MRN AU8206119

(INIS)

AAEC/E528

AAEC/E528

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RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

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PART II - THE DEVELOPMENT OF A CRITICAL HEAT FLUX CORRELATION FOR UNIFORMLY HEATED TUBES

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December 1981

ISBN 0 642 59728 6

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ABSTRACT

Based on the parameter groups derived from a dimensional analysis, a correlation for predicting critical heat fluxes (CHF) in a uniformly heated tube, cooled internally by Freon-12, has been developed by systematically examining experimental data to establish the inter-relationship of these dimensionless groups. This correlation is:

$$\frac{\phi D}{\mu_v \lambda} = \frac{1}{17000} Re_v^n \left(\frac{\rho_\ell}{\rho_v}\right)^m \left(\frac{\sigma}{\rho_v D \lambda}\right)^p f(L_s/D)\, Pr_v^{-m}$$

where $f\left(L_s/D\right) = e^{4.25\, e^{-0.00366\, L_s/D}}$

(Continued)

$$n = 1 - e^{-0.0067\ L_s/D}$$

$$p = -0.5\ (0.15 + e^{-0.007\ L_s/D})$$

$$m = 0.1 + e^{-0.007\ L_s/D}$$

and L_s/D is a dimensionless saturation or boiling length.

Although this basic correlation agrees with much experimental data, it is inaccurate for short tubes or low mass fluxes. To compensate for these effects, corrective terms were introduced to provide the more generalised form:

$$\frac{\phi D}{\mu_v \lambda} = (1 + \delta)(1 - \delta_1)\left(\frac{\phi D}{\mu_v \lambda}\right)_{\text{basic}}$$

where δ is a modifier to account for short tube effects,

δ_1 is a modifier to account for low mass flux effects, and

$\left(\frac{\phi D}{\mu_v \lambda}\right)_{\text{basic}}$ is the CHF number obtained from the basic correlation.

The correlation has been tested against approximately 2000 experimental data. It was found that, apart from data at low exit qualities (less than 0.1) or short boiling lengths (L_s/D less than approximately 50), the correlation agrees with the data to within ± 10 per cent for L_s/D ratios less than approximately 150; for L_s/D values greater than 150, more than 90 per cent of points agree with the correlation to within ± 5 per cent.

National Library of Australia card number and ISBN 0 642 59728 6

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CRITICAL HEAT FLUX; HEAT TRANSFER; CORRELATIONS; COOLANTS; DRYOUT; FREONS; REACTOR COOLING SYSTEMS; TUBES; COMPUTER CODES

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1. INTRODUCTION

In Part 1 of this series [Green and Stevens 1981], experimental critical heat flux (CHF) data obtained for uniformly and non-uniformly heated vertical tubes, internally cooled by Freon-12, were found to be inconsistent with correlations developed specifically for uniformly heated tubes with the same coolant. At best, these correlations apply only for limited ranges of coolant conditions.

Recent generalised correlations, claimed as being suitable for a wide range of coolants, have been proposed by Katto [1978] and Shah [1979]. So far, these correlations have been compared with only a small amount of experimental data for Freon-12 and accuracies are only within ± 20 per cent.

Accordingly, a correlation needs to be developed which can be used for accurately predicting CHF values for Freon-12 over as wide a range of coolant conditions as possible. To achieve this, a dimensional analysis approach was used with attention being paid to the concept that dimensionless groups may be inter-related with other dimensionless groups, not only in a simple product relationship, but also as power functions of one another, e.g. if ϕ,A,B and C are dimensionless groups, then a correlation may exist in the form $\phi \propto A^x B^y C^z$, where the indices x and y are themselves functions of dimensionless group C.

2. DIMENSIONAL ANALYSIS

There have been several attempts [Griffiths 1959; Barnett 1963; Brevi and Cumo 1972] to use dimensional analysis techniques to develop a general dryout correlation for uniformly heated tubes. These approaches, however, assumed correlations which comprise non-dimensional groups related to one another in a simple product form, and incorporating the overall heated length and inlet subcooling as independent variables.

For this work it was considered that, since computer codes for analysing transients in a water-cooled system ultimately require correlations based upon local conditions, the local quality and boiling length should appear in the final correlation. However, since quality is a dimensionless quantity, it was unnecessary to include it directly in the dimensional analysis. Instead, it was introduced via the mean local density of the coolant.

Thus, by considering the critical heat flux as a function of the densities, velocities, viscosities, specific heats and thermal conductivities of both the vapour and liquid at saturation conditions, together with the diameter of the tube, the saturation length, the surface tension, the latent heat, the total mass flux and a temperature difference (as suggested by Griffiths [1959]), it can be shown, by dimensional analysis, that a CHF number, $\phi D/\mu_v \lambda$, is a function of the following groups:

$$\left(\frac{\rho VD}{\mu}\right)_v \;;\; \left(\frac{\rho VD}{\mu}\right)_\ell \;;\; \left(\frac{C_p \mu}{k}\right)_v \;;\; \left(\frac{C_p \mu}{k}\right)_\ell$$

$$\frac{\sigma}{\rho_v D \lambda} \;;\; \frac{\rho_\ell}{\rho_v} \;;\; \frac{\mu_\ell}{\mu_v} \;;\; \frac{k_\ell}{k_v} \;;\; \frac{C_{p_\ell}}{C_{p_v}} \;;$$

$$\frac{GD}{\mu_v} \;;\; \frac{k_v \Delta T}{\mu_v \lambda} \;;\; \frac{L_s}{D}$$

Of these groups, $k_v \Delta T/\mu_v \lambda$ was eliminated as it was difficult to evaluate accurately owing to the smallness of ΔT and the accuracy with which wall temperatures are recorded.

Moreover, it if is assumed that there is thermal equilibrium between the vapour and liquid phases of the coolant and that the flow is homogeneous with the slip ratio equal to unity (i.e. $V_v = V_\ell$), then the vapour and liquid Reynolds numbers may be expressed as follows:

$$\left(\frac{\rho VD}{\mu}\right)_v = \frac{GD}{\mu_v}\left\{X + (1-X)\frac{\rho_v}{\rho_\ell}\right\}$$

and

$$\left(\frac{\rho VD}{\mu}\right)_\ell = \frac{GD}{\mu_\ell}\left\{\frac{\rho_\ell}{\rho_v}X + 1-X\right\}$$

In summary, the CHF number may be considered to be a function of eleven dimensionless groups, which include vapour, liquid and overall Reynolds numbers, vapour and liquid Prandtl numbers, four coolant property ratios, a surface tension number, and a dimensionless saturation length (L_s/D).

3. DETERMINATION OF INTER-RELATIONSHIPS AMONG DIMENSIONLESS GROUPS

3.1 Analytical Codes

A computer program was written which, when given the outlet pressure, mass flowrate, inlet subcooling, tube diameter, heated length and critical heat flux, calculates the equilibrium coolant mass fraction (i.e. quality) at dryout and the values of all the dimensionless groups listed above. Property data for Freon-12 were ascertained using subroutines developed for the transient thermal code THETRAN [Green and Jacobs 1980]. The program is also able to estimate the pressure drop along the tube (and hence the outlet pressure) if only the inlet pressure is given. This is done using a homogeneous flow model to evaluate pressure losses and changes in gravitational head.

Using this computer program, the general procedure adopted in developing a correlation was to calculate the numerical values of each dimensionless group for all available experimental data, then to scrutinise these values to determine for as many groups as possible, relationships between the CHF number and the other dimensionless groups, each group being considered in turn at conditions where all other dimensionless groups were constant. Having determined these relationships for some of the dimensionless groups, the next step was to normalise the critical heat flux number by dividing it by the derived functions of these groups, then to examine the dependence of the normalised group on another of the remaining dimensionless groups, all other groups being constant.

The procedure was repeated until as many as possible of the dimensionless groups had been considered. This type of analysis requires a wide range of experimental data but uses only a limited number of tests as explained below.

3.2 Analysis of Experimental Data

Because of the extensive range of conditions covered by the data that Merilo and Ahmad [1979] had obtained for dryout in vertical uniformly heated tubes, these were used to develop the basic correlation. These ranges of experimental conditions are given in Table 1.

3.2.1 Effect of Reynolds number

For experimental data obtained at a constant pressure in a uniformly heated tube in which only the flow rate and inlet enthalpy were varied, and assuming that for fluid physical properties saturation conditions apply, only five of the twelve dimensionless groups listed in Section 2 vary in value, namely

$$\frac{\phi D}{\mu\lambda}, \left(\frac{\rho VD}{\mu}\right)_v, \frac{GD}{\mu_v}, \left(\frac{\rho VD}{\mu}\right)_\ell, \frac{L_s}{D}$$

Furthermore, since homogeneity and thermal equilibrium have been assumed and viscosity and density ratios occur as dimensionless groups, the vapour and liquid Reynolds numbers defined above are effectively interchangeable, hence only one need be considered when formulating a correlation. Since the vapour Reynolds number is a derivative form of the overall Reynolds number, (GD/μ_v), it is not expected that both would appear as prime dimensionless groups in any correlation at the same time.

Also since the data of Merilo and Ahmad cover reasonably wide ranges of mass flux, inlet subcooling, tube diameter and heated length at three different pressures, sufficient experimental data could be selected at each coolant pressure to cover a range of vapour Reynolds numbers for an approximately constant L_s/D ratio. It was therefore possible, for any particular coolant pressure when the saturation properties, Prandtl numbers and surface tension number are constant, to investigate relationships between CHF number and vapour Reynolds number over a range of L_s/D ratios.

In Figures 1a-b and 2a-c, CHF number has been plotted logarithmically against vapour Reynolds number for a number of values of L_s/D ratio which are approximately constant. From the figures, it can be seen that for any particular L_s/D ratio, the CHF number is a power function of the vapour Reynolds number. To examine the hypothesis that, if the vapour Reynolds number is an important prime dimensionless group in the correlation, it would be unnecessary to include the overall or liquid Reynolds numbers, relationships between CHF number and liquid and overall Reynolds number were also examined. Whereas CHF number against liquid Reynolds number exhibited a relationship very similar to that of CHF number against vapour Reynolds number, there was no rational relationship between CHF number and overall Reynolds number. At this stage, therefore, the correlation was based only upon the vapour Reynolds number. Figures 1a-b and 2a-c indicate that

$$\phi_N \text{ (the dryout number) } \propto Re_v^n$$

and as n is apparently dependent upon L_s/D, the indices 'n' were examined in relation to L_s/D. A log-linear plot (Figure 3) indicated that

$$(1-n) = e^{-0.0067\, L_s/D}$$

from which it was concluded that the CHF number is proportional to Re_v^n, where $n = 1-e^{-0.0067\, L_s/D}$.

3.2.2 Effect of surface tension number

The effect of surface tension number $(\sigma/\rho_v D\lambda)$ on CHF number $(\phi D/\mu_v\lambda)$ was determined by examining data for which the vapour Reynolds number, the Prandtl numbers, the property ratios and L_s/D were constant. Under these conditions, the only means of varying the surface tension number is to consider data from tubes of different diameter. Consequently, the data given on Figures 1a-b and 2a-c were examined at constant Re_v, L_s/D, and coolant pressure to obtain values of CHF number corresponding to surface tension numbers obtained for different tube diameters. The results of this exercise (see Figures 4a-b) were rather imprecise since only two tube sizes were used. Nevertheless the information obtained suggested that if there is a relationship between CHF number (ϕ_N) and surface tension number (σ_N), the index of such a relationship is dependent upon L_s/D, i.e. $\phi_N \propto (\sigma_N)^p$, where p is a function of L_s/D.

This observation was investigated further by determining values of p from Figures 4a-b and plotting them against L_s/D. Figure 5 shows that p could reasonably be equated to L_s/d by an expression of the form

$$P = \left\{-0.5 \quad 0.15 + e^{-0.007 L_s/D}\right\}$$

This expression does not represent a 'best fit' to the points shown on Figure 5 but is the result of a trial and error procedure involving comparisons of values of CHF number calculated from the correlation with those corresponding to the experimental data.

3.2.3 Effect of density ratio

The effect of density ratio on CHF number was more difficult to identify since the density ratio is dependent on pressure. Changes in pressure affect all the relevant properties of the coolant, thereby altering the values of all the dimensionless groups described in Section 2 except L_s/D.

Since a change in pressure produces a change in the surface tension number as well as in the density ratio, it is not possible to obtain a relationship between CHF number and density ratio by a simple, direct examination of the data shown in Figures 1a-b and 2a-c. To determine the effect of density ratio on CHF number at a particular vapour Reynolds number (and tube diameter), the corresponding changes in surface tension number have to be taken into consideration. This can be achieved by ascertaining the CHF number at a chosen vapour Reynolds number, tube diameter, and L_s/D ratio, normalising it by dividing by the surface tension number raised to the power p, and comparing the result with the density ratio. Values of the CHF number normalised in this manner are shown in Figures 6a-b and, although these relationships are not very accurate, it appears that they are a function of L_s/D; as L_s/D increases, the effect of the density ratio decreases. This relationship can be represented by

$$\phi_N / \sigma_N^p \propto \left(\frac{\rho_\ell}{\rho_v}\right)^m$$

where, to a fair approximation, as can be seen from Figure 7,

$$m = 0.1 + e^{-0.007\, L_s/D}$$

3.2.4 Effect of Prandtl number

The range of Prandtl number values for the Freon-12 data is quite small but, to retain the potential for a more generalised correlation, it was assumed, on the basis of a preliminary inspection of CHF data for water [Lee 1965], that a Prandtl number term should be included as Pr_v^{-m}.

Evaluation of a more precise power index of the Prandtl number and verification that the correlation is applicable to water is currently in hand and will be the subject of a further report [Green, forthcoming].

3.2.5 Effect of saturation length

The data in Figures 1a-b and 2a-c were re-examined to determine the prime relationship between CHF number and L_s/D. So far, it has been found that

$$\phi_N \propto Re_v^n \, \sigma_N^p \left(\frac{\rho_\ell}{\rho_v}\right)^m Pr_v^{-m}$$

where $n = 1 - e^{-0.0067 \, L_s/D}$

$$p = -0.5 \left\{ 0.15 + e^{-0.007 \, L_s/D} \right\}$$

and $m = 0.1 + e^{-0.007 \, L_s/D}$

To determine the direct effect of the dimensionless saturation length, it was necessary to normalise the CHF numbers shown on Figures 1a and 2a-c into the form:

$$\frac{\phi N}{Re_v^n \, \sigma_N^p \left(\frac{\rho_\ell}{\rho_v}\right)^m \, Pr_v^{-m}}$$

and to plot these values against L_s/D. Various attempts were made to produce a relatively simple relationship between the normalised values of CHF number and L_s/D; these led to the inclusion of the complex function

$$\frac{e^{4.25 \, e^{-0.00366 \, L_s/D}}}{17000}$$

in the correlation. The basic correlation (see Figure 8) is then:

$$\phi_N = \frac{1}{17000} Re_v^n \left(\frac{\rho_\ell}{\rho_v}\right)^m Pr_v^{-m} \, \sigma_N^p \, e^{4.25 \, e^{-0.00366 \, L_s/D}}$$

4. COMPARISON OF EXPERIMENTAL DATA WITH PROPOSED CORRELATION

Since the development of the correlation described in the previous section was performed using only some of the data presented by Merilo and Ahmad [1979], its validity was investigated by comparing CHF values calculated from the correlation with more data from this source, covering a wide range of fluid conditions, and with other data available from the literature.

4.1 Merilo and Ahmad [1979] Data

Values of CHF calculated from the correlation are compared with measured values in Figures 9 to 12 as the ratio of calculated to experimental CHF plotted against dimensionless saturation length for the two vertical uniformly heated tubes used by Merilo and Ahmad.

From Figures 9 to 11, it can be seen that for exit qualities above 0.10 all data points are within ± 10 per cent of the calculated value with the majority within ± 5 per cent. For exit qualities less than 0.10, the variation between calculated and experimental values increased and underpredictions by up to 35 per cent were obtained (see Figures 10 and 12).

Some increase in the difference between calculated and experimental values is to be expected with a reduction in the dimensionless saturation length since an error in determining the boiling length will have an increasingly significant effect. Also, as boiling length decreases, it becomes increasingly dependent on subcooled boiling effects. Discrepancies between calculated and experimental data greater than approximately ± 10 per cent were examined closely to determine whether any observations could be made concerning the correlation. Such an examination of experimental data points, for which the correlation underpredicted values by more than 10 per cent (Figures 10 and 12), showed that the correlation was inaccurate when the exit quality was very low (between 0 and 10 per cent) which occurred when the mass flux was high (greater than 5000 kg m^{-2} s^{-1}). The worst inaccuracies occurred at mass flux values of approximately 8000 kg m^{-2} s^{-1} with corresponding exit qualities less than 5 per cent.

These observations lead to a plausible explanation for the divergence of the calculated and observed CHF values. It has been assumed in the analysis that thermal equilibrium is present and that the coolant can be considered as homogeneous; but for conditions where the exit quality is low and L_s/D is small, it is highly probable that such assumptions lead to substantial errors and even more so as burnout quality decreases below zero.

