

EFFECT OF SCALES ON OVERALL HEAT TRANSFER COEFFICIENT DURING NUCLEATE POOL BOILING OF WATER *

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ABSTRACT

The effect of scales on overall heat transfer coefficient during nucleate pool boiling of water heated by a platinum strip was investigated. The platinum test strip, placed between two electrodes was submerged into a pool of distilled water which was kept at the saturation temperature by means of an immersion heater. The experiments were conducted with the bare test strip and with various scale thicknesses deposited on the strip. The results show that the overall heat transfer coefficient «h» decreases with the scale thickness and the «(h) versus wall superheat ($T_w - T_s$)» curve shifts to the right as the scale thickness increases. In the initial stage of nucleate boiling the overall heat transfer coefficient «h» increases slowly, then it becomes almost constant so that in some cases the slope of «(h) versus ($T_w - T_s$)» curve approaches to zero. In the later stages of the nucleate boiling the overall heat transfer coefficient starts to increase again steeply.

ÖZET

Bu çalışmada, kazan taşının platin bir şeritten elektrik akımı geçirmek suretiyle ısıtılan durgun su içerisinde kabarcıklı kaynama ile olan ısı transferine etkisi incelendi, iki elektrot arasına yerleştirilen test şeridi doyma sıcaklığında tutulan bir ısı ve yumuşak su havuzuna daldırıldı ve önce şerit yüzeyi temiz olarak, daha sonra da üzerine çeşitli kalınlıklarda kazantaşı çökeltilerek deneyler yapıldı. Alınan sonuçlara göre ısı transferi katsayısı kazantaşı kalınlaştıkça azalmaya ve test şeridi sıcaklığı ile su sıcaklığı arasındaki farka göre ısı transferi katsayısının değişimini ifade eden eğri, kazantaşı kalınlığı arttıkça sağa doğru kaymaktadır. Ufak sıcaklık farklarında ısı transferi katsayısı yavaş olarak artmakta, daha büyük sıcaklık farklarında ise katsayının değeri hemen hemen sabit kalmakta ve kabarcıklı kaynamanın daha sonraki kademelerinde ısı transferi katsayısı hızlı olarak tekrar büyümeye başlamaktadır.

INTRODUCTION

In recent years Boiling Water Heat Transfer has found a considerably large field of application extending from conventional boilers to nuclear reactors. The basic mechanism of nucleate boiling is as yet not understood very well. One of the schools of thought attributes the very high heat transfer rates associated with nucleate boiling to some convection currents induced by the stirring action of the bubbles [1].

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All waters contain impurities either as suspended solids or as solids and gases in solution. Some of these impurities deposit themselves on the warm metal surfaces to form scale when water is heated. Since the thermal conductivity of the scale is much smaller than that of metals which are used as the surface in practice, the scale acts as an insulating layer which reduces the rate of heat transfer. As a result of the nonuniform precipitation of the hardness agents in water on the smooth heated surface the surface roughness increases and this leads to the formation of larger size cavities.

At the beginning of the formation of scale on the heated surface, the value of overall heat transfer coefficient « h » would decrease because of the added resistance to heat transfer from wall by scale formation. It might be thought that at a certain thickness of scale, the cavities introduced on the heated surface by scale formation would help to the initiation of nucleate boiling and this would lead to a larger heat transfer rate from the surface. Therefore the overall heat transfer coefficient from the heated wall would be expected to be under the combined influence of surface insulation by scale formation and of the liquid agitation by the moving bubbles during pool boiling of water.

Berenson [2] studied the effects of surface conditions on heat flux in pool boiling and concluded that for a fixed wall superheat degree the heat flux from the heated wall would increase as the surface roughness increases. Castello and Frea [3] boiled tap water on stainless steel heater surfaces to obtain deposits as a surface coating of the heaters. This coating was found to be effective in attainment of extremely high heat fluxes. Farber and Scoriah [4] reported critical heat flux values in pool boiling that were about 2 - 3 times greater than those found by other investigators. The difference is attributed to the hard deposit on the Farber - Scoriah test wires. Tamer [5] investigated the influence of the scale formation on the nucleate pool boiling heat transfer from a horizontal platinum wire of 0.1 mm diameter. The experiments were conducted in distilled water and in tap water. The nucleate boiling started earlier in tap water and the boiling curve of the platinum wire in tap water, having some scale thickness, was shifted to the right of the one having no scale in distilled water. For a particular surface temperature of the platinum wire, the heat transfer rate was higher in distilled water than the one in tap water.

