Pergamon

Int. J. Heat Mass Transfer. Vol. 40, No. 12, pp. 2879–2885, 1997

0017–9310/97 $17.00+0.00

PII: S0017-9310(96)00345-6

Experimental evaluation of the onset of subcooled flow boiling at high liquid velocity and subcooling

GIAN PIERO CELATA, MAURIZIO CUMO and ANDREA MARIANI
ENEA—Energy Department, Via Anguillarese 301, 00060 S.M. di Galeria, Roma, Italy

(*Received* 5 *February* 1996 *and in final form* 11 *September* 1996)

Abstract—The knowledge of the onset of subcooled boiling in water forced convective flow at high liquid velocity and subcooling is of importance in thermal hydraulic studies of high heat flux components in fusion reactors. The present paper reports the results of an experimental research on the onset of subcooled boiling in water forced convective flow. From the measurement of the pressure drop along the heated test channel ($D = 8$ mm, $L = 100$ mm) it is possible to evaluate the heat flux at which the subcooled boiling occurs. As far as the coolant is in single-phase flow, it is possible to simply calculate its pressure drop, also taking into account the temperature effect on the friction factor, for the temperature variation along the heated channel and in the cross section (due to the steep thermal gradients). The classical corrections available in the literature have been used. Once bubble formation is established, the additional, significant contribution of the bubbles presence to the pressure drop leads to a deviation of the experimental pressure drop curve from the single-phase theoretical line. This latter identifies the onset of subcooled boiling. A comparison of the experimental heat flux at the subcooled boiling incipience with that provided by the major correlations available in the literature is given. A further comparison with measurements performed with an accelerometer device is provided in the paper. The accelerometer detects the additional noise due to bubbles formation close to the heated wall and subsequent collapse in the subcooled bulk of the liquid. The results given by the accelerometer and those obtained with the present evaluation method are in close agreement. © 1997 Elsevier Science Ltd.

INTRODUCTION

A knowledge of the subcooled flow boiling curve, including the onset of subcooled boiling, is essential in the thermal hydraulic design of fusion reactor components, as well as in other engineering applications, such as high-power synchrotron and optical components and advanced electronic components. Such examples are characterized as high heat flux applications, up to 30–40 MW m^{-2} in the case of plasma facing components of fusion reactors, and water subcooled flow boiling proved to be able to accommodate such high heat fluxes provided that high coolant velocity (up to 10–15 m s^{-1}) and subcooling (up to 200 K) can be guaranteed [1].

Water subcooled flow boiling was extensively studied in the past with reference to thermal hydraulics of light water reactor cores [2–4]. Information is, therefore, limited to low heat flux conditions, i.e. around 1 MW m^{-2}, which may be achieved using water at low velocity (about 1 m s^{-1}) and low subcooling (as low as 30 K).

Subcooled flow boiling for high heat flux applications was recently studied by Boyd [5–7] to overcome the many uncertainties and inaccuracies still existing in this region. Concerning the onset of subcooled flow boiling, most of the existing work in the literature is devoted to low heat flux levels [8–19] and only very recently Yin *et al.* presented a preliminary investigation on highly subcooled flow boiling for cooling of high heat flux components in fusion reactors [20]. Also Vandervort *et al.* [21] tackled the problem of determining the onset of water subcooled flow boiling at high liquid velocity and subcooling.

The present work reports an experimental research for the determination of the onset of water subcooled flow boiling at high liquid velocity (up to 10 m s^{-1}) and subcooling (up to 190 K), based on the single-phase pressure drop measurement in the heated channel and its theoretical calculation. The method is checked against available correlations and against some tests performed using an accelerometer which detects the additional noise due to the bubbles formation close to the heated wall and subsequent collapse in the liquid subcooled bulk [22].

EXPERIMENTAL APPARATUS AND TEST SECTIONS

The schematic diagram of the employed water loop is drawn in Fig. 1. The loop is made of Type 304 stainless steel and filled with tap water passed through deionizing particulate beds (not shown in the figure). The alternative pump (a three-head piston pump), the maximum volumetric flow rate of which is 2000 l h^{-1}, is connected to a damper to further reduce pressure

NOMENCLATURE

D	channel diameter [m]
f	friction factor
L_a	entrance length [m]
p	pressure [MPa]
q''	heat flux [MW m^{-2}]
T	temperature [°C]
u	velocity [m s^{-1}].

Greek symbols

Δp	pressure difference [MPa]
Δt	temperature difference [K]
γ	subcooled boiling location, measured from inlet as a fraction of the total length
μ	viscosity [kg m^{-1} s^{-1}].

