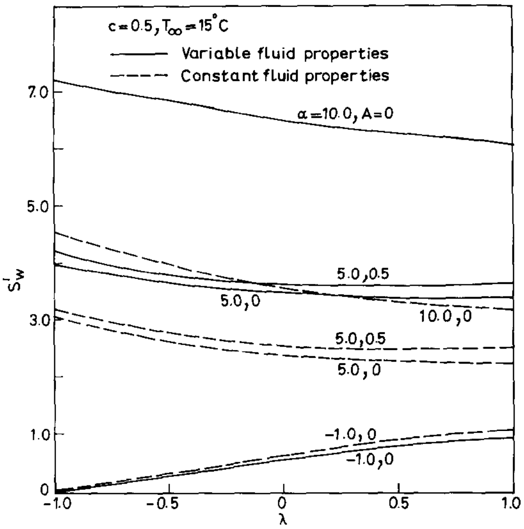


FIG. 5. Skin-friction parameter in the $y$-direction (self-similar flow).

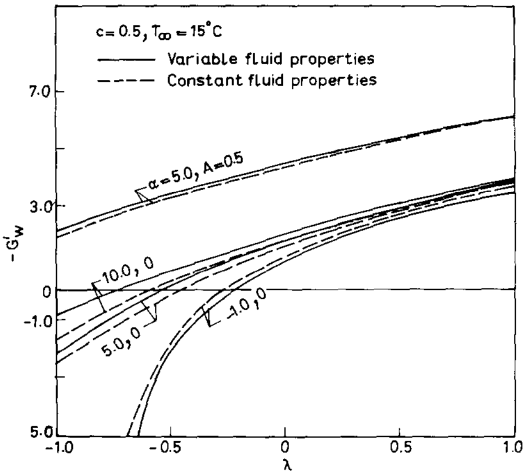


FIG. 6. Heat transfer parameter (self-similar flow).

## CONCLUSIONS

The skin friction and heat transfer are found to be strongly dependent on the variation of viscosity and Prandtl number with temperature especially for large values of buoyancy forces. The effect of mass transfer is found to be more pronounced on the heat transfer than on the skin friction.

## REFERENCES

1. M. Kumari and G. Nath, Unsteady mixed convection near the stagnation point in three-dimensional flow, *J. Heat Transfer* **104**, 132–138 (1982).
2. J. G. Marvin and Y. S. Sheaffer, A method for solving nonsimilar laminar boundary-layer equations including foreign gas injection, *NASA Tech. Note* D-5516 (1969).
3. L. S. Yao, Variable viscosity effect on the laminar water boundary layer on heated cones, *J. Appl. Mech.* **45**, 481–486 (1978).

*Int. J. Heat Mass Transfer.* Vol. 27, No. 2, pp. 315–317, 1984
Printed in Great Britain

0017 9310/84 $3.00 + 0.00
Pergamon Press Ltd.

# THE EXISTENCE OF NUCLEATE BOILING IN DIABATIC TWO-PHASE ANNULAR FLOW

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(*Received* 24 *April* 1983)

DURING recent years, there has been much speculation on the possible existence of nucleate boiling in high quality diabatic annular flows [1–7]. Hypotheses have been formulated and experimental data re-analysed [1, 2] in an effort to show that nucleate boiling may occur in the liquid film region at the wall. A recent paper [7] describes experiments designed especially to test the hypothesis of annular flow nucleate boiling, and involving the determination of heat transfer coefficients at constant quality and film flow. Data were obtained using a tube, 367.2 cm long by 9.6 mm diameter, the first 182.9 cm of which was heated to produce a desired quality for a given flow; the next 138.6 cm (or 144 diameters) was unheated to ensure flow development; and the last heated 45.7 cm was the section in which heat transfer coefficients were determined. The heat transfer characteristics were determined from wall temperatures monitored by seven thermocouples uniformly spaced along the final section, power input measurements, and local coolant conditions. Experiments were performed with steam–water at near atmospheric pressure; mass fluxes were 105 and 203 $kg\,m^{-2}\,s^{-1}$, and qualities ranged from 0.05 to 0.42.

On the basis of linear relationships between heat flux and wall superheat at constant mass flows and qualities, Aounallah *et al.* [7] concluded that nucleate boiling was not present for the range of annular flow conditions covered by their experiments.