4.2 Groeneveld [1969] Data

In Part 1 of this work it was intimated that some of Groeneveld's experimental data appeared to be at variance with both the Merilo and Ahmad [1979] and the Stevens and Miles [1980] data. It was therefore of interest to ascertain how they compared with the proposed correlation. The range of experimental conditions covered by Groeneveld are given in Table 1, but only data with thermodynamic exit qualities greater than 0 have been examined since the assumption of homogeneous flow could not be expected to apply for qualities less than 0 (i.e. CHF data for thermodynamic subcooled coolant conditions at the exit have been excluded).

It can be seen from Figure 13 that for L_s/D values greater than approximately 100 the experimental data agree with calculated values to within ± 6 per cent. For data having L_s/D values less than approximately 100, agreeement is poorer with some calculated values of CHF being more than 20 per cent lower than those observed.

Closer examination of the Groeneveld data showed that the data which were at variance with the calculated values had ratios of the total heated length to the tube diameter of less than approximately 120. In the tests by Merilo and Ahmad, the values of this dimensionless ratio were all much greater than this. This led to the following hypothesis: apart from the dimensionless saturation length (L_s/D), the aspect ratio of heated length to tube diameter (L/D) needs to be included in the correlation as a minor correction factor. To investigate this hypothesis, the ratios of the calculated critical heat fluxes to observed values for the shorter tube data were expressed in the form $(1 + \delta)$, where δ may be interpreted as a secondary, modifying or trimming component of the basic correlation. The relation between this modifier and the other non-dimensional numbers was then considered. Firstly, the relation with surface tension number was examined. This was done by using data for which the vapour Reynolds number, dimensionless saturation length, aspect ratio and coolant pressure were as near as possible the same. As can be seen from Figure 15, such data show that, to a reasonable approximation, the modifier δ is related to the surface tension number in a simple exponential manner. Having established this relationship, the modifier values, calculated from comparisons with the experimental data, were normalised by dividing them by the exponential function of the surface tension numbers. These quantities were then plotted against the aspect ratio (L/D) to ascertain whether there is a suitable relationship (see Figure 16).

Although the scatter on this graph appears to be large, it needs to be remembered that the differences between experimental and calculated CHFs ranged from less than 5 per cent to approximately 30 per cent, and that when experimental error is taken into account the scatter is not as significant as it would first appear. Bearing in mind these considerations, there appeared to be some relationship between the normalised modifier and L/D. Furthermore it seemed that for L/D values of approximately 200 or more the calculated values would have only a very small error, which is consistent with the fact that the minimum value of this ratio in the investigation by Merilo and Ahmad was 194. From Figure 16, it was deduced that the relationship between the heated length ratio (L/D) and the modifying factor could be represented approximately by

$$\text{modifier } (\delta) = e^{-0.14 \times 10^{8} \sigma_N} \, e^{-0.02 \, L/D}$$

The revised correlation now becomes

$$\phi_N = (1+\delta) \frac{1}{17000} \mathrm{Re}_v^{n} \left(\frac{\rho_\ell}{\rho_v}^{m} \right) \sigma_N^{p} \, \mathrm{Pr}_v^{-m} \, e^{4.25 \, e^{-0.00366 \, L_s/D}}$$

$$\text{where } \delta = e^{-0.14 \times 10^{8} \sigma_N} \, e^{-0.02 \, L/D}$$

The Groeneveld data are compared with this revised correlation in Figure 17 where it can be seen that, as before, for L_s/D values greater than 100, agreement is essentially within ± 5 per cent. For L_s/D ratios less than 100, apart from three experiments, all data agree within ± 10 per cent. Data with exit qualities < 10 per cent have been excluded from this plot since, as described in Section 4.1, the validity of the proposed correlation is questionable at these conditions.

4.3 Stevens, Elliott and Wood [1964, 1965] Data

One of the most extensive test programs to investigate the influence of mass flux, inlet subcooling, tube diameter and heated length on critical heat flux in a uniformly heated, Freon-12 cooled tube was conducted by Stevens, Elliott and Wood [1964, 1965]. The ranges of conditions covered by their experimental work are given in Table 1. Since the proposed correlation was developed assuming homogeniety and thermal equilibrium of the fluid, the small amount of data (less than 0.5 per cent of the total data) in which the thermodynamic exit quality was either less than 0 (i.e. it is calculated that the bulk coolant is subcooled) or greater than unity (i.e. the bulk coolant is thermodynamically superheated) have not been included in any comparisons between calculated and observed values. With this minor exception, all the experimental data given by Stevens, Elliott and Wood [1964] have been compared with the proposed correlation and this has provided some interesting observations. Firstly, as with the Merilo and Ahmad [1979] data, it was found that at low exit qualities (less than 10 per cent, which occurred at relatively high mass fluxes (>2000 m^{-2} s^{-1})), there was a considerable difference (up to approximately 30 per cent between calculated and observed values (Figure 18)). However, in this case, values calculated from the proposed correlation were greater than the experimental values, which is contrary to the result obtained with the Merilo and Ahmad data for similar conditions.

Examination of the remaining data showed that where (i) exit qualities are greater than 10 per cent, (ii) mass fluxes are greater than approximately 400 kg m^{-2} s^{-1}, and (iii) the dimensionless saturation lengths are greater than 20, agreement between calculated and observed values is, apart from 7 data points, within ± 10 per cent and, for dimensionless saturation lengths greater than 100, within ± 5 per cent. For clarity, since so many data are involved, this information is plotted in Figures 18, 19a-c and 20. However, for mass fluxes less than 400 kg m^{-2} s^{-1}, an experimental condition which has been investigated by neither Merilo and Ahmad nor Groeneveld, there is a greater discrepancy between the observed and calculated values. As the mass flux decreases, the correlation overpredicts the experimental data by an increasing margin (see Figure 20).

It was therefore necessary to examine these low mass flux data in more detail. The magnitude of the difference between the calculated and observed CHF values was not systematically influenced by exit quality, nor by the ratio of boiling length to tube diameter. It appeared to be strongly dependent on the mass flux and, to a lesser extent, on the ratio of the total heated length to tube diameter, but not directly on D, L_s or L.

To take into account this low flow effect, it appeared that a dimensionless group had to be introduced into the correlation which was dependent on mass flux but not directly on D, L_s, L or X. Such an observation meant that a simple Reynolds number would not be satisfactory. However, a mass flux number $G\sigma/\lambda\rho_\ell\mu_\ell$, could be suitable. Ratios of calculated critical heat fluxes to observed values were considered in terms of a factor ($1-\delta_1$), where δ_1 is a low-flow rate modifying (or trimming) component. Using this approach, the values of the modifier necessary to align experimental data with calculated values were plotted against the mass flux number $G\sigma/\rho_\ell\mu_\ell\lambda$ for various L/D ratios.

Although it showed some promise, this approach was not entirely satisfactory since it indicated a complex effect of the ratio L/D. By plotting the modifying component against the dimensionless group $G\sigma/\rho_\ell\mu_\ell\lambda$ on log:linear paper, it was seen that with increasing L/D the slope of the line initially decreased, but that for L/D values greater than approximately 150 it increased. However, when the modifier was plotted against $G\sigma L/\rho_\ell\mu_\ell\lambda D$, the influence of L/D became more tractable from a correlation viewpoint. As can be seen from Figure 21, for any particular ratio there appears to be a simple exponential relationship between the modifying component and the group $G\sigma L/\rho_\ell\mu_\ell\lambda D$. However, from a more important analytical viewpoint, increasing values of L/D caused this relationship to vary in a systematic manner, i.e. the slopes of the lines shown in Figure 21 continually decreased with increasing values of L/D.

These observations implied that

$$\delta_1 = A \exp\left\{-B\,\frac{G\sigma}{\rho_\ell\mu_\ell\lambda}\cdot\frac{L}{D}\right\}$$

where the values of B are a further function of L/D. Examination of the values of B calculated from Figure 21 and the corresponding values of L/D led to the relationship $\ell n\,(B/130.5) = 5.0 \exp\,(-0.02L/D)$ - see Figure 22. Hence it was possible to derive from Figures 21 and 22 a complex function of the form

$$\delta_1 = 0.75 \exp\left\{-B\,.\,L/D\,.\,\frac{G\sigma}{\rho_\ell\mu_\ell\lambda}\right\}$$

$$\text{where } B = 130.5 \exp\left\{5.0 \exp\,(-0.02\,L/D)\right\}$$

Thus, for low mass flux effects to be satisfactorily taken into account, it appeared that the correlation needed to be multiplied by a factor (1- δ_1), where δ_1 is as defined above. The general form of the correlation then became:

$$\phi_N = (1+\delta)(1-\delta_1)\,\frac{Re_v^n}{17000}\left(\frac{\rho_\ell}{\rho_v}\right)^m \sigma_N^p\, Pr_v^{-m}\, e^{4.25\, e^{-0.00366\, L_s/D}}$$

This generalised correlation is compared with the experimental data of Stevens, Elliott and Wood [1964] in Figures 23a-c and 24. It can be seen that, excluding data whose exit quality was less than 10 per cent, all except 7 data points are within the range ± 10 per cent and, for L_s/D ratios greater than 100, within ± 5 per cent. (Comparisons with the data of Stevens, Elliott and Wood [1964] are shown on four separate figures for clarity since so many data are involved.)

Other experimental data published by Stevens, Elliott and Wood [1965] are compared with values from the general correlation in Figure 25. It can be seen that the correlation accurately predicts experimental results, except for L_s/D ratios less than approximately 50 where it is somewhat less accurate, with five data points lying outside the range ± 10 per cent. None of the experimental data were omitted; in fact, the data points lying outside the range ± 10 per cent correspond to experiments in which the quality at dryout was less than 0.10.

4.4 Barnett and Wood [1965] Data

Barnett and Wood [1965] conducted experiments using Freon-12 at low coolant pressures, the range of conditions being as given in Table 1. Comparison of these experimental CHF data with values calculated by the generalised correlation was an important test of the accuracy of the correlation, since these conditions are substantially different from those for the data used in its derivation. As can be seen from Figure 26, apart from a small number of tests at exit qualities less than 10 per cent (the small L_s/D values), the experimental data and calculated values agree within ± 6 per cent.

4.5 Stevens and Miles [1980] Data

The data obtained by Stevens and Miles [1980] covered similar experimental conditions to those of Groeneveld [1969] except that they also investigated a large bore tube and the heated lengths for all three tubes were considerably longer than those used by Groeneveld. The range of conditions investigated is given in Table 1.

As can be seen from Figure 27, the scatter between calculated and observed CHFs is a little greater than for other data, but nevertheless it is within ± 10 per cent except for data with exit qualities less than 10 per cent.

4.6 Green and Stevens [1981] Data

The data presented for a uniformly heated tube in Part 1 of this work (see Table 1) have also been compared with the proposed generalised correlation; as can be seen in Figure 28, the predicted values are within ± 10 per cent of the experimental data with a great majority of the points lying within the range +2 to -8 per cent. In fact it appears that, in general, the proposed correlation underpredicts the experimental values by 3 per cent. This may be attributable to the fact that in obtaining the uniformly heated data, only one thermocouple was used as a dryout indicator, hence this technique may not have been as precise as for other experiments.

5. DISCUSSION AND SUMMARY

When attempting to derive a CHF correlation from dimensional analysis considerations, Griffiths [1959] concluded that "further improvements in DNB (departure from nucleate boiling, which is equivalent to the critical heat flux condition at low qualities) correlations will probably result from better assumptions for the functional relationships and the use of larger numbers of undetermined constants. There is no reason to expect that a function of one variable alone multiplied by a function of another variable alone, etc. will suffice in correlating the data." In the present work, using a dimensional analysis approach, a basic correlation has been developed in which there are complex relationships between variables and in which dimensionless groups are power functions of other dimensionless groups. Moreover, the correlation includes a significant number of constants determined empirically from experimental data. In these respects it would seem, therefore, that the correlation fulfils Griffiths' expectations.

In its basic form, the correlation was developed as

$$\phi_N = \frac{1}{17000} \mathrm{Re}_v^n \left(\frac{\rho_\ell}{\rho_v}\right)^m (\sigma_N)^p f(L_s/D) \mathrm{Pr}_v^{-m}$$

$$\text{where } f(L_s/D) = e^{4.25\, e^{-0.00366 L_s/D}}$$

$$n = 1 - e^{-0.0067 L_s/D}$$

$$p = -0.5 \left\{0.15 + e^{-0.007 L_s/D}\right\}$$

$$m = 0.1 + e^{-0.007 L_s/D}$$

Comparison of the basic correlation with experimental data showed that, although it accurately predicted most data, it was deficient for three types of experimental conditions, namely, low exit qualities, low mass fluxes and values of aspect ratio less than approximately 120. To overcome the two latter defects, trimming factors involving combinations of dimensionless groups were introduced into the basic correlation, and a generalised correlation was produced which is consistent with all the experimental data, except at low exit qualities ($X < 10$ per cent) to within ± 10 per cent and, in most cases, to within ± 5 per cent.

It was not possible to resolve the differences between calculated and experimental critical heat flux values for low exit quality conditions since the correlation overestimated test data in some instances, and underestimated them in others. This variation is most probably attributable to the fact that the proposed correlation is based upon the assumption of thermal equilibrium and is particularly sensitive to the dimensionless saturation length (L_s/D) at small values of this ratio (< approx. 50). Precise knowledge of the boiling length is dependent on determining the axial position at which boiling commences; this depends not only on having accurate physical property data for the fluid but more importantly on the subcooled boiling length. For conditions in which the ratio L_s/D is greater than 100, estimation of the saturation boiling length from thermal equilibrium assumptions is adequate.

However, with decreasing values of L_s/D, a small change in saturation or boiling length becomes increasingly important; this could account for the inability of the proposed correlation to calculate experimental data at low qualities to better than ± 20 per cent.

With respect to the possible use of this correlation for fluids other than Freon-12, several points should be made. Firstly, the modifiers for both low mass fluxes and short tubes contain dimensionless groups with ranges that have not been extensively tested owing to the limited amount of data available. The validity of these factors would need to be examined for other coolants. With the basic correlation, reasonable ranges have been covered for all dimensionless groups except Prandtl numbers, and this must be borne in mind when considering other fluids.

6. CONCLUSIONS

An empirical CHF correlation has been developed with generalised form:

$$\phi_N = (1+\delta)(1-\delta_1)\ \phi_{N,\mathrm{basic}}$$

where

δ is a modifying component for short tube effects and is equal to

$$e^{-0.014 \times 10^8\ \sigma_N}\ e^{-0.02\ L/D}$$

δ_1 is a modifying component for low mass flux effects and is equal to $0.75 \exp \left\{-130.5 \exp (5.0 \exp (-0.02\ L/D))\ L\ G\sigma/\rho_\ell \mu_\ell \lambda\ D)\right\}$ and

$$\phi_{N,\mathrm{basic}} = \frac{1}{17000}\ \mathrm{Re}_v^n \left(\frac{\rho_\ell}{\rho_v}\right)^m (\sigma_N)^p\ f\left(\frac{L_s}{D}\right) \mathrm{Pr}_v^{-m}$$

with

$$f(L_s/D) = e^{4.25\ e^{-0.00366\ L_s/D}}$$

$$n = 1 - e^{-0.0067 L_s/D}$$

$$p = \left\{ -0.5 \quad 0.15 + e^{-0.007 L_s/D} \right\}$$

$$m = 0.1 + e^{-0.007 L_s/D}$$

Apart from experimental conditions in which the exit quality is low (< 0.1) or the dimensionless saturation length (L_s/D) small (< approximately 50), the correlation is satisfactory for Freon-12 and suitable for calculating CHFs to within ± 10 per cent for L_s/D ratios up to approximately 150 and generally to ± 5 per cent for L_s/D ratios greater than 150.

7. ACKNOWLEDGEMENT

The author wishes to thank Mr C. Evans for his assistance in the preparation of experimental data for analysis.

