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Analysis of Heat Transfer in Two-Phase Two-Component Mixtures

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Abstract. The present paper analyzes the work done on the two-phase (gas-liquid) two-component (non-boiling) heat transfer system. The effect of gas addition into flowing liquid on the heat transfer rate is fully studied. Various mechanisms of this complex system are analyzed and discussed in order to improve the understanding of heat transfer enhancement as a result of the presence of gas phase accompanying a flowing liquid-phase. Various factors (either of design type or operating one) affecting the two-phase heat transfer system are searched, analyzed and discussed in detail. The present study reveals the significance of the various flow patterns and its vital reflections on the physical visualization of the two-phase heat transfer problem. Various hydrodynamic classifications of two-phase two component system, which best describe the heat transfer trend, are attempted. A simplified classification based on void fraction, which is easily determined, is established and therefore recommended for future work. Available two-phase heat transfer coefficient correlations are summrized and analyzed with suggestions for application. From literature analysis it is found that significant gaps exist, e.g. the urgent need for reliable design correlations concerning the two-phase sytem. Finally, this study will summarize the major conclusions derived from the present analysis together with recommendations for future work.

Introduction

Two-phase systems are largely found in industry but in most cases only single-component is present. A major difference which exists between two-phase single-component and two-phase two-component is that, while in the former case boiling normally constitutes the main mechanism, it is not the case in the latter system.

Two-phase two-component is attractive mainly because it could simulate the situation of the two-phase single-component, but with an independent control of the gas-phase rate and properties [1,2,3].

Although numerous published works on the single-component systems are available, limited number of works on two-component systems have appeared.

In the present work a detailed analysis and exploration of heat transfer mechanisms and the significant factors affecting the two-phase heat transfer coefficient will be carried out with special attention given to experimental work. Short discussion of available correlations for heat transfer coefficient is presented here, while a detailed study of correlation will be done separately later on. In addition, recommendations for future areas of research will be given later.

Effect of Introducing a Gas in a Flowing Liquid

All previous investigators have observed that the introduction of a gas (mostly air) into a flowing liquid enhanced the heat transfer process and resulted in a higher heat transfer coefficient than that for single-phase liquid at the same rate [4] (Fig. 1). In general the two-phase heat transfer coefficient increased with the increase in gas rate.

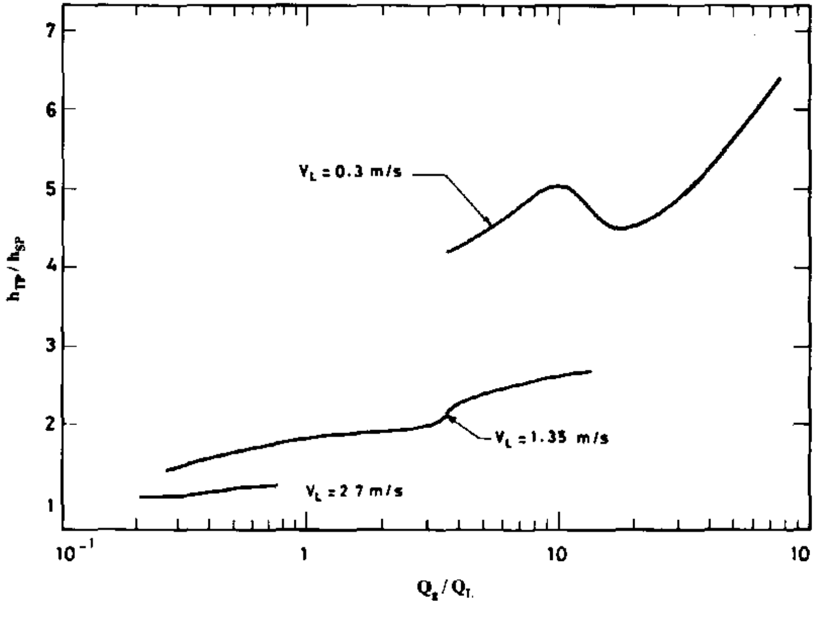

Fig. 1. Effect of gas addition (air) to flowing liquid (water) on heat transfer coefficient [2].

The effect of the presence of gas accompanying the liquid was not always positive. The published data of many investigators [2,3,5,6] showed that at very high liquid rates (much higher than 1 m/s) the effect of gas addition on heat transfer coefficient is not significant. This is clear especially at low gas rates as reported by Istayev [7] and Kudirka [2] (Fig. 1).