This communication draws attention to similar experiments performed nearly two decades ago, by Bertoletti *et al.* [8] whose results were at variance with the conclusions of Aounallah *et al.*

Bertoletti *et al.* [8] heated water at a pressure of 7 MPa to required coolant qualities in an electrically heated section corresponding to the 182.9 cm preheated section used in the more recent experiments [7]. Heat transfer measurements were made near the inlets and exits of two heated tubes 80 cm long by 4.99 mm diameter and 139.9 cm long by 9.18 mm diameter, respectively. In each case the heated test section was

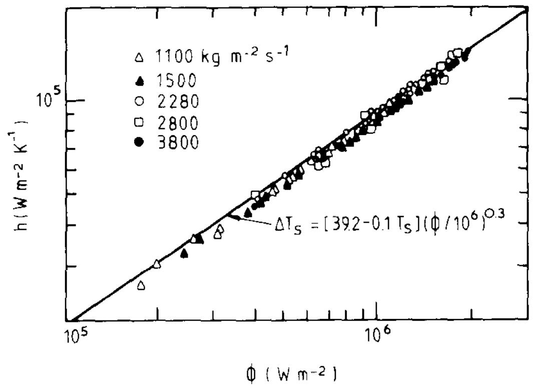


FIG. 1. Comparison of heat transfer data obtained at the inlet of a 9.18 mm diameter tube [8] with fully-developed forced convective nucleate boiling correlation of Aladiev *et al.* [10].

preceded by a 250 cm length of calming section of the same diameter. The flow development lengths were thus 501 and 272 diameters, respectively. Mass fluxes were in the range 1100–3900 kg $m^{-2}$ $s^{-1}$, and qualities ranged from 0 to 1. Flow conditions were representative of those occurring in many industrial situations.

Unlike the heat transfer data of Aounallah *et al.* [7], a significant fraction of the data of Bertoletti *et al.* [8] did *not* show a linear relation between heat flux and wall superheat for constant mass flux and quality. Instead, heat transfer coefficients varied significantly with heat flux, having negligible dependence on mass flux, quality, tube diameter, and distance from the inlet of the heated section. Furthermore, these data are close to the predictions of several of the fully developed forced convection nucleate boiling correlations summarized in the survey of Guglielmini *et al.* [9].

To illustrate these factors, typical experimental data of Bertoletti *et al.* [8] have been compared with the correlation of Aladiev *et al.* [10] (Fig. 1). The ability of a correlation obtained specifically for nucleate boiling to describe these data suggests that nucleate boiling may well be present.

The upper limit to which the correlation of Aladiev *et al.* [10] may be applied to the data of Bertoletti *et al.* [8] is indicated in Fig. 2 by broken lines; included in this figure is a flow regime map obtained by Bennett *et al.* [11] for similar flow conditions (i.e. $P = 7$ MPa, $D = 12.7$ mm), and the critical heat flux (CHF) boundaries of annular flow for the data of refs. [8, 11]. (The irregular CHF boundaries for the data of ref. [8] reflect arbitrarily chosen maximum inlet qualities for different mass fluxes.)

From the comparisons shown in Figs. 1 and 2, it can be seen that those data obtained by Bertoletti *et al.* [8] at qualities up to the maximum values achieved by Bennett *et al.* [11] correspond to the annular flow regime yet are well described by a nucleate boiling correlation.

The above observations are based solely on the examination of heat transfer coefficient data in a manner similar to that of Aounallah *et al.* [7]. However, it has been indicated elsewhere [5], that pressure loss data and qualitative trends in heat transfer data during approach to the heat transfer crisis can both be used to indicate nucleate boiling. Such data were obtained concurrently with the heat transfer data of ref. [8] and reported by Gaspari *et al.* [12] and Bertoletti *et al.* [13].

For conditions in which the correlation of Aladiev *et al.* describes the heat transfer data, the pressure loss data [12] are consistent with roughened wall friction factors having rugosity elements equivalent to attached wall bubbles. Also, abrupt improvements in heat transfer were noted just before CHF [13]. These are consistent with the boiling mechanism proposed by Mesler [1]. The pressure loss data [12] and CHF data [13] thus both support the hypothesis that nucleate boiling is present for the annular flow test conditions of ref. [8] up to the limits indicated in Fig. 2.

In summary, although heat transfer data obtained from a special experiment [7], which was designed to test the presence of nucleate boiling in steam–water annular flows at atmospheric pressure, suggest its absence, heat transfer data obtained from earlier similar experiments [8] performed at a pressure of 7 MPa support an earlier hypothesis [5] that nucleate boiling can occur in the liquid film at the wall in annular flow, even at relatively high qualities.