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9. NOTATION

A	constant defined in text
B	variable defined in text
C_p	specific heat
D	tube bore
G	mass flux
k	thermal conductivity
L	total heated length
L_s	saturation boiling length
m n p	indices defined in text
Pr	Prandtl number
Re	Reynolds number
V	velocity
X	thermodynamic mass fraction (quality)
δ	short tube modifier
δ_1	low mass flux modifier
ρ	density
μ	viscosity

σ	surface tension
σ_N	surface tension number
λ	latent heat of vaporisation
ΔT	temperature difference between the wall and saturation at the onset of dryout
ϕ	critical heat flux
ϕ_N	critical heat flux number

Subscripts

v	vapour
ℓ	liquid

TABLE 1

EXPERIMENTAL CONDITIONS FOR VARIOUS CHF INVESTIGATIONS

Source of Data	Inlet Pressure (MPa)	Outlet Pressure (MPa)	Mass Flux (kg $m^{-2}s^{-1}$)	Heat Flux (kW m^{-2})	Inlet Subcooling (kJ kg^{-1})	Outlet Quality	Tube Diameter (mm)	Heated Length (mm)
Groeneveld [1969]		1.05 to 1.10	500 to 3255	60 to 271	0 to 30	-0.06 to 0.79	7.8 10.9 16.1	610 to 1829
Merilo and Ahmad [1979]		1.00 1.28 1.52	1500 to 8600	38 to 417	-4.2 to 40	0.013 to 0.764	5.3 12.6	1030 to 4880
Stevens and Miles [1980]		0.96 to 1.05	450 to 3850	62 to 193	2.8 to 35.0	0.007 to 0.784	15.34 16.08 21.54	2850 to 3940
Green and Stevens [1981]		0.90 to 1.32	380 to 2800	55 to 128	0.26 to 41.0	0.19 to 0.86	8.48 16.76 21.34	2870 to 3700
Barnett and Wood [1965]	0.57 to 1.07		410 to 2100	49 to 248	0.1 to 33	0.02 to 1.0	7.7 9.7	440 to 2413
Stevens, Elliott and Wood [1964]	1.07		200 to 4070	22 to 300	1.6 to 34	-0.05 to 1.13	5.3 8.5 11.5 16.1	241 to 3576
Stevens, Elliott and Wood [1965]	1.07		508 to 2034	64 to 308	3.25 to 34	0.005 to 0.83	9.7	324 to 2591

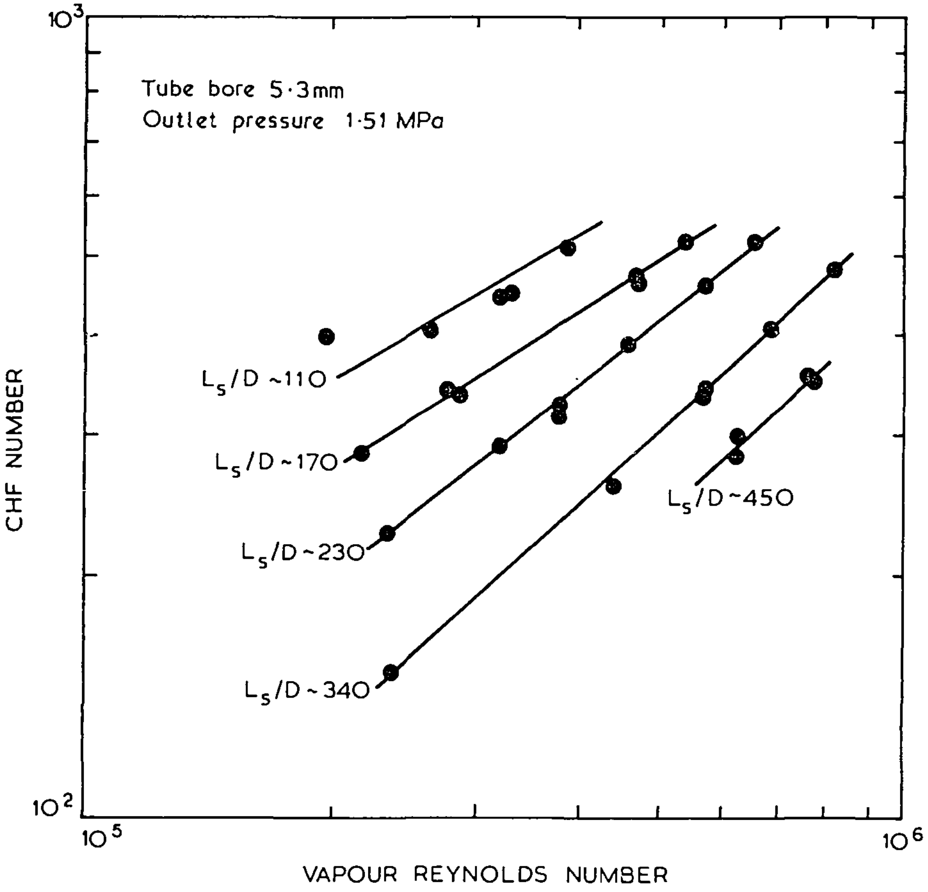

FIGURE 1a. RELATIONSHIP BETWEEN CHF NUMBER AND VAPOUR REYNOLDS NUMBER FOR 5.3 mm BORE TUBE DATA (1.51 MPa)

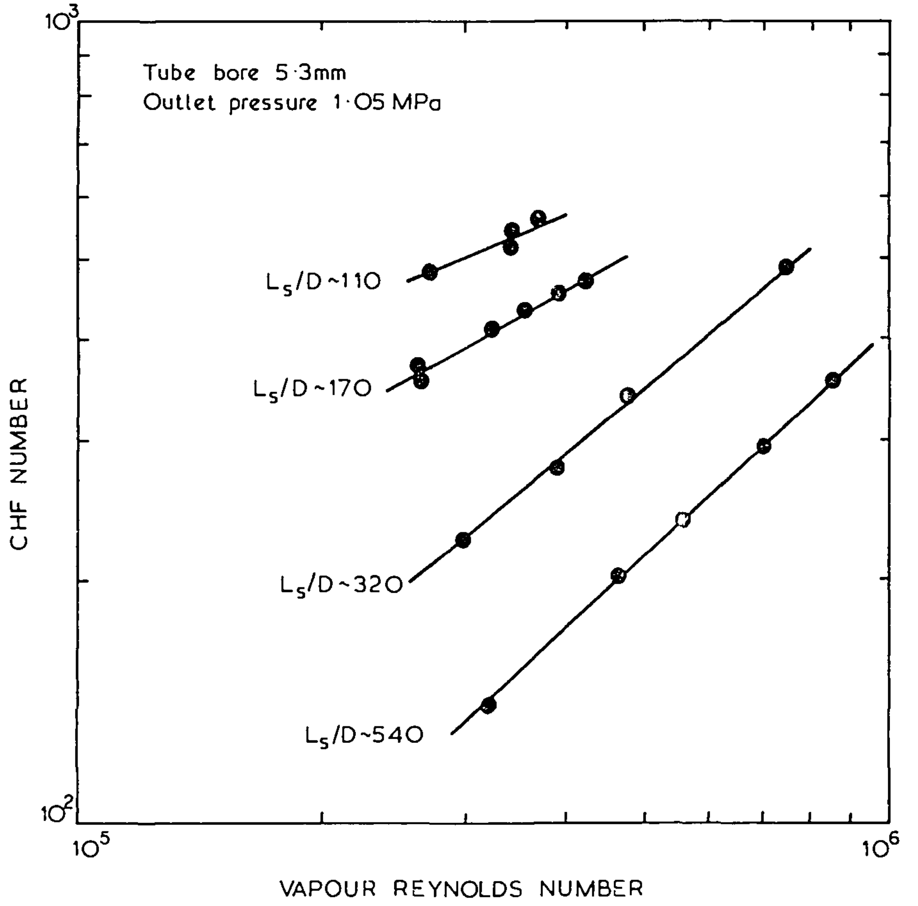

FIGURE 1b. RELATIONSHIP BETWEEN CHF NUMBER AND VAPOUR REYNOLDS NUMBER FOR 5.3 mm BORE TUBE DATA (1.05 MPa)

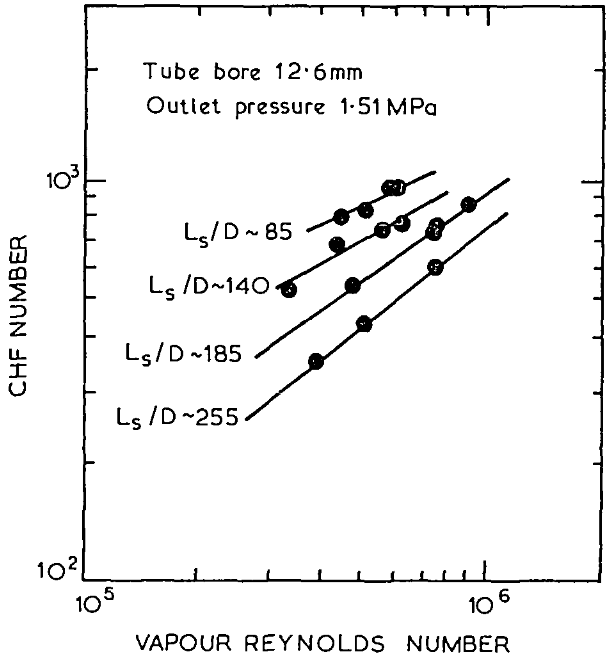

FIGURE 2a. RELATIONSHIP BETWEEN CHF NUMBER AND VAPOUR REYNOLDS NUMBER FOR 12.6 mm BORE TUBE DATA (1.51 MPa)

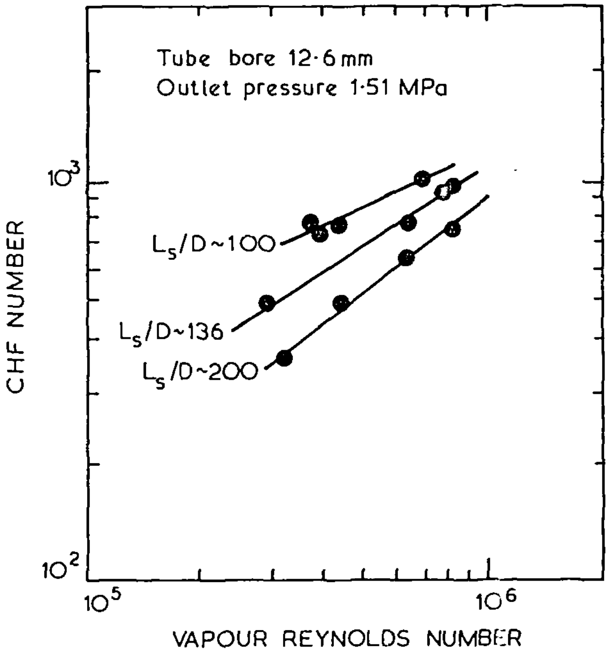

FIGURE 2b. RELATIONSHIP BETWEEN CHF NUMBER AND VAPOUR REYNOLDS NUMBER FOR 12.6 mm BORE TUBE DATA (1.28 MPa)

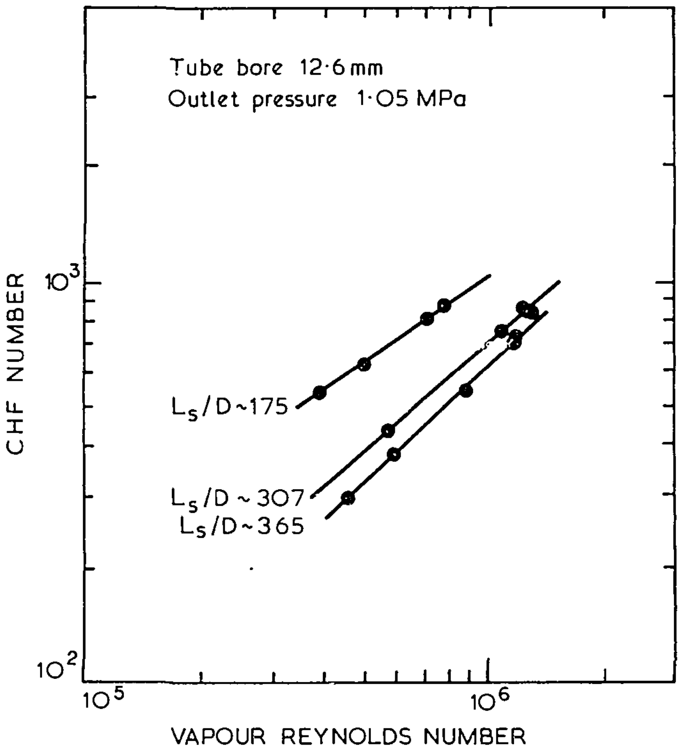

FIGURE 2c. RELATIONSHIP BETWEEN CHF NUMBER AND VAPOUR REYNOLDS NUMBER FOR 12.6 mm BORE TUBE DATA (1.05 MPa)

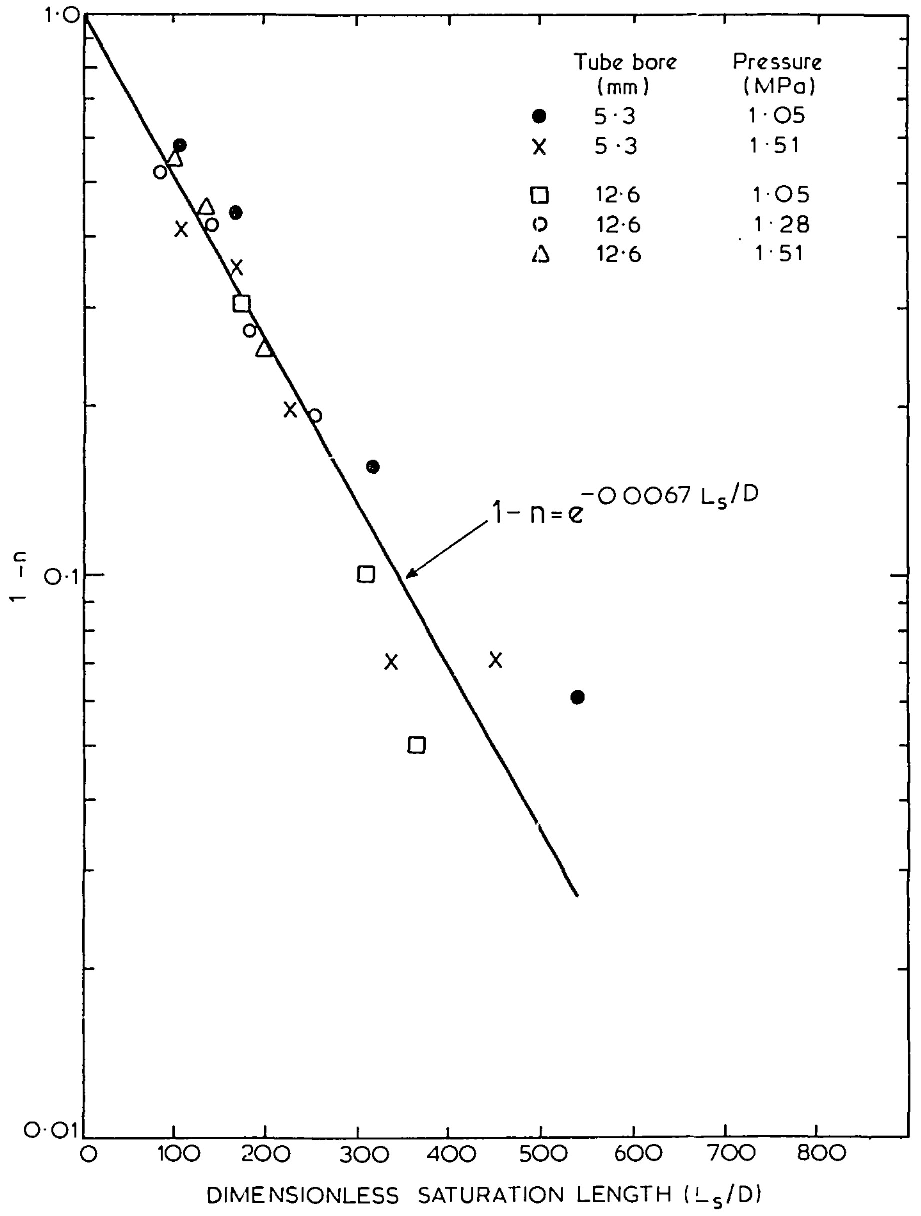

FIGURE 3. RELATIONSHIP BETWEEN INDEX n AND DIMENSIONLESS SATURATION LENGTH (L_s/D)

