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The influence of bubbly flow on boiling from a tube in a bundle

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Abstract—The forms of bubbly flow occurring within a tube bundle are discussed and the boiling process in the bundle is notionally divided into mechanisms due to liquid forced convection, sliding bubbles and nucleation. A novel experimental analysis of heat transfer from a tube in a bundle indicates the predominance of the sliding bubble part. There is a virtual absence of nucleation in a bundle except at the lowest tubes indicating that, once enough bubbles have been produced, the other mechanisms are sufficient to transfer the heat from the tubes.

1. BUBBLY FLOW IN TUBE BUNDLES

EVAPORATING flow on the outside of immersed tube bundles results in predominantly bubbly flow. In the higher quality regions this may become churn flow where bubbles coalesce to form elongated vapour regions. As dryness is approached the remaining liquid is distributed as a spray which wets the outsides of the upper tubes thus delaying tube dryout until the quality is virtually unity.

This differs from the flow regimes observed in evaporation on the insides of tubes at the same vapour/liquid flow conditions. The Hewitt–Roberts flow regime map [1] for in-tube flow indicates progression from slug through churn to annular flow. Slug flow is physically difficult in bundles and boiling within the stagnant regions vertically between the tubes will always tend to induce bubbly flow. Annular flow is also more difficult in bundles as the tubes tend to provide impact surfaces leading to spray flow rather than an annular formation at high vapour flow rates.

For vertical flow through bundles the Grant–Chisholm [2] Flow Map has been widely used. Recently Schrage *et al.* [3] successfully correlated their two-phase pressure drop data for air–R113 flow using the regimes identified in this Flow Map. The flow regimes are limited to three types—bubbly flow, chugging or slug flow and spray flow.

Experimental studies on heat transfer to discrete bubbles in bubbly flow through tube bundles have been attempted by Neils [4] using water and Cornwell and Schuller [5] using R113. Figure 1 shows the area of the map covered by these fluids for typical operating ranges in immersed bundles under normal evaporating conditions. It is evident that for water the flow may be spray, chugging or in the upper regions of bubbly flow while the refrigerant flow is well within the bubbly regime. This difference is corroborated by visual inspection of the flow in bundles as shown in Figs. 2 and 3. The water flow is a mixture of very large bubbles or slugs together with smaller bubbles and could well be described as chugging, while the rather more homogeneous flow of small bubbles in the refrigerant is characteristic of bubbly flow. For this reason Neils [4] using water has concentrated on the analysis of large bubbles or slugs while our work [5, 6] has assumed small bubbles.

2. HEAT TRANSFER MECHANISMS IN BUBBLY FLOW

Ample experimental evidence [4, 7–15] has been provided of the general increase in heat transfer of a tube or tubes in bubbly flow over that for nucleate boiling alone. In this work an attempt is made to furcate the total heat transfer coefficient h into

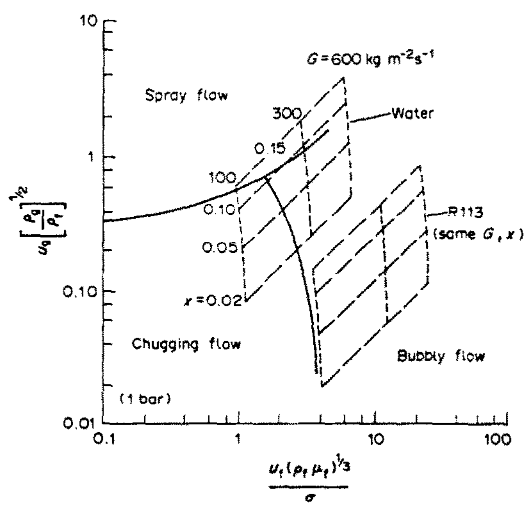

FIG. 1. Typical operating areas for water and R113 on the shell-side Grant–Chisholm flow pattern map [2].