Subscripts

b	pertains to liquid bulk
cal	calculated value
ex	exit conditions
exp	experimental value
f	pertains to the liquid base
in	inlet conditions
ONB	onset of nucleate boiling conditions
sat	saturation conditions
sub	subcooling conditions
w	pertains to the wall.

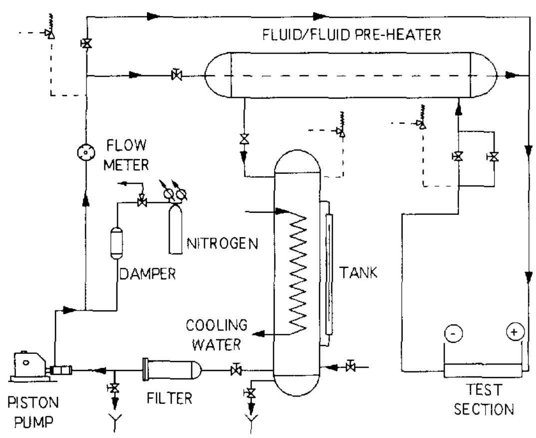

Fig. 1. Schematic of the experimental facility.

oscillations while maintaining stable flow conditions (residual pulsation 2.5%). A turbine flow meter (maximum error 0.5%) is installed to measure the water flow rate. The test section is horizontal and is made of Type 304 stainless steel (electric resistivity at 500 K is equal to 93 $\mu\Omega$ cm), 8.0 ± 0.01 mm inner diameter, 0.25 mm in wall thickness, uniformly heated by Joule effect over a length of 0.1 m, using a 90 kW (50 V and 1800 A, dc) electric feeder. The test section is connected to copper feed clamps, by means of which it is possible to transfer the electric current to the tube. The power was computed by evaluating the product of the voltage drop across the test section and the current flowing through the walls of the test section. The current was computed from the measurement of the voltage drop (in millivolts) across a precision shunt resistor. Before entering the test section, the water flows through an unheated tube, of the same diameter as the test section, to assure that the liquid velocity profile is fully developed. The unheated tube length is twice the entrance length, L_a, calculated, under the most severe conditions (highest value of Reynolds number), using [23]:

$$\frac{L_a}{D} = 0.008\, Re^{0.685}. \quad (1)$$

Pressure taps are placed just in the middle of the copper clamps. The static pressure is measured by unsealed strain-gauge absolute pressure transducers, (maximum error 0.5%), while the pressure drop is measured using a differential pressure transducer (maximum $\Delta p = 0.07$ MPa, maximum error 0.25%). The pressure at the exit of the test channel is regulated by an electrically controlled valve. The bulk fluid temperature is measured just upstream, $T_{f,in}$, and downstream, $T_{f,ex}$, of the test section using 0.5 mm K-type thermocouples placed at the center of the channel. The exit fluid temperature, $T_{f,ex}$, is measured after a mixing of the fluid, obtained with a cross mixer. This allow to make the vapour condensing in the subcooled liquid bulk and to get the temperature profile flat and, consequently, to obtain the accurate measurement of the average exit temperature, and therefore of the heat balance. This method is in a good agreement with the thermal power measurement ($\pm 5\%$). The knowledge of $T_{f,in}$ and $T_{f,ex}$ together with the measurement of the water mass flow rate, allows the computation of the thermal power delivered to the fluid by the heat balance in the coolant (calorimetric method). In fact, in all the tests performed the outlet bulk fluid temperature measurements always revealed the subcooling conditions of the water bulk at the test section exit. In this way the heat loss computation from the test section is bypassed. The employed test sections are not instrumented with wall thermocouples.

Downstream of the test section, the fluid passes through the fluid-to-fluid pre-heater and then in the water cooled tank, where the fluid is cooled down to 25°C even at the maximum thermal power delivered to the fluid, closing the loop through the filter, towards the piston pump. The maximum pressure of the loop is 7.0 MPa, while the maximum operating temperature of the pump is 70°C. The fluid-to-fluid pre-heater

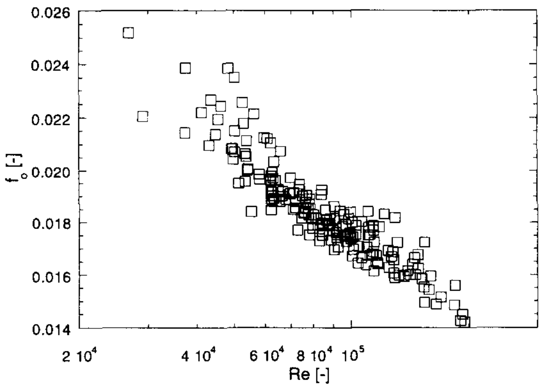

Fig. 2. Friction factor vs Reynolds for all the cold tests.

