3. RESULTS AND DISCUSSIONS

The variation of the non-dimensional bulk temperature θ_{B_1} is presented in Fig. 1. It is observed that θ_{B_1} continues to vary beyond the location of $\delta_{t_1} = 1$ for $Pr = 0.1$ and 1.0 corresponding to cases (i) and (ii). The thermal development is delayed till the flow is hydrodynamically developed.

Numerical corroborations are noted in Tables 1(a) and (b). The thermal boundary layers meet at $\xi = 0.0053$ whereas the 99% invariance of θ_{B_1} is attained at $\xi = 0.057$ for $Pr = 0.1$ ($T_w = C$). In case of $Pr = 1.0$, θ_{B_1} attainment is again at $\xi = 0.057$, although the meeting of δ_ts was at $\xi = 0.048$. The corresponding values for the constant heat flux boundary are given in Table 1(b).

Variation of the free stream temperature in the thermal development region are observed for $Pr = 0.1$ and 1.0. Apart from confirming the needed corrections, the γ values are helpful in deciding the useful length of a heating duct. For example, an isothermal duct of $\xi = 0.47$ is not wholly useful for $Pr = 0.1$, whereas the full length is effective for a fluid with $Pr = 10.0$ [Table 1(a)].

As long as the thermal boundary layers meet in the fully developed hydrodynamic zone, as for example when $Pr = 10.0$ (case iii), the boundary layer meeting criterion is synonymous with full thermal development.

In this light the values of thermal entrance lengths as $\xi Pr^{-1} = 0.051$ ($T_w = C$) and 0.069 ($Q_w = C$) reported by Bhatti and Savery [2, 3] stand reviewed for low Prandtl numbers.

The average heat transfer rates for the constant wall temperature computed in the manner

$$\overline{Nu} = \frac{1}{\xi}\int_0^{\xi} Nu_x \, \mathrm{d}x,$$

following Kays [7], are summarized through correlations, within accuracies of ±10%. These are

$$\overline{Nu} = 3.77 + 0.25\xi^{-0.78}Pr^{0.38} \quad \text{for} \quad 0.1 \leqslant Pr \leqslant 3.0, \tag{6}$$

$$\overline{Nu} = 3.77 + 0.25\xi^{-0.78}Pr^{(3\xi/Pr)^{0.2}}, \quad \text{for} \quad 0.65 \leqslant Pr \leqslant 10.0. \tag{7}$$

The correlation given at (6) valid for all gases and water, is particularly simple and affords convenient design calculations.

4. CONCLUSIONS

The salient features of the present study of simultaneous hydrodynamic and thermal developments in a parallel plate channel are (i) the inclusion of the hydrodynamic filled region, and (ii) accounting for variation of the centre-line temperature after the meeting of the thermal boundary layers. The latter is particularly important for low Pr fluids.

Acknowledgements—Support of the CSIR for the work and for a fellowship to one of the authors (Reeta Das) is gratefully acknowledged.

REFERENCES

1. R. Siegel and E. M. Sparrow, Simultaneous development of velocity and temperature distributions in a flat duct with uniform wall heating, *A.I.Ch.E. Jl* **5**, 73–75 (1959).
2. M. S. Bhatti and C. W. Savery, Heat transfer in the entrance region of a straight channel: laminar flow with uniform wall temperature, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **100**, 539–542 (1978).
3. M. S. Bhatti and C. W. Savery, Heat transfer in the entrance region of a straight channel: laminar flow with uniform wall heat flux, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **99**, 142–144 (1977).
4. A. K. Mohanty and S. B. L. Asthana, Laminar flow in the entrance region of a smooth pipe, *J. Fluid Mech.* **90**, 433–447 (1979).
5. A. K. Mohanty and Reeta Das, Laminar flow in the entrance region of a parallel plate channel, *A.I.Ch.E. Jl* **28**, 830–833 (1982).
6. Reeta Das, Momentum and energy transport in duct entrance and in finite rod-bundle assemblies, Ph.D. thesis, Indian Institute of Technology, Kharagpur (1982).
7. W. M. Kays, *Convective Heat and Mass Transfer*, Chapter 8. McGraw-Hill, New York (1975).

Int. J. Heat Mass Transfer. Vol. 26, No. 9, pp. 1405–1408, 1983
Printed in Great Britain

0017-9310/83 $3.00 + 0.00
Pergamon Press Ltd.