NOMENCLATURE

G	total mass flux	ρ	density
h	heat transfer coefficient	σ	surface tension.
q	heat flux		
ΔT_s	surface saturated temperature difference	Subscripts	
u	velocity (based on minimum area)	B	total bundle
x	mass dryness fraction.	f	liquid
		fc	forced convection
		g	vapour
Greek symbols		nb	nucleate boiling
μ	viscosity	sb	sliding bubble.

notional parts in order to quantify the influence of the bubbly flow on heat transfer. Thus

$$h = h_{fc} + h_{sb} + h_{nb}. \quad (1)$$

The first term on the right-hand side is the heat transfer coefficient due to liquid convection at the local liquid velocity. This is provided by the appropriate expression for the Nusselt number. The second term is that due to the heat passed to the tube as a result of bubbles existing in the approaching free stream. In a tube bundle these bubbles originate from tubes below. In this work no attempt is made to characterize the origin of the bubbles in the free stream as undertaken by Fujita *et al.* [13] as the mechanism occurring after impingement on the tube is being investigated. It should be noted that this term is composed of a

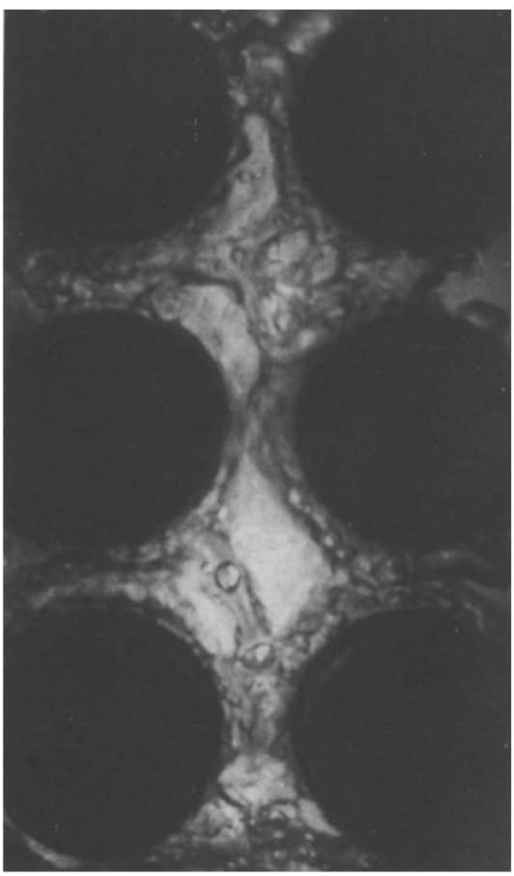

FIG. 2. Water at 1 atm boiling on 19 mm diameter tubes at 50 kW m^{-2} and ~5% quality from ref. [19].

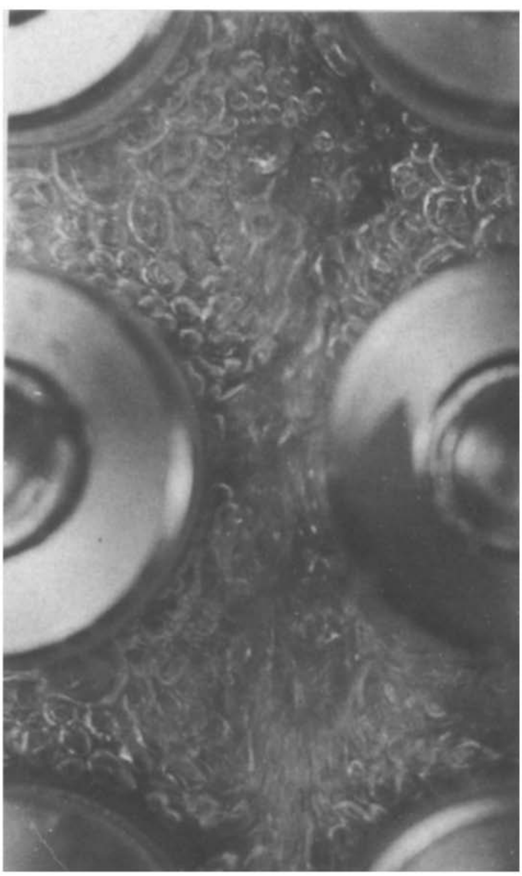

FIG. 3. R113 at 1 atm boiling on 19 mm diameter tubes at 15 kW m^{-2} and ~5% quality (this work).

