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FRACTIONAL VAPOUR CONTENT OF A LIQUID POOL THROUGH WHICH VAPOUR IS BUBBLED

G. C. GARDNER
Central Electricity Research Laboratories, Leatherhead, Surrey, England

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Abstract—Data from a large number of Russian, American and German sources are examined and found to be correlated in general by

$$\frac{\alpha}{(1-\alpha)^{1/2}} = K[F_D P^m]^n$$

where α is voidage or fractional vapour content, K is a constant, F_D is a Froude number and P is a physical properties group. However, the exponent m is found to vary from 0 to 0.3 and the exponent n from 2/3 to 0.79, depending upon the sources of the data.

The most probable value for n is 2/3 but a firm choice cannot be made for m, which is either 0.16 or 0.3. The different values of m depend chiefly upon the method of measurement of the voidage.

1. INTRODUCTION

The natural or buoyancy induced separation of steam from water is important in conventional boiler drums and in boiling and pressurized water reactors. It is true that cyclones are provided in all these cases but interest remains in the separation of steam from water in the pool in which the cyclones are immersed. Natural separation is a dominant factor in conventional drums.

The separating velocity of the steam is dependent upon the steam throughput and the essential information can be obtained by a study of the variation of the voidage or steam content of a water pool as the steam throughput is increased. The results can be applied to cases where the water has a net upwards or downwards motion as long as the system dimensions are large enough, so that the influence of vessel walls can be neglected.

The first experimental study was that of Behringer (1934) with steam and water and covering pressures from 1.07 to 40 bar. However, the diameter of his vessels only varied up to 82 mm and the influence of the vessel walls cannot therefore be regarded as negligible.

In the two decades following World War II a substantial amount of work on the water system was carried out in Russia and is summarized as follows:

(1) Kolokol'tsev (1952). 300 mm diameter vessel at 1.27 bar.
(2) Margulova (1953). 216 mm diameter vessel at 91, 150 and 190 bar.
(3) Sterman & Surnov (1955). 238 mm diameter vessel at 17 and 91 bar.
(4) Filimonov *et al.* (1957). 63 mm diameter vessel at 17, 36, 71, 111, 141 and 180 bar.
(5) Styrikovich *et al.* (1961). 238 mm diameter vessel at 6, 33, 60 and 77 bar.
(6) Bartolomei *et al.* (1963). 1219 mm diameter vessel at 22, 33 and 46 bar.

Work was then carried out in the U.S.A.

(7) Wilson *et al.* (1961). 483 mm diameter vessel at 21.7, 28.6, 35.5 and 42.4 bar.
(8) Wilson *et al.* (1965). 437 mm diameter vessel at 42.4, 56.2, 69.9, 83.7, 97.5 and 138.9 bar.

Finally work has been carried out with Freon-12 (refrigerant 12) by

(9) Viecenz & Mayinger (1979). 82 mm diameter vessel at 5.8, 7.5, 9.0 and 10.8 bar.

All this work has been variously correlated and some confusion now exists as to the best predictions. First the previous correlations will be summarized and then the data will be re-examined to formulate preferred correlations.

2. EXISTING CORRELATIONS

Only those correlations will be reviewed that seek generality and do not merely attempt to represent the results for one system over a limited range. The dimensionless groups employed and their arrangement will be described.

The basic dimensionless group is, of course, the voidage α. Otherwise it is universally accepted that the other primary dimensionless group should be a Froude number. However, since there is no physical linear dimension of the system, unless vessels of small diameter are employed, it is again accepted that the Laplace length scale

$$L = \left[\frac{\sigma}{\Delta\rho g}\right]^{1/2} \qquad [1]$$

should be used; the reason being that the surface tension σ is assumed to be of major importance. $\Delta\rho$ is the density difference between the phases and g is acceleration due to gravity. Thus the Froude number is

$$F = U\left[\frac{\Delta\rho}{g\sigma}\right]^{0.25} \qquad [2]$$

where U is the superficial vapour velocity or that which would obtain if there were no liquid.