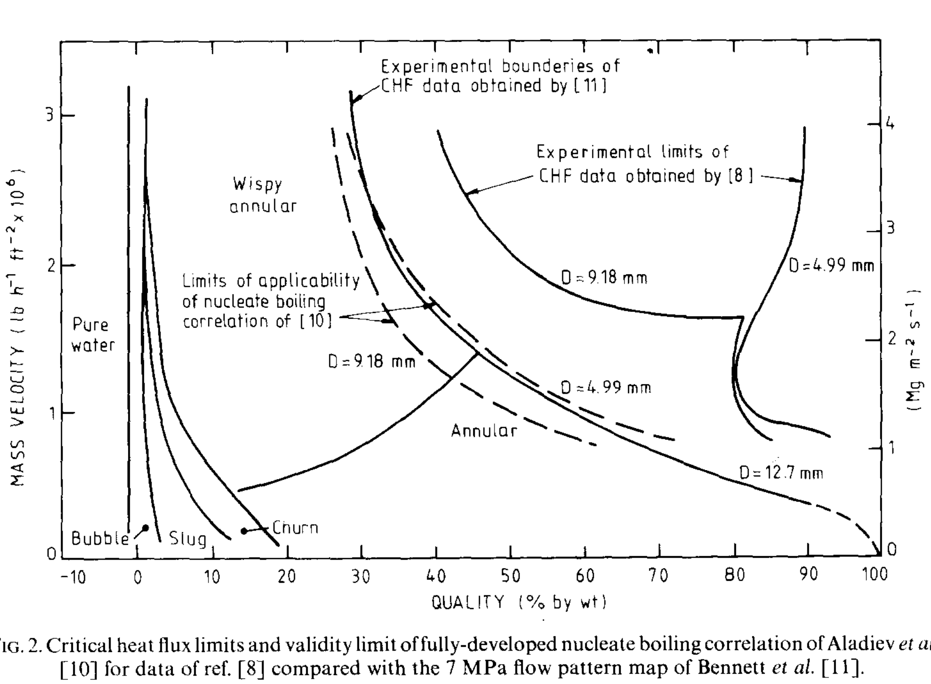


FIG. 2. Critical heat flux limits and validity limit of fully-developed nucleate boiling correlation of Aladiev *et al.* [10] for data of ref. [8] compared with the 7 MPa flow pattern map of Bennett *et al.* [11].

**REFERENCES**

1. R. B. Mesler, A mechanism supported by extensive experimental evidence to explain high heat fluxes observed during nucleate boiling, *A.I.Ch.E. Jl* **22**, 246–252 (1976).
2. R. B. Mesler, An alternate to the Dengler and Addoms convection concept of forced convection boiling heat transfer, *A.I.Ch.E. Jl* **23**, 448–453 (1977)
3. C. R. Hsieh, Letter to the Editor, *A.I.Ch.E. Jl* **24**, 560 (1978).
4. F. C. Stanesford, Letter to the Editor, *A.I.Ch.E. Jl* **24**, 750 (1978).
5. D. R. H Beattie and K. R. Lawther, Letter to the Editor, *A.I.Ch.E. Jl* **25**, 384 (1979).
6. D. Butterworth and R. A. W. Shock, Flow boiling, *Proc. 7th Int. Heat Transfer Conf.*, Munich, paper RK15 (1982).
7. Y. Aounallah, D. R. B. Kenning, P. B. Whalley and G. F. Hewitt, Boiling heat transfer in annular flow, *Proc. 7th Int. Heat Transfer Conf.*, Munich, paper FB3 (1982).
8. S. Bertoletti, C. Lombardi and M. Silvestri, Heat transfer to steam–water mixture, CISE report R-78 (1964).
9. G. Guglielmini, E. Nannei and C. Pisoni, Survey of heat transfer correlations in forced convection boiling, *Wärme- und Stoffübertragung* **13**, 177–185 (1980).
10. I. T. Aladiev, L. D. Dodonov and U. S. Udalor, *Teploenergetika* **4**, 9 (1957).
11. A. W. Bennett, G. F. Hewitt, H. A. Kearsey, R. K. F. Keeys and P. M. C. Lacey, Flow visualisation studies of boiling at high pressure, AERE report R-4874 (1965).
12. G. P. Gaspari, C. Lombardi and G. Peterlongo, Pressure drops in steam–water mixtures. Round tubes–vertical upflow, CISE report R-83 (1964).
13. S. Bertoletti, G. P. Gaspari, C. Lombardi, G. Soldaine and R. Zavattarelli, Heat transfer crisis with steam–water mixture—experimental data in round tubes and vertical upflow obtained during the CAN-2 program, CISE report R-90 (1964).