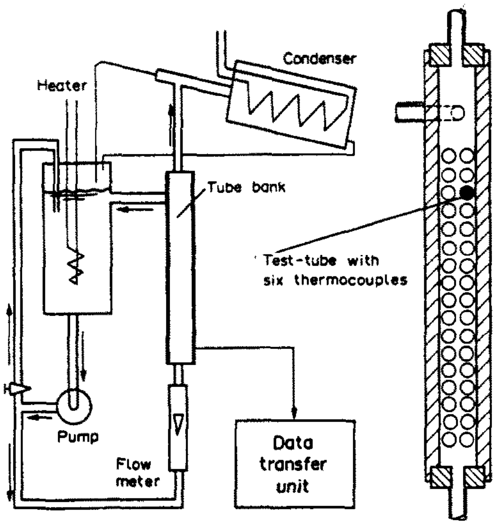

FIG. 4. Arrangement of rig and boiling cell.

part due to the turbulence caused in the liquid boundary layer as the bubble slides across the surface and a part due to evaporation of the layer under the bubble. For small bubbles it can be shown [6] that the evaporation term is very small while for large bubbles both may be significant. The third term relates to bubbles which nucleate and grow on the surface as in pool boiling on a single tube.

The following experimental work is aimed at differentiating between the three constituent parts of h in equation (1) and determining their relative importance. The working conditions and fluid used lead to small bubbles in the flow as shown in Fig. 3.

3. EXPERIMENTAL STUDY

3.1. *Basis of study*

Tests on tube bundles where individual tubes have been monitored generally involve operation with the test-tube acting as a normal tube within the bundle. The following method is more revealing and allows direct division into the components of equation (1).

All the tubes in the bundle columns shown in Fig. 4 except the test-tube were heated to give a constant mean bundle heat flux. Initially the test-tube, which had separate electrical heating and instrumentation, had no heat supplied and therefore remained at the local saturation temperature. A small amount of heat, insufficient to cause nucleation, was then passed to the test-tube. The resulting value of h was attributed to the liquid convection and the sliding bubbles within the surrounding bubbly flow. *The nucleation component was therefore separated out.*

Further heating of the test-tube yielded a constant value of h until nucleation led to an increase in the number of bubbles on the surface and an increase in h. The commencement of nucleation was therefore clearly defined. At one point the test-tube flux was equal to that of the rest of the bundle and under this condition was comparable with normal tube bundle studies.

Separate runs under single phase liquid conditions allowed *measurement of the forced convective heat transfer coefficient.* This value was adjusted to the local liquid velocity to give the convective component. Subtraction from the previous values of h then gave the sliding bubble part.

3.2. *Apparatus and results*

The boiling cell and flow loop (Fig. 4) are the same as those used in previous work [16] and the tests were run using R113 at 1 atm (b.p. 47.6°C) at a constant mass flux, G, of 95.1 kg s^{-1} m^{-2}. The Perspex boiling cell contained 34 tubes in two in-line columns and the stainless-steel tubes were of 19.05 mm (3/4 in.) diameter and 25.4 mm (1 in.) pitch. The test-tube only was of copper with six radially positioned chromel–alumel thermocouples calibrated and tested to give readings within 0.1°C of each other. The tubes were heated using 250 W cartridge heaters and thermocouple data were logged using a microprocessor. Five sets of results were taken as described earlier and the sets were consistent in form, with a slight variation at the higher heat fluxes. The second set is presented in Fig. 5, together with results from the single phase liquid at the same flow rate, but at a lower temperature (~30°C) to avoid the possibility of boiling.

4. EXPLANATION OF RESULTS

The single phase liquid convection data in Fig. 5 is correlated well by the Zukauskas relationship [17] for in-line tubes over the appropriate Re range:

$$Nu_f = 0.27 Re_f^{0.63} Pr^{0.36}. \quad (2)$$

The results are of slightly higher value of h due to the short length of the tubes. The next curve up from the abscissa effectively gives the flow saturated boiling curve for the tube with no heat input to the bundle ('effectively' because the lower tubes had to be heated slightly to limit subcooling at the test-tube to less than 2°C). The next three curves were obtained from the test-tube with the bundle heaters set at the given heat fluxes. They are much steeper than the boiling curve, even at very low ΔT_s when there is no possibility of any nucleation. This is due to the stream of bubbles passing over the tube from lower tubes and the increasing liquid velocity.

