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Experimental Investigation of Air-water Two Phase

Upflow across Horizontal Tube Bundles*

(Part I Flow Pattern and Void Fraction)

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The present paper deals with experiments of air-water mixtures flow pattern and their mean void fraction in horizontal tube bundles. The tube bundles are staggered with equilateral triangular arrangement of three different pitch/tube diameter ratios (1.4, 1.28, 1.08) and they consist of six different tube rows (7, 9, 11, 13, 15, 20) for each ratio. Experimental ranges are as follows;

Superficial air velocity (cm/s) 1.5 - 50
 Superficial water velocity (cm/s) 0.032 - 0.32
 Flow direction upward flow

The observed mixture flows can be classified into 1. bubbly flow 2. slug flow 3. froth flow 4. spray flow with liquid forming a film around the tubes and spraying from tube to tube downstream. Besides, a simple empirical equation for void fraction is proposed.

1. Introduction

In horizontal thermosiphon reboilers used in a chemical plant, fluid circulation is provided by a difference in density between two phase mixture boiling in shell and static head of liquid in the distillation column or liquid reservoir. Therefore, an accurate average density of the two phase mixture in shell is required to predicted the circular liquid flowrates. Besides, recent works for boiling outside horizontal tube bundles indicate that boiling heat transfer coefficients in tube bundles are affected by vapor rate from the lower tubes or void fraction in tube bundles. For these reasons, the inherent hydraulic characteristics of a two phase flow across tube bundles should be fully understood for design of evaporators.

Only limited amounts of data are available on the flow pattern observed in a vertical two phase upflow across tube bundles, and no studies are concerned with void fraction. I.D.R. Grant proposed a flow regime map from visual observations of the flow patterns in an ideal tube bundle. This model consisted of thirty-nine 19mm outside diameter tubes in an equilateral triangular layout of 1.25 pitch/tube diameter ratio. Tests were carried out for large flowrates of mixture giving mass velocity over 60 kg/sq.m.s. Therefore, the flow regime map is not

applicable in the range of the circular liquid flowrates of a horizontal thermosiphon reboiler.

For the purpose of developing a general relation on void fraction, the effect of pitch/tube diameter ratio, number of tube rows and flowrates were investigated experimentally using an air and water mixture. The present paper deals with void fraction and flow pattern for upflow of two phase mixtures across staggered tube bundles.

2. Nomenclature

C; Bubble length/height ($=l/k$)
 d; Tube diameter
 D; Width of a bubble (= clearance between tubes)
 Fr; Froude number ($=Vg/\sqrt{p \cdot g}$)
 g; Acceleration due to gravity
 H; Spacing of tube rows ($=p \cdot \sin 60^\circ$)
 K; Height of a bubble along flow direction
 l ; Length of a bubble in the axial direction of tube
 L; Tube length
 n; Volume of tube bundles
 N; Number of bubbles passing through a tube clearance per unit tube length and unit time
 No; Total volume of tube bundles
 P; Tube pitch
 Vo; Superficial velocity
 Vmax; Superficial velocity at minimum flow area
 vg; Average rise velocity of bubble
 ϵ ; Void fraction
 τ ; Passing period of a bubble at a favored point on the tube surface
 ρ ; Density
 σ ; Interfacial tension
 μ ; Viscosity
 Σ ; Total number of bubbles included in control surface.

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Subscripts

- A; Entrance zone (the dynamics of flow in entrance zone depends on flow created at the mixing section)
 B; Characteristic zone in tube bundles (fully developed flow)
 C; Exit zone (the dynamics of flow in the exit zone depends on flow cre-

ated at exit)

- g; Gas
 l; Liquid
 oi; Minimum free area
 i; Free position
 -; Average

3. Experimental apparatus

The experimental apparatus is shown schematically in Fig. 1. Water was poured

1 Water	8 Nozzle
2 Pump	9 Orifice
3 Head tank	10 Test section
4 Solenoid valve	11 Manometers
5 Control valve	12 Pressure transducers
6 Rotameter	13 Recorder
7 Air surge tank	