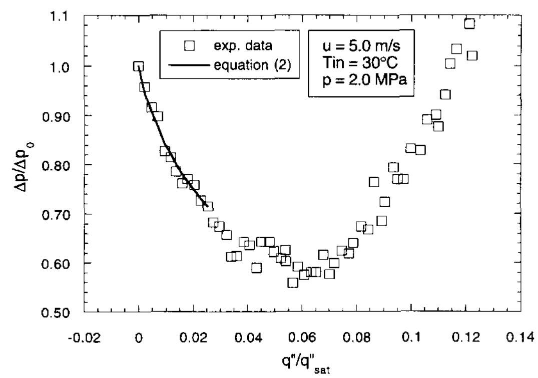

Fig. 3. Typical measured-to-adiabatic pressure drop ratio vs the measured-to-saturation heat flux ratio.

allows to carry out experiments with a water inlet temperature above 70°C.

TEST PROCEDURE AND TEST MATRIX

The test procedure is as follows. For each test a measurement of the pressure drop with cold water is accomplished to get the friction factor of the test channel. After that, the inlet temperature is fixed at the test value and the pressure drop is measured to have the friction factor at the inlet temperature. Once the exit pressure is set, the heat flux is delivered to the test channel with an increase of about 0.2 MW m^{-2} for each step, up to a value for which the subcooled flow boiling regime is certainly reached along the whole test channel. After each heat flux increase and possible adjustments of exit pressure, inlet mass flow rate and temperature, data acquisition is accomplished under steady-state conditions. Once the electric power has been turned off and the test is over, the initial procedure is repeated to verify friction factors before and after the test. After each test, the test section is cleaned because of surface oxidation in order to allow the repeatability of the tests.

Friction factors calculated from pressure drop measurements for all the runs are plotted in Fig. 2 vs the Reynolds number. As all data points lie close to a single curve, the tube hydraulic behaviour may be considered as constant through all the tests.

Test conditions are as follows:

water velocity	from 5 to 10 m s^{-1}
exit pressure	from 1.0 to 2.5 MPa
inlet temperature	30 and 60°C
inlet subcooling	from 120 to 194 K.

EXPERIMENTAL RESULTS AND DATA ANALYSIS

General features

A typical plot of the measured pressure drop as a function of the heat flux is shown in Fig. 3. In particular, it is plotted the ratio between the actual pressure drop (for the given heat flux) and that measured under adiabatic conditions at the same inlet temperature, versus the ratio between the heat flux, q'' and the heat flux necessary to bring the liquid to saturated conditions at the exit pressure, q''_{sat} (theoretical value). The trend is in close agreement with previous findings [21, 24–26]. For increasing heat flux, in the single-phase region, a reduction in the pressure drop is observed, due to the steep near-wall temperature gradient and consequent lower near-wall viscosity. Such a reduction is proportional to the partial derivative of the viscosity with respect to the temperature. This quantity decreases for increasing temperature. Therefore, for increased bulk temperature (i.e. for increased heat flux), the pressure drop ratio will decline less for the same increment in heat flux, as exhibited by the data of Fig. 3.

As also noted by Vandervort *et al.* [21], "the location of the minimum of the curve plotted in Fig. 3 does not necessarily coincide with the initial wall nucleation (near the tube exit), but represents a trade-off between reduced single-phase diabatic pressure gradient through the afore-mentioned viscosity effect, and the increasing acceleration and two-phase friction pressure drop that coincides with the generation of vapour along the tube wall." Once subcooled boiling starts, the pressure drop ratio increases with increasing heat flux due to vapour formation and increased void fraction.

