Int. J. Heat Mass Transfer. Vol. 32, No. 3, pp. 459–464, 1989
Printed in Great Britain

0017-9310/89 $3.00+0.00

Flow boiling—the 'apparently nucleate' regime

M. G. COOPER
Wolfson College, Oxford University, Oxford OX2 6UD, U.K.

(*Received* 21 *March* 1988 *and in final form* 17 *July* 1988)

Abstract—This paper re-examines the nucleate boiling term in the Chen correlation (ASME Paper 63-HT-34 (1963)) for the heat transfer coefficient in flow boiling, which he derived from a correlation then current for pool boiling. The re-examination employs all available data published for water, with results of a recent simplified analysis of pool boiling which used reduced pressure (*Advances in Heat Transfer*, Vol. 16, pp. 157–239 (1984)), and also employs additional data from flow boiling experiments at Oxford, in which the 'apparently nucleate' regime can be distinguished with some confidence. It is concluded that a term based on the new pool boiling analysis would probably be better as well as simpler, but, in view of the extremely wide scatter present in these and all other nucleate boiling data, there is no strong case for altering existing calculation methods based on the term derived by Chen.

INTRODUCTION

It has long been considered that, in flow boiling, two regimes of heat flow can be distinguished, the apparently nucleate and the apparently convective. In the long-standing Chen correlation [1], the overall heat transfer coefficient α_{OA} is regarded as a modified sum of nucleate and convective heat transfer coefficients, α_{NB} and α_{CB}, as

$$\alpha_{OA} = \alpha_{CB} + S\alpha_{NB}$$

where the transition from nucleate to convective is governed by the summation, modified by S, a suppression factor which is always less than 1.0 and was regarded by Chen as dependent on a two-phase Reynolds number.

It has also long been considered that the heat transfer coefficient in 'purely nucleate' flow boiling is similar to that in pool boiling for the same fluid at the same pressure. Chen, for example, based his term α_{NB} on an existing correlation for pool boiling, derived by Forster and Zuber [2].

Many workers have attempted to improve the prediction of α_{OA} by adjusting the terms α_{CB} or S or α_{NB} and comparing the resulting prediction for α_{OA} with the published data of the experimental heat transfer coefficient. They generally used or extended an existing data bank or established a new one but apparently incorporated nucleate and convective data indiscriminately, making no attempt to distinguish between them, though the distinction can be made with some confidence in some cases as discussed below.

This seems an appropriate time for detailed re-consideration of nucleate flow boiling as a separate term. There are now more data for flow boiling and for pool boiling, and the latter have recently been re-examined using a simplified approach [3], based on reduced pressure ($p_r = p/p_{crit}$) in a way suggested by the dependence of thermodynamic properties on p_r. The other terms, α_{CB} and S, are not examined in this paper.

The approach here is to examine original publications on flow boiling, seeking to identify individually the data points which are 'apparently purely nucleate', and use those for comparison with data for nucleate pool boiling.

IDENTIFICATION OF 'APPARENTLY NUCLEATE' DATA

The possibility of making trustworthy distinctions between nucleate and convective data in flow boiling was clear from the accurate data recently produced by the vertical tube flow boiling apparatus formerly supported by SERC at Oxford [4]. Figure 1 shows

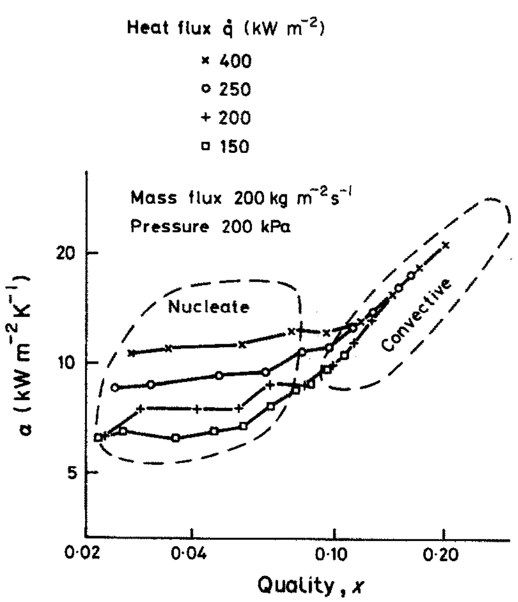

FIG. 1. Typical batch of data from Oxford apparatus [4], α against x.