Many investigators who present their data in the form of ratio of two-phase to single-phase heat transfer coefficient, (h_{TP}/h_{sp}) have reported that this ratio increases with the decrease in liquid velocity at the same gas rate supporting the argument that the effect of gas addition was most pronounced at lowest liquid rates (Figs. 2 and 3).

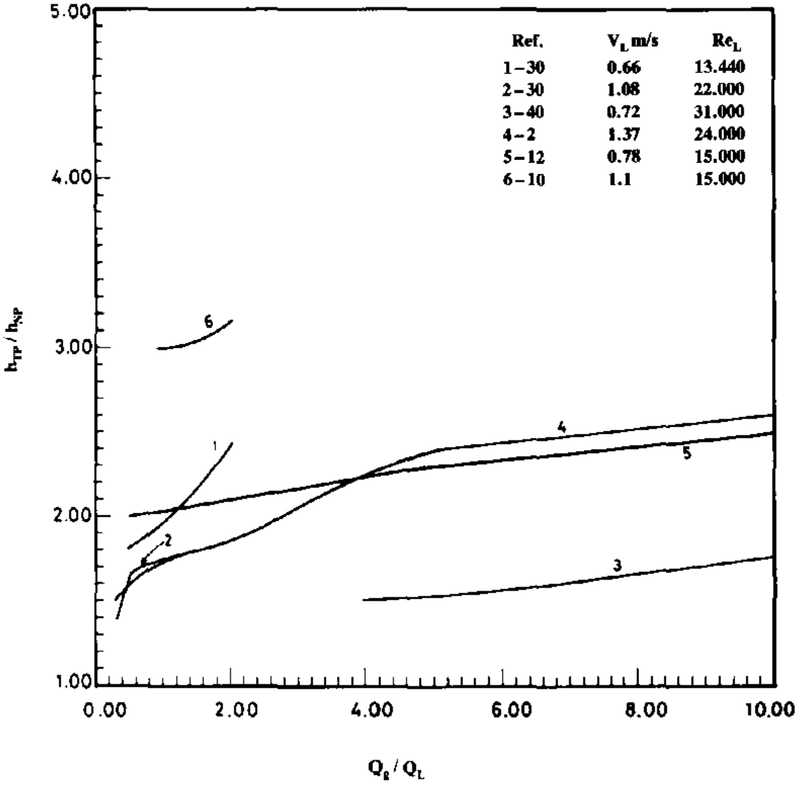

Fig. 2. Data of Mishiyoshi [8] with air injection through the heated surface.

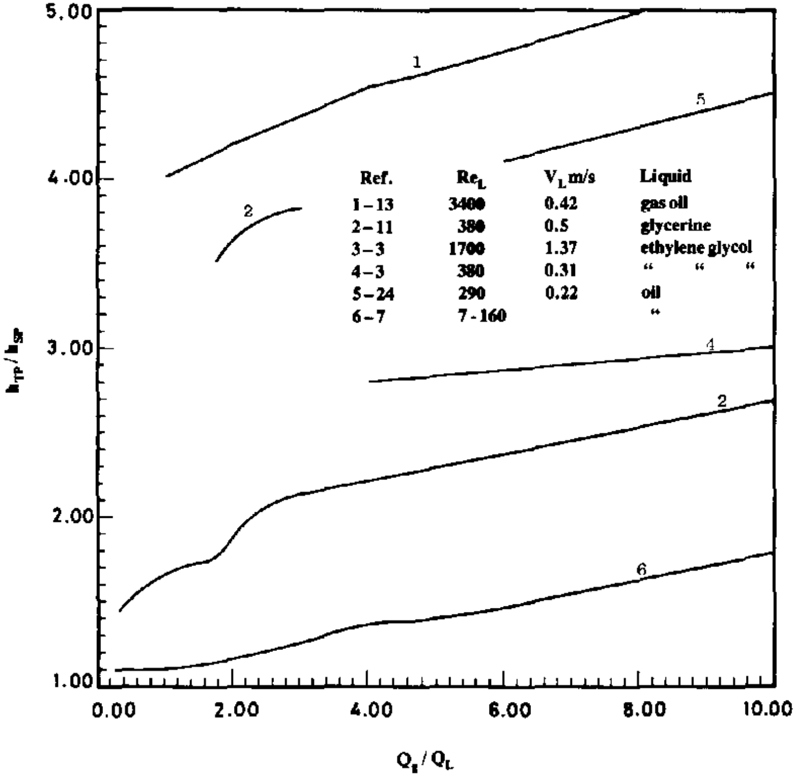

Fig. 3. Data of Mishiyoshi [8] with air mixed with water prior the heated suction.