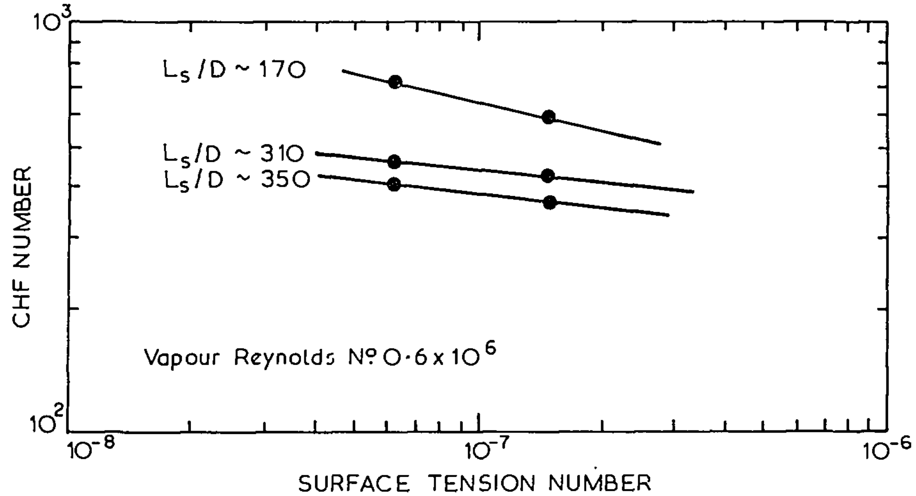

FIGURE 4a. RELATIONSHIP BETWEEN CHF NUMBER AND SURFACE TENSION NUMBER AT A COOLANT PRESSURE OF 1.05 MPa

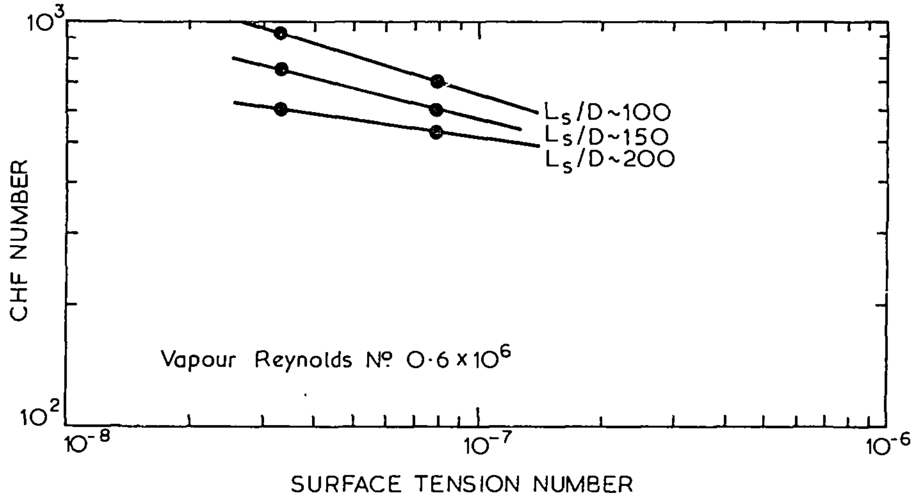

FIGURE 4b. RELATIONSHIP BETWEEN CHF NUMBER AND SURFACE TENSION NUMBER AT A COOLANT PRESSURE OF 1.51 MPa

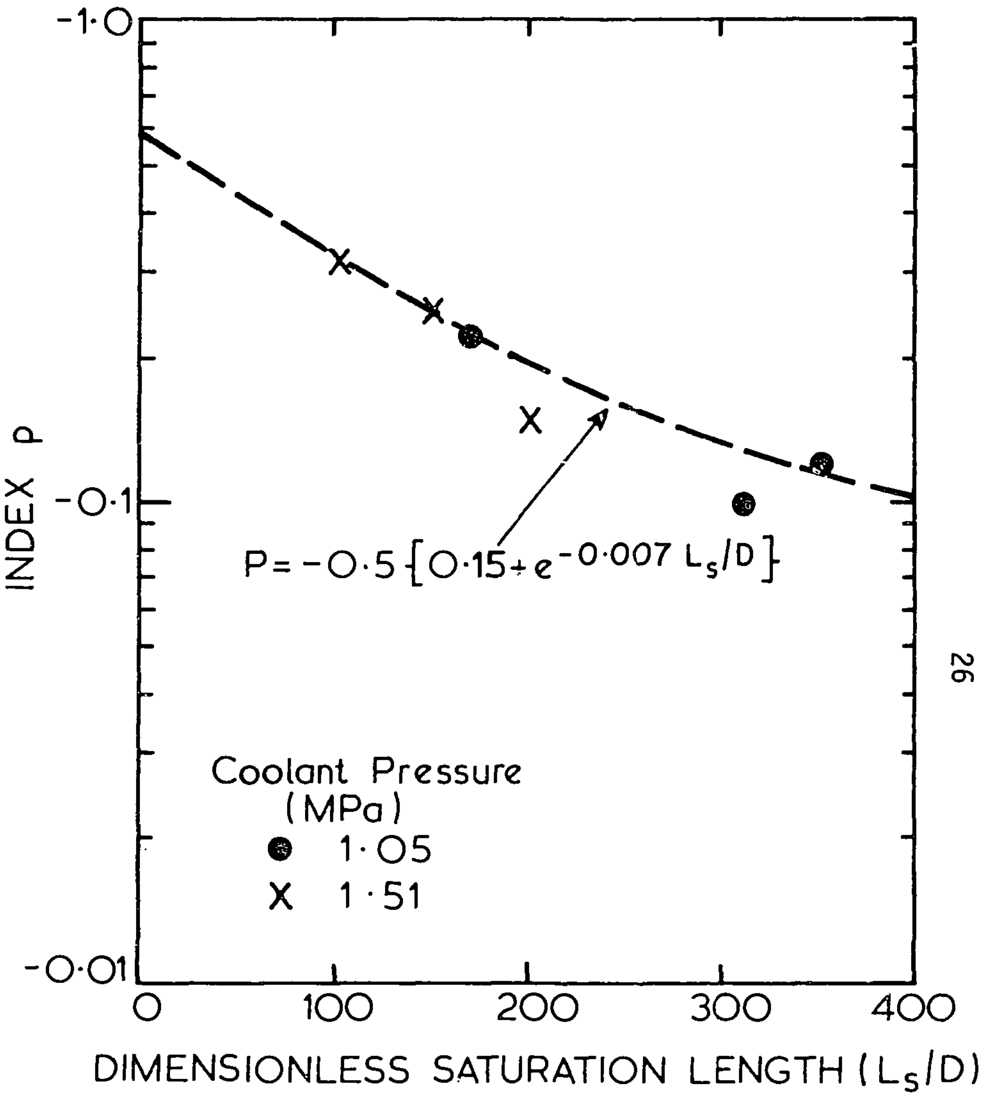

FIGURE 5. RELATIONSHIP BETWEEN INDEX p AND DIMENSIONLESS SATURATION LENGTH (L_s/D)

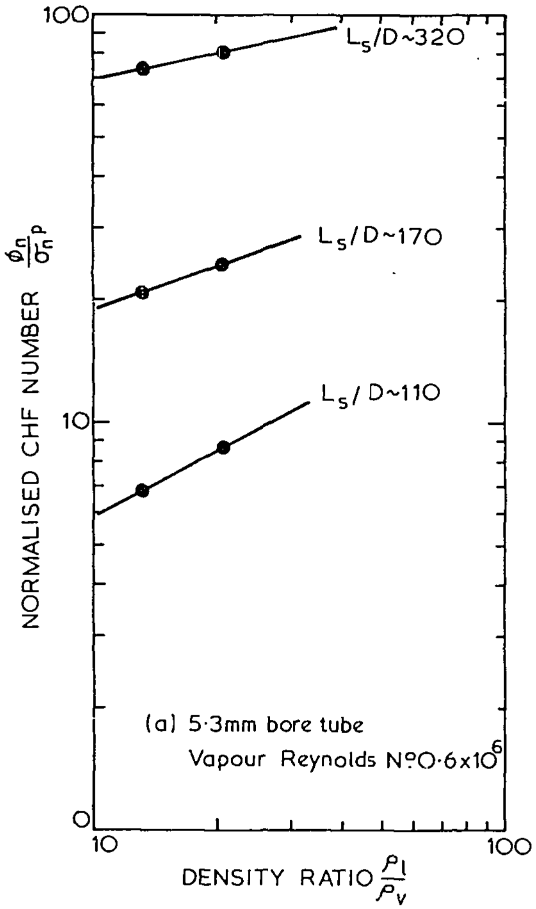

FIGURE 6a. EFFECT OF DENSITY RATIO ON CHF NUMBER (5.3 mm BORE TUBE)

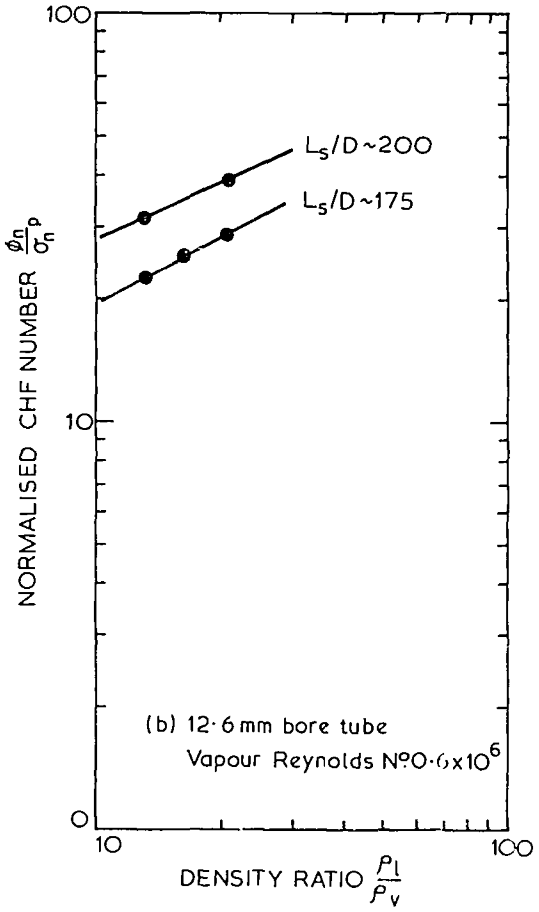

FIGURE 6b. EFFECT OF DENSITY RATIO ON CHF NUMBER (12.6 mm BORE TUBE)

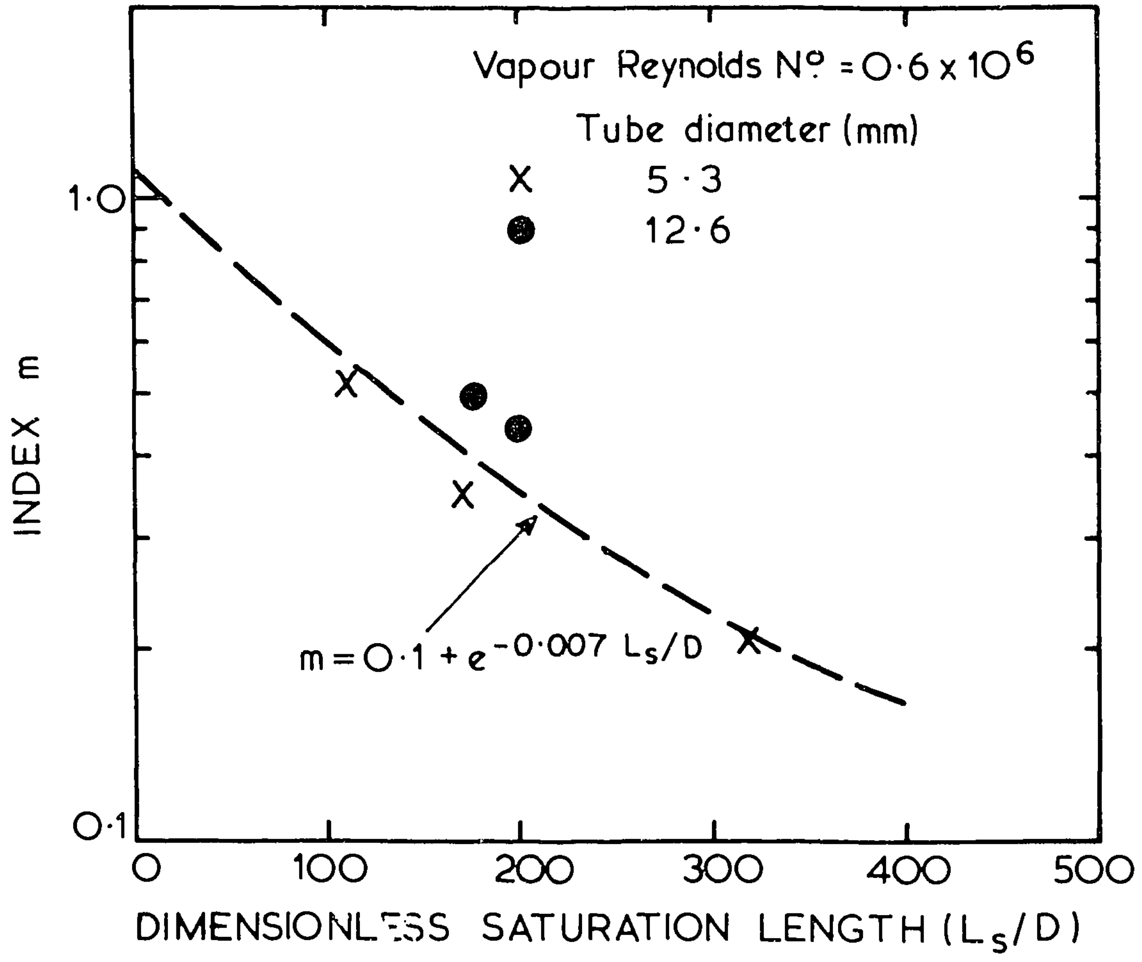

FIGURE 7. RELATIONSHIP BETWEEN INDEX m AND DIMENSIONLESS SATURATION LENGTH (L_S/D)

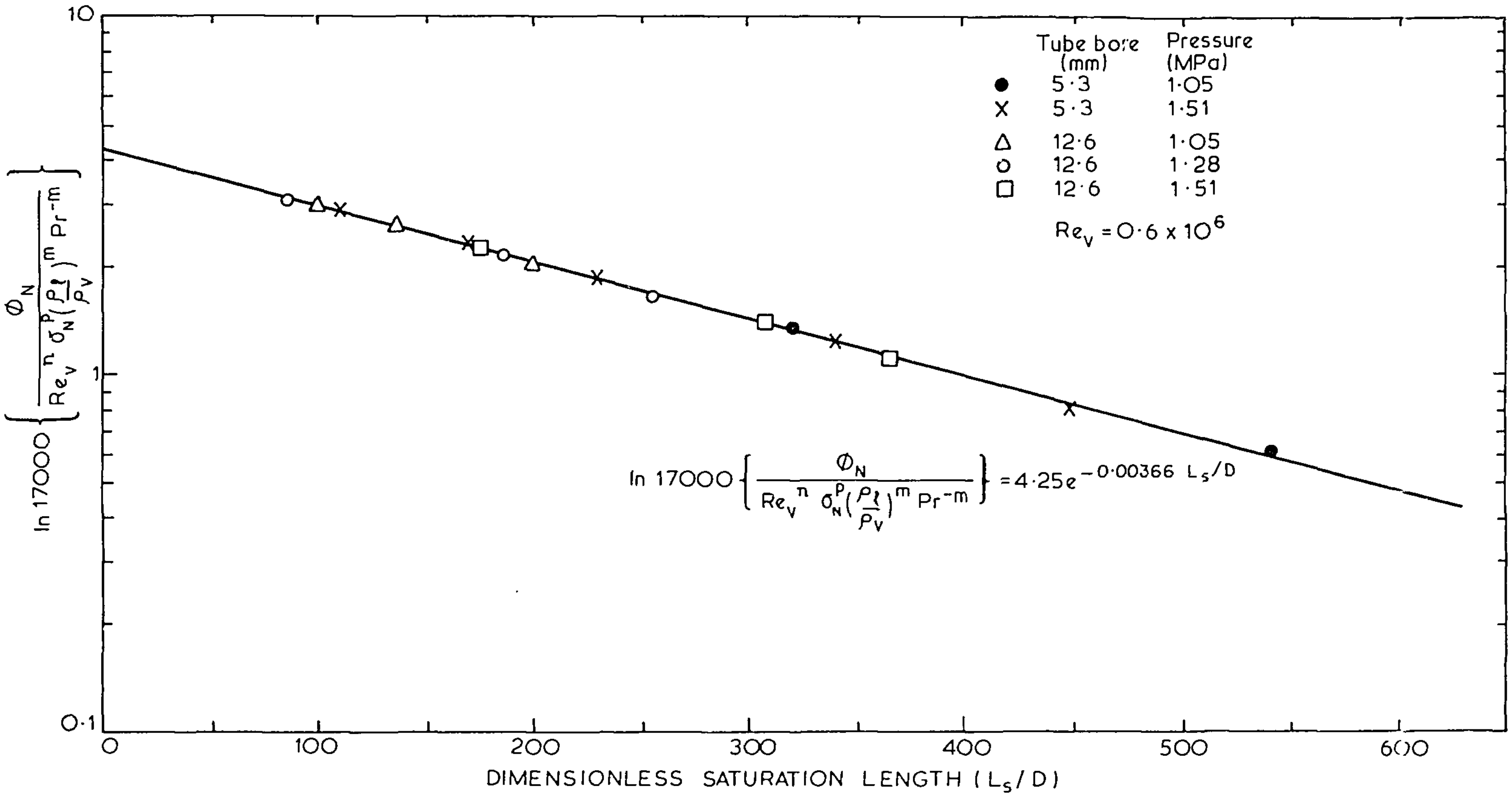

FIGURE 8. RELATIONSHIP BETWEEN REDUCED CHF NUMBER AND DIMENSIONLESS SATURATION LENGTH (L_S/D)