VAPOUR BUBBLE FORMATION DURING FAST TRANSIENT BOILING ON A WIRE

K. Derewnicki

Simon Engineering Laboratories, University of Manchester, Manchester M13 9PL, U.K.

(*Received* 26 *June* 1982 *and in revised form* 26 *November* 1982)

1. INTRODUCTION

Transient boiling phenomena have been receiving considerable attention due to their significance to the safety of water-cooled nuclear reactors. A number of researchers have tackled this problem before, and have used a variety of experimental techniques ranging from heating a thin metallic strip by a laser beam [1], to electrically heated foils [2, 3] and wires [4, 5] immersed in water and various organic fluids. Perhaps the most relevant work to that described here is the contribution by Sakurai [6]. The author used a platinum wire heated electrically by exponentially increasing power, thus simulating a step input of reactivity in a nuclear reactor.

The purpose of this study was to investigate the heat transfer mechanisms accompanying rapid heating of a fine platinum wire (0.025 mm in diameter) immersed in sub-cooled water at a range of pressures up to 14 bar and of rates of increase of the heating surface temperature up to 10^7 K s^{-1} [7]. With such rapid heating, especially at elevated pressures, nucleation occurs in a homogeneous rather than heterogeneous manner. The results presented here, however, were obtained from transient boiling tests with relatively low heating rates, i.e. below 10^6 K s^{-1} and at atmospheric pressure. Such rates of heating were found to lead to stable nucleate boiling following a brief period of local and highly unstable film boiling.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The apparatus is shown in Fig. 1. Its primary part is a test heater in the form of a platinum wire 0.025 mm in diameter and

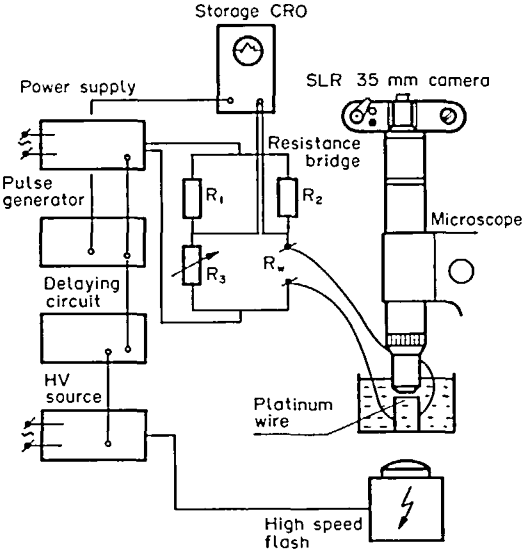

FIG. 1. Schematic diagram of experimental arrangement.

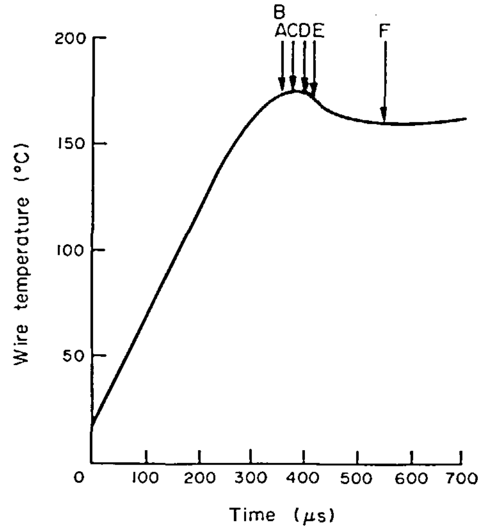

FIG. 2. Wire temperature as a function of time (atmospheric pressure, water temperature 20°C, average rate of heating $\dot{T} = 0.47 \times 10^6$ K s^{-1}, average power input into the wire per unit surface area $q = 34 \times 10^6$ W m^{-2}.

approximately 10 mm long, immersed in pure, demineralized and degassed water at atmospheric pressure and ambient temperature. Before tests, the wire is cleaned first in acetone and then rinsed in clean boiling water. The wire constitutes a part of a resistance bridge circuit, which is fed by a power supply producing a constant voltage pulse. The amplitude and duration of the pulse can be varied.

