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ON EVALUATION OF CORRELATIONS FOR PREDICTION OF HEAT TRANSFER COEFFICIENT IN NUCLEATE FLOW BOILING

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NOMENCLATURE

FCV,	forced convective vaporization;
G,	mass velocity;
h,	heat transfer coefficient $[\mathrm{W\,m^{-2}\,K^{-1}}]$;
MABFD,	mean absolute fractional deviation;
MFD,	mean fractional deviation;
NB,	nucleate boiling;
N30,	number of data points predicted within 30% of the experimental value;
q,	heat flux $[\mathrm{W\,m^{-2}}]$;
RMSE,	root mean square error;
x,	vapour fraction.

Greek symbols

ΔT,	difference between wall and bulk temperatures [K];
ε,	fractional error.

Subscripts

exp,	experimental value;
pred,	predicted value;
mac,	macroconvective component;
mic,	microconvective component;
ib,	incipience of boiling.

INTRODUCTION

THE PHENOMENON of flow boiling is known to be extremely complex, and therefore, for the sake of simplicity of analysis, heat transfer data are usually classified as lying in the forced convective vaporization (FCV) zone, nucleate boiling (NB) zone or transition zone [1–3]. This classification is most conveniently made by plotting the data on q–ΔT coordinates, as is indicated for a typical case in Fig. 1, adopted from Dembi [3]. The straight-line portion of the curve, AB, passing through origin corresponds to the FCV zone while the steeply rising portion, including the highest heat flux point indicates the NB zone, with the knee of the curve corresponding to the transition zone. The main distinguishing feature of the FCV zone is that for a given fluid–tube combination the heat transfer coefficient is dependent only on vapour quality, x, and mass velocity, G, and not on the heat flux. In contrast, in the NB zone the heat transfer coefficient is strongly dependent on the heat flux. Consequently, most of the correlations developed for predicting the heat transfer coefficient h, in NB zone incorporate a dependence on heat flux q, in the form

$$h = C\,q^n \tag{1}$$

Values of n of 0.7 [1] and 0.6 [3] have been reported and are dependent on the system conditions. Some other correlations, however, interpret this dependence of h on q in a different manner, by making the nucleate boiling component of the heat transfer coefficient a function of the temperature gradient ΔT.

Thus Chen [4, 5] suggests that

$$h = h_{\mathrm{mac}} + h_{\mathrm{mic}} \tag{2}$$

where the microscopic component h_{mic}, which accounts for the various effects of nucleation can be reduced to a form

$$h_{\mathrm{mic}} = C_1\,\Delta T^{0.99} \tag{3}$$

Similarly, Hall *et al.* [6] suggest

$$h = h_{\mathrm{FCV}} + h_{\mathrm{NB}} \tag{4}$$

where

$$h_{\mathrm{NB}} = C_3\,\Delta T^2\left[1 - \left(\frac{\Delta T_{\mathrm{ib}}}{\Delta T}\right)^3\right] \tag{5}$$

Conventionally, while evaluating these correlations against various data banks as, for example, Chen [4], Dembi [3], have done with a view to identify the best amongst these for a particular application, no distinction is made between the correlations of the type represented by equations (1) and (2) or equation (4). In the present paper it is shown that this is not correct since the results of statistical evaluation are strongly dependent on whether the heat flux q or the temperature difference ΔT is treated as a known parameter.

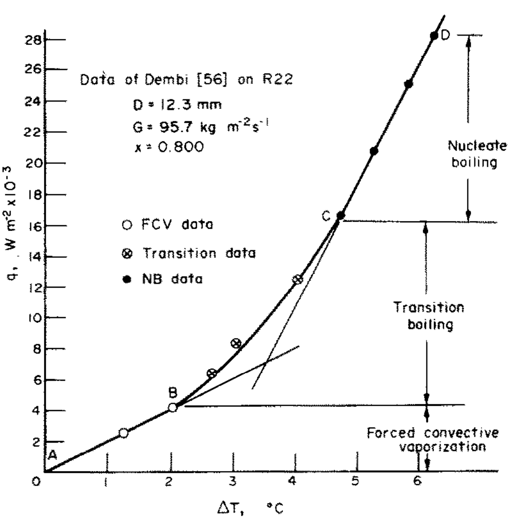

FIG. 1. Classification of boiling zones heat flux vs temperature difference.