Table 1. 'Apparently nucleate' data

Ref.	Source Name	Pressure (bar)	Tube diameter (mm)	Direction of flow	Number of points	Length / Diameter
5	Bertoletti *et al.*	71	5	up	10	90
6	Perroud *et al.*	60	10	down	4	80
6	Perroud *et al.*	34	10	down	9	80
7	Morozov	41	32	up	121	8
7	Morozov	31	32	up	67	8
4	Kenning and Cooper	6	9.6	up	3	52
4	Kenning and Cooper	4	9.6	up	16	52
4	Kenning and Cooper	2	9.6	up	13	52
8	Stone	1.25	12.2	up	15	100
8	Stone	0.25	12.2	up	7	100

diagrammatically the relation between the heat transfer coefficient and quality x for a typical 'batch' of data. For such a 'batch', the pressure, the mass flux and the steam quality x at the inlet to the tube were all held constant. The 'batch' contained several tests at different heat fluxes from wall to fluid, each test giving rise to several data points, from measuring stations along the test section, data from the same test being given the same type of symbol in Fig. 1.

A region towards the left of the figure is marked 'nucleate' because the heat transfer coefficient there is seen to be dependent on heat flux, but almost independent of quality x. A region towards the right is marked 'convective' because the heat transfer coefficient there is seen to be dependent on quality x, but almost independent of heat flux. These are the characteristics expected for nucleate-dominated and convective-dominated flow boiling respectively, and many 'batches' from the Oxford apparatus show clearly such 'apparently nucleate' data. The data in Fig. 1 yield four data points for the nucleate heat transfer coefficient against heat flux, at the given pressure and mass flux, such as 12 kW m^{-2} K^{-1} at 400 kW m^{-2}. On examination, it is found that mass flux has little influence, so these can be taken as data points at the given pressure.

Some other published data sets enable nucleate data points to be identified in a similar way; in some cases the originators of the data set carried out the identification; in other cases it was necessary to plot the data at each pressure, and try to identify nucleate points. This was done preferably by identifying cases where the heat transfer coefficient depended on heat flux but not on quality, or alternatively by identifying cases for which the heat transfer coefficient was well above the value expected for convective boiling.

By these means, five sources [4–8] of 'apparently nucleate' points were identified, containing in total ten data sets in the sense of data from a given source at a given pressure. The ten sets are listed with sources, pressure and some parameters in Table 1. They include three sets from the recent experiments at Oxford [4].

The data points are plotted as heat flux against wall superheat on logarithmic scales in Fig. 2, where different symbols indicate which points refer to which data set (source and pressure).

There are here some 250 points for water in vertical tubes at seven different pressures, which may seem a helpfully large amount of data, but they come from five different experiments (75% of them from one source) and no single experimenter covered a wide range of pressures. Tube sizes varied, some data were for upflow, some for downflow and one source (the one providing 75% of the data) used a short tube with a heated length of about eight diameters. These differences may have important effects, but there are not enough data sets to determine that. By contrast, for pool boiling, there are over 30 sources for water, most of them containing many data sets, covering a range of pressures. Two of those sources are very wide-ranging, with pressures from a few bar up to 150 bar or more (admittedly the data from those two sources do not agree in detail, but they do establish a trend).

PROCESSING

Thus, for nucleate flow boiling, the data are few and disconnected, so it is hazardous indeed to attempt to find a pattern among them. Nevertheless, if those are all the data one has, then some attempt must be made to use them.

Figure 2 shows that each data set provides a group of points lying in a band sloping upwards to the right on this logarithmic plot, corresponding to a relation heat flux proportional to ΔT^n where n is the slope, but there is much scatter. In some cases the general slope is steeper than 3; in other cases it is less than 2.