3. Heat Transfer Mechanisms

From the analysis of the published data of the previous investigators [2,4,8,9,10], the reason for high increase in heat transfer coefficient in two-phase two-component mixtures over that of the single-liquid could be attributed to the following mechanisms:

1. Increased turbulence near the heated wall produced by the gas bubbles resulting in the decrease and the disturbance of laminar boundary sublayer, which is the major resistance to heat transfer. This could explain why the effect is more pronounced in the laminar flow (low liquid rate), in which the layer is originally

thick, than in turbulent flow as observed by the majority of investigators. This could also explain the high jump in heat transfer coefficient when first amount of gas is added (Figs. 2 and 3).

2. Increased turbulence and mixing action in the main stream due to the continuous interaction of the two phases. This is clear, especially when liquid is originally in laminar region where turbulence in the main stream is low.

3. Liquid and mixture velocity increase caused by the addition of the gas as a result of less cross-sectional area [2,4,8,11]. This mechanism is efficient only when the liquid is originally in a highly turbulent state, where the effect of the increased turbulence intensity is less significant. This could mainly explain the continuous increase in heat transfer coefficient, but with less significance, for most experimental data with the continuous increase in amount of gas added.

In fully turbulent region mechanism 3 seems controlling, while in the laminar and transition regions both mechanisms 1 and 2 are affecting. Meanwhile, Collier [9] claimed that mechanism 3 is the main mechanism in turbulent flow as well as in laminar and transition for bubble and slug regimes while mechanism 2 is only a source of additional increase in heat transfer coefficient for $Re_L < 10{,}000$. At very low liquid rates ($RE_L < 500$), the addition of gas may be insufficient to promote turbulence in which mechanism 3 is controlling.

Although Collier's explanation seems promising, no experimental evidence has been found for it [4]. Actually, the selection of the correct mechanism from those mentioned above depends on the flow pattern of the two-phase system and hence this will be considered later in more detail.

4. Factors Affecting Heat Transfer in Two-Phase Two-component Mixtures

Exploration of heat transfer data in two-phase mixtures available from different experimental work has been carried out throughout this study. During this work the author noticed that these data are scattered and large deviations are present in the results.

In spite of the difficulties encountered in comparing some reported work of various investigators, as it appears in Figs. 4 and 5 the author tried his best to overcome the problems concerning specific range of operation, method of data presentations and various apparatus design parameters in order to find out conclusive results of their work. Alahmad [4] has also reported the significant deviations between some investigators' data (Fig. 6).

The discrepancies between investigators' results are mainly due to interactions of many factors affecting the heat transfer. Because two-phase two-component is a

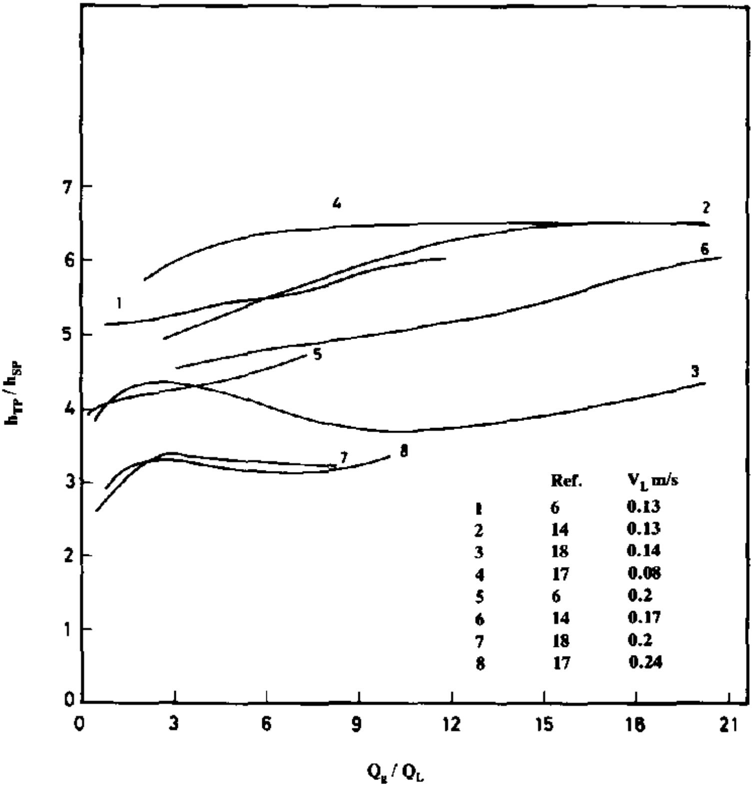

Fig. 4. Air/Water mixture data from various investigators results.

complex mixture, it is sensitive to any changes in apparatus configuration and/or operating conditions.