Fig. 1 Schematic diagram of experimental equipment

(a) Detail of tube bundle

(b) Detail of mixing section

(c) Position of pressure taps in mixing section

Fig 2

from the reservoir ① to the head tank ③ by the pump ② and passed through the solenoid valve ④, the control valve ⑤, the rotameter ⑥ and went into the mixing section located under the tube bundles. Air from the surge tank ⑦ passed through the solenoid valve ④, the control valve ⑤, the flow meter (orifice ⑨ or nozzle ⑧) at high flowrate, and rotameter ⑥ at low flowrate), the solenoid valve ④ and went into the mixing section. Air-water mixture passed through tube bundles and finally went into the separator, where air was vented to the atmosphere and water returned to the reservoir. Details of the mixing section and tube bundles are shown in Fig. 2. The mixing section consisted of tubes feeding water and porous tubes injecting air. Pressure distributions in the mixing section are measured at 0, 2.7, 10.7, 30.7, 52.7, 72.7 and 112.7 mm downward from tube bundles as shown in Fig. 2. The water feed tubes were made of 530 mm long acrylic tube of 30 mm O.D. with 9 holes of 2 mm I.D. at the bottom of tubes. The four acrylic tubes were arranged in line on the plane. The clearance of tubes was equal to the tube gap in bundles and was varied according to each test bundle with different tube pitch. The five air injection tubes were also arranged in line and with same tube pitch for each bundle. The air injection tubes were 25 mm O.D., 600 mm long synthetic resinous porous tubes with 50 μ mesh particles and the upper

(a)

(b)

(c)

(I)

sketch 1

(d)

(e)

(II)

sketch 2

(f)

(g)

(h)

(III)

sketch 3

Fig.4

part of tubes was coated to inject air downward only. For the purpose of controlling the initial velocity and homogenizing, air and water were injected downward as explained above. Tube bundles were constructed of transparent acrylic resin tubes, dimensions of each tube bundle being given in Table 1.

The water temperature in the reservoir and the separator was measured with alcohol thermometers. Atmospheric temperature was measured with mercury thermometers. The water temperature in the separator was adopted as characteristic temperature of air-water mixtures, since the difference of water temperatures between the reservoir and the separator was less than 1 degree.

The pressure taps were connected to manometers ① with damp systems (0.7mm I.D. 100mm long) and the water purge tanks which ensure that all manometer lines are filled up with water. The differential pressures between every two pressure taps were measured by pressure transducers ② and recorded by oscillographs. Since the average differential pressures from the oscillographs and manometers were in satisfactory agreement within 3%, the average differential pressures in this experiment were measured by manometers.

Table 1 Experimental condition and dimensions of tube bundle

tube pitch P mm	35	32	27
tube outside diameter d mm	25		
tube length L mm	600		
tube layout	equilateral triangular arrangement		
number of tube lines	5		
number of tube rows	7, 9, 11, 13, 15, 20		
position of pressure taps	odd number of tube rows		
range of superficial water velocities V_{lo} cm/s	0.032 - 0.32		
range of superficial air velocities V_{go} cm/s	1.5 - 50.0		
range of qualities	0.005 - 0.9		
water temperature	18 - 20

Fig. 3 Comparison between void fractions by quick shut method and by manometer

4. Experimental procedure

The flow patterns in tube bundles were discriminated by means of visual observation and photographic technique with 35mm still camera and 16mm high speed camera. Air holdup in tube bundles was measured by the quick shut method using a quick closing solenoid valve ④ in inlet line.