The crude correlation between α and F is not satisfactory over a wide range and therefore various physical property groups are introduced and these are

$$D_v = \frac{\rho_v}{\Delta\rho} \qquad [3]$$

$$D_L = \frac{\rho_L}{\Delta\rho} \qquad [4]$$

where ρ_v and ρ_L are the vapour and liquid densities and

$$V = \frac{\mu_v}{\mu_L} \qquad [5]$$

where μ_v and μ_L are the vapour and liquid viscosities.

Only Bartolomei & Alkhutov (1967) implicitly introduced the Reynolds number into a correlation. They used the group

$$G = \frac{\mu_L}{\sigma}(gL)^{1/2}. \qquad [6]$$

By employing [1] to remove σ and writing $F = U/(gL)^{1/2}$, [6] becomes

$$G = \frac{FD_L}{R} \qquad [7]$$

where the Reynolds number is

$$R = \frac{\rho_L UL}{\mu_L} = \frac{\rho_L U}{\mu_L}\left[\frac{\sigma}{\Delta\rho g}\right]^{1/2}. \qquad [8]$$

Lastly, before the correlations are enumerated in detail, it should be noted that most correlations consider the ratio of the vessel diameter d to the Laplace length scale L as a factor but some only consider it a factor as long as D is less than a critical value.

The most recent correlation of each particular authority will be given. The first correlation was that of Kurbatov (1953)

$$\alpha = 0.67 F_D^{2/3} V^{-2/9} \left(\frac{L}{d}\right)^{1/6} \qquad [9]$$

where

$$F_D = D_L^{1/2} F = \frac{\rho_L^{1/2} U}{(\Delta\rho g\sigma)^{1/4}}. \qquad [10]$$

Sterman (1956, 1958) gave

$$\alpha = 0.27 F^{0.8} D_v^{0.12} \left(\frac{d_1}{d}\right)^{0.25} \qquad [11]$$

where

$$d_1 = 260 L D_v^{0.2} \qquad [12]$$

but (d_1/d) is set equal to unity if its calculated value exceeds unity.

Bartolomei and Alkhutov (1967) gave

$$\alpha = 1 - \exp\left[2.9 F^{0.7} G^{0.2} V^{0.1} D_v^{0.18} \left(\frac{d_2}{d}\right)^{0.15}\right] \qquad [13]$$

where

$$d_2 = 20{,}000\, L D_v^{-0.25} \qquad [14]$$

but (d_2/d) is set equal to unity if its calculated value exceeds unity.

Wilson *et al.* (1961, 1965) based their correlation on that of Sterman but split the field into two ranges.

For $F < 2$

$$\alpha = 0.56157\, F^{0.62086} D_v^{0.0917} \left(\frac{L}{d}\right)^{0.11033} \qquad [15]$$

and for $F \geqslant 2$

$$\alpha = 0.68728\, F^{0.41541} D_v^{0.10737} \left(\frac{L}{d}\right)^{0.11033}. \qquad [16]$$

Viecenz & Mayinger (1979) based their correlation on that of Kurbatov but again split the field into two ranges.

For $F < 3$

$$\alpha = 0.73\, F^{0.752} D_L^{-0.585} V^{0.256} \left(\frac{L}{d}\right)^{0.174} \qquad [17]$$

and for $F \geqslant 3$

$$\alpha = 0.86\, F^{0.586} D_L^{-0.585} V^{-0.256} \left(\frac{L}{d}\right)^{0.174}. \qquad [18]$$

However, the (L/d) group was only used in dealing with Behringer's (1934) results in forming the correlation. Otherwise (L/d) was set equal to unity. It is also noted that D_L has a negative exponent instead of the positive one of Kurbatov.

3. METHOD OF ANALYSIS

It soon becomes apparent when the raw data of voidage vs superficial steam velocity are examined that there are inconsistencies between the various experimental groups. Most of the work has been done with the water system and it is observed that results from one group do not agree with those of another group at the same or similar pressure. It was therefore decided to set up a correlation scheme and determine the form of correlation needed to explain the results of each experimental group and then to make a comparison.

Alpha (α) was the obvious choice of one primary dimensionless group but it was decided not to modify the correlation by multiplying α by property groups. The reason was that it was felt that dimensional similarity between, say, the water system at two different pressures could only be assumed to exist if the voidage was the same at each pressure. Thus modifications were only made to the other primary dimensionless group, which was chosen to be the Froude number F_D.

