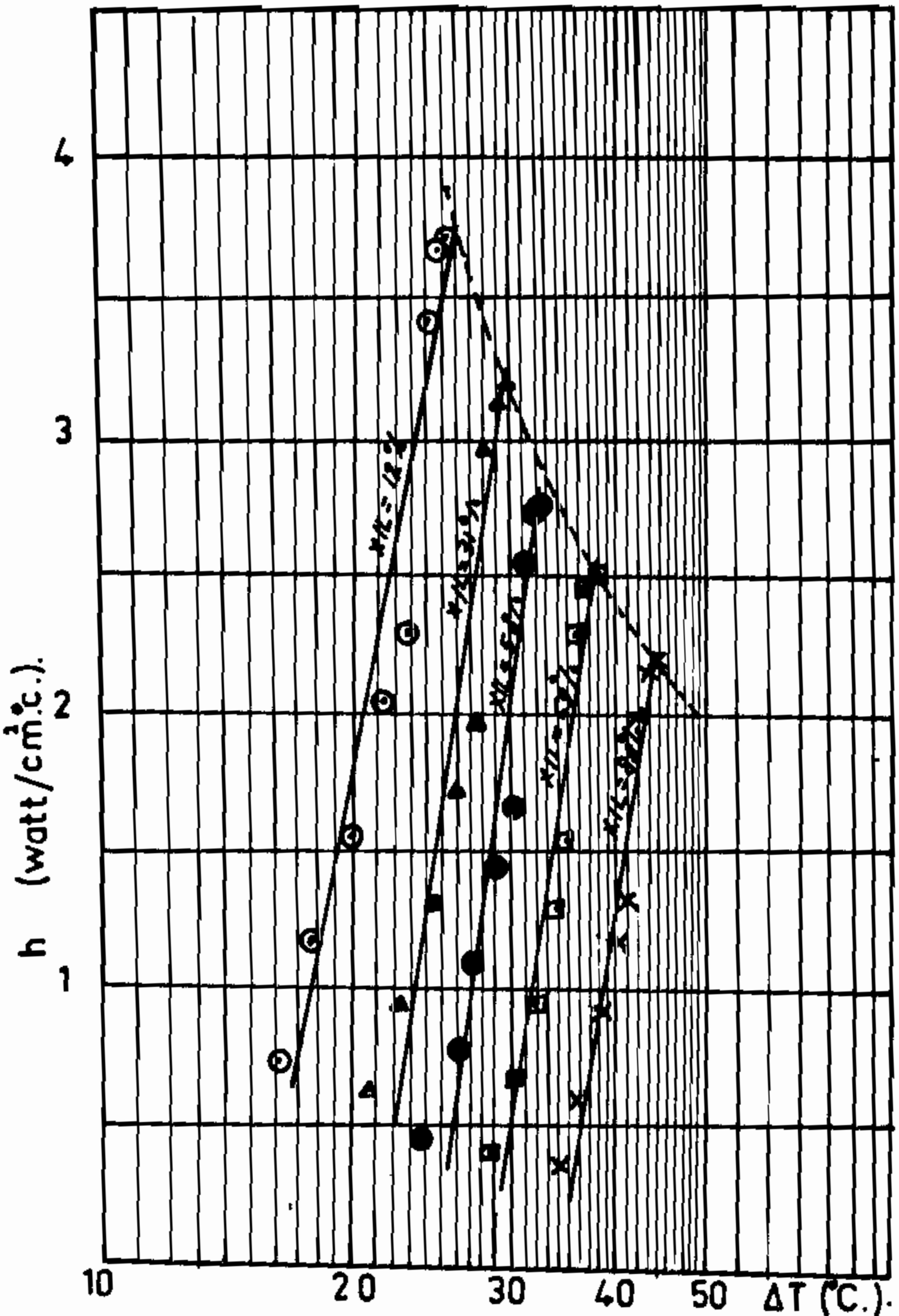

Fig.(11): Heat Transfer Coefficient h Versus Temperature Difference ΔT for(l=21cm., s/d=1.8, Middle Rod).