The elements in the bridge are chosen so that the power input into the wire remains almost constant as its temperature varies between 20 and 300°C, even though the wire resistance changes. The power supply is controlled by a pulse generator which also triggers a storage oscilloscope for recording the output of the bridge. The pulse generator also controls a delaying circuit which controls the triggering of a high speed flash at a required instant of time during the wire heating period.

The flash used is an argon-stabilized electrical discharge device fed from a 10 kV high voltage source and discharging 2 J of energy in less than 1 μs. It should be appreciated that although the resistance bridge used for wire temperature measurements is generally not in balance during the pulse (except for one instant), its response can be calibrated by placing the wire in a fluid at a range of known temperatures and noting the value of R3 required to balance the bridge.

The cumulative error in the transient temperature measurement is estimated at about $\pm 6\%$ owing to stray capacitance and inductance of the bridge, end effects in the wire, as well as inaccuracies in the calibration procedure.

High speed photographs were taken with a standard SLR camera coupled to a laboratory microscope. Various stages of bubble growth were recorded by varying the delay of the flash with respect to the beginning of the heating pulse, but only one exposure during each heating pulse was possible.

3. EXPERIMENTAL RESULTS

An example of experimental results obtained from a typical transient boiling test illustrating the change of the wire temperature with time is shown in Fig. 2. The power input was 34×10^6 W m^{-2} (surface area) which was sufficient to raise the wire temperature before nucleation at an average rate of 0.47×10^6 K s^{-1}. The wire temperature during this period conforms to the theoretical values based on transient conduction to water. There is a certain temperature overshoot immediately following the transient conduction period and from there the temperature falls to what appears to be an equilibrium value. No burn-out will occur if the heating is maintained beyond the period shown in Fig. 2.

The example of experimental results in Fig. 2 has been chosen from a family of traces obtained from tests at a variety of different heating rates. It has to be emphasised that the curves obtained, as well as the photographed stages of boiling, were remarkably reproducible. For higher values of power input, the temperature trace rose more steeply, whilst displaying similar basic features (i.e. fast initial rise, overshoot and then fall to a steady state value), for rates of heating up to 10^6 K s^{-1}.

Photographs of the wire surface taken during the rapid heating-up period reveal no vapour bubbles. The wire surface during this period is in direct contact with superheated liquid. It should be appreciated that for the experimental conditions, the theoretical predictions of the thermal layer thickness give a value of about 2.5 μm after 300 μs (i.e. just before nucleation) which is much smaller than the wire diameter of 25 μm.

The process of nucleation begins from a few isolated active sites on the wire surface from which the bubbles grow and spread rapidly along the wire [Figs. 3(a) and (b)]. The bubbles grow to a considerable size compared to the wire diameter, and in particular the thickness of the thermal layer, at the expense of the energy stored in the superheated layer during the transient heating-up period; shortly after initiation they penetrate well into the cold liquid [Fig. 3(c)] and cover a considerable portion of the wire length.

Figure 3(d) shows the subsequent collapse of this short-lived local form of film boiling. The collapse of large bubbles and growth of much smaller secondary bubbles creates rapid movement of liquid near the wire surface and mixing of cold and hot liquid [Fig. 3(e)]. This mechanism is presumably responsible for cooling the wire from its peak temperature to the steady state value. The subsequent stage is a steady subcooled nucleate boiling with a larger number of nuclei, as shown in Fig. 3(f). The bubbles formed now are much smaller, as there is no possibility of accumulating enough energy to facilitate the growth of large ones, as was the case at the beginning of nucleation.

It is of interest to compare at various time intervals the amount of energy generated during the transient E_{gen} with the amounts of energy transferred into the liquid, E_{tr}, stored in the wire itself, E_{st}, and finally the amount of energy present as visible vapour, E_{vap}. As shown in Fig. 3, the latent energy