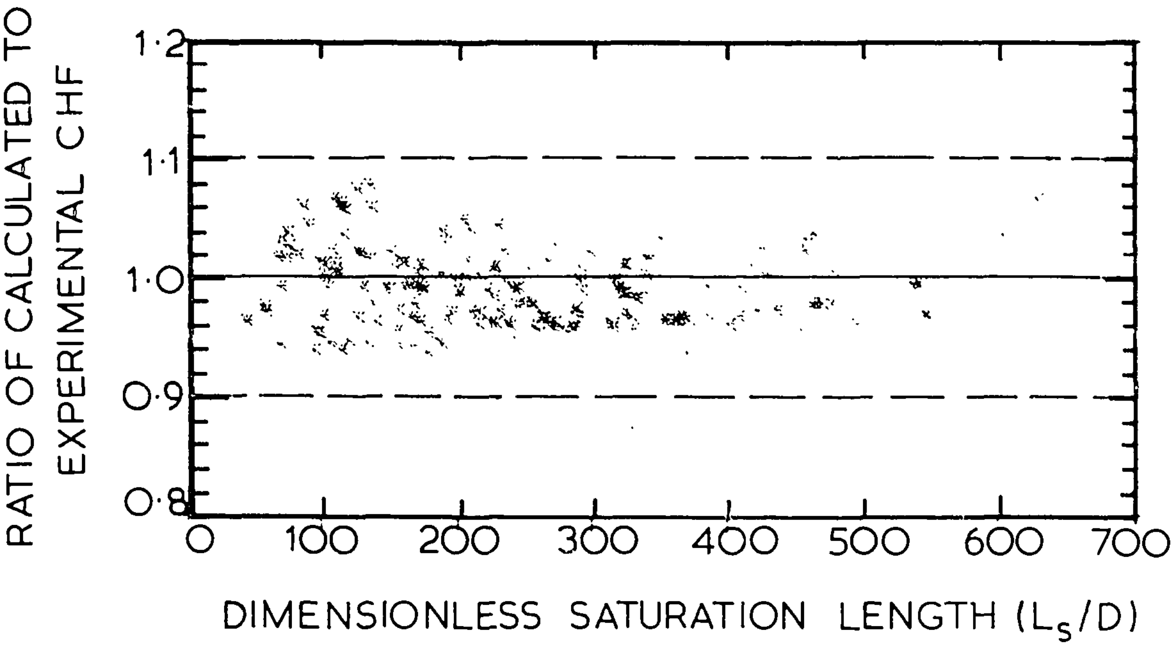

FIGURE 9. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE MERILO AND AHMAD 5.3 mm TUBE DATA EXCLUDING DATA WITH EXIT QUALITY LESS THAN 0.1

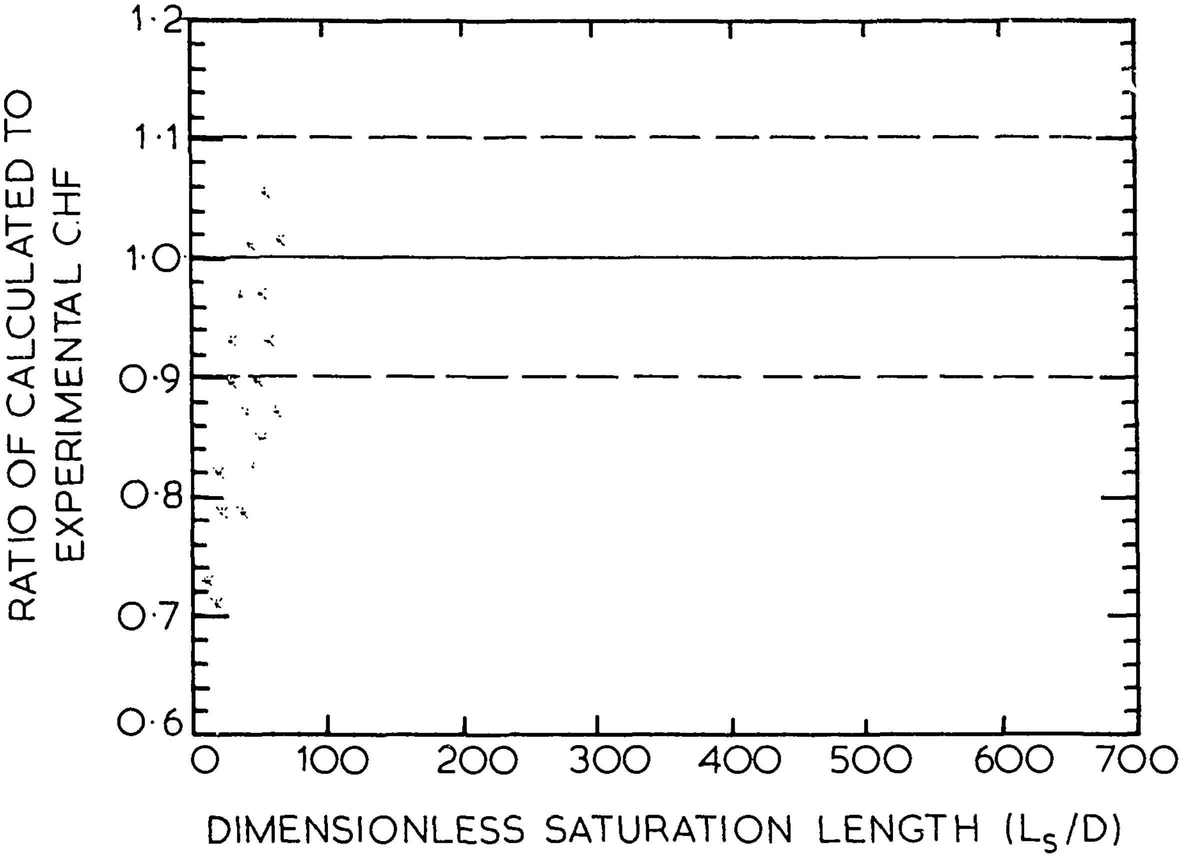

FIGURE 10. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE MERILO AND AHMAD 5.3 mm TUBE DATA WITH EXIT QUALITIES LESS THAN 0.1

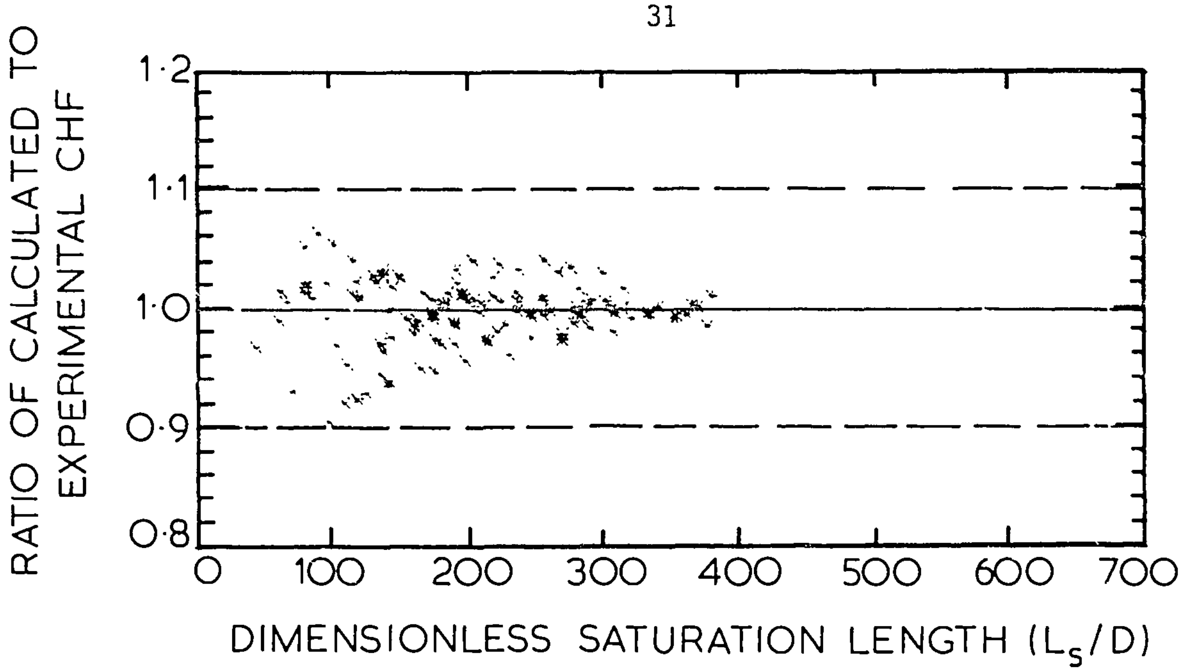

FIGURE 11. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE MERILO AND AHMAD 12.6 mm TUBE DATA EXCLUDING DATA WITH AN EXIT QUALITY LESS THAN 0.1

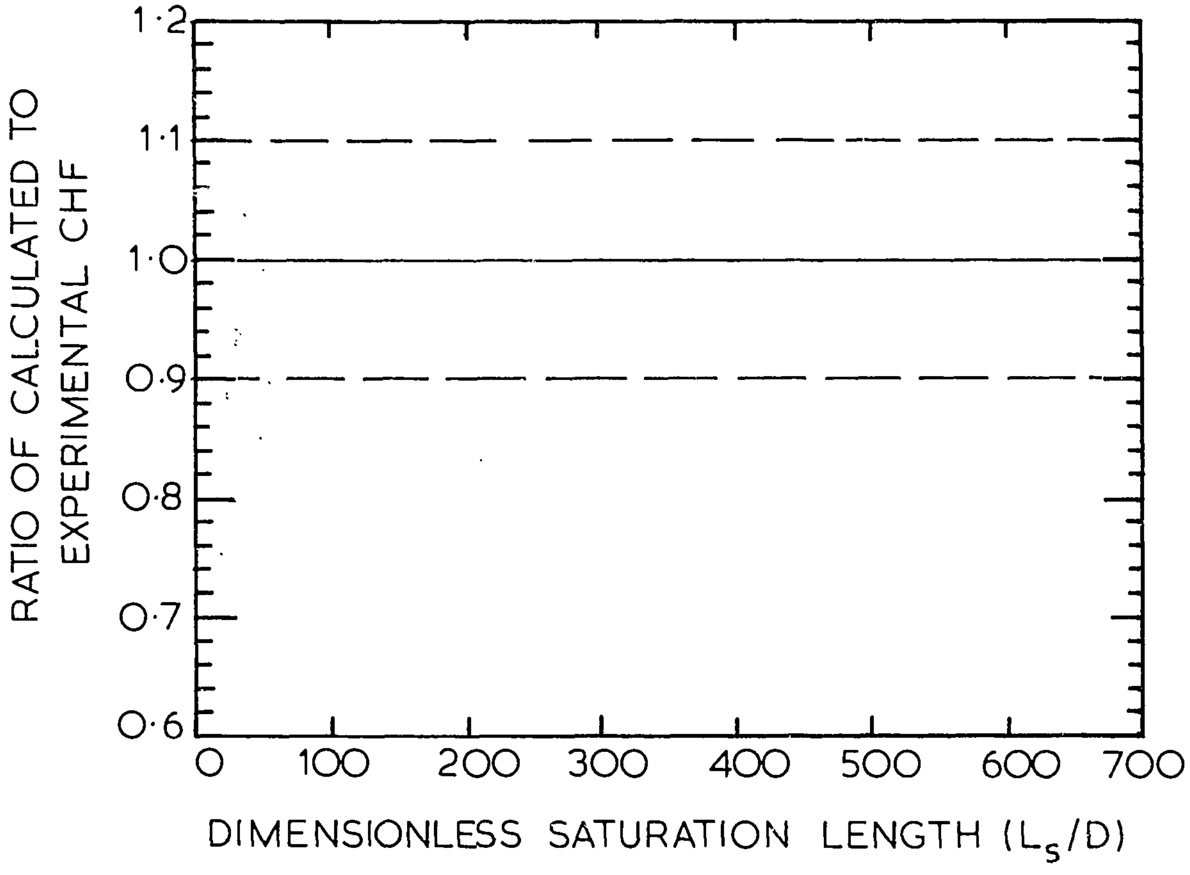

FIGURE 12. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE MERILO AND AHMAD 12.6 mm TUBE DATA WITH EXIT QUALITIES LESS THAN 0.1

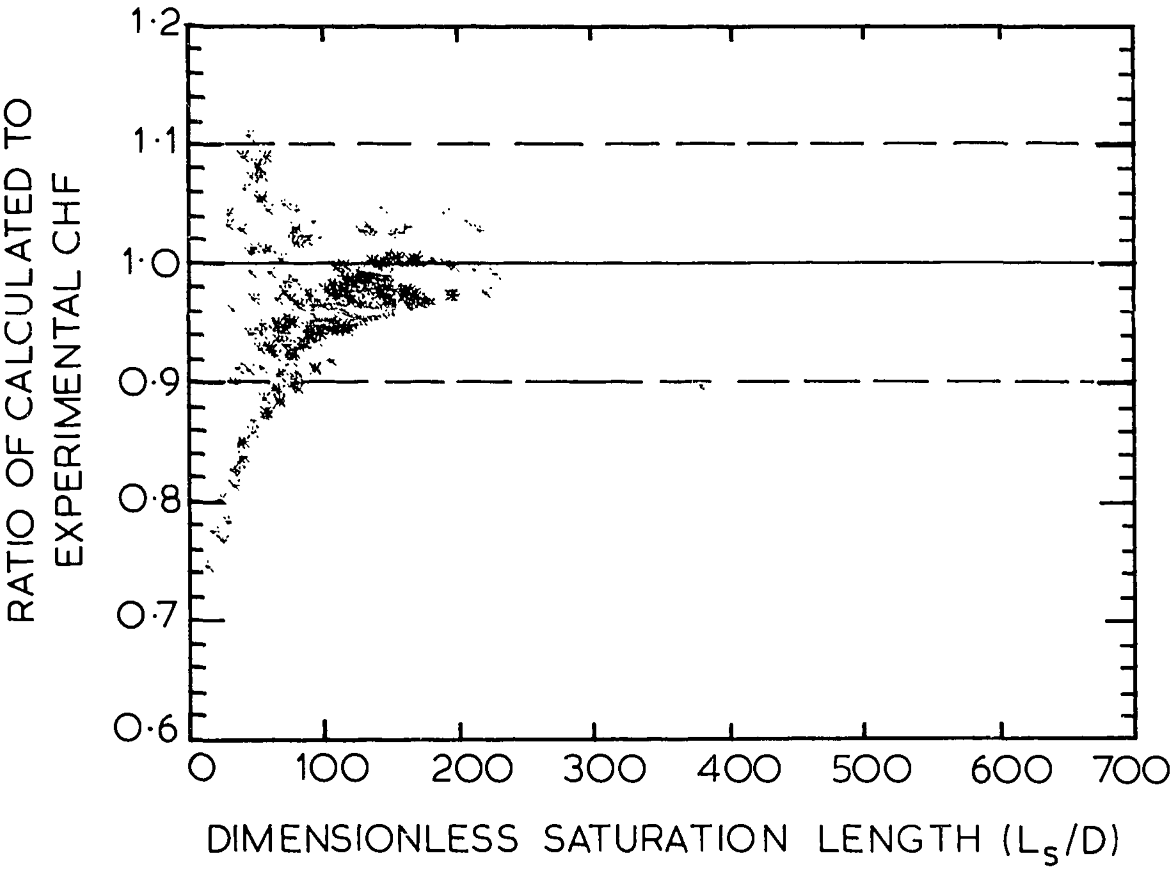

FIGURE 13. COMPARISON OF EXPERIMENTAL CHFs WITH VALUES CALCULATED BY THE BASIC CORRELATION FOR THE GROENEVELD DATA EXCLUDING DATA WITH EXIT QUALITIES LESS THAN 0.1

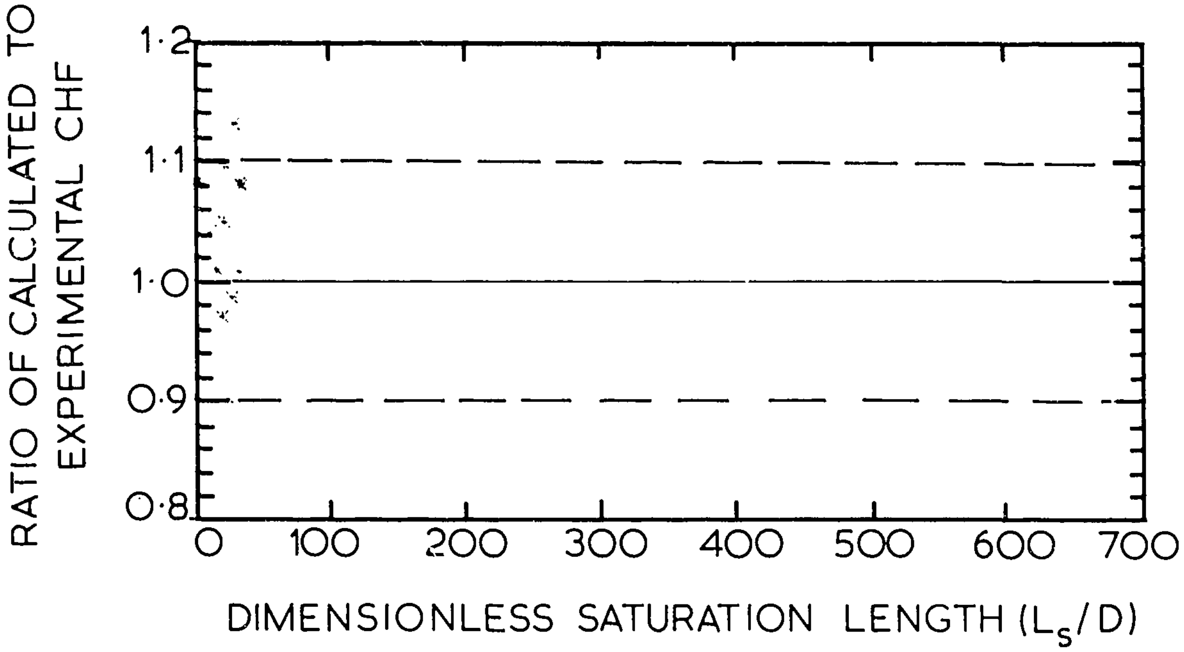

FIGURE 14. COMPARISON OF EXPERIMENTAL CHFs WITH VALUES CALCULATED BY THE BASIC CORRELATION FOR THE GROENEVELD DATA WITH EXIT QUALITIES LESS THAN 0.1