At a point during the increase of heating to the test-tube the heat flux is the same as that to the surrounding tubes. The joining of these points (spots on the curves) gives the normal bundle boiling curve which appears to fit well with the mean bundle boiling curve under almost the same conditions from previous work [18].

Analysis of the curve for bundle boiling at 15 kW m^{-2} as outlined in Section 3.1 is shown in Fig. 6. The local liquid forced convection heat flux q_{fc} is obtained from equation (2) with Re_f at the local liquid velocity

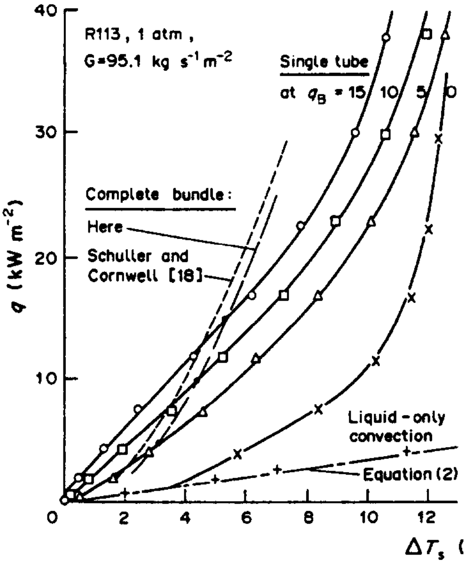

FIG. 5. q–ΔT curves for test-tube under various bundle heat flux q_B conditions.

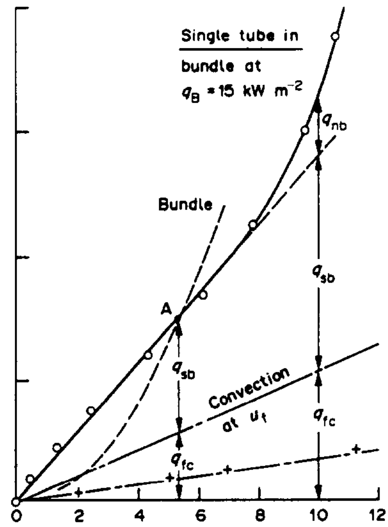

FIG. 6. Analysis of the q–Δt curve at a bundle heat flux of 15 kW m^{-2}.

estimated from the void fraction based on the Lockhart–Martinelli model. Table 1 gives the quality (known precisely for constant-q heating) and slip ratios for the test-tube estimated from Lockhart–Martinelli, Baker and Chisholm models. The resulting heat transfer coefficients from this analysis of the test data for each of the bundle heat fluxes is summarized in Table 2 for an arbitrary selected ΔT_s of 10°C and also for the important condition when the test-tube is at the same heat flux as the bundle.

From Fig. 3 and Table 2 it is clear that a heat transfer mechanism, which is neither liquid convection (at the local velocity) nor nucleation, is responsible for a large part of the heat transfer from the tube. *It is postulated that this mechanism is due to bubbles within the flow which slide around the tube.*

Furthermore, while nucleate boiling does occur at high ΔT_s values, it would appear that at these fairly low bundle heat fluxes the forced convective and sliding bubble components fully account for the heat transfer when the test-tube operates at the bundle heat flux. That is to say *there is no nucleate boiling at the upper tubes* under these conditions. This is very clear from Fig. 6 where the start of nucleate boiling is at a higher ΔT_s than point A where the local test-tube heat flux equals q_B. This result is somewhat surprising in view of the general assumption that nucleation occurs (albeit suppressed) on all tubes within the bundle. It appears that nucleation only occurs on the lower tubes and that when sufficient bubbles have been generated the combined effects of liquid convection and the sliding bubbles higher in the bundle are sufficient to meet the heat flux.