ANALYSIS

Let us consider a typical experimental data set consisting of the experimental values of the heat transfer coefficient (h_{exp}), the heat flux (q_{exp}) and the temperature difference (ΔT_{exp}), which are related as

$$q_{exp} = h_{exp} \Delta T_{exp}. \quad (6)$$

If we use the heat flux as the known parameter in equation (1) the predicted value of heat transfer coefficient is

$$h_{pred} = C\, q_{exp}^{n} \quad (7)$$

which corresponds to a fractional error, ε given as

$$\varepsilon = 1 - h_{pred}/h_{exp}. \quad (8)$$

Now, in the case when the temperature difference is to be used as the known independent parameter, equation (1) would first be rewritten as

$$h^{1-n} = C\, \Delta T^{n}$$

or

$$h = C^{1/(1-n)} \Delta T^{n/(1-n)} \quad (9)$$

and the new predicted value of heat transfer coefficient would be

$$h'_{pred} = C^{1/(1-n)} \Delta T_{exp}^{n/(1-n)}. \quad (10)$$

Using equation (6) this can be rewritten as

$$h'_{pred} = C^{1/(1-n)} \left(\frac{q_{exp}}{h_{exp}}\right)^{n/(1-n)} = \frac{(C\, q_{exp}^{n})^{1/(1-n)}}{h_{exp}^{n/(1-n)}}. \quad (11)$$

Using equation (7), this becomes

$$h'_{pred} = \frac{h_{pred}^{1/(1-n)}}{h_{exp}^{n/(1-n)}} = h_{pred} \left(\frac{h_{pred}}{h_{exp}}\right)^{n/(1-n)}. \quad (12)$$

Thus, the new fractional error, ε' is given as

$$\varepsilon' = 1 - h'_{pred}/h_{exp} = 1 - \left(\frac{h_{pred}}{h_{exp}}\right)^{1/(1-n)} \quad (13)$$

which can be related to the previous error ε, using equation (8).

$$\varepsilon' = 1 - (1 - \varepsilon)^{1/(1-n)} \quad (14)$$

Assuming ε to be a small quantity, and using the binomial theorem, we get, as a first order approximation

$$\varepsilon' \simeq \frac{\varepsilon}{1-n} = 2.77\, \varepsilon \text{ for } n = 0.64 \quad (15)$$

Thus the errors in prediction of heat transfer coefficient are roughly tripled if the temperature difference ΔT is the known independent parameter rather than the heat flux. In other words, the use of heat flux as an independent correlating factor results in artificial suppression of the errors in prediction of heat transfer coefficient.

Obviously, similar results can also be derived, with a little complicated algebra, for correlations using dependence of heat transfer coefficient on ΔT, as typified by equations (3) and (5).

This is also confirmed by the results of statistical evaluation of some of these correlations against a data file [7] containing 535 data points (collected from experimental data of Chawla [1], Bandel [2], Dembi [3] and Jain [7]) lying in the NB zone pertaining to flow boiling of refrigerants inside horizontal tubes. Table 1 gives a summary of the results obtained both while using q and ΔT as independent parameters. It can be seen that, in consonance with equation (15), in the latter case the errors in prediction of heat transfer coefficient are greater by a factor of roughly 2–3 than those obtained in the former.

CONCLUSIONS

It can thus be concluded that in order to get an unbiased comparison of various correlations for prediction of heat transfer coefficient in nucleate flow boiling, it is desirable to recast all of them in such a manner that ΔT is used as the known independent parameter*. Only then are the error levels obtained true indicators of the predictability of these correlations, especially from the point of view of equipment designers since in most of the situations (barring nuclear reactors) it is the driving temperature potential which is known *a priori*.

*It may be pointed out that often even the correlations explicitly using ΔT as the known independent parameter are evaluated in a circuitous manner treating q as the known independent parameter resulting in artificial suppression of errors as mentioned above [8].

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Table 1.

Estimation method	Error levels							
	q as known parameter				ΔT as known parameter			
	N30	MFD	MABFD	RMSE	N30	MFD	MABFD	RMSE
Dembi	520	−0.02	0.09	0.12	361	−0.03	0.24	0.32
Chawla	258	−0.24	0.27	0.31	68	−0.30	0.61	0.67
Bennett and Chen	205	0.25	0.60	0.84	149	0.71	1.14	1.88