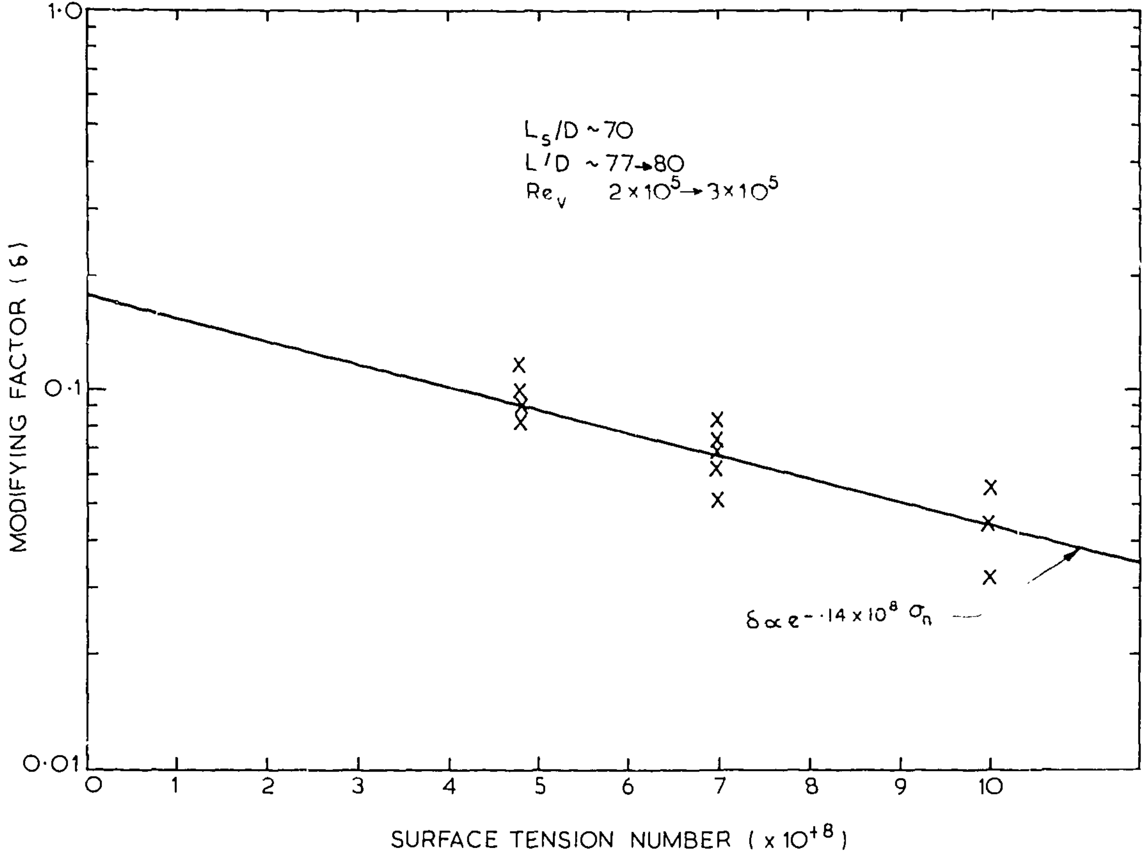

FIGURE 15 INFLUENCE OF SURFACE TENSION NUMBER ON SHORT TUBE MODIFYING PARAMETER δ

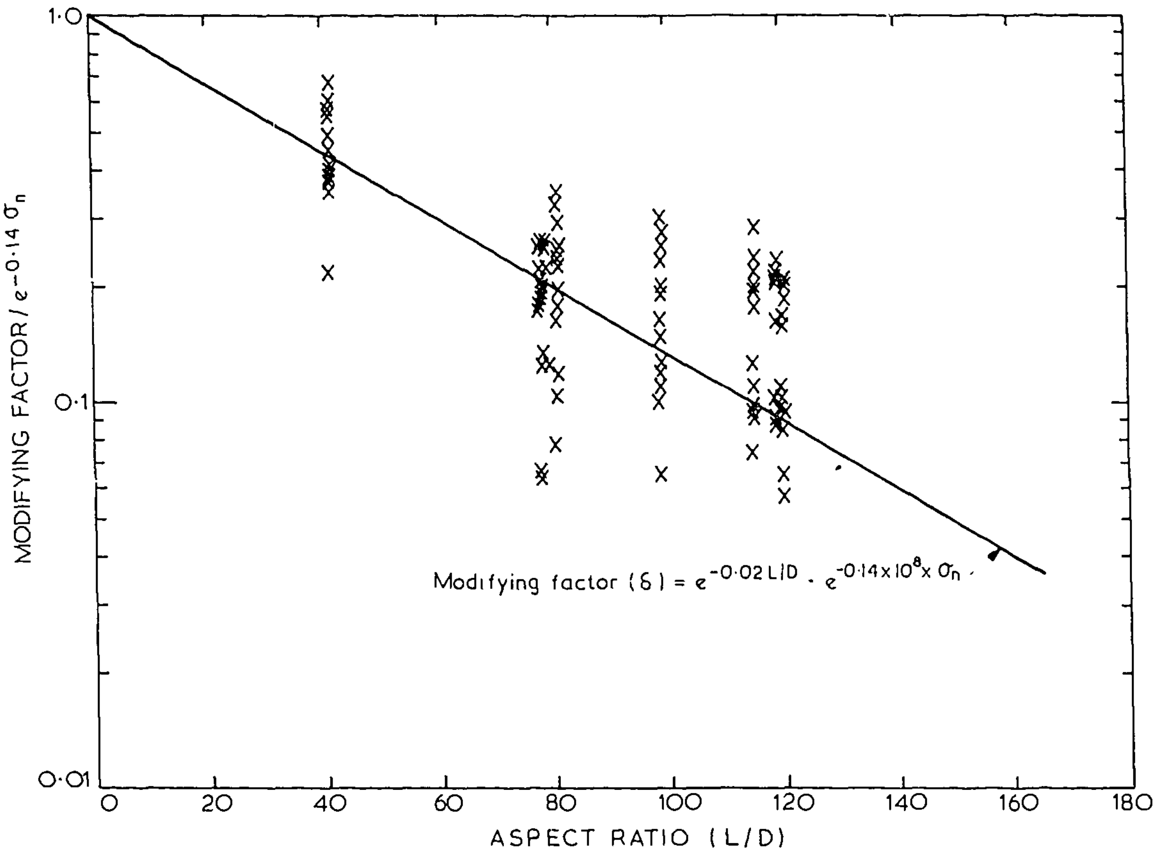

FIGURE 16. RELATIONSHIP AMONG SHORT TUBE MODIFIERS, SURFACE TENSION NUMBER AND ASPECT RATIO

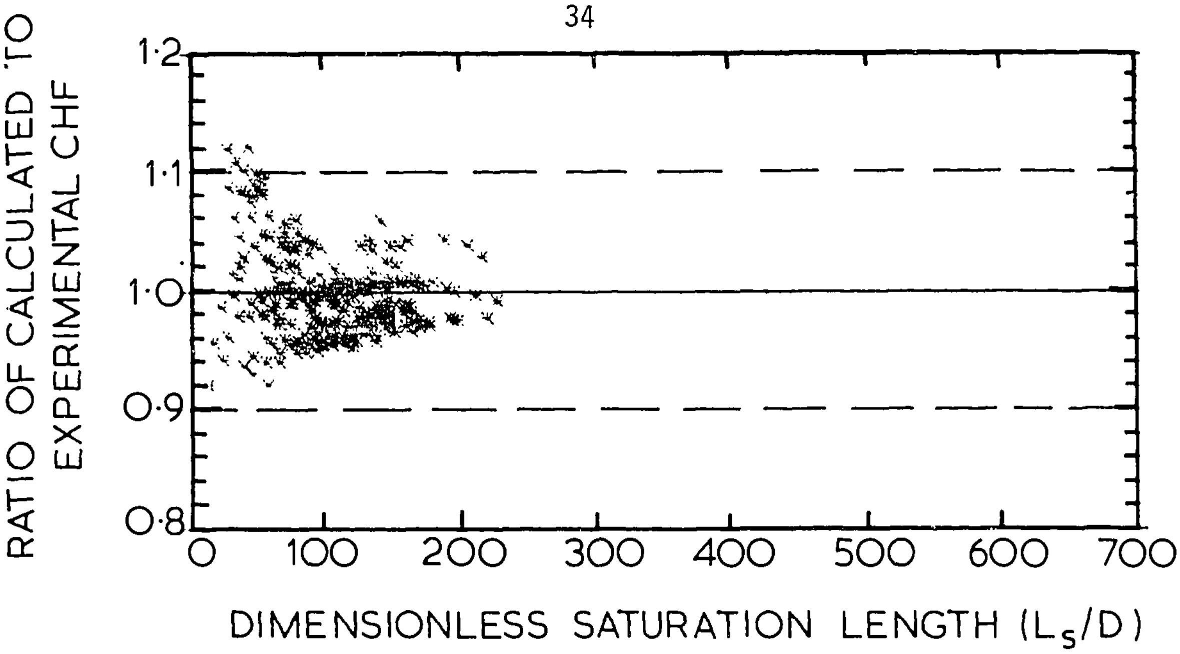

FIGURE 17. COMPARISON OF EXPERIMENTAL CHFs AND VALUES CALCULATED BY THE BASIC CORRELATION MODIFIED TO ACCOUNT FOR SHORT TUBE EFFECTS (GROENEVELD DATA)

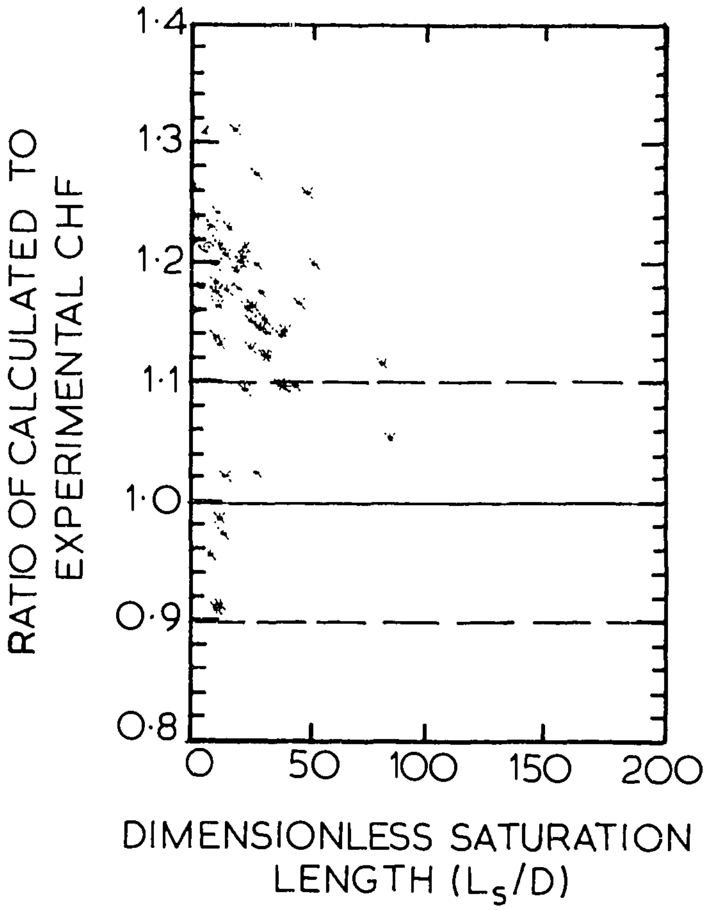

FIGURE 18. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE STEVENS, ELLIOTT AND WOOD (1964) DATA WITH EXIT QUALITIES LESS THAN 0.10

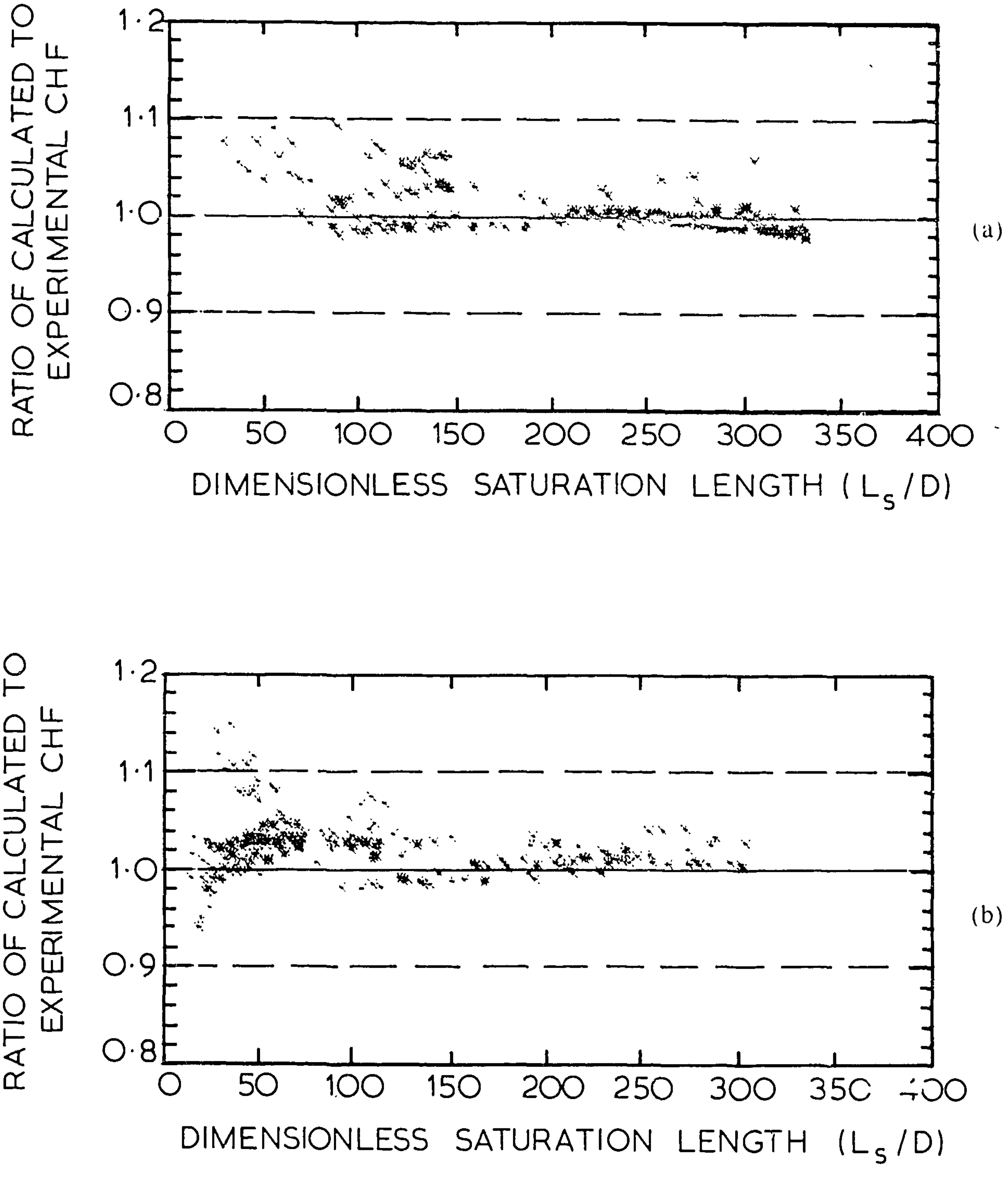

FIGURE 19. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE STEVENS, ELLIOTT AND WOOD (1964) DATA EXCLUDING DATA WITH EXIT QUALITIES LESS THAN 0.10 AND EXCLUDING DATA AT LOW MASS FLUXES ($G < 400$ kg $s^{-1} m^{-2}$)