A good prediction of the single-phase diabatic pressure drop is obtained using a wall-to-the bulk viscosity correction, as suggested by Kays and Crawford [27]:

$$\frac{f}{f_o} = \left(\frac{\mu_w}{\mu_b}\right)^{0.25} \qquad (2)$$

where f_o is the isothermal friction factor (determined experimentally for each test as reported in the test procedure), μ_w is the viscosity calculated at the wall temperature and μ_b is the viscosity at the liquid bulk temperature. This is, of course, a simplification of the complex relationship between friction factor and the near-wall temperature gradient, but it may be sufficient for engineering purposes. Using equation

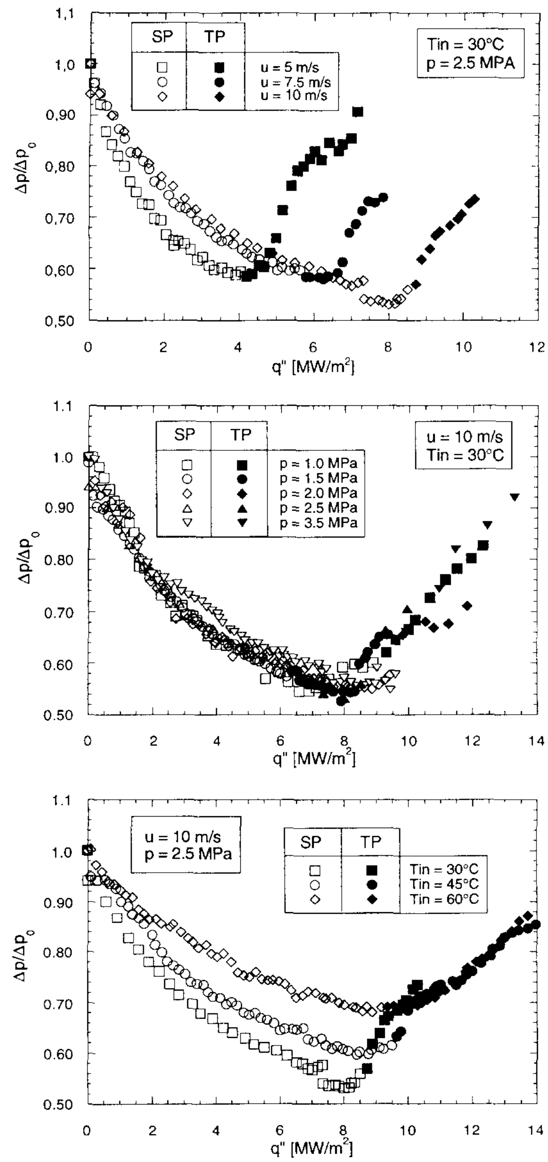

Fig. 4. Diabatic-to-adiabatic pressure drop ratio vs heat flux, as a function of the liquid velocity (top graph), pressure (center graph) and inlet temperature (bottom graph).

(2) has shown a very close agreement with present single-phase data, confirming the goodness of the power 0.25.

Parametric trends of pressure drop data

Figure 4 shows the trend of the ratio between the diabatic and the adiabatic pressure drop versus the heat flux, as a function of the liquid velocity (top graph), the pressure (middle graph), and the inlet temperature (bottom graph), the other two parameters being constant for each graph. Black symbols refer to the situation after the onset of subcooled boiling, while the empty ones refer to single-phase flow in the whole channel. The method for the determination of the onset of nucleate boiling will be given in the next chapter.

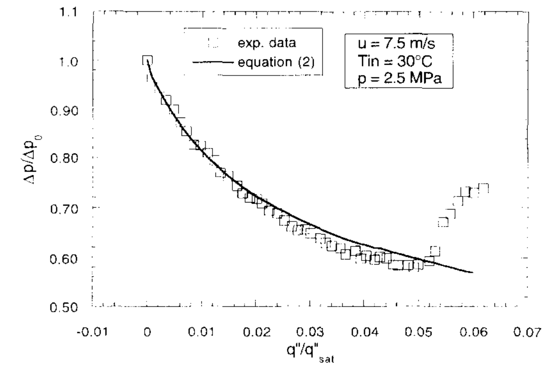

Fig. 5. Diabatic-to-adiabatic pressure drop ratio vs measured-to-saturation heat flux; experimental data and single-phase pressure drop calculation curve.

Although the onset of subcooled boiling is not strictly linked to the minimum of the curve, it is obvious that the incipient boiling heat flux is higher if the minimum of the curves plotted in Fig. 4 is shifted towards the right of the graph. Under this consideration, the following observations may be derived from Fig. 4:

(1) The higher the velocity the higher the incipient boiling heat flux, while the pressure drop trend does not show significant variations.
(2) Practically no influence of the pressure is observed.
(3) The influence of the inlet temperature (i.e. the inlet subcooling) on the incipient boiling heat flux is detectable but not dramatic. On the contrary, the slope of the pressure drop curve is sensibly affected by the inlet subcooling: the lower the subcooling the lower the curve slope. As mentioned in the first part of this chapter, the slope of the curve is linked to the partial derivative of the viscosity with respect to the temperature, which, in turn, decreases for increasing temperature. Therefore, the slope of the pressure drop curve is directly proportional to the inlet subcooling.