This is the choice made by Kurbatov (1953) and it was made since the only way that acceleration due to gravity enters problems such as these is as a product with the density difference $\Delta\rho$. It was then necessary to balance the density difference introduced by the density of one of the phases and it was thought most reasonable that the liquid density should be employed. It is conceived that it multiplies the square of a liquid velocity, which, for α held constant, is proportional to the superficial steam velocity U.

The basic form of correlation was therefore to be between α and F_D but F_D could be multiplied by property groups, as found necessary. It was thought that a Reynolds number should define such a group. One way to argue its incorporation is to consider the bubble bed in a moving frame of reference such that the steam is stationary. We then observe liquid flowing through a bed of dispersed phase, in an analogous manner to liquid flowing through a bed of particles and it is known that the pressure drop in the analogy is a function of Reynolds number.

If we take R and F_D defined by [8] and [18], we can formulate, in a similar manner to the formulation of G by Bartolomei & Alkhutov (1967),

$$\left(\frac{F_D}{R}\right)^2 = \frac{\mu_L{}^2(\Delta\rho g)^{1/2}}{\rho_L \sigma^{3/2}}. \qquad [19]$$

Now it is also noted that many of the correlations observe an influence of the vapour phase density. In fact, as noted by Bartolomei & Alkhutov (1967), Petukhov & Kolokol'tsev (1965) observed that the voidage increased as the air density to the power of 0.22 when bubbling air at pressures between 1 and 25 bar through water and glycerine solutions. In these experiments all physical properties except the light phase density were kept constant for any one liquid. In the light of these results it is more reasonable to introduce the density ρ_v than the vapour phase viscosity μ_v. It was empirically determined that this could be done by defining the group

$$P = \frac{\rho_v}{\rho_L}\left(\frac{F_D}{R}\right)^2 = \frac{\rho_v \nu_L{}^2(\Delta\rho g)^{1/2}}{\sigma^{3/2}} \qquad [20]$$

where ν_L is the kinematic viscosity of the liquid. Thus the chosen correlation has the form

$$\alpha = f[[F_D P^m]^n] \qquad [21]$$

where n and m are constant exponents and f is read as "function of".

However, it was also found that a straight line correlation could be made on logarithmic paper to give a more explicit functional dependence of α on the argument of the r.h.s. of [21]. It is

$$\frac{\alpha}{(1-\alpha)^{1/2}} = K[F_D P^m]^n \qquad [22]$$

where K is a constant.

It is important to note that this correlation was attained by the insistence that the voidage should not be multiplied by modifying groups. The form has the advantage that the field is not split into ranges, as done by Wilson *et al.* (1961, 1965) and Viecenz & Mayinger (1979). It is also noted that [22] is a quadratic in α and thus easily used computationally.

4. RESULTS

All the data to be examined, with one exception, were taken from graphs of voidage vs superficial vapour velocity. It can be assumed that the velocity was accurately determined from raw experimental results by established methods and using accurately known physical properties. However, two different methods were employed to measure voidage and differences and inaccuracy may have arisen. This will be discussed further in section 5.

The exception concerns the results of Bartolomei *et al.* (1963) which were taken from a plot of the correlation of Bartolomei & Alkhutov (1967). However, these authors collected all the values of physical constants together in the correct proportions to formulate a dimensional constant which varied with pressure and which was used in the correlation as a multiplying factor on the superficial vapour velocity. Values of the constant were presented graphically. Therefore any differences in the assumed physical property values and those employed here were eliminated.

Following the spirit of Bartolomei & Alkhutov (1967), values of the physical property group P for both water and Freon-12, which were used to reduce the data, are given in figure 1.

The most recent data—that of Wilson *et al.* (1961, 1965) and Viecenz & Mayinger (1979)—were treated first and a good correlation was found, as illustrated in figure 2. It is to be noted that the ordinate of that figure, as with all similar figures, is linear in the logarithm of $\alpha/(1-\alpha)^{1/2}$ but values of α are shown.