The main object of the experimental work reported here was to investigate the effects of scale formation on overall heat transfer coefficient during nucleate pool boiling of water heated by a platinum strip.

The overall heat transfer coefficient « h » accounts for the combined effects of the conduction through the scale thickness and through the

liquid thermal layer, of the convection caused by the agitation of bubbles and, of the latent heat exchange due to the vaporization.

DESCRIPTION OF APPARATUS

In the experiments a platinum strip, 30 mm long, 2.5 mm wide and 0.025 mm thick was used as the heated surface. The test strip was mounted on two copper electrodes by two holders and was submerged into a pool of distilled water, having its width in the vertical and its length in the horizontal positions. Water in the test tank was kept at its saturation temperature by an electrical immersion heater. The water temperature was measured both by a thermocouple and by a mercury-in-glass thermometer. In the test tank a dividing plate was placed between the immersion heater and the test strip. This plate prevented the agitation effects of the bubbles generated by the heater. The front wall of the test tank was replaced with a 5 mm thick glass for a better vision of the test strip (Fig. 1). The joints were sealed with a silicon rubber compound. The other three faces of the container were insulated with glass wool.

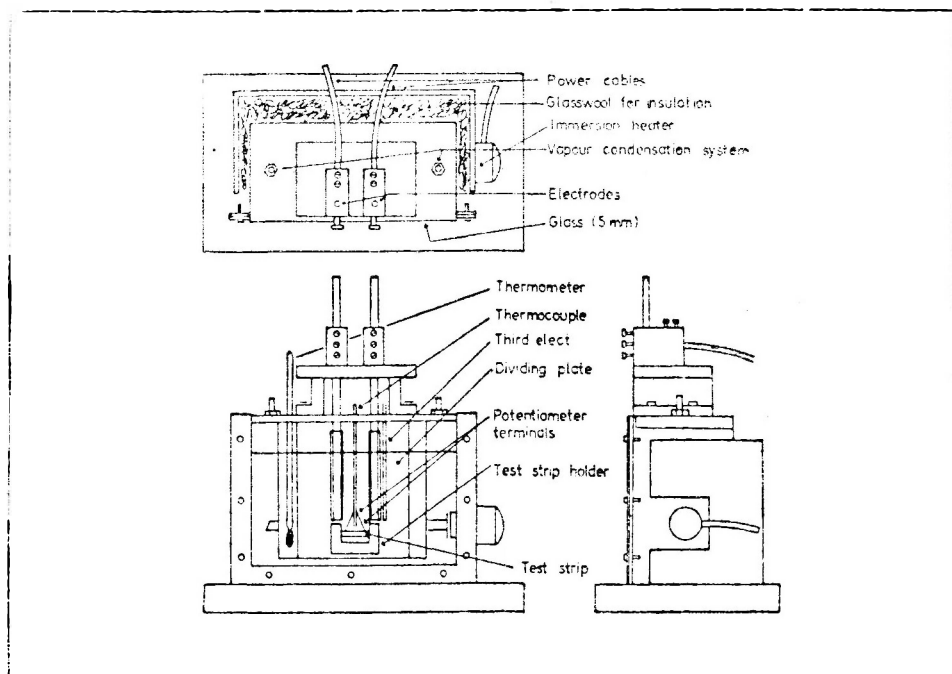


Fig. 1. Test set-up

The copper electrodes were covered by glass tubes in order to prevent the electrolyzation of water. Also, for the same reason, a third electrode was added to the system. Consequently, there would be no

tentiometer. To be able to read the voltage drops within the same range of the potentiometer a voltage divider was used.

In order to deposit scale on the test strip, the electrodes and the platinum strip were submerged into another container which was full of tap water and heated by an immersion heater. The test strip was connected to a AC source. By means of a regavolt, the current across the test strip was regulated until nucleate boiling regime was obtained. Because of impurities existing in the tap water, some scale was formed on the test strip surface.