Determination of the onset of nucleate boiling (ONB) in subcooled flow boiling

First of all, it is necessary to clarify what we mean using the term ONB, as this term has been widely used in the past with different meanings. An excellent definition of the term is given in ref. [19], together with a review of nine different definitions of the onset of boiling in forced convection identified in the literature. Let us refer to Fig. 5, where the pressure drop ratio is plotted versus the heat flux (referred to the saturation heat flux), together with the theoretical pressure drop for single-phase flow calculated as described above. We consider as the ONB, the point at which the theoretical curve detaches from the experimental curve. Under the considerations reported in the previous two sections, it is clear how the above point could be considered as the subcooled boiling incipience. In fact, the deviation of the experimental

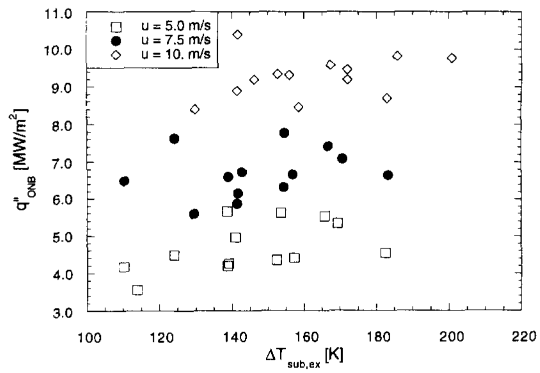

Fig. 6. Experimental incipient subcooled boiling heat flux vs exit subcooling, as a function of water velocity.

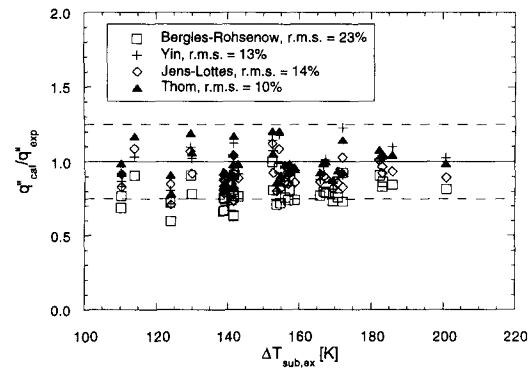

Fig. 8. Calculated-to-experimental incipient boiling heat flux vs exit subcooling; predictions obtained using Bergles–Rohsenow [16], Yin [17], Jens-Lottes [14] and Thom [15] correlations.

pressure drop curve from the theoretical curve is due to the bubble formation in the near wall region. This is not found, generally, in the minimum of the experimental curve. Due to experimental uncertainty it may happen on the left- or right-hand side of the minimum in the experimental pressure drop curve. From graphs as that reported in Fig. 5, it is possible to graphically obtain unambiguously the value of the heat flux at the ONB.

ONB experimental data

The values of the heat flux at the onset of subcooled boiling, q''_{ONB}, are reported in Fig. 6 vs the exit subcooling, for three different water velocities. As it can be observed, the incipient boiling heat flux is an increasing function of both the water subcooling and velocity.

The influence of water subcooling on q''_{ONB}, is less dramatic and may be estimated, roughly, in about 0.02 MW $\mathrm{m}^{-2}\ \mathrm{K}^{-1}$. It is practically linear and independent on water velocity (the slope of the three series of data at different velocities is almost the same). The latter shows a great influence on the incipient boiling heat flux, which increases as the water velocity increases showing almost a factor of two passing from 5 to 10 m s^{-1}. The influence of the pressure, as shown in Fig. 7, is not unambiguously determined, even though its effect, as a first approximation, may be considered negligible in comparison with the other parameters and other conditions being equal.

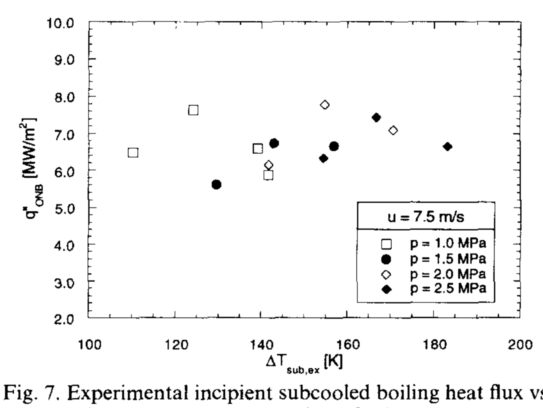

Fig. 7. Experimental incipient subcooled boiling heat flux vs exit subcooling, as a function of exit pressure.