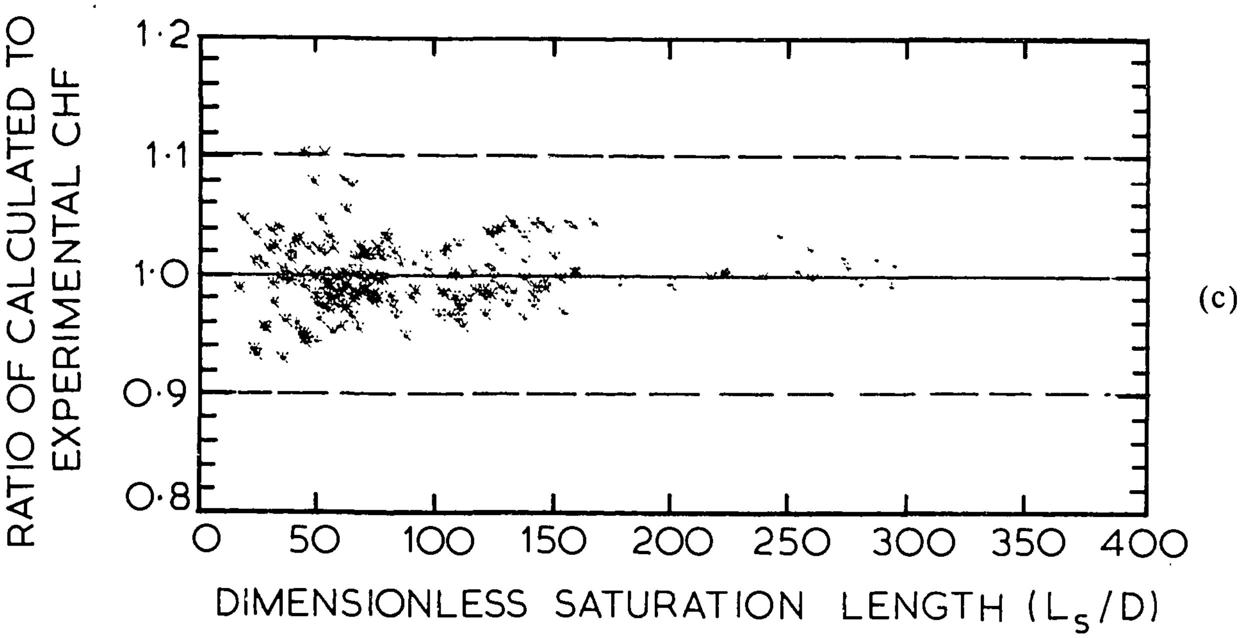

FIGURE 19. (Continued)

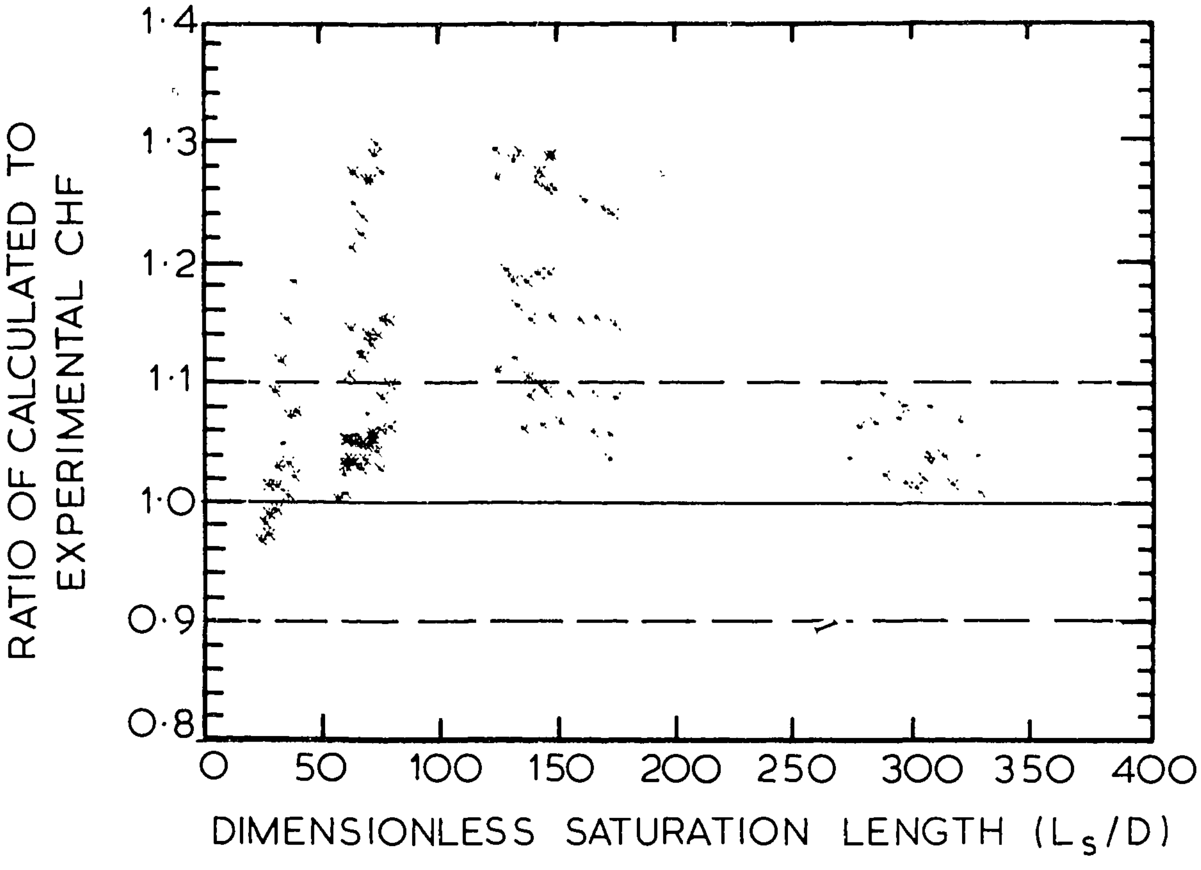

FIGURE 20 COMPARISON OF EXPERIMENTAL AND PREDICTED CHFs FOR THE STEVENS, ELLIOTT AND WOOD (1964) DATA AT LOW MASS FLUXES (G <400 kg s^{-1} m^{-2})

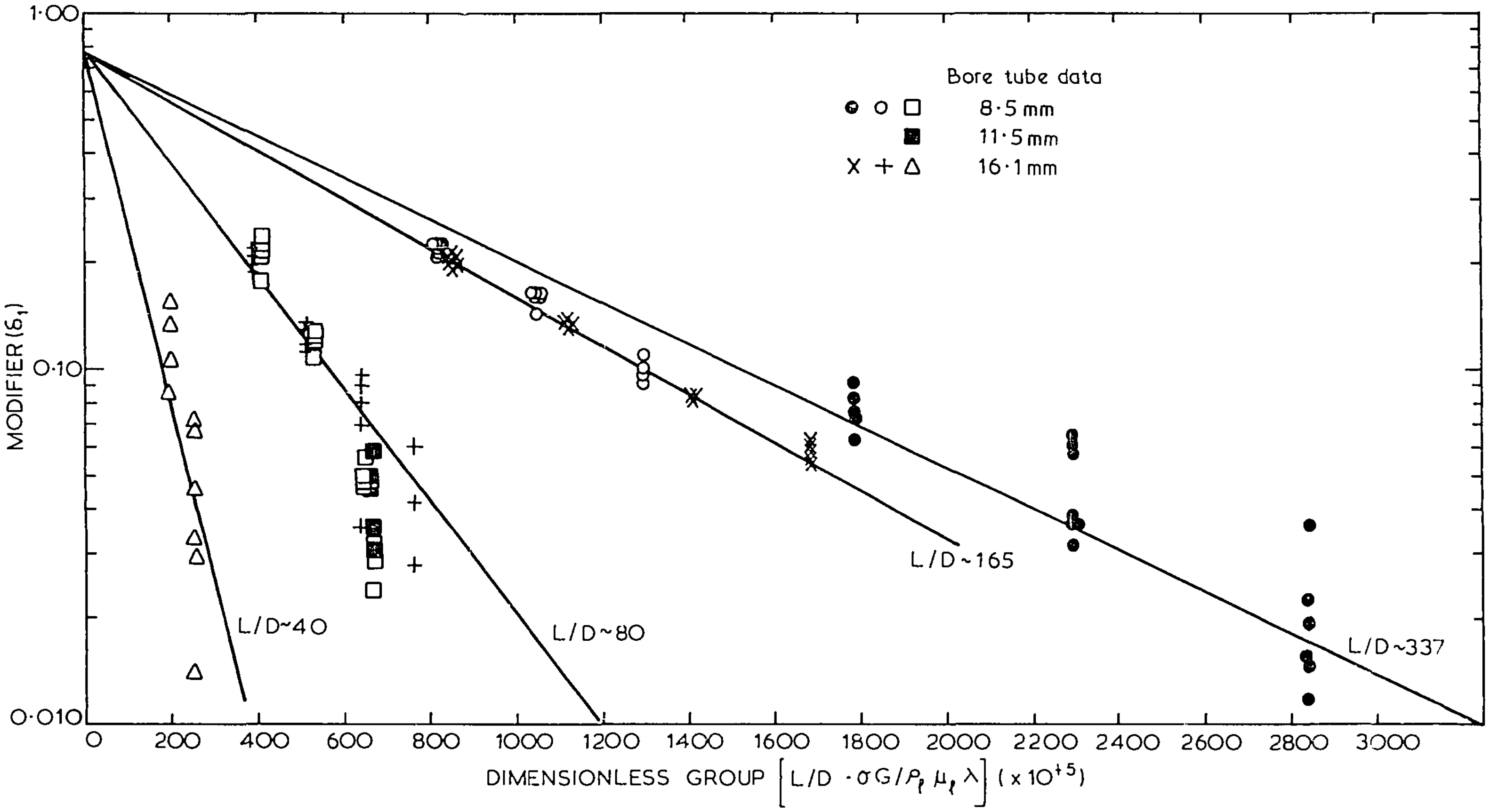

FIGURE 21. RELATIONSHIP BETWEEN LOW FLOW MODIFIER FACTOR AND DIMENSIONLESS GROUP $L\sigma G/D\rho_{\ell}\mu_{\ell}\lambda$

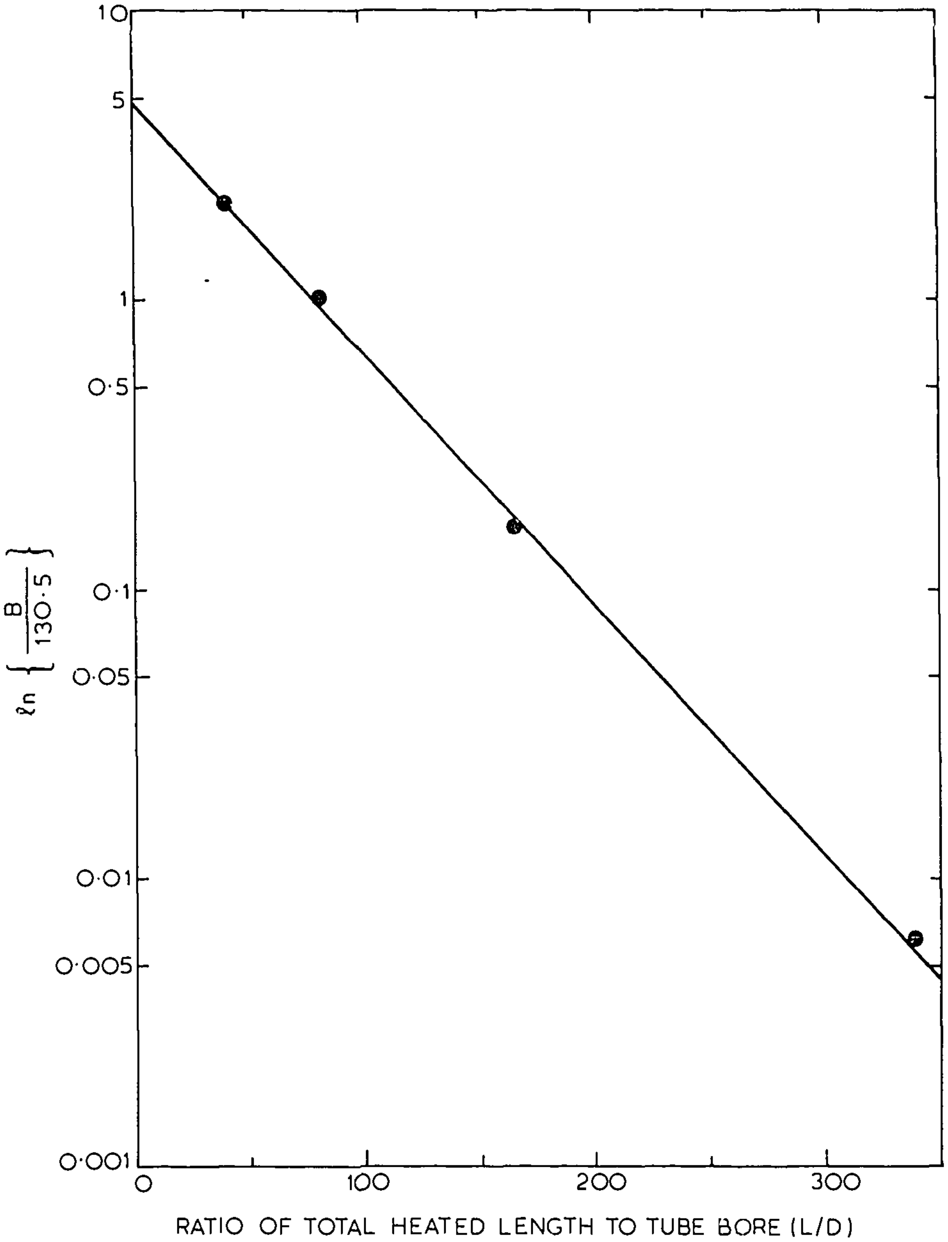

FIGURE 22. RELATIONSHIP BETWEEN EXPONENTS DERIVED FROM FIG. 21 AND RATIO OF TOTAL HEATED LENGTH TO TUBE BORE (L/D)

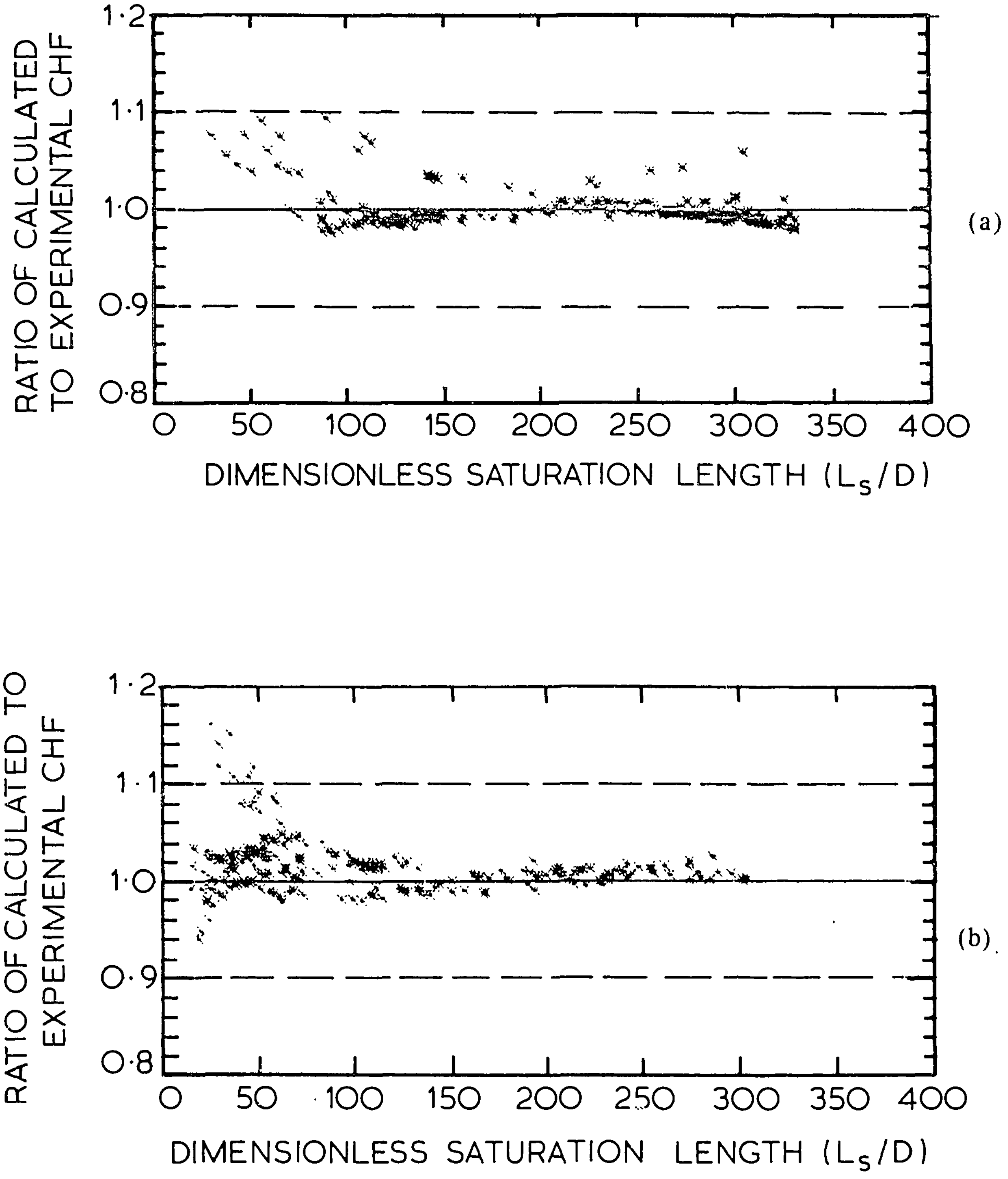

FIGURE 23. COMPARISON OF EXPERIMENTAL CHFs AND VALUES CALCULATED FROM THE GENERAL CORRELATION-STEVENS, ELLIOTT AND WOOD DATA (1964) EXCLUDING DATA FOR EXIT QUALITIES LESS THAN 0.1 AND EXCLUDING DATA FOR LOW MASS FLUXES ($G < 400$ kg s^{-1} m^{-2})