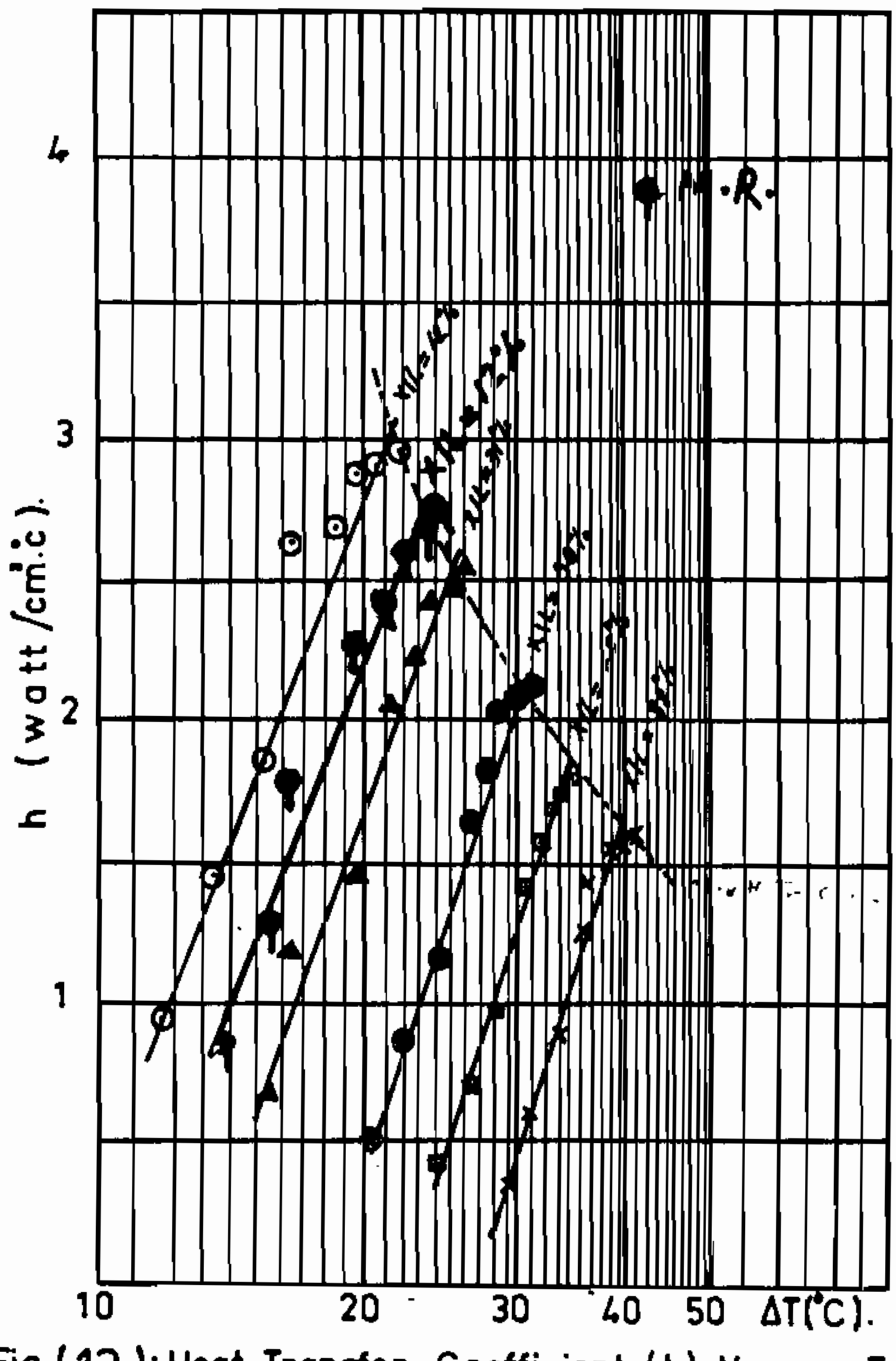

Fig.(12): Heat Transfer Coefficient (h) Versus Temperature Difference (ΔT) for(l=21cm., s/d=2.2, Periphery Rod).

