Int. J. Heat Mass Transfer. Vol. 28, No. 3, pp. 724–727, 1985
Printed in Great Britain

0017-9310/85 $3.00 + 0.00
Pergamon Press Ltd.

A dryout correlation for R12 and R113 flowing vertically upwards in uniformly and non-uniformly heated tubes

H. C. ÜNAL
MT-TNO, P.O. Box 342, 7300 AH, Apeldoorn, The Netherlands

(*Received* 4 *June* 1984)

NOMENCLATURE

A	cross-sectional area [m^2]
B	boiling number [$Q/(Gr)$]
Bo	boiling number for dryout
d	inner tube diameter [m]
Fr	Froude number [$G^2/(dg\rho_l^2)$]
G	mass velocity [kg m^{-2} s^{-1}]
g	acceleration of gravity [m s^{-2}]
H	enthalpy [J kg^{-1}]
ΔH	inlet subcooling enthalpy [J kg^{-1}]
L	heated length [m]
L_e	equivalant length [m]
M	molecular weight [kg mole^{-1}]
n	number of data
P	pressure [N m^{-2}]
P_c	critical pressure [N m^{-2}]
Q	heat flux [W m^{-2}]
q	dryout heat flux [W m^{-2}]
r	latent heat of evaporation [J kg^{-1}]
Re	Reynolds number [Gd/μ_l]
X	steam quality.

Greek symbols

ρ	density [kg m^{-3}]
μ	dynamic viscosity [kg m^{-1} s^{-1}].

Subscripts

1	refers to main test section
2	refers to exit test section
d	refers to dryout location
l	refers to liquid at the state of saturation
M	refers to measured value
P	refers to predicted value
R12	refers to Freon-12
v	refers to vapour at the state of saturation
x	refers to fluid to which equation (1) is applied.

INTRODUCTION

THIS STUDY deals with the determination of dryout for R12 (i.e. Freon-12) and R113 (i.e. Freon-113) flowing vertically upwards in uniformly and non-uniformly heated circular tubes. Dryout is of practical importance for the design and safe operation of evaporators and liquid cooled nuclear reactors. Therefore, it has been extensively studied during the last two decades. For a detailed literature survey on the subject, the reader is referred to a textbook [1] and a survey paper [2]. Only the literature data found to be pertinent to the present study are briefly mentioned in the following sections.

Dryout for R12 and R113 flowing vertically upwards in uniformly heated circular tubes has been experimentally studied by several investigators [3–9]. The principal aim of the most of these studies was to establish a scaling law for dryout. In ref. [10], a quite extensive dryout correlation is given for water and R12 and for uniform heating. Shah [11] has developed a graphical method for determining dryout heat flux for water and refrigerants among other fluids and for uniform heating.

Dryout data for R12 flowing vertically upwards through non-uniformly heated circular tubes have been published by Green and Stevens [7]. Using 'local conditions' hypothesis, these investigators compared their data with two correlations based on data obtained from uniformly heated tubes for R12. The correlations did not fit the data well. A similar result had been previously reported by TNO for water [12].

A practising engineer deals mainly with dryout in non-uniformly heated tubes. However, dryout correlations for such tubes are rarely to be found in the relevant literature. To the knowledge of the author, no correlation is available to predict dryout heat flux for refrigerants flowing vertically upwards through non-uniformly heated circular tubes. Reference [12] shows that the use of the so-called equivalent-length hypothesis yields a satisfactory result for the correlation of dryout heat flux data for water obtained from non-uniformly sodium-heated tubes.