Different types of data point are used in figure 2 to define the Wilson low pressure work of 1961, the Wilson high pressure work of 1965 and Viecienz & Mayinger's work with Freon-12. No further differentiation of the particular pressures is indicated since it does not appear necessary. The extra scatter in Wilson's work at higher values of voidage is formed by consistent trends in

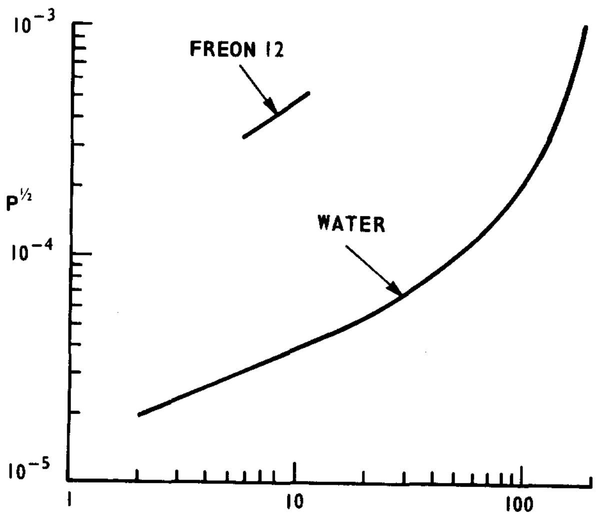

Figure 1. The property group P over the experimental ranges of pressure.

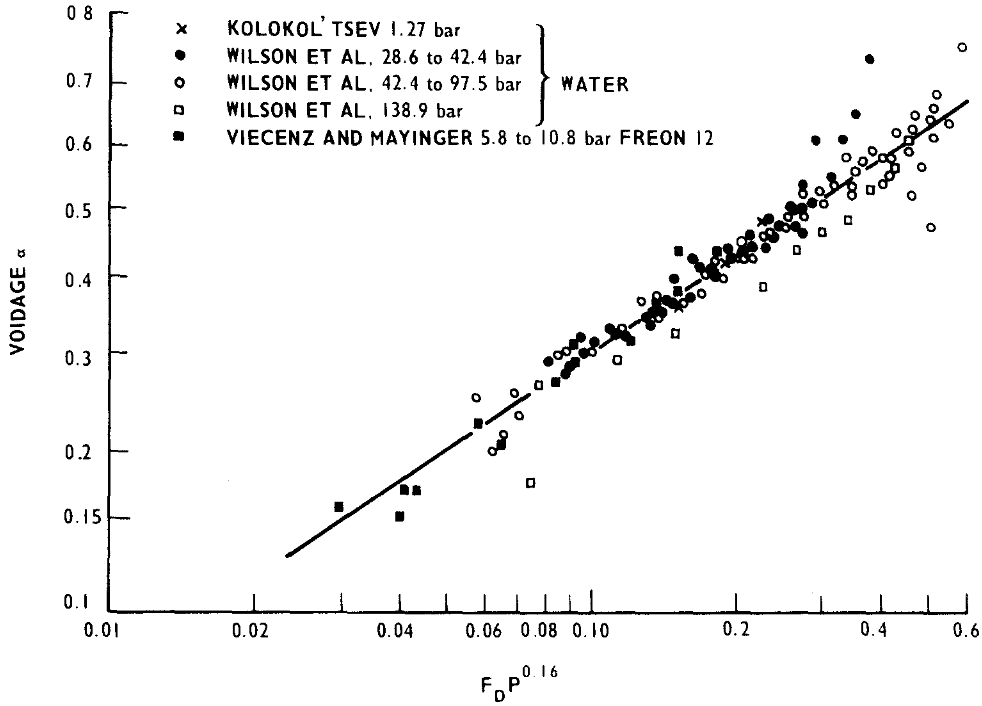

Figure 2. Correlation indicated by part of the data (the ordinate is not a logarithmic scale).

runs at particular pressures but there appears to be no ordered trend as pressure is changed. An exception is Wilson's run at 138.9 bar where all the data points lie substantially below the correlating line and these points are distinguished. Finally it may be noted that three points representing Kolokol'tsev's (1952) results, as presented by Sterman (1956), are plotted in figure 2, since these results fit the correlation well.