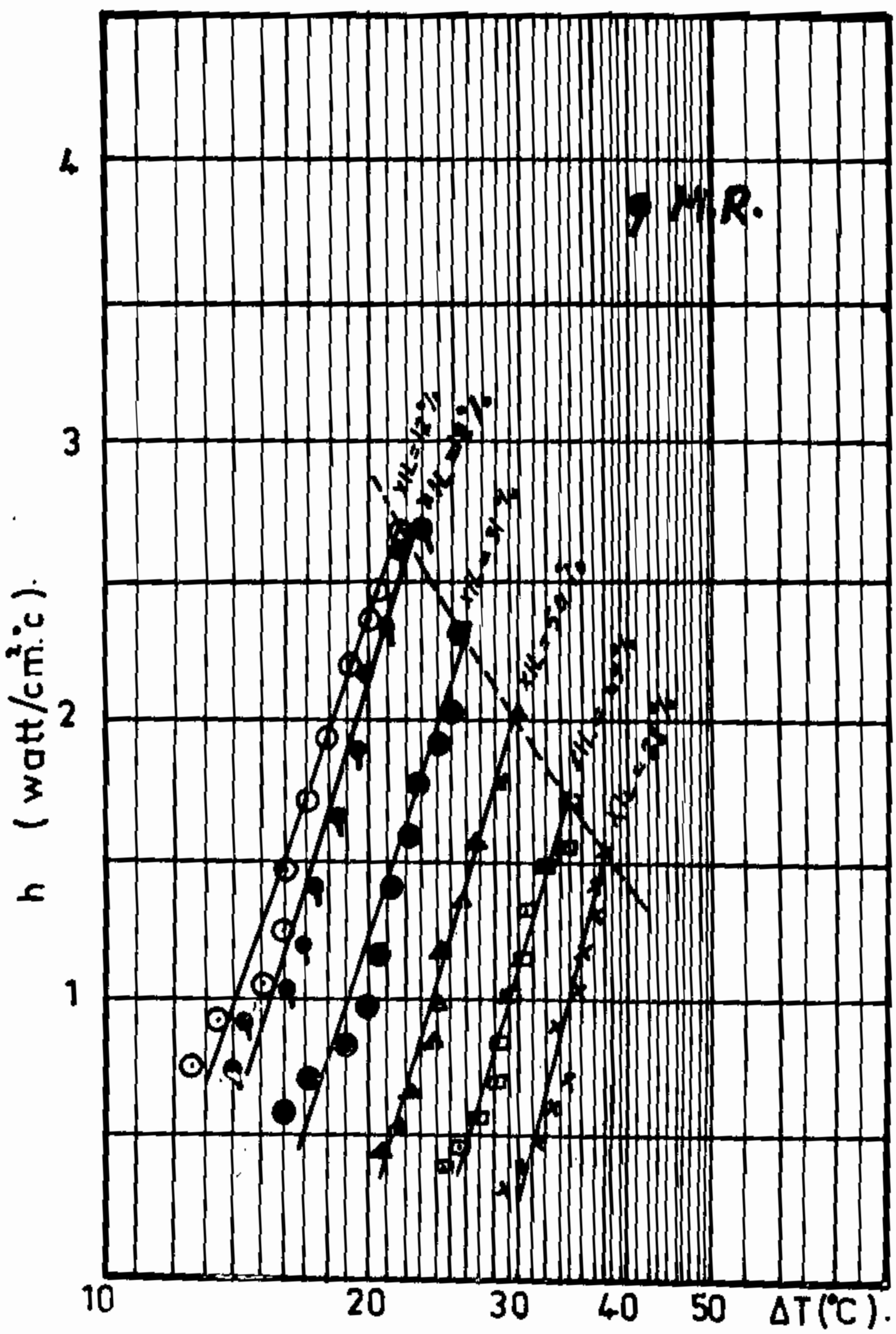

Fig.(13): Heat Transfer Coefficient (h) Versus Temperature Difference (ΔT) for (l=21cm., s/d=2.5, Periphery Rod).