The principal objective of the study presented is to demonstrate the application of the foregoingly quoted hypothesis to R12. For this purpose, an accurate dryout heat flux correlation was first developed using 131 data of ref. [7] obtained for R12 flowing upwards in vertical uniformly heated circular tubes for L/d = 171–338; P = 0.78–1.3 MN m^{-2}; G = 382–2790 kg m^{-2} s^{-1} and ΔH = −0.01–41 kJ kg^{-1}. The correlation derived herefrom was then compared with 737 data of ref. [3] for R12, and 23 data of ref. [8] for R113, taken in uniformly heated tubes (see Table 1). The correlation appeared to fit these data reasonably well. Thereafter, using the equivalent-length hypothesis it was shown that the correlation well predicted dryout heat flux from the data of ref. [7]. These data were measured for R12 flowing in vertical non-uniformly heated circular tubes for the ranges of geometry, mass velocity, pressure and inlet subcooling on which the correlation was based.

EXPERIMENTAL DATA

The data of Stevens *et al.* [3] and Green and Stevens [7] for R12, and the data of Lazarek and Black [8] for R113 have been considered. The ranges of operating conditions and geometries for these data are summarized in Table 1. The data were obtained for vertical upflow in electrically heated circular tubes. The data of refs. [3, 8] were taken for axially uniform heating.

Green and Stevens [7] used three round test tubes to obtain dryout heat flux for both axially uniform and non-uniform heating. Each test tube consisted of a main test section and a short exit test section with separately controlled power supply. The heated lengths of the main test sections were 2.87 m (for 8.48 mm and 16.76 mm tube bores) and 3.7 m (for 21.34 mm tube bore). The heated length of each exit test section was 0.23 m. The following procedure was used to obtain the data [7]:

Step 1. With little or no power on the exit test section, the power on the main test section was gradually raised until dryout was obtained at the end of the latter.

Step 2. The power on the main test section was then reduced by approx. 1–2% to bring it out of dryout and the power to the

Table 1. Ranges of data analyzed

P (MN m^{-2})	G (kg m^{-2} s^{-1})	ΔH (kJ kg^{-1})	q_1 (kW m^{-2})	q_2 (kW m^{-2})	$\frac{L}{d}$	d (mm)	X_d (%)	n	Ref.
0.78–1.27	1646–2790	−0.01–37.7	69–129	—	338*	8.48	19–44	33	7
0.78–1.26	1663–2780	−0.3–38	67–124	38–119	366†	8.48	21–42	33	7
0.89–1.30	422–912	0.3–39.3	61–107	—	171*	16.76	38–86	43	7
0.89–1.30	425–912	0.2–39.5	58–105	45–92	185†	16.76	41–86	37	7
0.89–1.31	382–1048	1.2–41.0	55–111	—	173*	21.34	31–85	55	7
0.89–1.30	382–968	1.2–40.4	52–106	50–92	184†	21.34	38–97	27	7
1.07	203–4068	0.1–34	35–302	—	28–337*	5.3–16.1	−5–113	737	3
0.11–0.41	232–740	3.7–74.0	183–333	—	40*	3.15	29–87	23	8

* Uniform heating.
† Non-uniform heating.

exit test section increased until dryout occurred at the end of the latter.

The tests corresponding to Step 1 yielded dryout data for axially uniform heating and those corresponding to Step 2 dryout data for axially non-uniform heating.

The data of ref. [3] were obtained from test tubes with length-to-diameter ratios of 28, 39, 40, 48, 56, 58, 71, 76, 78, 81, 113, 114, 123, 143, 152, 156, 161, 178, 229, 240, 249, 304, 305, 312 and 337. The tube diameters were 5.26, 8.48, 9.65, 11.48 and 16.08 mm.

The data of ref. [8] were taken with a very short tube of a small diameter.

CORRELATION OF DATA FOR UNIFORM HEATING

For this purpose (and taking into consideration only the data of ref. [7]), the dryout heat flux correlation given in ref. [13] for water was modified. On the basis of the equivalent length hypothesis, this correlation fitted with the data obtained from a non-uniformly heated tube rather well [12]. The correlation was made non-dimensionally and altered by taking the effects on dryout of tube diameter, Froude number and fluid properties. This yielded

$$Bo_1 = a_0 a_1 a_2 a_3 a_4 / a_5 \quad (1)$$

where

$$a_0 = 0.208 \quad (2)$$

$$a_1 = (MP_c)_{R12}/(MP_c)_x \quad (3)$$

$$a_2 = Fr^{-0.3} \quad (4)$$

$$a_3 = 1 + \frac{1.84 + 1.1 \times 10^{-5}\, Re}{H_1} \Delta H \quad (5)$$

$$a_4 = (\rho_v d g 10^5 / P)^{-0.749} \quad (6)$$

$$a_5 = L_e/d + 28 Fr^{0.22}. \quad (7)$$

It follows from equation (8) that $L_e = L_1 = L$ for uniform heating.