Comparison with available correlations

Among the many correlations available in the literature, some of them gave poor predictions [9–13, 28–29]. This is of course due to the fact that all of them are recommended for thermal hydraulic conditions very far from present ones. Few of the available correlations [15–18] provided a reasonable good agreement with experimental data, and are reported here:

Jens-Lottes [15]

$$\Delta T_{\mathrm{sat}} = 25(q'')^{0.25}\exp\left(-\frac{p}{62}\right) \tag{3}$$

with p [bar], ΔT_{sat} [K] and q'' [MW m^{-2}].

Thom [16]

$$\Delta T_{\mathrm{sat}} = 22.65(q'')^{0.5}\exp\left(-\frac{p}{87}\right) \tag{4}$$

with p [bar], ΔT_{sat} [K] and q'' [MW m^{-2}].

Bergles–Rohsenow [17]

$$\Delta T_{\mathrm{sat}} = 0.555\left(\frac{q''}{1082\,p^{1.156}}\right)^{p^{0.0234}/2.16} \tag{5}$$

with p [bar], ΔT_{sat} [K], q'' [W m^{-2}].

Yin [18]

$$\Delta T_{\mathrm{sat}} = 7.195\,q''p^{1.82}\gamma^{-0.072} \tag{6}$$

with p [bar], ΔT_{sat} [K] and q'' [W m^{-2}]. The parameter γ is the subcooled boiling location, measured from inlet as a fraction of total heated length, in our case equal to unity.

The comparison between prediction given by the above correlations and experimental data are reported in Fig. 8, where the ratio between the calculated and the experimental incipient boiling heat flux is plotted vs exit subcooling. Apart from the Bergles–Rohsenow correlation, which shows a systematic underprediction of data points, the other three correlations provide

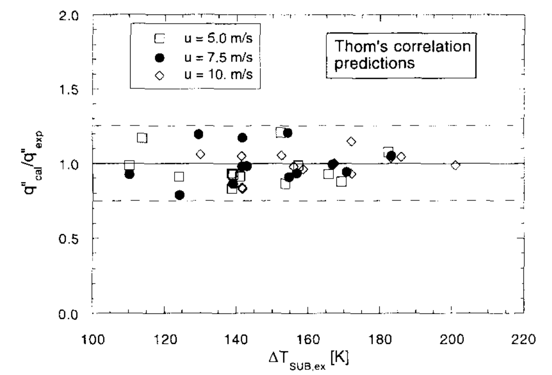

Fig. 9. Predictions of the incipient boiling heat flux vs exit subcooling, as a function of water velocity, obtaining using the Thom correlation [15].

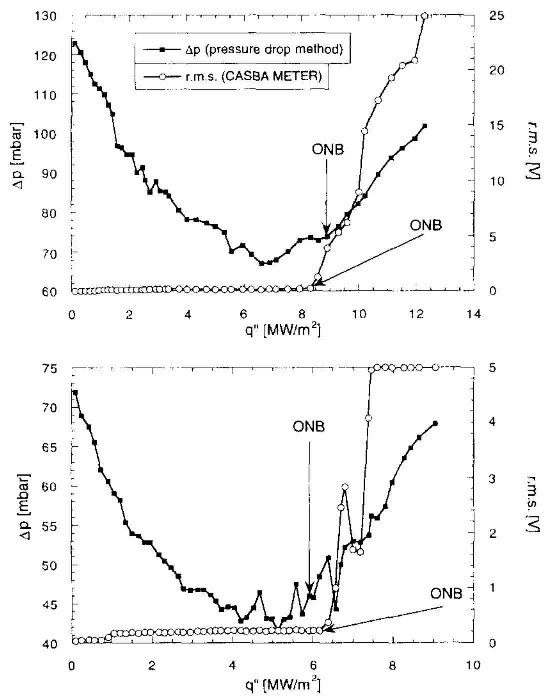

Fig. 10. Predictions of the ONB obtained using the accelerometric device (CASBA meter); comparison with the pressure drop method.

a similar good prediction of experimental data. In absolute terms, the best prediction is given by Thom's correlation, which is characterized by an r.m.s. error as low as about 10%, with all experimental data predicted within $\pm 22\%$. Predictions obtained by Thom's correlation do not show any systematic effect as a function of exit subcooling and water velocity and exhibit a perfectly symmetric distribution between overpredictions and underpredictions (Fig. 9).