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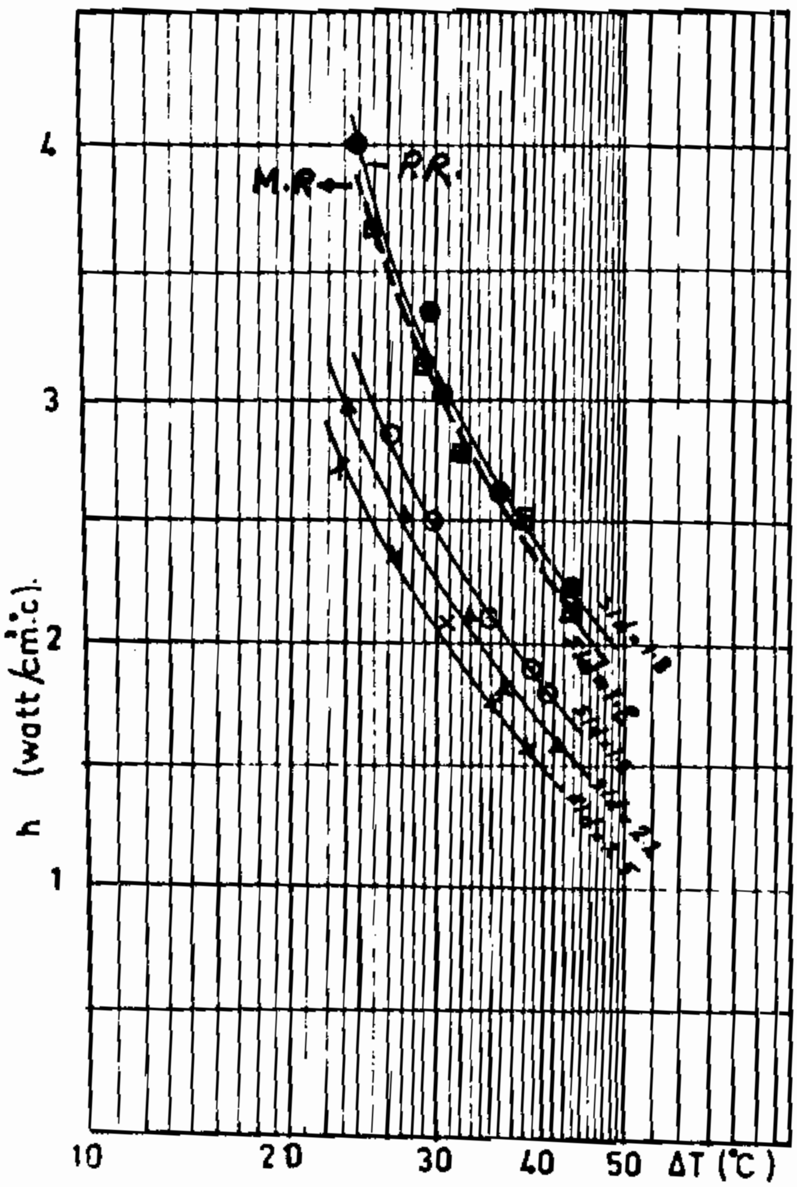

Fig.(14):Heat Transfer Coefficient h Versus Temperature Difference ΔT for (l=21cm.,I=775amp., Periphery Rod).

$$\theta_m = \frac{\int_0^L \theta \, dL}{\int_0^L dL}$$

$$h = \frac{q''}{\theta_m} \qquad (w/cm^2.°C)$$

Also, the parameters $\bar{h}$, θ_m and s/d are correlated with each other by using the least square method as shown in the following relation:

$$\bar{h} = c \, (\theta_m)^n \, (s/d)^m$$

where

$$c = 6.79 \times 10^{-10} \ \text{watt/cm}^2. \ (°C)^{n+1}$$

$$m = 8.524$$

$$n = (4.99 \rightarrow 4.11)$$

For s/d= (1.8 $\rightarrow$ 2.5)

Figure (15) shows a comparison between the experimental values of (h) and (θ_m) with their values determined by the above mentioned relation. The maximum error of the mean heat transfer coefficient is determined as the following.

$$Sh = \frac{\bar{h}_{th.} - \bar{h}_{act.}}{\bar{h}_{act.}}$$

$$= \frac{\delta \bar{h}_{max.}}{\bar{h}_{act.}} = 0.125$$

5. CONCLUSIONS:

From the previous results we conclude that:

1- The heat transfer coefficient along the periphery rod is higher than that along the middle one.

2- The surface temperature along the middle rod is higher than those along the periphery rods.