Equation (1) is compared with the data of ref. [7] in Fig. 1. With two exceptions only, the correlation predicts the dryout heat flux from these data within 6% accuracy. The RMS error for all the 131 data analyzed was found to be 2.9%. This implies that the accuracy of the correlation is within the range set by the experiments, including the error involved in predicting the properties of R12.

After the correlation had been established, it was compared with 737 data of ref. [3] for R12 and 23 data of ref. [8] for R113. If a_0 is taken equal to 0.155 for $L/d < 161$, the correlation predicts the dryout heat flux reasonably well from the data of refs. [3, 8], i.e. it is accurate to 25% for 97% of the time. The

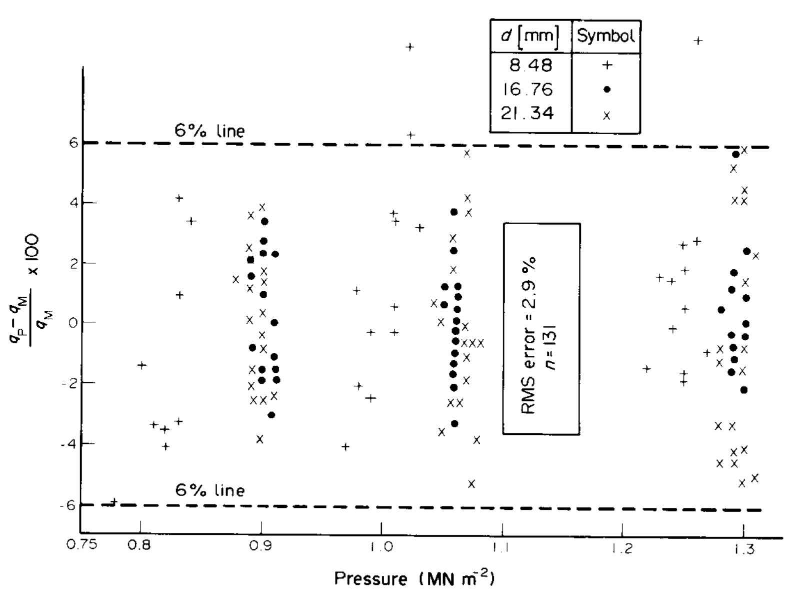

FIG. 1. Errors in predicting dryout heat flux from data of ref. [7] for uniform heating.

RMS error for these 760 data is 12.9%. This accuracy is considered to be quite satisfactory at the present state of the art. The correlation does not appear to be a brute force correlation but a simple one since the ranges of operating conditions and geometries for the data used to verify the correlation are quite extensive. The reason why the data of ref. [7] were correlated with an exceptional accuracy is explained later.

The properties of R12 and R113 were evaluated from the data of refs. [14, 15]. The reference point for enthalpy is 200 kJ kg^{-1} for the saturated liquid at 0°C. The viscosity of both refrigerants was determined from the equation given in ref. [16].