The chemical composition of the tap water used during the test was determined as :

Ca :	131.0 p.p.m	Mg :	46.5 p.p.m	Fe :	0.8 p.p.m
Al :	1.0 p.p.m	HCO ₃ :	420.0 p.p.m	CO ₂ :	None
SO ₄ :	111.0 p.p.m	Cl :	162.5 p.p.m		

EXPERIMENTAL PROCEDURE

The platinum test strip was used as a resistance thermometer and it was calibrated for each test. The test strip may be assumed to be an infinite slab of finite thickness; and the large ratios of its length and width to its thickness reduce the end effects and edge effects considerably [6]. The thermal resistance of the test strip is assumed to be negligible, so that the temperature across its thickness is uniform. Therefore it seems to be reasonable to assume that the surface temperature of the platinum test strip is equal to its average temperature.

The first run was performed with the platinum strip immersed into distilled water with no scale on it. Then some scale was deposited on the test strip in a pool of tap water. The scale thickness was measured with a precision vernier measuring microscope. The test assembly was then immersed into the distilled water tank and the test was run. By means of the standard resistances, the voltage drops and the currents at certain parts of the circuit were determined. The instantaneous resistance of the platinum test strip was evaluated by using the method of comparison of voltage drops across the standard resistance and the test strip :

$$R_2 = \frac{V_2}{V_3} R_3 \quad (1)$$

where « V_2 » and « V_3 » are the voltage drops across the test ribbon and the standard resistance respectively (Fig. 2). The temperature coefficient of resistance of platinum test strip was calculated as 0.00368 1/°C. The average temperature of the test strip, T_w , was determined from the «resistance versus temperature» calibration curve.

The heat balance for the test strip can be written as :

$$Q_g = Q_a + Q_i \quad (2)$$

where Q_g = heat generated per unit time in the strip by electric current
 Q_a = heat absorbed per unit time by the test strip
 Q_i = heat transferred to water per unit time.

Q_g is determined from;

$$Q_g = V \times I \quad (3)$$

where V = Voltage drop across the test strip
 I = Current through the test strip

Since the heat absorbed by the platinum strip was so small in comparison with the heat transferred to water per unit time [7], the latter might be expressed as :

$$Q_i = V \times I = h \times A \times (T_w - T_s) \quad (4)$$

where h = overall heat transfer coefficient at the test strip surface
 A = total surface area of the test strip
 T_w = average temperature of the test strip
 T_s = saturation temperature of distilled water at environmental pressure.

Hence, the overall heat transfer coefficient can be obtained from :

$$h = \frac{V \times I}{A \times (T_w - T_s)} \quad (5)$$

The overall heat transfer coefficient was determined for a heated wall superheat ($T_w - T_s$) range of about 1–20 °C. The saturation temperature of distilled water at environmental pressure was measured as 94.6 ± 0.1 °C. Then, the scale thickness was increased gradually and the same procedure was repeated. Finally, the variation of the overall heat transfer coefficient « h » with wall superheat « $T_w - T_s$ » was determined and the results were plotted. In order to verify the reproducibility of the results the tests were repeated three times at about the same conditions (Figs. 3–5).

DISCUSSION OF RESULTS

During experiments it has been observed by means of enlarged photographs that the surface roughness of the scale deposited on the test strip increases as its thickness increases [7]. It is expected that the size of the cavities would also increase as the scale thickness increases.