The measured holdup contained the holdup both in the tube bundle and in the mixing section, which was equivalent to water volume refilled to recover to water level to the former state. Therefore, the air volume fraction in tube bundle was obtained by subtracting the air holdup in the mixing section which was calculated by static pressure distribution, from the total air holdup. This estimation method was calibrated by the quick shut method, using the mixing section and the same scaled hollow duct. The measured and calibrated air volume fractions agree within $\pm 5\%$ as shown in Fig. 3. These results show that acceleration loss in the mixing section is negligible in comparison with static head loss in the range of the experimental mass flowrates.

5. Flow pattern

Visual observation of flow patterns occurring in tube bundles indicated no effects of water flowrates throughout the present experiment.

At low air flowrates, bubbles are much smaller in diameter than tube outside diameter and distribute uniformly in the water phase. The shape of bubble is elliptical, when the bubble size is smaller than the tube clearance. Elliptical bubbles are found to change as if they were pressed against the tube wall, as the bubble size is larger than the tube clearance (Fig.4-(I), sketch 1).

As air flowrates increase, some of bubbles grow and fill up the tube clearance. Height and length of the bubbles are comparable to a tube pitch. In this range of air flowrates, a flow contains various sizes of bubbles. Some small size of bubbles flow backward due to a rising of large bubbles (Fig.4-(II), sketch 2).

At high air flowrates, height of the large bubbles extends over several times the tube pitch and their width is equivalent to the tube clearance. Adverse flow of some of the small bubbles becomes strong and a violent pulsation flow of mixture is caused to occur. Air phase begins to blow through tube bundles, but it never covers the tubes. Some fractions of flow area are air phase remaining thin liquid film on tube wall such as annular flow in tube and the other parts are a bubbly flow which holds relatively small bubbles. Fig.4-(III) and sketch 3 illustrate this flow pattern. However, in this case of 1.08 pitch/tube diameter ratio, with an increasing air flowrates large bubbles which flow through tube bundles and flow area of annular parts expanded and became gradually larger. Finally the

greater fraction of flow area in tube bundles is occupied with air phase, while flow pulsations (pressure fluctuation) are damped (Fig.4-(IV)).

The above flow patterns on visual observation are quantitatively classified as follows;

(1) Bubbly flow (Fig.4-(I), sketch 1)

A relative frequency distribution of bubble sizes is shown in Fig. 5. Fig. 6

(i) (IV)

Fig 4

Fig. 5 Relative frequency distribution of bubble sizes in the case a

shows a relative frequency distribution of bubble height/length ratios C . In this flow regime, it is clear that K and l are much smaller than the outside diameter. The range of C is from 0.7 to about 2.5 and limited to a relatively narrow band.

(2) Slug flow (Fig.4-(II), sketch 2)

A relative frequency distribution of bubble sizes is shown in Fig. 7. Fig. 8 shows a relative frequency distribution of bubble height/length ratios C . In this flow regime, maximum value of K and l reaches the tube pitch, but great majority of K and l exists in the range of 3mm to 10mm.

(3) Froth flow (Fig.4(III), sketch 3)

A relative frequency distribution of bubble sizes is shown in Fig. 9, Fig. 10 shows a relative frequency distribution of bubble height/length ratios C . When the flow pattern changes from slug flow to froth flow, K and l distribute continuously from large size of bubbles over several times the tube pitch to small size of bubbles.

In this region, as air flowrates increase, the number of bubbles changes in various ways for 3 groups of bubble sizes; smaller bubbles less than tube diameter, bubbles as large as tube pitch, and bubbles extending over several times the tube pitch.

The number of small bubbles does not change noticeably. The number of medium size bubbles, however, decreases with air flowrate, while the number of large bubbles increases. Contrariwise, in the highest range of air flowrates, medium

Fig. 6 Relative frequency distribution of bubble height/length ratios in the case a

Table 2 Experimental condition for measurement of bubble size
 $V_{lo} = 0.32 \text{ cm/s}$

Fig.4-(I)	P/d	$V_{go} \text{ cm/s}$	Fig.4-(II)	P/d	$V_{go} \text{ cm/s}$	Fig.4-(III)	P/d	$V_{go} \text{ cm/s}$	Fig.4-(IV)	P/d	$V_{go} \text{ cm/s}$
a	1.4	2.2	d	1.4	5.61	f	1.4	41.3	-	-	-
b	1.28	3.56	e	1.28	7.12	g	1.28	45.1	-	-	-
c	1.08	1.75	-	-	-	h	1.08	9.26	i	1.08	31.8

size bubbles can not be observed. Within the limits of this experiment, data of K and l indicate that flow pattern is affected by air flowrates and tube pitches, but is not affected by water flowrates.