CORRELATION OF DATA FOR NON-UNIFORM HEATING

For this purpose, the equivalent-length hypothesis was applied to equation (1). In accordance with this hypothesis, the power developed up to the dryout point in a non-uniformly heated tube is the same as that of a uniformly heated tube of the same bore and of a hypothetical length found from the condition that the local heat fluxes are equal at the dryout location in both tubes. The equivalent length is then per definition

$$L_e \pi d q = AG(\Delta H + rX_d). \quad (8)$$

Although this hypothesis was extensively used at mid-sixties, recent work dealing with its application is scarce in the literature [12]. This may be due to the following reason: there appear to be more than 400 empirical or semi-empirical dryout correlations quoted in the literature. Some of these correlations have been expressed as a function of dimensional variables. Furthermore the dimensionless numbers fully characterizing a two-phase flow phenomenon are numerous and it is impossible, therefore, to take all of them into account when correlating the data. The foregoing implies that, strictly speaking, a dryout correlation is only applicable to the range of data from which it has been derived.

In the present work, the data of ref. [7] for non-uniform heating are considered. These data were obtained for the ranges of geometry, mass velocity, pressure and inlet subcooling from which equation (1) was derived (see Table 1). Furthermore the accuracy of this equation is within the range set by the experiments. Therefore it was considered to be fair to verify this equation with the foregoing data on the basis of the equivalent-length hypothesis.

For the tests reported in ref. [7], the equivalent length becomes

$$q_2 L_e = Q_1 L_1 + q_2 L_2. \quad (9)$$

Since Q_1, q_2, L_1 and L_2 are known (i.e. measured quantities), L_e was solved from equation (9) and inserted into equation (1). In this case, the latter predicted the dryout heat flux from the data of ref. [7] within 8.8% accuracy (with three exceptions). The RMS error for the 97 data considered was found to be 4.9%. For these data, the ratio (Q_1/q_2) varies between 0.88 and 1.80.

In order to determine the dryout heat flux in a liquid or gas-heated steam generator tube where the axial heat flux distribution is monotonously decreasing or increasing, a simultaneous solution of equations (1) and (8) is not permitted. A kind of iterative method has to be followed. First the equivalent length has to be solved from equation (8) for a given axial position in a tube and thereafter this equivalent length has to be inserted into equation (1) to determine the dryout heat flux. This procedure has to be repeated until the calculated dryout heat flux equals the heat flux at the axial location under consideration.

For the data of ref. [7], the axial heat flux does not monotonously vary, but has approximately the shape of a step-wise distribution. In fact, the quantity to be determined from these data with the aid of equations (1) and (9) is q_2, the dryout heat flux for the exit test section. For practical applications, all the quantities in these equations are known with the exception of q_2. In such a case, the determination of q_2 with the help of equations (1) and (9) reduces to a simultaneous solution of these equations. This should, however, give large errors in predicting q_2 from the data of ref. [7], as explained below. If L_e is solved from equation (9) and inserted into equation (1), the latter becomes

$$Bo_2 = \frac{a_6 - B_1 L_1/d}{L_2/d + a_7} \quad (10)$$

where

$$a_6 = a_0 a_1 a_2 a_3 a_4 \quad (11)$$

$$a_7 = 28\, Fr^{0.22}. \quad (12)$$

Since for the tests of ref. [7], $Bo_1 \cong B_1$ and $Bo_1 = a_6/(L_1/d + a_7)$ [see equation (1)], the numerator of equation (10) becomes

$$a_6 - B_1 L_1/d \cong Bo_1(L_1/d + a_7) - Bo_1 L_1/d. \quad (13)$$

For the data under consideration, $a_7 \ll Bo_1 L_1/d$. It follows from equation (13) that the determination of the numerator of equation (10) should be quite erroneous due to measurement errors involved in the evaluation of a_6 and B_1. For this reason, the numerator of the equation is replaced with the RHS of equation (13), yielding

$$q_2 = \frac{q_1 a_7}{L_2/d + a_7}. \quad (14)$$

Equation (14) has one interesting feature. If L_2, the heated length of the exit section, is equal to zero, the equation yields q_1 but not zero. This is physically true, i.e. a boundary condition. This equation applies only to the condition that $q_1 > q_2$. For the purpose of the present study this is not an objection since one data of ref. [7] has been disregarded with this connection, as will be explained in that following hereon.