It has long been recognized that, in pool boiling at a given pressure, the heat flux $\dot{q}$ is broadly proportional to a power (about the cube) of the wall superheat $\Delta T = (T_w - T_{sat})$. An alternative presentation of the same information is that the heat transfer coefficient $(\dot{q}/\Delta T)$ is proportional to $\dot{q}^{0.67}$, hence $\alpha/\dot{q}^{0.67}$ is a constant at a given pressure. Correlations for α in pool boiling are often cast as

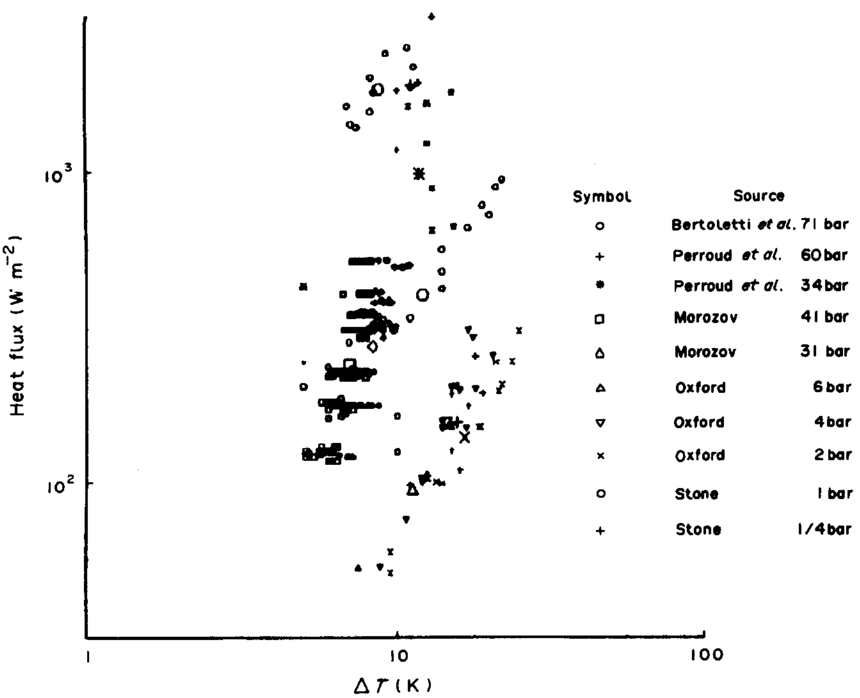

FIG. 2. Nucleate flow boiling—$\dot{q}$ against ΔT for the data sets in Table 1. Larger symbols indicate centroids.

$$\frac{\alpha}{\dot{q}^m} = f(\text{properties}) \quad \text{or} \quad = f(p_r)$$

and the form using $f(p_r)$ was adopted in ref. [3], leading to the correlation for pool boiling when the surface finish is unknown

$$\frac{\alpha}{\dot{q}^{0.67}} = 55p_r^{0.12}(-\log_{10} p_r)^{-0.55}M^{-0.5}. \qquad (1)$$

This is shown as the solid line in Fig. 3, which relates $\alpha/\dot{q}^{0.67}$ (SI units) to pressure. To compare this expression with the data in Fig. 2, one requires, for

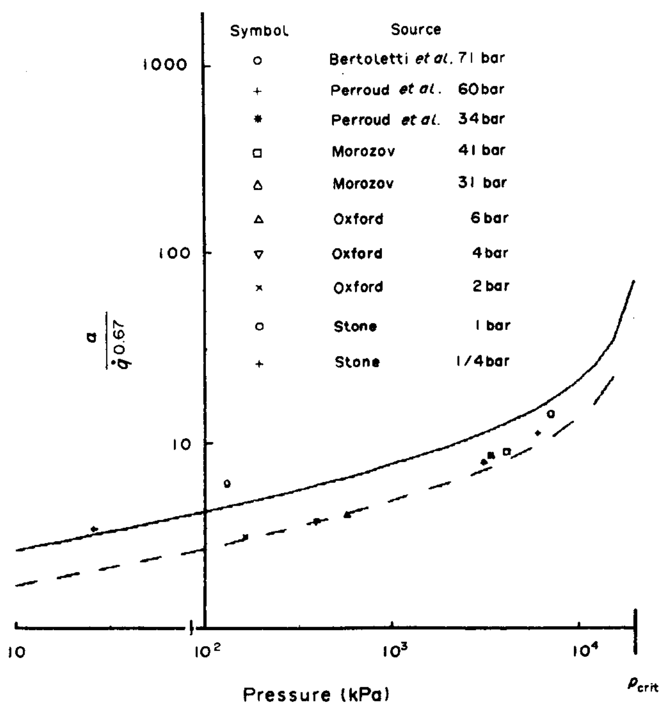

FIG. 3. $\alpha/\dot{q}^{0.67}$ against pressure for the data sets in Table 1, to be compared with the correlation in ref. [3].