The correlating line of figure 2 is represented by

$$\frac{\alpha}{(1-\alpha)^{1/2}} = 1.70[F_D P^{0.16}]^{2/3}. \qquad [23]$$

It may be regarded as particularly successful in that it includes data for a wide range of water pressure as well as for Freon-12.

The correlating line of figure 2 is reproduced in the same coordinates in figure 3, together with all the remaining data. In this figure all the different operating pressures, as well as the source of data, are defined by the data points. All the data are for the water system. It is seen that the data of Styrikovich *et al.* (1961) at 6 bar and of Sterman & Surnov (1955) at 17 bar agree with the correlation of [23]. The data of Bartolomei at pressures between 22 and 46 bar also agree fairly well with [23]. All the rest of the data are for higher pressures and it may therefore be concluded that [23] is satisfactory for the water system at pressures up to at least 40 bar.

The remaining data in figure 3 not only disagrees with [23] but disagrees from source to source within itself. It is also clear from figure 3 that there is no way in which the correlation could be juggled to obtain satisfactory agreement. For example, Sterman and Surnov's data at 92 bar clearly cannot be made to agree with Margulova's data at 91 bar and neither could be made to agree with Wilson *et al.*'s data at a similar pressure because figure 3 is then, in effect, simply a plot of voidage against superficial steam velocity.

The data of Sterman & Surnov (1955), Styrikovich *et al.* (1961) and Bartolomei *et al.* (1963) is replotted in figure 4 and this time an excellent correlation is found in the form