Verification of equations (14) and (1) with the data of ref. [7] taken for non-uniform heating yields the following results:

- For the condition, $0.88 \leqslant Q_1/q_2 \leqslant 1.15$, equation (1) is sufficient to predict the dryout heat flux from the data, provided that $L_e = L_1 + L_2$. This means that for the aforesaid condition, a uniform heat flux approximation yields a satisfactory result. For the 33 data analyzed, equation (1) predicts the dryout heat flux from the data accurate to 16.3% with a RMS error of 8.1%, as can be deduced from Fig. 2.
- For $1.15 < Q_1/q_2 \leqslant 1.80$ and for the 64 data considered, equation (14) predicts the dryout heat flux from the data accurate to 20% (with three exceptions). The RMS error for these 64 data is 11%, as can be deduced from Fig. 2.
- Six data of ref. [7] were taken for the condition, $1.92 \leqslant Q_1/q_2 \leqslant 2.68$. Equation (14) failed to predict accurately the dryout heat flux from these data, i.e. the errors varied between 30.1 and 80.4%. It is most logical to assume that equation (14) does not apply to this condition. However, the data taken at conditions identical to these six data fitted the correlation well. This and the aforesaid RMS error imply that these six data were taken probably either under non-stationary conditions or in the presence of dryout at the end of the main test section. If dryout occurred there, then the liquid layer attached to the wall of the exit test section should have been periodically disturbed. The behaviour of this layer is of vital significance for dryout [1] and equation (14) is invalid for such a condition.

SUMMARY AND CONCLUSIONS

A dryout correlation has been established for R12 and R113 flowing vertically upwards in uniformly heated circular tubes.

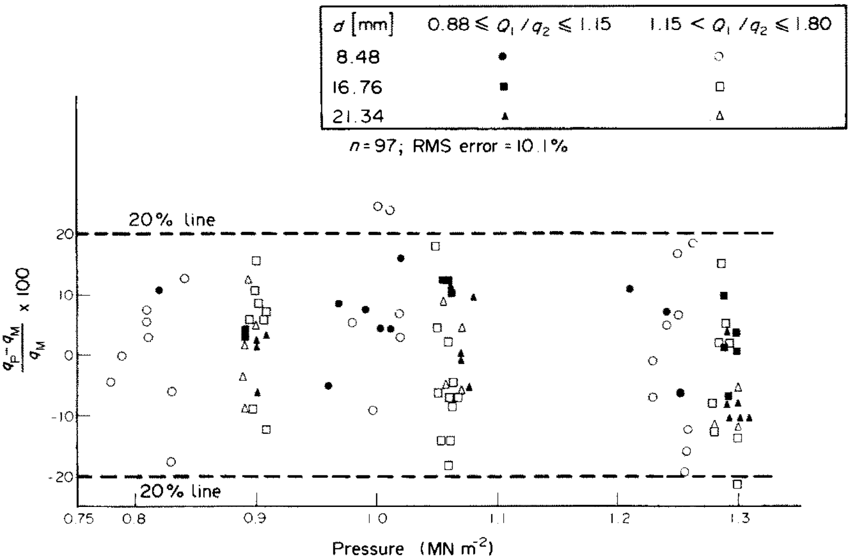

FIG. 2. Errors in predicting dryout heat flux from data of ref. [7] for non-uniform heating.

The ranges of geometries and operating conditions for the 891 data considered are as follows: L/d = 28–338; d = 3.15–21.34 mm; L = 0.126–3.7 m; P = 0.11–1.3 MN m^{-2}; G = 203–4068 kg m^{-2} s^{-1}; ΔH = −0.01–74 kJ kg^{-1}; q = 35–333 kW m^{-2}. The correlation predicts the dryout heat flux from these data accurate to 25% for 98% the time. The RMS error for all the 891 data under consideration is 12%.

