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ON S-SHAPED BOILING CURVES

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Abstract—The phenomenon of S-shaped boiling curves is analyzed in terms of the nucleation characteristics of the heat-transfer surface. The heat flux of such curves is correlated by both the temperature driving force and the active nucleation centers' density. The unexpected drop of the temperature driving force is shown to be caused by an abnormal increase of the active sites density, attributed to a disruption of the normal mechanism of nucleation.

INTRODUCTION

RECENTLY Tang and Rotem [1] reported another of the rare cases of S-shaped boiling curves. The purpose of this communication is to explain this phenomenon in terms of the nucleation characteristics of the heat-transfer surface.

There exist in the literature several examples of boiling curves which, in a certain region, exhibit a definite *decrease* in the temperature difference driving force as the heat flux rises. Such curves have been termed S-shaped boiling curves. Figures 1 and 2 illustrate the phenomenon using the data of Rallis and Jawurek [2] and Van Stralen [3].

S-shaped curves have been found during boiling of a variety of liquids on metallic heat-transfer surfaces of different geometries and finishes and under various operating pressures, regardless of whether the heat flux was progressively increased or decreased [1–5]. It is important to note that in all the reported cases the boiling apparatus was heated electrically.

The phenomenon seems puzzling and inexplicable. Here a progressive increase of the heat flux (q/A) is made possible in spite of a definite decrease in the temperature driving force (ΔT).

The inadequacy of the use of two parameters, q/A and ΔT, for explaining the shape of the S surves suggests that a third factor should be considered, namely the often-neglected contribution of the surface nucleation characteristics to boiling heat transfer.

It will be shown here that the phenomenon under consideration can best be explained by considering the interrelationship of three vari-

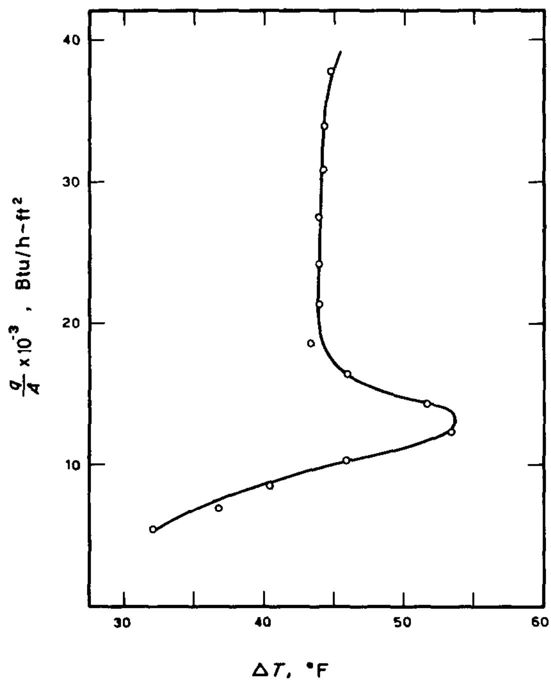

FIG. 1. S-shaped curve for ethanol boiling on a horizontal nickel wire of 0·02 in dia. at 0·396 atm [2].

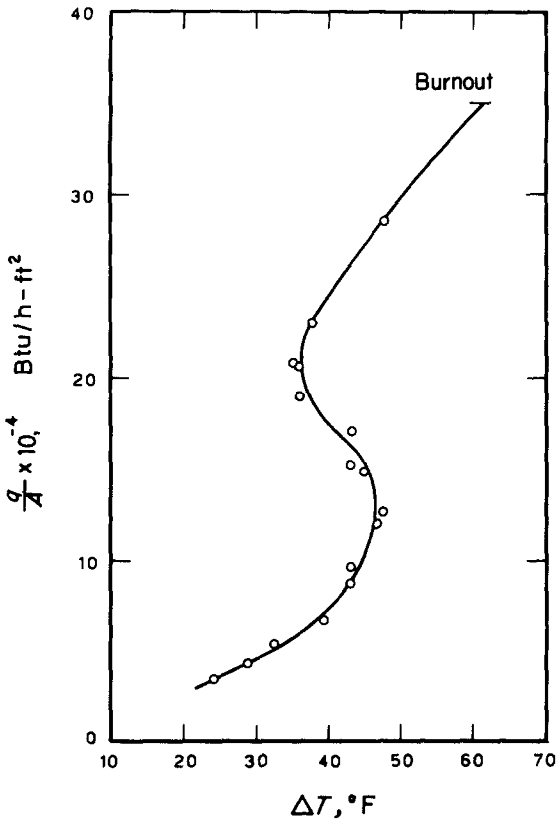

FIG. 2. S-shaped curve for a 3·2% solution of whey in water boiling on a horizontal wire of 0·008 in dia. at 0·131 atm [3].

ables: the heat flux, the active nucleation centers' density (N/A), and the temperature driving force.