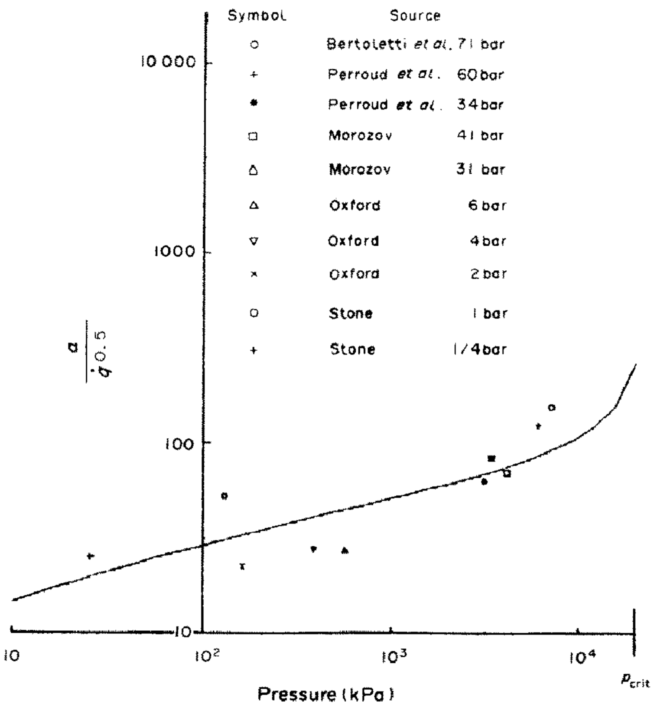

FIG. 4. $\alpha/\dot{q}^{0.5}$ against pressure for the data sets in Table 1, to be compared with the correlation in ref. [1].

each of the data sets in Fig. 2, the average value of $\alpha/\dot{q}^{0.67}$. This was obtained by locating on Fig. 2 the centroid ($\dot{q}_c$, ΔT_c) for each data set. The ratio ($\dot{q}_c/\Delta T_c^3$) was then evaluated, giving the logarithmically averaged value of the corresponding ratio $\dot{q}/\Delta T_c^3$ for that data set; taking the cube root gives the ratio $\alpha/\dot{q}^{0.67}$. The latter ratio was evaluated for each of the ten data sets and the ten points obtained were added to Fig. 3.

A similar process can compare the data in Fig. 2 with the predictions from the nucleate part of the Chen correlation. This predicts the heat flux proportional to the square of the wall superheat, so the ratio $\dot{q}/\Delta T^2$ was evaluated, the ratio $\alpha/\dot{q}^{0.5}$ was determined and plotted against pressure in Fig. 4, with a curve representing the nucleate term in the Chen prediction.

COMMENTS

The graphs, Figs. 2–4, must be treated with great caution.

(1) They involve results from different experimental apparatus.

(2) Data points from each apparatus were identified as 'apparently nucleate' by the non-rigorous methods described above.

(3) Even within one apparatus, large scatter can occur with phenomena for which nucleation is important. An illustration of this is the effect on readings in the Oxford rig when the inner tube surface was altered by rubbing with emery paper, as described in ref. [4]. Nucleate heat transfer coefficients at a given heat flux went up by about 30%, producing a rise of 1.3 in $\alpha/\dot{q}^{0.67}$. The data in Figs. 2–4 refer only to tests before application of emery paper to the bore.

However, since one must use what one has got, some tentative comments are now made.

(a) However disconnectedly, the data do span more than two decades of pressure.

(b) The pool boiling predictions are such that the hundred-fold variation in pressure would cause the ratio $\alpha/\dot{q}^{0.67}$ or $\alpha/\dot{q}^{0.5}$ to rise by about a factor of five, and that is roughly what these flow boiling data do.