$$\frac{\alpha}{(1-\alpha)^{1/2}} = 11.2[F_D P^{0.3}]^{2/3}. \qquad [24]$$

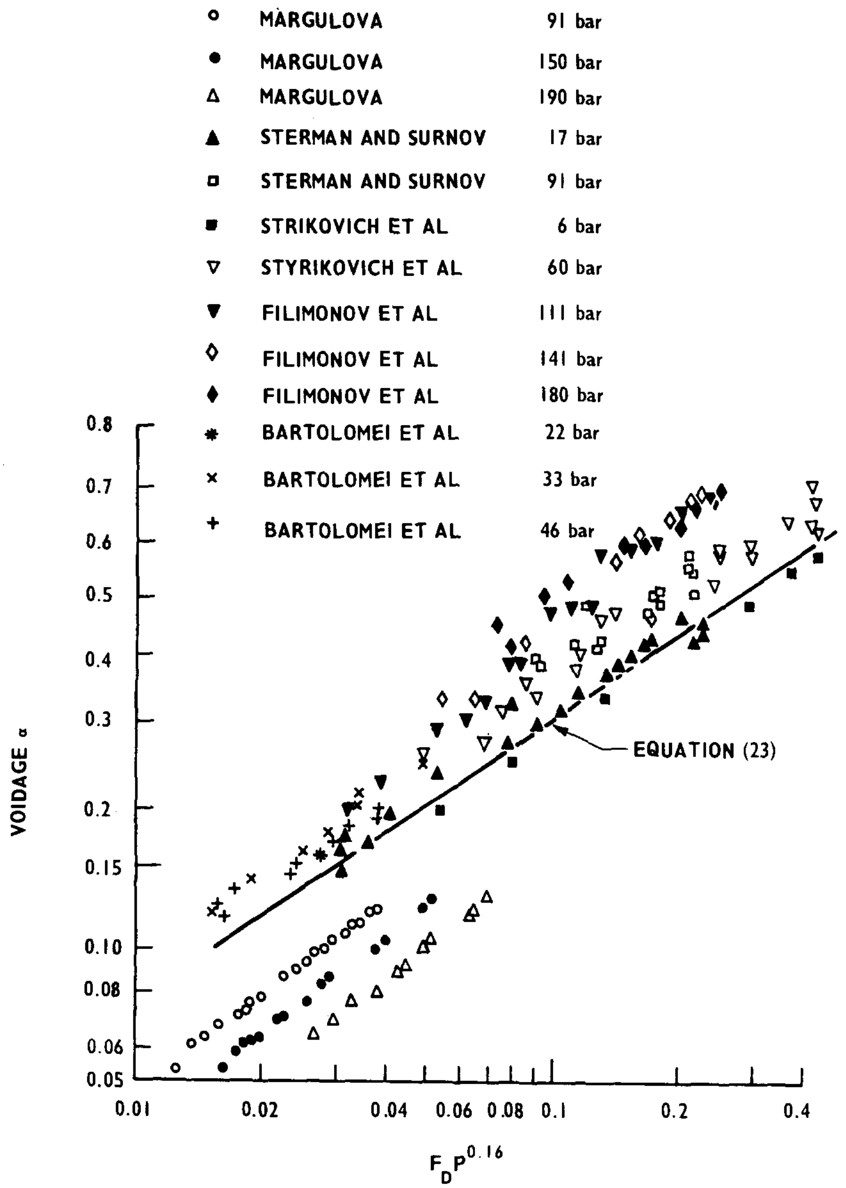

Figure 3. Comparison of remaining data with the correlation of figure 2 and [23] (the ordinate is not a logarithmic scale).

It is seen that the influence of velocity on the voidage through F_D remains unchanged but the exponent on the property group P is altered.

Figure 5 presents the results of Filimonov *et al.* (1957) in the same co-ordinates as figure 4. Only data for the three higher pressures of 111, 141 and 180 bar are treated, since data for the lower pressures may be influenced by the vessel walls according to Bartolomei & Alkhutov criterion of [13]. A fair correlation is apparent and it is

$$\frac{\alpha}{(1-\alpha)^{1/2}} = 2.13[F_D P^{0.3}]^{0.79}. \qquad [25]$$

It is to be noted that the data points for voidage up to 0.5 and all the data at 180 bar agree quite well with the correlation of [24] and figure 4 but the different exponent on $F_D P^{0.3}$ and thus on the superficial steam velocity is clearly indicated by the data. It may be noted that Filimonov

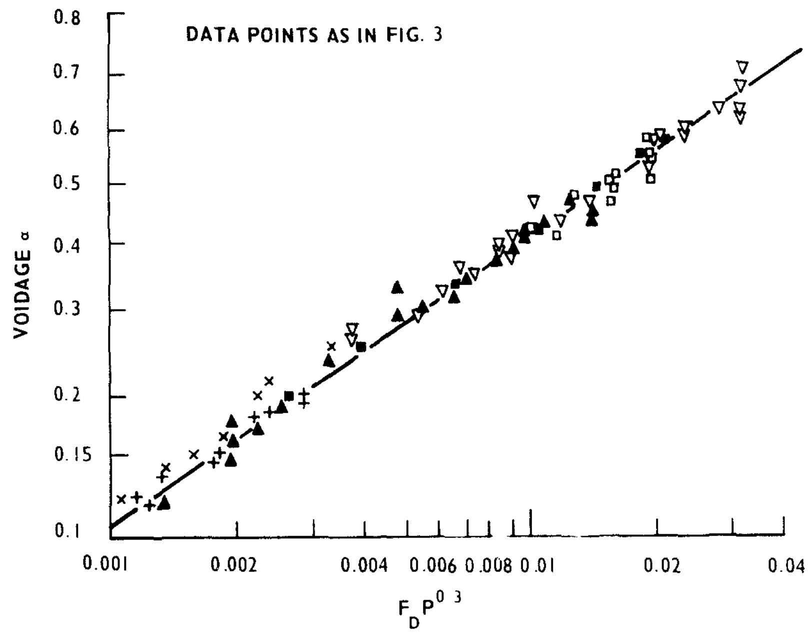

Figure 4. Correlation of data of Sterman, Styrikovich & Bartolomei (the ordinate is not a logarithmic scale).