NUCLEATION CHARACTERISTICS

It is now established that the slope of the "normal" boiling curve in the nucleate boiling region depends upon the nucleation characteristics of the heat-transfer surface, namely on the size distribution of the nucleation centers. Consequently, the heat flux is not a single valued function of ΔT alone, but also of the nucleation centers density. The functional relationship between these three variables is of the general form

$$q/A \sim (N/A)^n \Delta T^m. \quad (1)$$

Both experimental [6, 7] and theoretical [8, 9] values for the exponents n and m have been offered in the literature.

Under ordinary boiling conditions a rise in the heat flux is made possible by an increase of both N/A *and* ΔT. Inspection of all the available data for S-shaped curves shows that here too N/A continues to grow with the heat flux despite a continuous decrease of ΔT. Clearly, a rise in the heat flux during such a ΔT drop can still be accommodated if it is accompanied by an increase in N/A which is large enough to compensate for this drop. To prove that this is actually the case, it is sufficient to show that the heat flux during a ΔT drop can still be correlated by the two parameters: temperature driving force and active sites density.

For such a correlation q/A–ΔT–N/A data are needed. Such data exist only in two cases

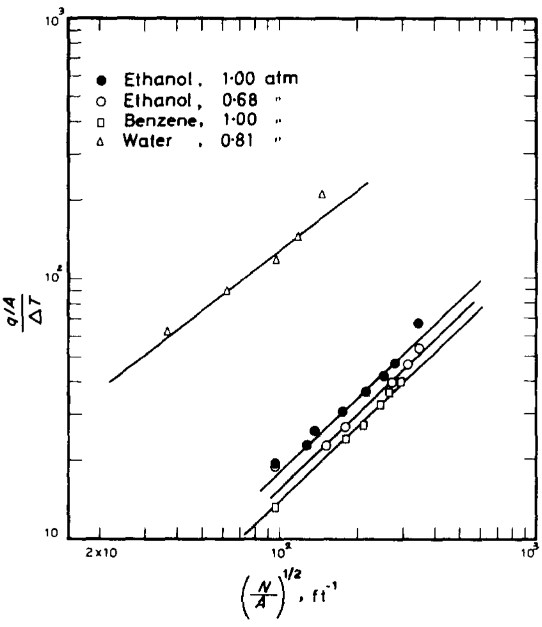

FIG. 3. Tien's heat flux correlation for boiling from a horizontal wire under normal conditions.

of boiling from thin horizontal wires under subatmospheric pressures [2, 3].

The available data for the S-shaped curves were correlated by Tien's theoretical equation [8], which is of the form

$$q/A \sim (N/A)^{\frac{1}{2}}\,\Delta T. \quad (2)$$

Tien's equation was chosen since it fits well (see Fig. 3) the data of Rallis and Jawurek for thin wires [2], obtained under normal boiling conditions in the same apparatus that exhibited the S curves.

The S curves data are plotted in Fig. 4. The experimental points in both cases fall on straight lines whose slope is higher than the theoretical value of 0·5. The correlation of the heat flux by the two parameters clearly demonstrates the unusually large contribution of the N/A term in the region of the observed temperature drop.

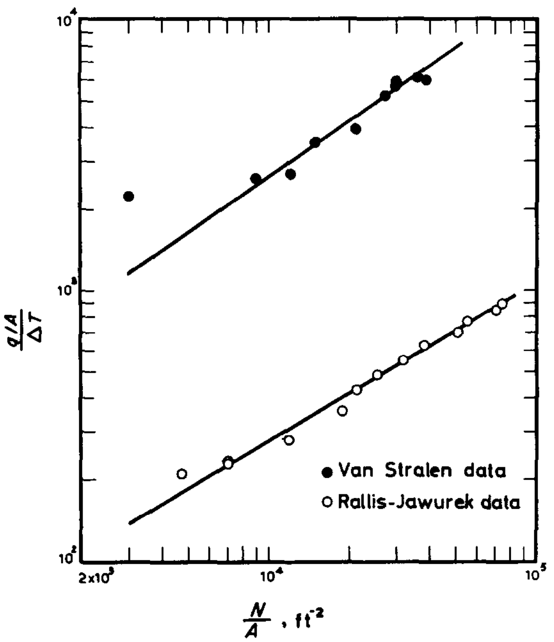

FIG. 4. Heat flux correlation for S-shaped boiling curves.

TEMPERATURE DROP

The decrease of the temperature driving force has been attributed to thermal hysteresis [4] and to boiling instability [1]. Thermal hysteresis, however, cannot explain such a behaviour, since S-curves were observed both under ascending and descending heat fluxes [1–3].