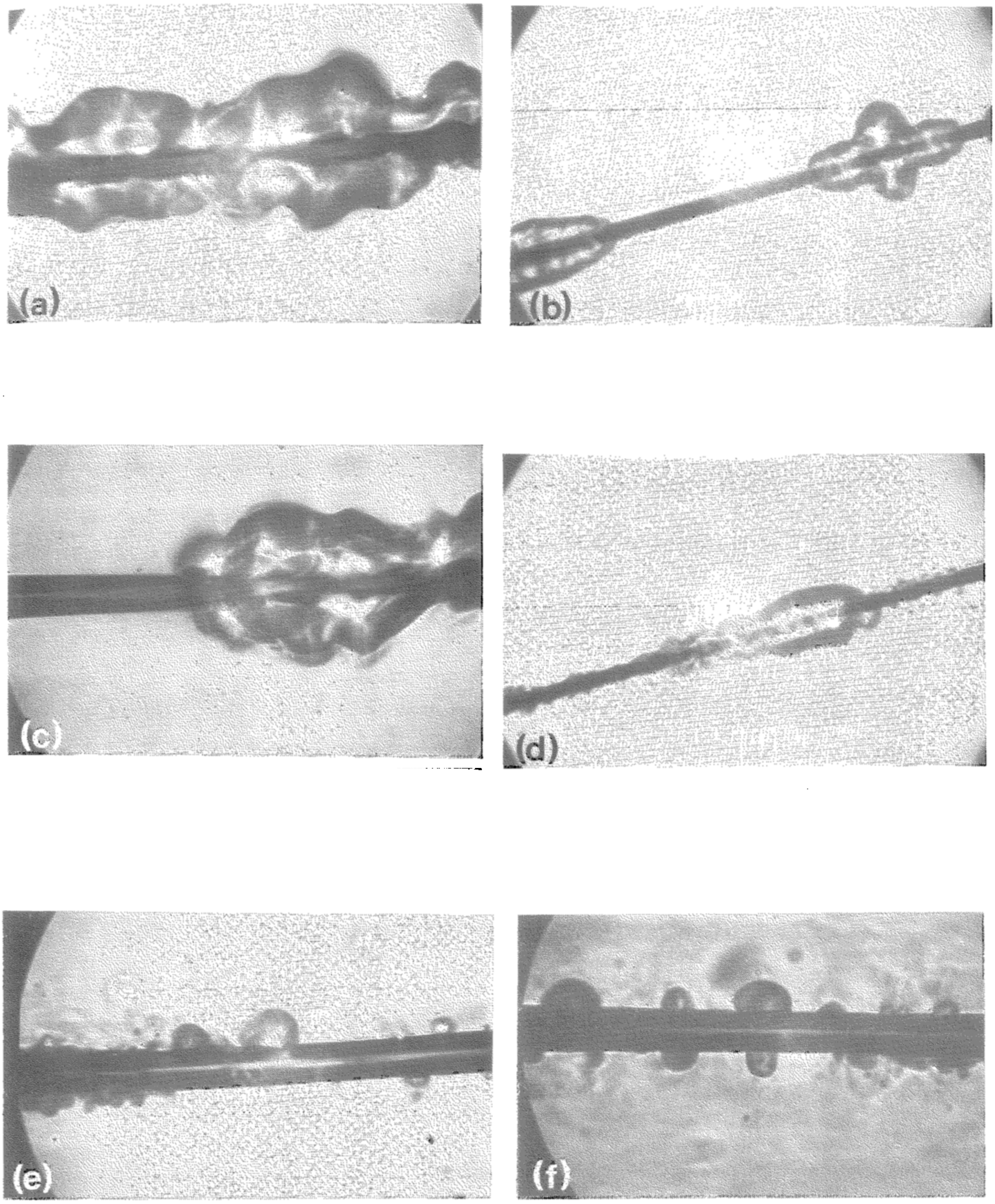

FIG. 3. Development of vapour bubbles on the wire surface (t^*, exposure delay time): (a), (b) $t^* = 350\ \mu s$; (c) $t^* = 370\ \mu s$; (d) $t^* = 380\ \mu s$; (e) $t^* = 410\ \mu s$; and (f) $t^* = 550\ \mu s$.

present in the bubbles is negligible in comparison with the energy transferred by conduction and convection into the liquid, E_{tr}.

The graph also shows the amount of heat generated $\dot{Q}'_{gen}$ and transferred into the liquid $\dot{Q}'_{tr}$ per unit time and per 1 cm of the wire length.

The interesting conclusion from the observations is that a state of stable sub-cooled nucleate boiling on a wire followed a brief stage of highly unstable film boiling covering a considerable portion of the wire length. An incoherent collapse of isolated regions of film boiling improves the heat transfer from the wire, reduces its temperature and leads to a prolonged period of nucleate boiling. This was found to be true for transient heating at an average rate below $10^6\ K\ s^{-1}$.