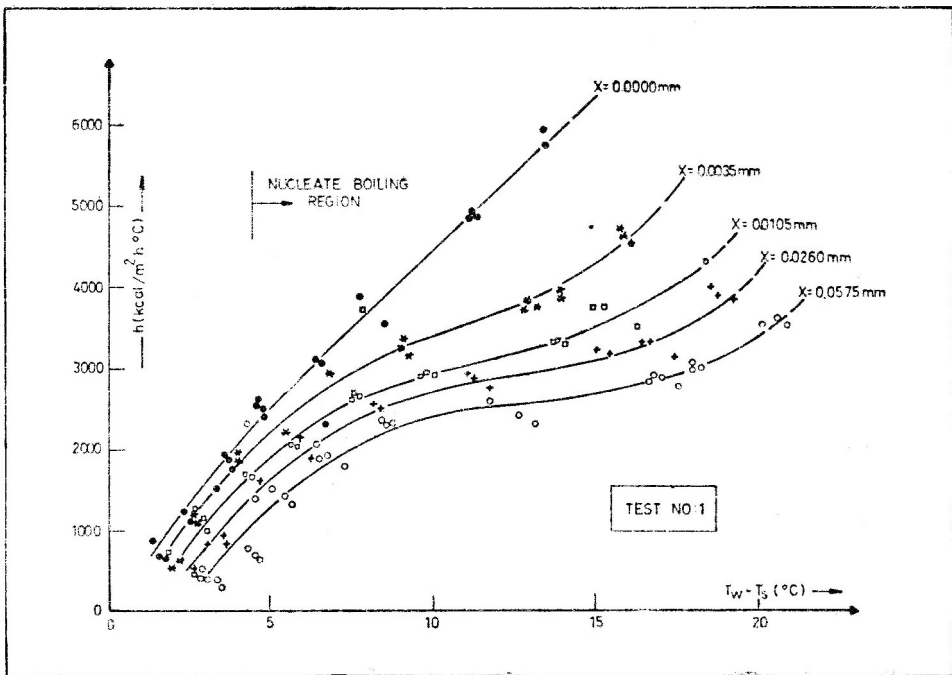


Fig. 3. Variation of overall heat transfer coefficient with wall superheat

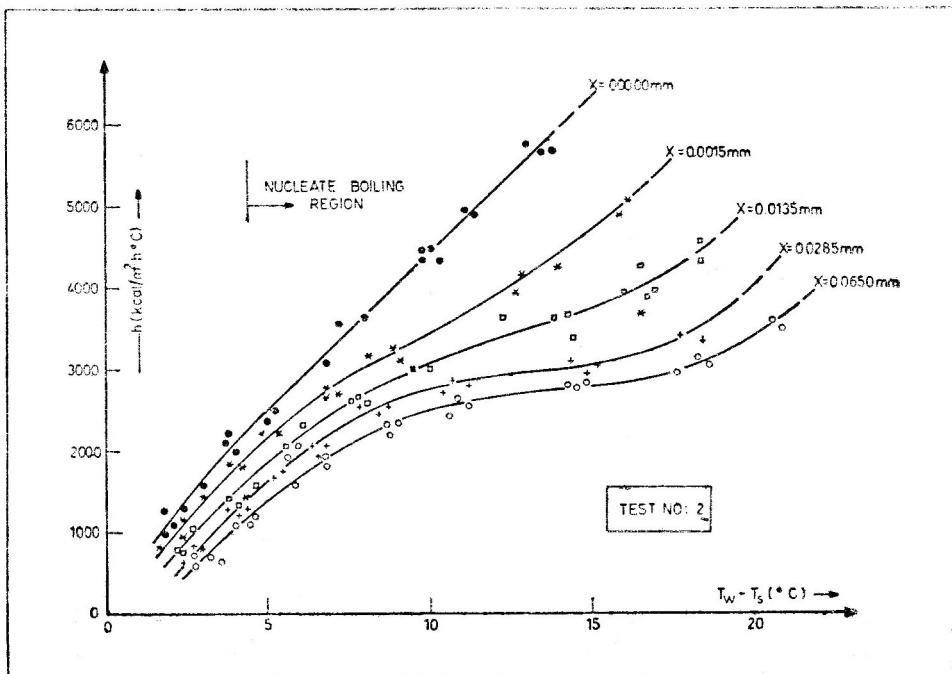


Fig. 4. Variation of overall heat transfer coefficient with wall superheat

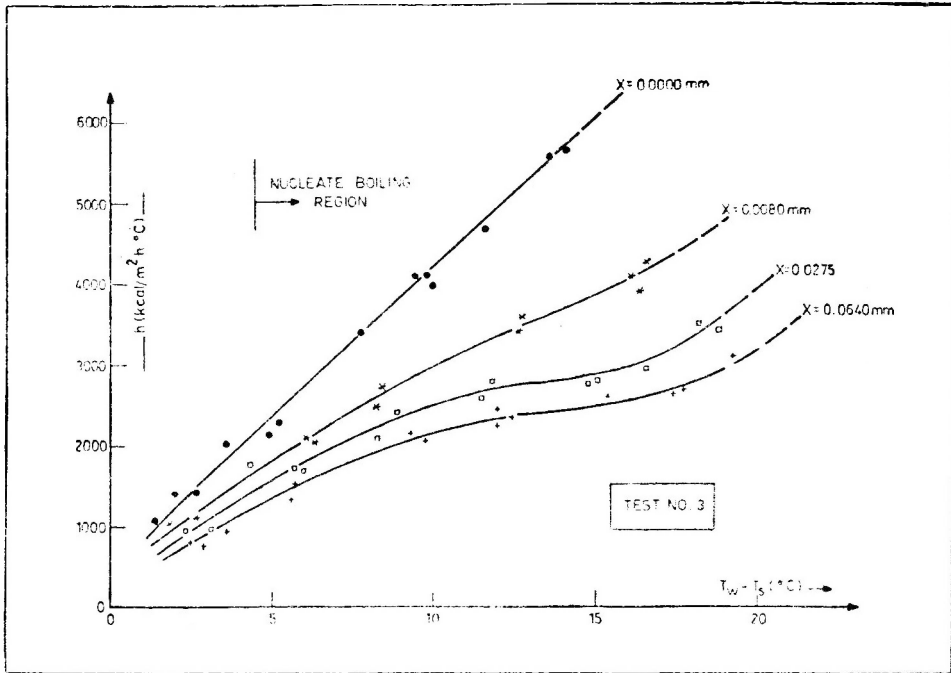


Fig. 5. Variation of overall heat transfer coefficient with wall superheat

The scale deposited on the test strip, dropped off at high surface temperatures, larger than about 116°C , because of the vibrations caused by the vigorous nucleate boiling occurring on the scale surface. Because of this, high temperatures of the test strip could not be reached at.

The accuracy of the measurements during the tests has been estimated as [7] :

Temperature measurements	: $\pm 0.1^\circ\text{C}$
Scale thickness measurements	: $\pm 0.0001 \text{ mm}$
Voltage measurements	: $\pm 0.000005 \text{ V}$
Overall heat transfer coefficient estimation	: $\pm 37 \text{ kcal/m}^2\text{h } ^\circ\text{C}$

The characteristic variations of overall heat transfer coefficient with the heated wall superheat are plotted in Figs. 3-5. When «(h) versus $(T_w - T_s)$ curves» are inspected, it is seen that, in general, as the scale thickness increases the overall heat transfer coefficient decreases.

In free convection region, up to about 5 degrees of wall superheat the overall heat transfer coefficient decreases with the increase of scale thickness on the test strip. This result seems to be reasonable since the most important factor effecting the overall heat transfer coefficient might be the added resistance to heat transfer by the scale formation.

In the second region, between 5-15 degrees of wall superheat the slopes of these curves decrease and in some of them the slope approaches to zero. This situation might be explained as follows: As the scale precipitates on the surface the formation of large size cavities at moderate wall temperatures would