The flow pattern changes generally to bubbly flow, slug flow, froth flow, and spray flow with air flowrate. But tube bundles of 1.08 pitch/tube diameter ratio are provided with extremely narrow tube clearance. It is, therefore, observed that flow pattern changes rapidly from bubbly flow to froth flow, in the case of slug flow occurring in narrow ranges of air flowrates. I.D.R. Grant proposed a flow map in tube bundle at high water flowrates ($V_{l0} 250 \text{ cm/s}$), which is a modified Baker map. The flow map for these results is indicated in Fig. 11 using Grant's param-

ters.

6. Void fraction

6-1. Number of tube rows required to measure void fraction without effects of the mixing section and the exit.

Flow in tube bundles is divided into 3 zones along a two phase flow as follows; Zone A; entrance zone affected by mixing section

Zone B; characteristic zone in tube bundles (fully developed flow)

Zone C; zone affected by exit

As void fraction in each zone is different, total void fraction in tube bundles is expressed by the following equation.

$$No\bar{\epsilon} = n_A\bar{\epsilon}_A + n_B\bar{\epsilon}_B + n_C\bar{\epsilon}_C \dots (1),$$

$$No = n_A + n_B + n_C \dots (1)$$

Where $\bar{\epsilon}_B$ is the void fraction in zone B which is independent of the number of tube rows. $\bar{\epsilon}_A$ is void fraction in zone A and $\bar{\epsilon}_C$ in zone C. Both fractions are affected by the number of tube rows. For purpose of obtaining $\bar{\epsilon}_B$, the present experiments were performed using various numbers of tube rows. If the following equation (2) is satisfied, $\bar{\epsilon}$ will correspond to $\bar{\epsilon}_B$.

$$\frac{n_A}{No}(\bar{\epsilon}_A - \bar{\epsilon}_B) + \frac{n_C}{No}(\bar{\epsilon}_C - \bar{\epsilon}_B) = 0 \dots (2)$$

A plot of the void fraction from eq.(1) vs. superficial air velocity for water flowrates, number of tube rows and 1.4 pitch/tube diameter ratio is shown in Fig. 12. Similar data are also obtained from experiment for the other tube bundles. The void fraction $\bar{\epsilon}$ increases with the superficial air velocity. From the figure, it is clear that the superficial water velocity does not affect the void fraction and the bubble rising ve-

Fig. 7 Relative frequency distribution of bubble sizes in the case d

Fig. 8 Relative frequency distribution of bubble height/length ratios in the case d

Fig. 9 Relative frequency distribution of bubble sizes in the case g

Fig. 10 Relative frequency distribution of bubble height/length ratios in the case g

Flow pattern Pitch	Bubble flow	Slug flow in tube bank	Froth flow in tube bank	Gas phase flow
35	○	△	□	
32	●	▲	■	
27	⊙	⬢	⬤	★

Fig. 11 Flow regime map

locity. With the purpose of indicating clearly that void fraction of eq. (1) is affected by the number of tube rows, a plot of the void fraction vs. number of tube rows for water and air flowrates is shown in Fig. 13. As is seen in the figure, void fraction changes according as the number of tube rows increases from 7 to 9 and 11. But when the number of tube rows is over 13, the void fraction ϵ approaches a constant value with negligible effect of the number of tube rows.