Comparison with an accelerometric device

A check of the experimental data was obtained using an accelerometric device, patented by ENEA and named CASBA meter, already successfully qualified [22]. Referring the reader to [22] for full details, the principle of the accelerometric device is based on the process of nucleation, growth and collapse of the vapour bubbles when the local wall temperature, exceeding the fluid saturation temperature, is able to sustain subcooled boiling in the near-wall region. Under these conditions, bubbles may nucleate reaching the low temperature bulk fluid region where collapsing occurs in the form of condensation shocks. The shocks produce vibrations, exciting an accelerometer screwed on a flange bolt at the exit of the channel. At the beginning, when bubbles start growing and collapsing, the noise emission is clearly evident in terms of the ratio of signals to the pedestal and for the typical range of ultrasonic frequencies involved.

Figure 10 reports the results obtained with the accelerometric device compared with the pressure drop experimental method described above. As it can be observed, the signal coming from the CASBA meter, i.e. the effective value given by pressure peaks due to bubble implosions (r.m.s.), sharply increases for a given power, indicating the onset of nucleate boiling. In the same plots, the curve obtained with the above described pressure drop method is also reported as a function of the power. The ONB condition is reported for both methods. It is observed the close agreement between the results obtained with the CASBA meter and those obtained with the proposed method.

CONCLUDING REMARKS

An analysis of the onset of nucleate boiling at high liquid velocity (up to 10 m s^{-1}) and high liquid subcooling (up to 195 K) has been performed using water in a horizontal uniformly heated channel ($D = 8$ mm, $L = 100$ mm). Through the measurement of the pressure drop along the channel the incipient subcooled boiling heat flux has been determined. The evaluation is based on the single-phase pressure drop calculated accounting for physical properties variations along the channel and in the cross-section (because of the steep thermal gradient along the radius). Identification of the ONB is obtained by the deviation between the pressure drop experimental trend versus the heat flux from the theoretical single-phase pressure drop calculation curve. Such a deviation is due to the significant contribution to the pressure drop along the channel given by the bubbles presence in the near-wall region.

Results obtained by the above method are quite in good agreement with Thom's correlation. Also, reasonable predictions are provided by Jens-Lottes and Yin correlations. Results obtained with the pressure drop method are also in very agreement with those obtained using an accelerometric device (CASBA meter). As far as parametric trends of the ONB heat flux are concerned we observed:

- the incipient boiling heat flux is directly dependent on the liquid velocity;
- the influence of the pressure may be considered negligible;

• the ONB heat flux increases as the subcooling increases; the latter also directly affects the single-phase pressure drop curve slope.

Acknowledgements—Authors wish to thank Mr A. Bigioni and Mr M. Morlacca for assembling the test facility and the execution of the experiments. Thanks are also due to Mrs A. M. Moroni for the editing of the paper.