3- The heat transfer coefficient is high in the region near the upper end of the test section. Thus, large length

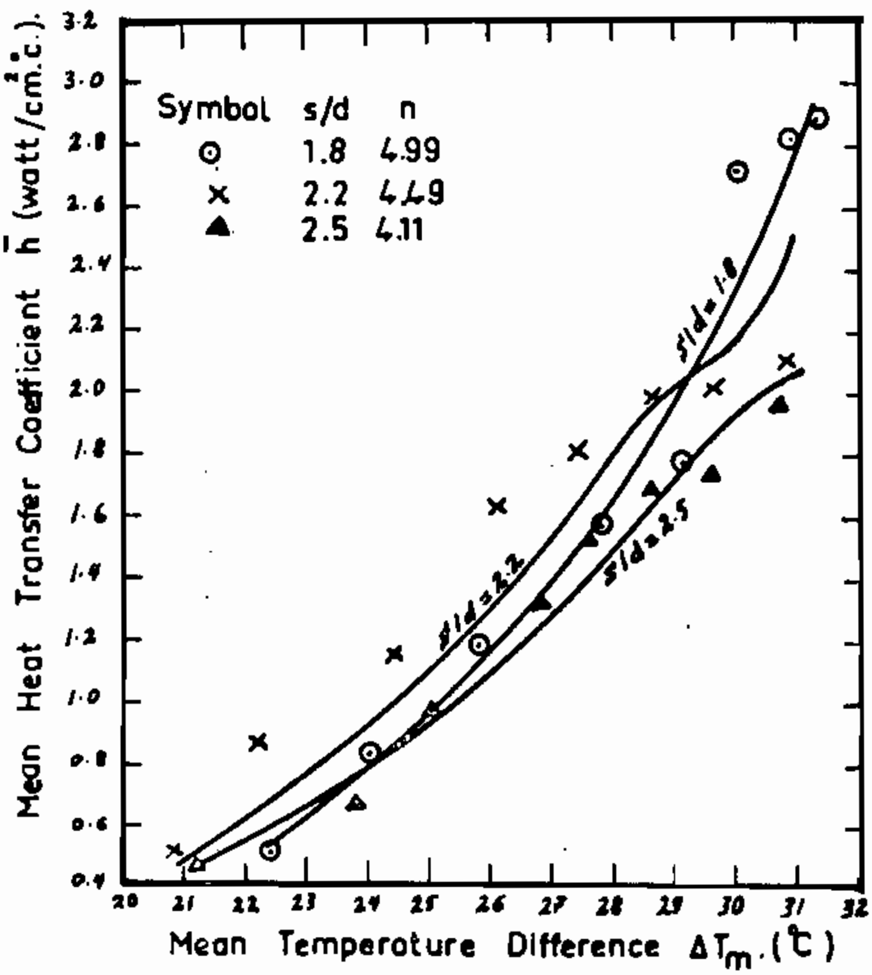

Fig.(15):Mean Heat Transfer Coefficient $\bar{h}$ Versus Mean Temperature Difference ΔT_m.

of the tube bundle gives large of high heat transfer coefficient.

4- The optimum pitch to diameter ratio is (s/d = 1.d) at atmospheric pressure.

5- It is expected that the boiling crisis occurs at the middle rod before the periphery rod.

Therefore outhous suggested that, releasing the middle rod and added its surface are at the surface area of the periphery rods, increase the heat transfer coefficient.

NOTATION:

Symbol	Description.
A	heat transfer surface area
d	test section diameter.
h	heat transfer coefficient
$\bar{h}$	mean heat transfer coefficient
$\bar{h}_{act}$	actual mean heat transfer coefficient
$\bar{h}_{th}$	theoretical mean heat transfer coefficient
I	current in the heater tube
L	heater tube length
P	absolute pressure
P_p	electric power Input (For periphery vod).
P_m	electric power Input (For middle rod).
q	heat input to test section
q''	heat flux
$t_{i.p.}$	inlet temperature
$t_{c.p.}$	center pool temperature
t_w	wall temperature
t_{wo}	outer wall surface temperature
t_{sat}	saturation temperature
s/d	pitch - diameter ratio
v	voltage drop across the heater pipe
X	distance measured from the test section top
θ	temperature difference
θ_m	mean temperature difference.

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