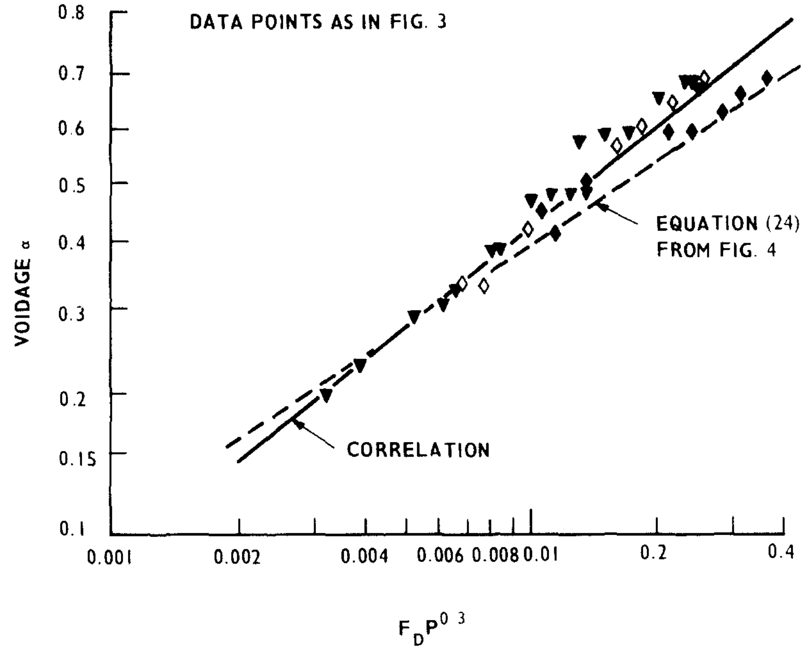

Figure 5. Correlation of data of Filimonov *et al.* (the ordinate is not a logarithmic scale).

et al. (1967) showed that their results were approximated by

$$\frac{\alpha}{1-\alpha} = aU \tag{26}$$

where a is a function of pressure. Equation [26] resembles the form or [25].

Lastly, Margulova's results are presented in figure 6, in which the abscissa is simply F_D. The correlation is very good and is

$$\frac{\alpha}{(1-\alpha)^{1/2}} = 0.20\,F_D^{0.75}\,. \tag{27}$$

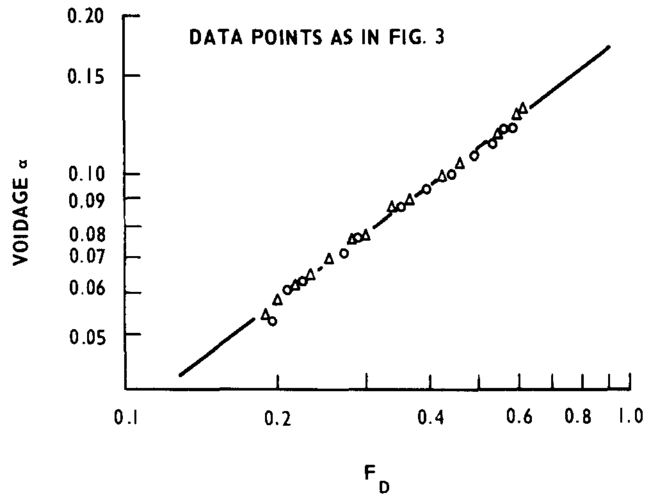

Figure 6. Correlation of data of Margulova (the ordinate is not a logarithmic scale).

5. DISCUSSION

The general form of correlation is simpler than most others and is satisfactory. However, there is disagreement between different experimentalists for water pressures above about 40 bar.

There is no certain choice of the best correlation. The writer's view is that the choice should be made between the correlation of figures 2 and 4 which are represented by [23] and [24]. Both are based on substantial numbers of data over wide pressure ranges and both agree that the voidage function $(\alpha/(1-\alpha)^{1/2})$ is dependent upon the superficial steam velocity to the power of 2/3. They also agree numerically for water pressures up to about 40 bar.

The reason for the difference between the correlations of [23] and [24] must be sought in the method of measuring the voidage α. In one method the pressure difference over a given height of the bubble bed is measured and the voidage is calculated from a knowledge of the vapour and liquid densities. This method was employed by Wilson *et al.* (1961) and Wilson *et al.* (1965). The other methods measure the absorption of γ-rays. The whole of the vessel cross-section has to be traversed and the voidage is calculated from a knowledge of the absorbtivities of vapour, liquid and the vessel walls. This method was employed by Sterman & Surnov (1955), Styrikovich *et al.* (1961), Bartolomei *et al.* (1963) and Viecenz & Mayinger (1979).