Acknowledgements—The author wishes to thank Professor W. B. Hall for his guidance in this work and to acknowledge the financial support of H. M. Nuclear Installations Inspectorate as a part of a collaborative programme of work on thermal explosions.

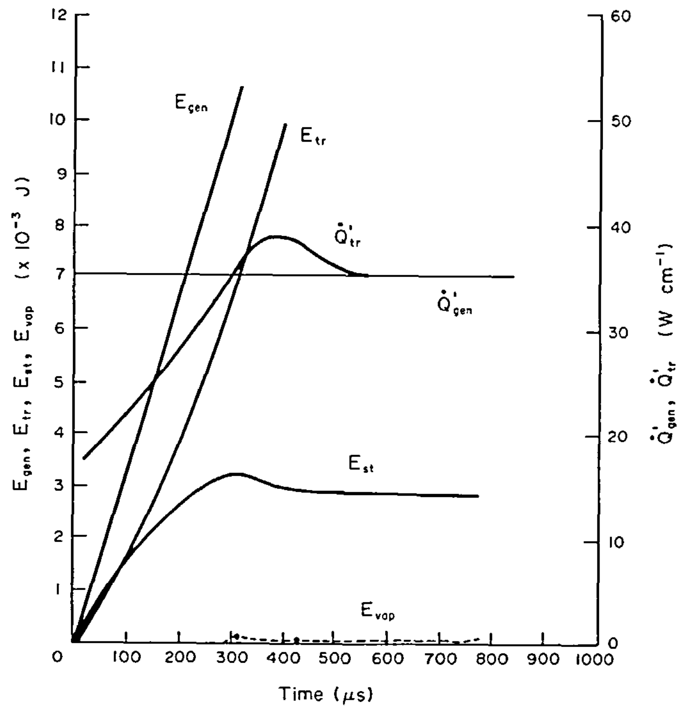

FIG. 4. Energy balance and heat transfer during the boiling transient shown in Fig. 2.

REFERENCES

1. R. B. Duffey, A. J. Clare, D. M. Poole, S. J. Board and R. S. Hall, *Int. J. Heat Mass Transfer* **16**, 1513–1525 (1973).
2. W. B. Hall and W. C. Harrison, International Heat Transfer Conference, Institution of Mechanical Engineers, pp. 186–192 (1966).
3. H. A. Johnson, V. E. Schrock, S. Fabic and F. C. Selph, Transient boiling heat transfer and void volume production in channel flow, Report No. 163, University of California (1961).
4. V. P. Skipov, *Metastable Liquids*, John Wiley, New York.
5. H. C. Simpson and A. S. Walls, *Proc. Inst. Mech. Engrs* **180**, Part 3C, 135–149
6. A. Sakurai and H. Shiotsu, *J. Heat Transfer*, **99**, No. 4 (1977).
7. K. Derewnicki and W. B. Hall. Homogeneous nucleation in transient boiling, 7th International Heat Transfer Conference, Munich (1982).

Int. J. Heat Mass Transfer. Vol. 26, No. 9, pp. 1408–1412, 1983
Printed in Great Britain
0017-9310/83 $3.00 + 0.00

HEAT TRANSFER FROM PARTIALLY INSULATED HEXAGONAL DUCTS

R. M. ABDEL-WAHED and A. E. ATTIA
Department of Mechanical Engineering, University of Alexandria, Alexandria, Egypt

(*Received* 28 *June* 1982 *and in revised form* 11 *January* 1983)

NOMENCLATURE

D_h	equivalent diameter
f	friction factor
N	dimensionless distance normal to the duct wall
Nu_{H_1}	Nusselt number—constant axial heat flux, isothermal local periphery
Nu_{H_2}	Nusselt number—constant axial heat flux, uniform heat flux on the periphery at a given axial location
P	pressure
p	duct perimeter
Pr	Prandtl number
Re	Reynolds number
u	axial velocity
s	arc length
T	temperature
x, y, z	spatial coordinates

Subscripts

b	bulk
w	wall

1. INTRODUCTION

HEXAGONAL passages are the subject of some modern engineering problems. Examples can be quoted from the design of hexagonal compact exchangers [1] and from the