Likewise, when the tube rows are over 11 for the tube bundles of 1.28 pitch/tube diameter ratio and over 9 for that of 1.08 pitch/tube diameter ratio, void fraction in tube bundles is not affected by the tube rows. Consequently, void fraction ϵ is approximately equal to ϵ_B . When the tube rows are more than 13 for 1.4 pitch/tube diameter ratio, 11 for the ratio 1.28 and 9 for the ratio 1.08 respectively. Fig. 14 describes qualitatively the effect of tube rows on void fraction in tube bundles. Though void fraction in each tube bundle is different at same superficial velocity, each void fraction is equally described in the figure. It can be seen that tube rows required to assume $\epsilon = \epsilon_B$ become few as the pitch/tube diameter ratio decreases.

6-2. Void fraction in zone B

The equation (3) was derived in previous reports as relation between void fraction and passing period of bubble at a favored point on the tube surface based on the following assumptions. Consequently, the empirical equation (4) was obtained from data of void fraction, as some variables can not be decided theoretically.

Fig. 12 The effect of superficial air velocity on void fraction

Assumptions; (1) Bubbles may collapse or coalesce before entering tube bundles, but not in crossing any tube rows.

(2) A shape of bubble is rectangular parallelepiped.

(3) A shape of bubble changes with variation of cross flow area. However, a proportional relation between bubble height K along the flow and bubble length ℓ in the tube axial direction is certainly maintained as $\ell = CK$.

(4) Bubble rising velocity is proportional to air flowrates, but is independent of a bubble size and a location in tube bundles. This assumes that the mean bubble rising velocity is adopted.

$$\epsilon_B = \sqrt{C \left(\frac{H}{PH - (\pi/4)d^2} \right)^2 \sqrt{P(P-d)V_{go}Nt}} \dots (3)$$

$$\epsilon_B = \left(\frac{V_{go}}{V_{gms}} \right)^{0.17} \dots (4)$$

The empirical equation (4) does not agree well with the present experimental results. Because eq. (4) was obtained in the range of superficial air velocities over 220 cm/s. New equations on void fraction will be derived for bubbly flow, slug flow and froth flow by using statistical method on bubble dimensions from photograph. As expressed by eq. (3), void fraction may be related with dimensions of bubbles and tube bundles, and superficial air velocity. Number of bubbles N which pass through unit length of tube per unit time can be also expressed by mean bubble length ℓ_{oi} at minimum area of flow, dimensions of tube bundles and void fraction as shown by

Fig. 13 The effect of tube rows on void fraction

Fig. 15 Mean bubble height/length ratio

eq. (5).

$$N = \frac{PH - (\pi/4)d^2}{\ell_{oi}(P-d)H} \epsilon_B \dots (5)$$

Void fraction ϵ_B is given from eqs. (3) and (5) as

$$\epsilon_B = C \frac{PHV_{go}}{(PH - (\pi/4)d^2) \ell_{oi}} \dots (6)$$

Mean passing period of bubble τ in eq. (6) is approximately constant regardless of water and air flowrates from previous reports. Mean bubble height/length ratio $\bar{C}$ is shown in Fig. 15, which was calculated from relative frequency distributions of C described in the chapter 5. Mean bubble length ℓ_{oi} is shown in Fig. 16, which was calculated from relative frequency distributions of ℓ_{oi} described in the chapter 5. Relation between mean bubble length ℓ_{oi} and superficial air velocity was obtained by best fitting the data as follows.

$$\frac{\ell_{oi}}{L} = 0.029 \left(\frac{V_{go}}{P \sqrt{g/L}} \right)^{2/3} \dots (7)$$

The following equation (8) is obtained by substituting eq. (7) and values of $\bar{C}$ and τ into eq. (6). Where arithmetic average of τ was approximately 0.02 sec according to our previous works.

$$\epsilon_B = K \left(\frac{V_{go}}{\sqrt{Pg}} \right)^{2/3} \dots (8)$$

Fig. 14 A plot of void fraction vs. number of tube rows

Fig. 16 Mean bubble length