Table 1. Local conditions at the test-tube

Bundle, q_B (kW m^{-2})	Quality, x	Slip ratio, u_g/u_f L–M	Baker	Chisholm	u_f (L–M) (m s^{-1})	h_{fc} (kW m^{-2} K^{-1})
0	0	—	—	—	0.063	0.35
5	0.048	3.9	6.4	3.3	0.22	0.78
10	0.097	5.1	7.8	4.6	0.30	0.95
15	0.145	6.2	8.8	5.6	0.36	1.06

Table 2. Local measured heat transfer coefficient and its components

Bundle, q_B (kW m^{-2})	$\Delta T_s = 10$°C h	h_{fc}	h_{sb}	h_{nb}	Test-tube, $q = q_B$ h	h_{fc}	h_{sb}	h_{nb}
0	1.07	0.35	0	0.72	0.35	0.35	0	0
5	2.26	0.78	0.90	0.58	1.68	0.78	0.90	0
10	2.73	0.95	1.35	0.43	2.30	0.95	1.35	0
15	3.27	1.06	1.71	0.50	2.77	1.06	1.71	0

5. CONCLUSIONS

(1) Two types of bubbly flow occurring in tube bundles are identified by observation and the Grant–Chisholm Flow Map. One type occurs with water at atmospheric pressure and has large bubbles or slugs between the tubes. The other type occurs in R113 and exhibits a large number of small bubbles. Heat transfer in the flow of the latter type was examined.

(2) There is a many-fold increase in the heat transfer from a tube to saturated liquid when there are bubbles in the flow. This is particularly evident at low ΔT_s before nucleation has commenced when the only other transfer mechanism is liquid convection.

(3) In the tube bundle at the medium heat fluxes used, liquid convection and the influence of the sliding bubbles account for the total heat transfer in the middle and upper tubes. Nucleation only occurs on the lowest tubes where the quality and void fraction are low.

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INFLUENCE DE L'ECOULEMENT AVEC BULLES SUR L'EBULLITION A PARTIR D'UN TUBE DANS UNE GRAPPE

Résumé—On discute des formes d'écoulement avec bulles qui apparaissent dans une grappe de tubes et le mécanisme d'ébullition dans la grappe est divisé en mécanismes dus à la convection forcée liquide, au glissement des bulles et à la nucléation. Une analyse expérimentale nouvelle du transfert thermique à partir d'un tube dans une grappe indique la prédominance de la part du glissement des bulles. Il y a une absence virtuelle de la nucléation dans une grappe, excepté pour les tubes inférieurs, ce qui indique qu'une fois les bulles produites, les autres mécanismes sont suffisants pour transférer la chaleur à partir des tubes.

EINFLUSS DER BLASENSTRÖMUNG AUF DAS SIEDEN AN EINEM ROHR IN EINEM BÜNDEL

Zusammenfassung—Die Formen der Blasenströmung in einem Rohrbündel werden diskutiert. Dabei wird der Siedevorgang im Bündel gedanklich in folgende Einzelmechanismen unterteilt: erzwungene Konvektion der Flüssigkeit, gleitende Blasen und Blasenbildung. Eine neuartige Analyse der Wärmeübergangsergebnisse an einem Rohr in einem Bündel zeigt die überragende Rolle des Anteils der gleitenden Blasen. Nur an den untersten Rohren des Bündels tritt eine Blasenbildung auf, die weiter oben vollständig fehlt. Dies bedeutet, daß die anderen Mechanismen für den Abtransport der Wärme von den Rohren vollständig ausreichen, wenn erst einmal genügend Blasen produziert sind.

ВЛИЯНИЕ ПУЗЫРЬКОВОГО ТЕЧЕНИЯ НА КИПЕНИЕ В ПУЧКЕ ТРУБ

Аннотация—Проведен анализ видов пузырькового течения в пучке труб. Кипение в пучке вызывается механизмами, обусловленными вынужденной конвекцией жидкости, скользящими пузырьками и нуклеацией. Экспериментальное исследование теплоотдачи от отдельной трубы пучка указывает на преобладание механизма, определяемого скользящими пузырьками. Процесс нуклеации в пучке практически отсутствует, за исключением самых нижних труб, что свидетельствует о том, что носле образования достаточного количества нузырьков теплоотдача от труб происходит за счет других механизмов.