(c) The solid line in Fig. 3 (equation (1)) is a passable approximation to the trend, so far as it can be seen, but one must be aware that scatter in this field is enormous and could produce a false apparent trend.

(d) The solid line in Fig. 3 (which is itself simply a line through a large amount of scattered pool boiling data) does not give a conservative value.

(e) There are not enough data to make a definite decision between Figs. 3 and 4, but inspection of the figures suggests that Fig. 3 shows a curve in better agreement with the general trend of the data points. Figure 4 cannot be said to be wrong, but it is less promising. It is possible to produce numerical measures, such as analysis of variance, but they contribute little to the choice between Figs. 3 and 4, because variance is dominated by the large scatter for individual data sets. The numbers simply confirm what is apparent to the eye: scatter in Fig. 2 is much greater than in Fig. 3 or 4. At this level of abstraction one has little to go on—ten data sets, each effectively one piece of information, from five sources, each potentially having an individual bias due to unidentified (and unidentifiable) quirks of the apparatus.

It is therefore suggested that, until further data become available, the correlation from ref. [3], equation (1) above, can be used to give the trend, or reduced by about a factor 0.7 to give the dotted curve lying just below the points in Fig. 3. This would be

$$\frac{\alpha}{\dot{q}^{0.67}} = 35p_r^{0.12}(-\log_{10} p_r)^{-0.55}M^{-0.5}. \qquad (2)$$

Again the scatter must not be overlooked. The appearance of a 'conservative' prediction in Fig. 3 is deceptive. Each point in Fig. 3 or 4 is a summary of many individual points in Fig. 2. Many of these lie below the value predicted by the 'conservative' equation (2). The points in Fig. 2 are themselves summaries of individual data points, which in turn are further scattered, as shown in Fig. 1.

CONCLUSIONS

There are surprisingly few data on nucleate boiling in vertical flow. The data for water in vertical tubes suggest that, within the broad scatter inherent in nucleate boiling, certain tentative conclusions can be drawn.

(1) As has long been believed, heat transfer coefficients for nucleate flow boiling are broadly similar to those for pool boiling of the same fluid under the same pressure.

(2) The shortage of data prevents any decision between differing pool boiling correlations as predictors of nucleate flow boiling. It is not even possible to decide whether in nucleate flow boiling $\dot{q}$ is proportional to ΔT^3 (as in ref. [2]) or to ΔT^2 (as in ref. [1]).

(3) The recent pool boiling correlation based on reduced pressure [3] is simpler than and rather more promising than the one used by Chen [1], but the difference may not justify changing established calculation methods.

Acknowledgements—This work was carried out at the Department of Engineering Science, Oxford University. Part of this work was carried out under the research programme of the Heat Transfer and Fluid Flow Service (HTFS) and was supported by the Department of Trade and Industry. Financial support is also gratefully acknowledged from SERC.

REFERENCES

1. J. Chen, Correlation for boiling heat transfer to saturated fluids in convective boiling, ASME Paper 63-HT-34 (1963).
2. H. K. Forster and N. Zuber, Dynamics of vapour bubbles and boiling heat transfer, *A.I.Ch.E. Jl* **1**, 531–535 (1955).
3. M. G. Cooper, Heat flow rates in saturated nucleate pool boiling—a wide-ranging examination using reduced properties. In *Advances in Heat Transfer*, Vol. 16, pp. 157–239. Academic Press, Orlando, Florida (1984).
4. D. B. R. Kenning and M. G. Cooper, Saturated flow boiling of water in vertical tubes, *Int. J. Heat Mass Transfer* **32**, 445–458 (1989). More results are given in M. G. Cooper, Saturated boiling heat transfer in vertical flow, nucleate and convective data re-examined and augmented, OUEL 1665/87, Department of Engineering Science, Parks Road, Oxford (1987).
5. S. Bertoletti, C. Lombardi and M. Silvestri, Heat transfer to steam–water mixtures, Topical Report No. 9 CISE-R-78, EURAC-929, Milan (1964).
6. P. Perroud, J. De La Marpe and J. Rabiere, Experimental investigation of the coefficient of heat transfer, of critical heat flux, and of pressure drop of water steam mixtures in turbulent flow in a vertical tube, Grenoble Centre of Nuclear Studies, Physico-Chemical and Low Temperature Laboratory, Rapport CENG-CEA-1853 (1960).
7. V. G. Morozov, Heat transfer during the boiling of water in tubes. In *Convective Heat Transfer in Two-phase and One-phase Flows* (Edited by V. M. Borishankii and I. I. Paluv), English Translation TT68-50328 AEC-tr-6877. Israel Programme for Scientific Translations (1968).
8. J. R. Stone, Subcooled and net boiling heat transfer to low pressure water in electrically heated tubes, Lewis Research Centre, Cleveland, Ohio, NASA (1971).