REFERENCES

1. Celata, G. P., Recent achievements in the thermal hydraulics of high heat flux components in fusion reactors. *Experimental Thermal and Fluid Science*, 1993, **7**(4) 263–278.
2. Bergles, A. E., Collier, J. G., Delhaye, J. M., Hewitt, G. F. and Mayinger, F., *Two-Phase Flow and Heat Transfer in the Power and Process Industries*. Hemisphere Publishing Corporation, New York, 1981, pp. 226–255.
3. Collier, J. G., *Convective Boiling and Condensation*. McGraw-Hill, New York, 1981, pp. 144–177.
4. Hsu, Y. Y. and Graham, R. W., *Transport Processes in Boiling and Two-Phase Systems*. American Nuclear Society, 1986, pp. 217–232.
5. Boyd, R. D. and Meng, X., Local heat transfer for subcooled flow boiling with water. *Fusion Technology*, 1992, **22,** 501–510.
6. Boyd, R. D., Local subcooled flow boiling assessment and development. *Proceedings of the 3rd Specialists' Workshop on High Heat Flux Component Cooling*, Cadarache, 22–24 September, 1993.
7. Boyd, R. D. and Meng, X., Boiling curve correlation for subcooled flow boiling. *International Journal of Heat and Mass Transfer*, 1995, **38**(4) 758–760.
8. Yin, S. T. and Abdelmessih, A. H., Prediction of incipient flow boiling from a uniformly heated surface. *AIChE Symposium Series*, 1976, **73**(164) 236–243.
9. Hsu, Y. Y., On the size range of active nucleation cavities on a heating surface. *Journal of Heat Transfer*, 1962, **84,** 207–216.
10 Hsu, Y. Y. and Graham, R. W., An analytical and experimental study of the thermal boundary layer and ebullition cycle in nucleate boiling. NASA TN-D-594, 1961.
11. Sato, T. and Matsumura, H., On the conditions of incipient subcooled-boiling and forced-convection. *Bulletin of JSME*, 1964, **7**(36) 392–398.
12. Davis, E. J. and Anderson, G. H., The incipience of nucleate boiling in forced convection flow. *AIChE Journal*, 1966, **12,** 774–780.
13. Shah, M. M., A general correlation for heat transfer during subcooled boiling in pipes and annuli. *ASHRAE Transactions*, 1970, **83,** 202–215.
14. Saha, P. and Zuber, N., Point of net vapour generation and vapour void fraction in subcooled boiling. *Proceedings of the 5th International Heat Transfer Conference*, Vol. 4, 1974.
15. Jens, W. H. and Lottes, P. A., Analysis of heat transfer, burnout, pressure drop and density data for high pressure water, ANL-4627, 1951.
16. Thom, J. R. S., Walker, W. M., Fallon, T. A. and Reising, G. F. S., Boiling in subcooled water during flow up heated tubes or annuli. *Symposium on Boiling Heat Transfer in Steam Generating Units and Heat Exchangers*, Manchester, 15–16 September 1965. IMechE, London, 1965.
17. Bergles, A. E. and Rohsenow, W. M., The determination of forced-convection surface-boiling heat transfer. *Journal of Heat Transfer*, 1964, **86,** 365–372.
18. Yin, S. T., Up-date on heat transfer package for high heat flux components cooling. *Proceedings of the 3rd Specialists' Workshop on High Heat Flux Components Thermal-Hydraulics*, Cadarache, September 22–24, 1993.
19. Zyatnina, O. A., Ivashkevich, A. A. and Mitrofanova, T. V., Analytical determination of the onset of nucleate boiling of subcooled water in pipes. *Heat Transfer—Soviet Research*, 1989, **21**(6) 742–752.
20. Yin, S. T., Jin, Z., Abdelmessih, A. H. and Gierszewski, P. J., Prediction of highly subcooled flow boiling for cooling of high heat flux components in fusion reactors. *Proceedings of the 3rd Specialists' Workshop on High Heat Flux Components Thermal-Hydraulics*, Cadarache, September, 22–24, 1993.
21. Vandervort, C. L., Bergles, A. E. and Jensen, M. K., An experimental study of critical heat flux in very high heat flux subcooled boiling. *International Journal of Heat and Mass Transfer*, 1994, **37,** (Supl. 1) 161–173.
22. Celata, G. P., Dell'Orco, G. and Gaspari, G. P., Detection of subcooled boiling heat transfer regimes up to critical heat flux by accelerometric equipment. *Fusion Engineering and Design*, 1994, **28,** 44–52.
23. Cumo, M., Farello, G. E. and Pinchera, G. C., Determinazioni sperimentali della lunghezza di assetto fluidodinamico in Canali a sezione circolare. *20th National Conference ATI*, Genova, 1965 (in Italian).
24. Inasaka, F., Nariai, H. and Shimura, T., Pressure drops in subcooled flow boiling in narrow tubes. *Heat Transfer—Japanese Research*, 1989, **18**(1) 70–75.
25. Boyd, R. D., Subcooled water flow boiling experiments under uniform high heat flux conditions. *Fusion Technology*, 1988, **13,** 131–142.
26. Tong, W., Bergles A. E. and Jensen, M. K., Pressure drop with highly subcooled flow boiling in small diameter tubes. *Proceedings of the International Symposium on Two-Phase Flow Modelling and Experimentation*, Edizioni ETS, Vol. 1, 1995, pp. 617–624.
27. Kays, W. M. and Crawford, M. E., *Convective Heat and Mass Transfer*, 2nd Edn. McGraw-Hill, New York, 1980, Ch. 14, p. 280.
28. Han, C. Y. and Griffith, P., The mechanism of heat transfer in nucleate pool boiling—part I: bubble initiation, growth and departure. *International Journal of Heat and Mass Transfer*, 1965, **8,** 887–964.
29. Murphy, R. W. and Bergles, A. E., Subcooled flow boiling of fluorocarbons—hysteresis and dissolved gas effects on heat transfer. *Proceedings of the 1972 Heat Transfer and Fluid Mechanics Institute*, Stanford University Press, 1972, pp. 400–416.