Now, it has to be noted that [23] and [24] agree at low pressures but disagree at higher pressures which suggests that the experimental techniques were satisfactory but that perhaps there were errors in the values of physical properties at higher pressures used to reduce the raw data to values of voidage. There is little doubt about the values of physical properties required with the pressure difference method and suspicion is directed at the values of absorbtivity for high pressure water and steam. This is reinforced by observing that the values of the property group for Freon-12, shown in figure 1, are of the same magnitude as for high pressure water, yet the results of Viecenz & Mayinger (1979) obtained with the γ-ray absorption technique agree with those of Wilson *et al.* (1961, 1965) obtained with the pressure difference technique.

It might therefore seem that the correlation of [23] should be accepted. However, the absorbtivities of steam and water for the results of the Russian workers given in figure 4 and by [24] were measured in the same vessel as employed to measure voidage and the source of any error is not obvious. It may also be noted that Wilson *et al.* (1965) found that the values of pressure difference obtained varied slightly as the measuring points were moved from the wall to the vessel axis, so that there are some doubts about this method of measurement. It is clear that a final choice between [23] and [24] cannot be made until further experimental results are obtained.

Lastly, it is sometimes of interest to know the downwards superficial water velocity U_w which will hold the steam in the water stationary. The derivation of the correlating equation and the properties of the equation are given in the Appendix.

6. CONCLUSION

It is shown that there are differences between the experimental results obtained by different groups of workers for the voidage when bubbling vapour through a stagnant liquid pool. It is therefore misleading to try and obtain a correlation for all data together. However, it is demonstrated that most of the data is correlated by

$$\frac{\alpha}{(1-\alpha)^{1/2}} = K[F_D P^m]^{2/3} \qquad [28]$$

with $m = 0.16$, $K = 1.70$ given by the data of one group of workers and $m = 0.30$, $K = 11.2$ given by another group.

The correlations for the data of the two groups agree exactly with each other at about 10 bar for water and agree within the scatter of data for pressures up to about 40 bar for water. A decision on the best correlation for higher pressures can only be made when further experimental data becomes available.

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NOMENCLATURE

d diameter of vessel
d_1, d_2 length scales defined by [11] and [13]
D_L $\rho_L/\Delta\rho$
D_v $\rho_v/\Delta\rho$
F Froude number defined by [2]
F_D $D_L^{1/2}F$
F_{DW} F_D with U_w replacing U
g acceleration due to gravity
G dimensionless group defined by [6]
K constant
L Laplace length scale, [1]
m exponent
n exponent
P dimensionless group defined by [20]
R Reynolds number defined by [8]
U superficial steam velocity with water stationary
U_w superficial water velocity with steam stationary
V μ_v/μ_w
α voidage or fractional steam content
μ_L liquid viscosity
μ_v vapour viscosity
ρ_L liquid density
ρ_v vapour density
$\Delta\rho$ density difference between phases
σ surface tension

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APPENDIX

It is justifiable for liquid pools with no influence from containing walls to choose a moving frame of reference such that the vapour appears stationary and the liquid moves downwards with a superficial velocity U_w. Since the true vapour velocity in one frame of reference will equal the true liquid velocity in the new reference frame,

$$\frac{U}{\alpha}=\frac{U_w}{1-\alpha} \qquad [A1]$$

and we can write

$$F_D = F_{DW}\left(\frac{\alpha}{1-\alpha}\right) \qquad [A2]$$

where

$$F_{DW}=\frac{\rho_L{}^{1/2}U_w}{(\Delta\rho g\sigma)^{1/4}}. \qquad [A3]$$

Now if the basic form of the correlation is

$$\frac{\alpha}{(1-\alpha)^{1/2}}=K[F_DP^m]^{2/3} \qquad [A4]$$

the form when the steam velocity is zero is

$$\alpha(1-\alpha)^{1/2}=K^3[F_{DW}P^m]^2. \qquad [A5]$$

F_{DW} has a maximum value, as shown by Gardner *et al.* (1973). Differentiation of [32] shows that it occurs when $\alpha = 2/3$ and thus the maximum value of F_{DW} is

$$F_{DW}^{\max} = \left(\frac{4}{27}\right)^{1/4} K^{-3/2} P^{-m}. \qquad \text{[A6]}$$

If F_{DW} exceeds this value, the steam cannot be held stationary and steam must be carried down with the water.