EBULLITION AVEC CONVECTION—LE REGIME "APPAREMMENT NUCLEE"

Résumé—Ce papier réexamine le terme d'ébullition nuclée dans la corrélation de Chen (ASME Paper 63-HT-34 (1963)) pour le coefficient de transfert de chaleur dans l'ébullition avec convection, dérivée d'une formule maintenant courante pour l'ébullition nucléée. On utilise toutes les données disponibles publiées pour l'eau, avec les résultats d'une récente analyse simplifiée de l'ébullition en réservoir qui considère une préssion réduite, et avec des données supplémentaires d'expériences faites à Oxford (*Advances in Heat Transfer*, Vol. 16, pp. 157–239 (1984)) sur l'ébullition avec convection et dans lesquelles le régime "apparemment nucléé" peut être distingué avec quelques confiance. On conclut qu'un terme basé sur l'analyse nouvelle de l'ébullition en réservoir serait probablement meilleur et aussi plus simple, mais du fait de la grande dispersion des données il n'y a pas de cas altérant fortement les méthodes existantes basées sur le terme dérivé par Chen.

STRÖMUNGS-SIEDEN—DAS GEBIET DER SCHEINBAREN BLASENVERDAMPFUNG

Zusammenfassung—In dieser Arbeit wird der Term für das Blasensieden in der Chen-Korrelation für den Wärmeübergangskoeffizienten beim Strömungssieden (ASME Paper 63-HT-34 (1963)), der auf einer damals geläufigen Korrelation für das Behältersieden beruht, noch einmal untersucht. Hierfür werden mittels einer kürzlich entwickelten einfachen Behältersiede-Korrelation, die den normierten Druck enthält (*Advances in Heat Transfer*, Vol. 16, pp. 157–239 (1984)), alle für Wasser veröffentlichten Daten verwendet; zusätzlich werden auch Daten aus Strömungssiede-Experimenten in Oxford benutzt, in denen das Gebiet des scheinbaren Blasensiedens mit einiger Sicherheit abzugrenzen ist. Es läßt sich folgern, daß ein auf der neuen Korrelation für das Behältersieden basierender Term möglicherweise sowohl besser als auch einfacher ist, daß es aber in Anbetracht der extremen Streubreite dieser und aller anderen Blasensiede-Daten keinen triftigen Grund gibt, die bestehenden Berechnungsverfahren auf der Basis des von Chen entwickelten Terms zu ändern.

ТЕЧЕНИЕ КИПЯЩЕЙ В ПУЗЫРЬКОВОМ РЕЖИМЕ ЖИДКОСТИ

Аннотация—Анализируется слагаемое, учитывающее пузырьковое кипение, в обобщенном выражении, найденном Ченом (ASME Paper 63-HT-34 (1963)) для коэффициента теплообмена потока кипящей жидкости. Это выражение получено им на основе соотношения, описывающего кипение в большом объеме. В работе использованы все опубликованные данные для воды, а также результаты недавно выполненного упрощенного анализа кипения в большом объеме в условиях пониженного давления (*Advances in Heat Transfer*, Vol. 16, pp. 157–239 (1984)) и дополнительные данные из проведенных в Оксфорде экспериментов, в которых выделяется пузырьковый режим. Показано, что полученное в результате анализа слагаемое, учитывающее кипение в большом объеме, является более точным и простым, однако, ввиду чрезвычайно большого разброса данных по пузырьковому кипению, нет смысла отказываться от существующих методов расчета, основанных на предложенном Ченом соотношении.