also be large in size and they might easily coalesce with each other leading to the formation of some large vapour patches on the surface. Due to the thermal insulation effect of these vapour patches, the overall heat transfer coefficient might, therefore decrease; and hence a corresponding decrease in the slope of «(h) versus $(T_w - T_s)$ curves» is observed.

In the third region beyond 15 degrees of wall superheat, the overall heat transfer coefficient starts to increase steeply. A possible explanation of this situation might be as follows: Since the active cavity size is inversely proportional to the wall superheat degree, at higher wall temperatures some smaller cavities might become active and the bubbles which nucleate from these cavities, without being coalescing due to their small size, would cause vigorous agitation in the liquid thermal layer and hence this would result in a steep increase in the overall heat transfer coefficient.

CONCLUSIONS

The overall heat transfer coefficient decreases with the scale thickness and «(h) versus $(T_w - T_s)$ curve» shifts to the right as the scale thickness increases. In the initial stage of nucleate boiling regime the overall heat transfer coefficient continues to increase gradually, and in some cases it may become almost constant. In the later stages of nucleate boiling the overall heat transfer coefficient starts to increase again steeply.

NOMENCLATURE

- A : Area, m^2
- h : Overall heat transfer coefficient, $kcal/m^2h^\circ C$
- I : Electric current, ampere
- Q_a : Rate of heat absorption by the test strip, $kcal/h$
- Q_g : Rate of heat generation in the test strip, $kcal/h$
- Q_t : Rate of heat transferred to water, $kcal/h$
- T_s : Saturation temperature of water, $^\circ C$
- T_w : Average temperature of test strip, $^\circ C$
- V : Electric voltage, Volt
- x : Scale thickness, mm

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