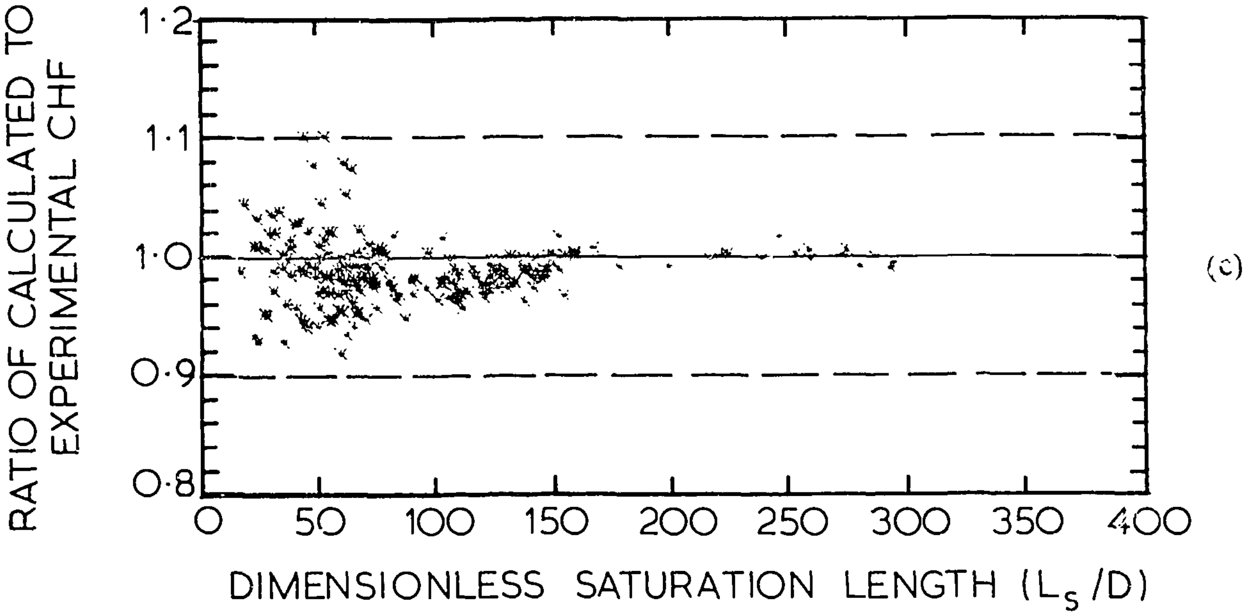

FIGURE 23. (Continued)

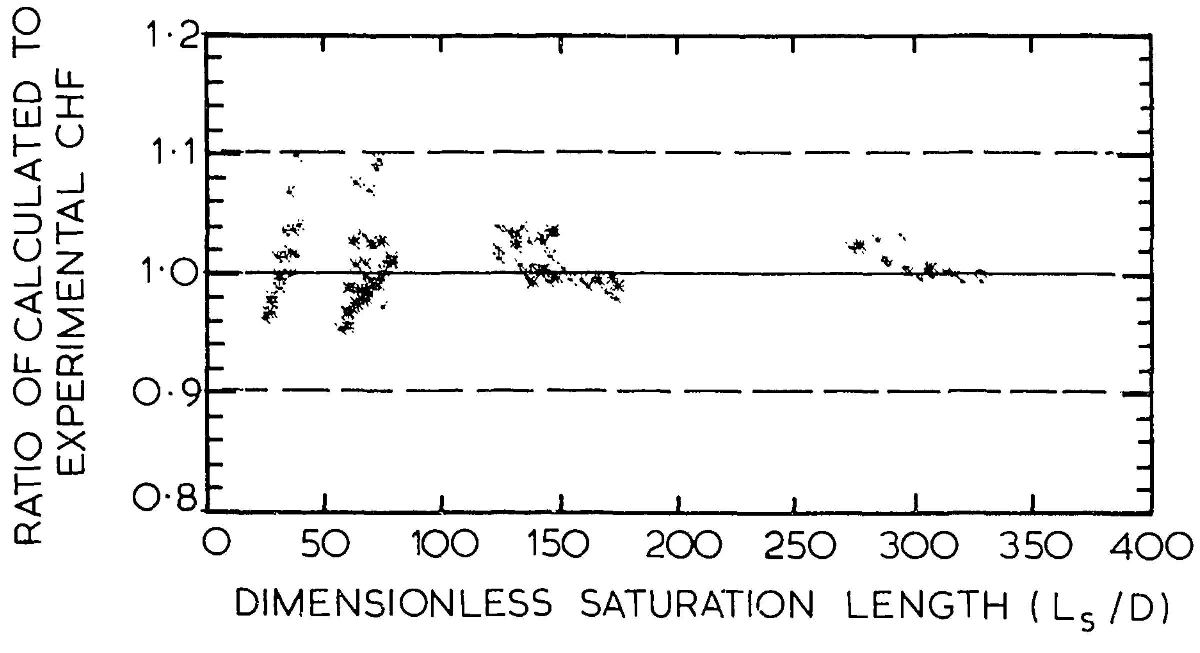

FIGURE 24. COMPARISON OF EXPERIMENTAL CHFs AND VALUES CALCULATED FROM THE GENERAL CORRELATION - STEVENS, ELLIOTT AND WOOD (1964) DATA FOR LOW MASS FLUXES ($G < 400$ kg s^{-1} m^{-2})

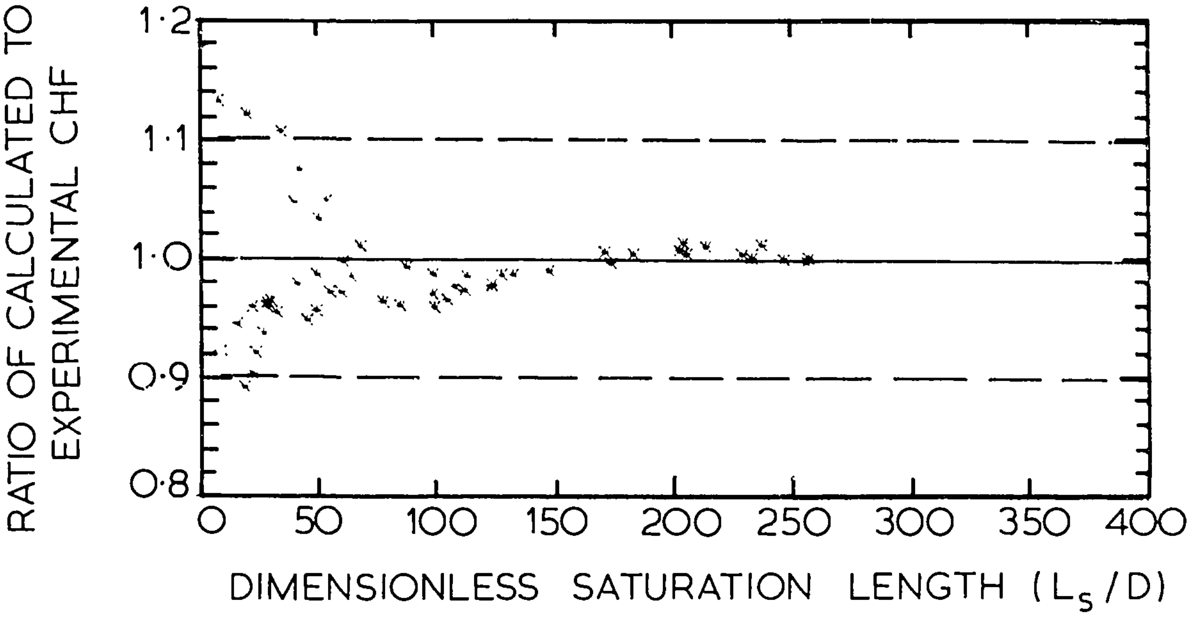

FIGURE 25. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE STEVENS, ELLIOTT AND WOOD DATA (1965)

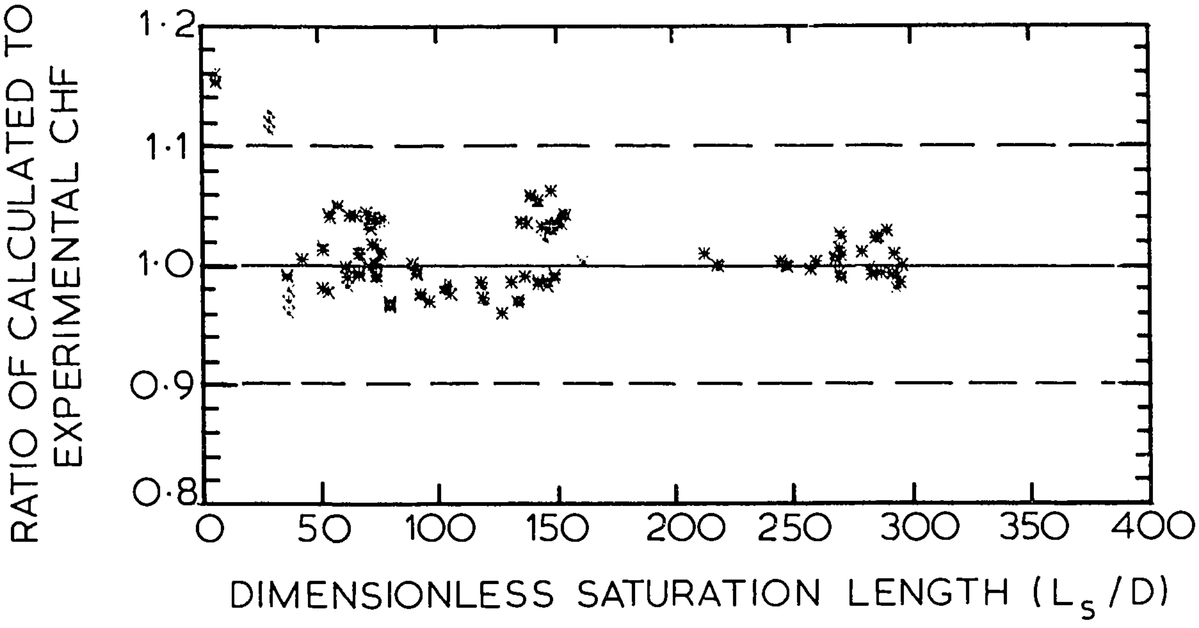

FIGURE 26. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE BARNETT AND WOOD DATA (1965)

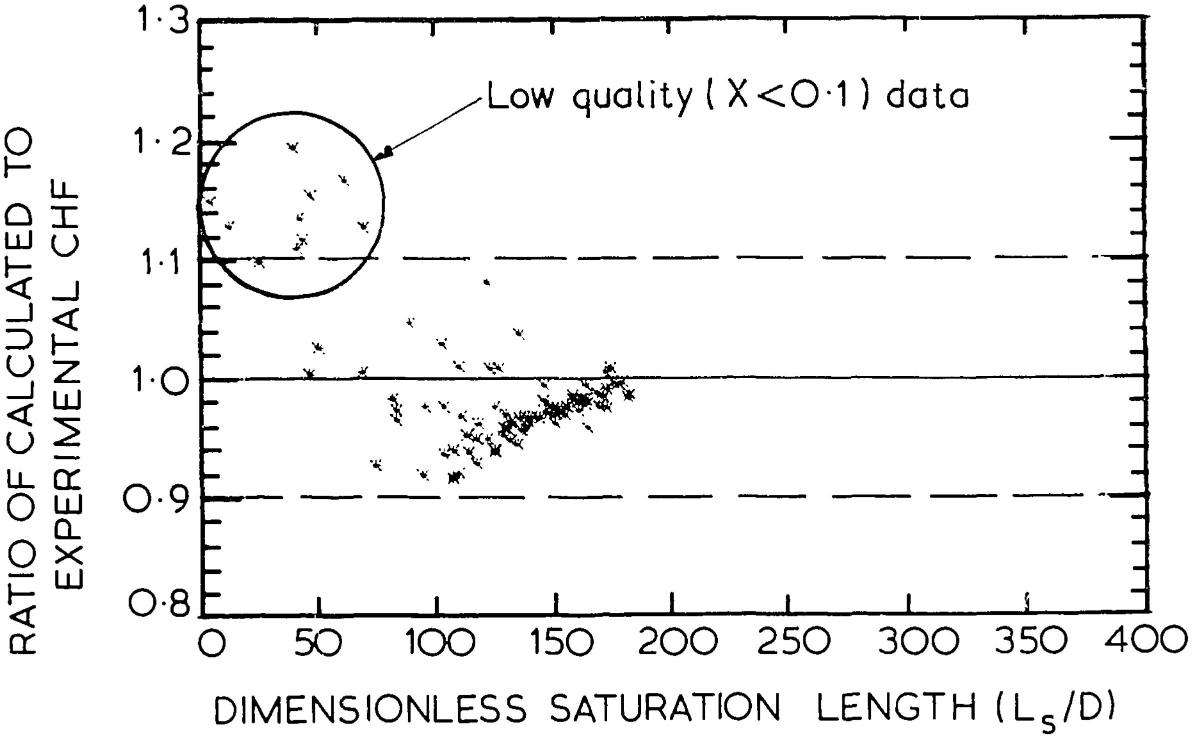

FIGURE 27. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE STEVENS AND MILES DATA (1980)

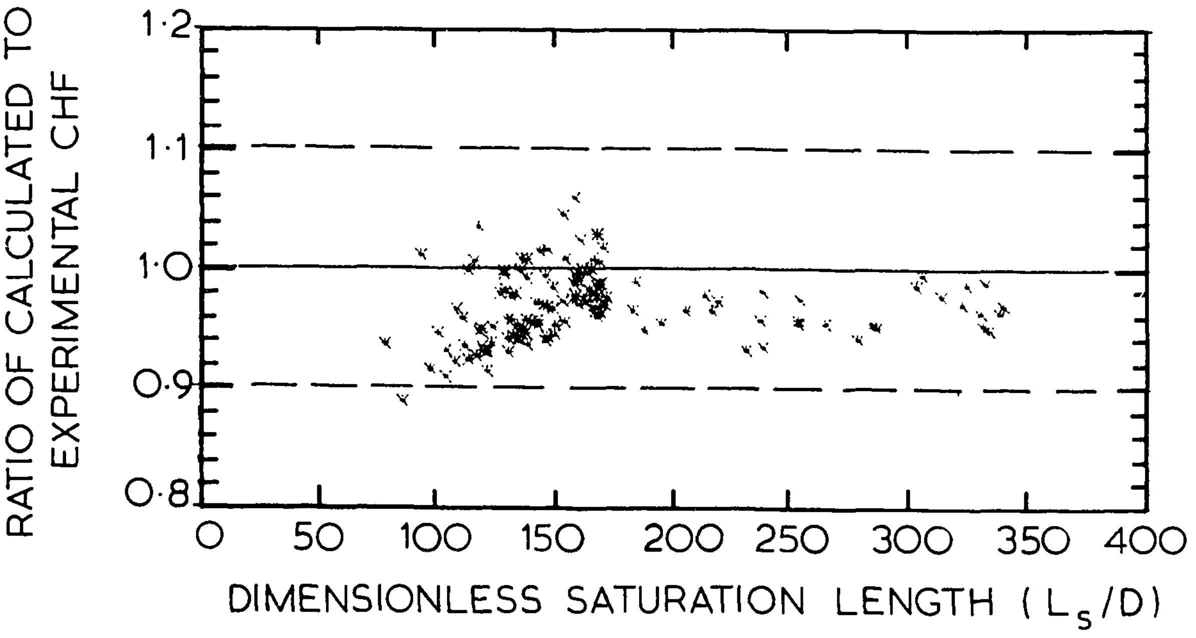

FIGURE 28. COMPARISON OF EXPERIMENTAL AND CALCULATED CHFs FOR THE GREEN AND STEVENS DATA (1981)

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