For an axial step-wise heat flux distribution and a heat flux ratio varying from 0.88 to 1.15, the correlation presented predicts the dryout heat flux within 16.3% accuracy with a RMS error of 8.1% from the 33 data taken for R12 flowing vertically upwards in circular tubes, i.e. for the quoted conditions, a uniform heat flux approximation yields a satisfactory result. For a heat flux ratio between 1.15 and 1.80 and on the basis of the equivalent length hypothesis, the accuracy of the correlation is within 20% with a RMS error of 11% for the 64 data considered. The ranges of geometries and operating conditions for the non-uniform heating data considered are: L/d = 184–366; d = 8.48–21.34 mm; L = 3.10–3.93 m; P = 0.78–1.31 MN m^{-2}; G = 382–2780 kg m^{-2} s^{-1} and ΔH = −0.3–40.4 kJ kg^{-1}. The number of data under consideration is 97.

—Dryout in non-uniformly heated tubes is probably not a local phenomenon.
—Further verification of the work presented is recommended.

Acknowledgement—Thanks are due to Professor J. Claus for his permission to publish this work and to H. van der Ree and D. J. van der Heeden for their comments.

REFERENCES

1. Y. Y. Hsu and R. W. Graham, *Transport Processes in Boiling and Two-Phase Flow Systems*, pp. 290–330. McGraw-Hill, New York (1976).
2. A. E. Bergles, Burnout in boiling heat transfer, Part III: High quality forced-convection systems, *Nucl. Safety* **20**, 676–687 (1979).
3. G. F. Stevens, D. G. Elliott and R. W. Wood, An experimental investigation into forced convection burn-out in Freon, with reference to burn-out in water. Uniformly heated round tubes with vertical up flow, AEEW-R321 (1964).
4. D. C. Groeneveld, Freon dryout correlations and their applicability to water, AECL-3418 (1969).
5. M. Merilo and S. Y. Ahmad, The effect of diameter on vertical and horizontal flow boiling crisis in a tube cooled by Freon-12, AECL-6485 (1979).
6. J. R. Stevens and D. N. Miles, Boiling crisis data for vertical upflow of Freon-12 in round tubes and annuli, AAEC/E506 (1980).
7. W. J. Green and J. R. Stevens, An investigation of critical heat fluxes in vertical tubes internally cooled by Freon-12. Part I: Critical heat flux experiments with axially uniform and non-uniform heating and comparisons of data with selected correlations, AAEC/E517 (1981).
8. G. M. Lazarek and S. H. Black, Evaporative heat transfer, pressure drop and critical heat flux in a small vertical tube with R-113, *Int. J. Heat Mass Transfer* **25**, 945–960 (1982).
9. Y. Katto and S. Ashida, CHF in high-pressure regime for forced convection boiling in uniformly heated vertical tubes of low length to diameter ratio, in *Heat Transfer* 1982 (edited by U. Grigull, E. Hahne, K. Stephan and J. Straub), Vol. 4, pp. 291–296. Hemisphere, Washington (1982).
10. W. J. Green and K. R. Lawther, A flow boiling burnout correlation for water and Freon-12, *Nucl. Engng. Des.* **67**, 13–25 (1981).
11. M. M. Shah, A generalized graphical method for predicting CHF in uniformly heated vertical tubes, *Int. J. Heat Mass Transfer* **22**, 557–568 (1979).
12. H. C. Ünal, M. L. G. van Gasselt and P. M. van't Verlaat, Dryout and two-phase flow pressure drop in sodium heated helically coiled steam generator tubes at elevated pressures, *Int. J. Heat Mass Transfer* **24**, 285–298 (1981).
13. K. M. Becker, Burnout conditions for round tubes at elevated pressures, paper presented at the International Symposium on Two-Phase Flow Systems, Technion City, Haifa, Israel (1971).
14. Thermodynamic and physical properties, R-12, Institut International Du Froid, Paris (1982).
15. Thermodynamic and physical properties, R-113, Institut International Du Froid, Paris (1982).
16. W. Scholten, Die dynamische Zähigkeit von Frigen-Kältemitteln, *Die Kälte und Klimatechnik* **35**, 226–228 (1982).