The phenomenon, no doubt, is associated with the fact that all the reported S-shaped boiling curves appeared in electrically-heated apparatus. Such a heating mode is characterized by constant heat flux conditions. Here q/A is an independent variable that determines the value of both N/A and ΔT. Now N/A depends directly on the heat flux level and as the flux rises, it causes a corresponding increase of N/A. Hsu's theoretical analysis [10] rationalizes this fact by showing that as the flux rises the size range of the active cavities broadens, leading in turn to higher bubble population densities.

It has already been demonstrated that the contribution of N/A to the heat flux of the S curves is unusually large. Consequently the temperature driving force *has* to decrease in order to still maintain a given heat flux level. This leads to the observed ΔT drop.

Such a phenomenon could not possibly occur were the experiments carried out in steam-heated apparatus. Under such constant temperature conditions ΔT can increase (or decrease) steadily since it is an independent variable.

CHANGE OF MECHANISM

The abnormal increase in the density of the active nucleation centers is, in all probability, caused by a change in the nucleation characteristics of the heat-transfer surface. Ample evidence exists to support this contention.

The exponents of the N/A term for the S-curves of ethanol and whey solution, as determined from Fig. 4, are 0·58 and 0·68 respectively. These exponents are definitely higher than Tien's theoretical value of 0·5 that fits the data of Rallis and Jawurek for normal boiling conditions.

In addition there are several descriptions in the literature of the unusual behaviour of the heat-transfer surfaces which exhibit the S-shaped curves. Rallis and Jawurek [2] reported that during the run shown in Fig. 1 nucleation became unstable, bubbles ceased to form at fixed nucleation sites and appeared at points that shifted their position on the heat-transfer surface.

Van Stralen [3] observed that during the ΔT drop illustrated in Fig. 2 the average size of the vapour bubbles decreased gradually. A very thin coagulation film deposited on the metallic wire apparently causing "a favourable effect on the formation of bubbles and on the coefficient of heat transfer".

S-shaped curves appeared during the experiments of Corty and Foust [4] who used copper surfaces polished with different grades of emery paper. In these cases the heat-transfer surface did not nucleate evenly. Local patches of bubbles appeared on which boiling occurred violently, while the rest of the surface remained bare. As the heat flux was raised the bubble patches expanded in area.

That copper surfaces polished by emery paper are susceptible to "patchy" distribution of active nucleation sites was also observed by Marcus [11]. It is, therefore, possible that uneven distribution of active sites is responsible for the ΔT decrease reported by Tang and Rotem [1] who boiled Freon-12 on a smooth copper surface.

Finally, it might be argued that the unusual behaviour of the heat-transfer surface is due to the oscillations of the heater temperature in time and space. It should be realized, however, that temperature oscillations under constant heat flux conditions can only happen as a result of a corresponding spatial and temporal changes of active nucleation sites density. Such oscillations do not normally occur under ordinary boiling conditions. Consequently, if temperature oscillations ever occur in surfaces exhibiting **S** curves they may only serve as an additional evidence that the nucleation mechanism causing such curves is different from the one operating under ordinary conditions.

CONCLUSIONS

The phenomenon of S-shaped boiling curves may be dealt with in terms of the nucleation characteristics of the heat-transfer surface. The phenomenon appears only in electrically heated apparatus, operating under constant-heat-flux conditions, when the normal nucleation mechanism ceases to function. Accompanying the change in mechanism is a sharp increase of the active nucleation centers' density which leads to the hitherto unexplained drop in the temperature driving force. The treatment of the phenomenon as presented here is based on the successful correlation of the heat flux with ΔT and the active sites density.

Additional observations of the heat-transfer surface during a ΔT drop are still needed to establish the cause of the abnormal nucleation mechanism.

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Résumé—Le phénomène des courbes d'ébullition en forme de S'est analysé en fonction des caractéristiques de nucléation de la surface chauffante. Ces courbes relient le flux de chaleur à la fois à la surchauffe et à la densité en centres actifs de nucléation. On montre que la chute inattendue de la surchauffe est produite par une augmentation anormale de la densité en sites actifs que l'on attribue à une rupture du mécanisme normal de la nucléation.

Zusammenfassung—Das Phänomen der S-förmigen Siedekurven wird analysiert auf Grund der Keimcharakteristik der wärmeabgegenden Oberfläche. Der Wärmefluss ist bei solchen Kurven korreliert sowohl mit der treibenden Temperaturdifferenz als auch mit der aktiven Keimstellendichte. Es wird gezeigt, dass der unerwartete Rückgang der treibenden Temperturdifferenz durch einen anormalen Anstieg der aktiven Keimstellendichte verursacht wird, die einer Störung des normalen Keimbildungsvorganges zuzuschreiben ist.

Аннотация—Приведен анализ S — образных кривых кипения в виде характеристик образования пузырьков на поверхности теплообмена. Тепловой поток таких кривых обобщается с помощью температурного напора и плотности центров образования пузырьков. Показано, что неожиданные падения температурного напора, вызванные чрезмерным увеличением плотности активных центров, обусловлено нарушением нормального механизма образования пузырьков.