Because many factors simultaneously affect the heat transfer results, it is not an easy task to discuss separately the effect of each factor on the heat transfer rate. However, in the following discussion much care has been taken to minimize the effect of side factors, which might affect the heat transfer process, and almost identical exchangers and operating conditions have been chosen for comparison purposes.

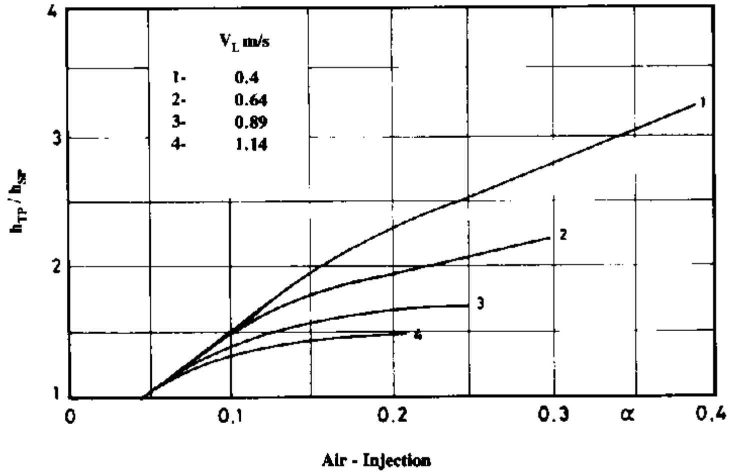

Fig. 5. Comparison between some investigators results.

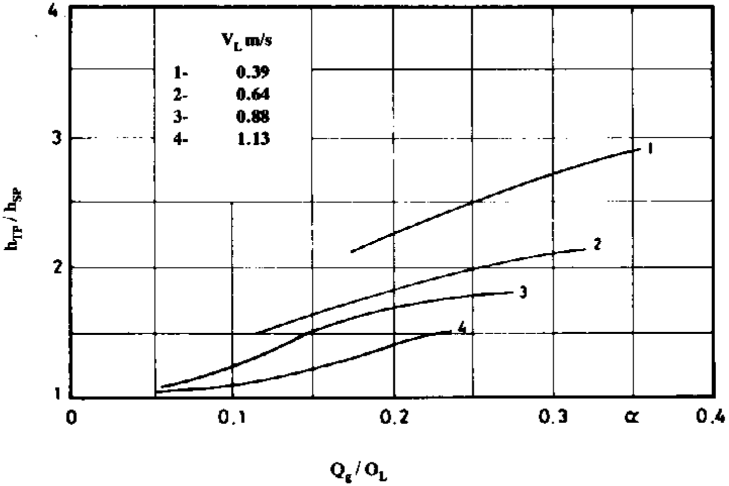

Fig. 6. Comparison of some investigators data carried out by Alahmad [4].

Apparatus geometry and configuration

Method of gas injection

The works of Gose [1], Kudirka [3] and Mishiyoshi [8] show that injection of the gas-phase through the heated wall results in higher heat transfer coefficient (Figs. 2 and 3) over that of gas/liquid mixture passing through the heated pipe. This could be mainly due to higher liquid film disturbance in the former case over that in the latter case. Evidence for this is observed from the work of Mishiyoshi, where peaks of local void fraction has been detected near the wall in the former case. Even though this phenomena is encouraging, this is true only in bubble flow and a limit for maximum gas rate injected through the wall is always present.

Gose [1] and Kudirka [3] reported that the rapid rate of increase of heat transfer coefficient did not persist and experimental values tended to level out, as larger volume of gas were injected through the heated wall. Mishiyoshi's explanation for this, that the liquid attempting to reach the heating surface is impeded by bubbling due to gas injection under a critical condition, seems reasonable. Actually the larger gas rate through the heated surface can build a gas film resistance for the heat transfer at the surface.

Exchanger tube length

The length of the heated section of the exchanger is found to be effective on the two-phase heat transfer coefficient especially at higher gas rates, corresponding to $Q_g / Q_L > 10$. The reason for this is the development of flow, which is likely to occur at longer heat exchanger, resulting in lower heat transfer coefficient. Meanwhile the stability of the flow regime (which is already developed) is affected significantly with different tube lengths. Comparison between the results of Groothius and Hendal [11] with that of Verschoor and Stemerding [12] at almost the same conditions but with different exchanger length supports the above argument (see Fig. 7).

Heat exchanger orientation (horizontal or vertical)

The exchanger geometry significantly affects the flow pattern, where different regimes have been detected in vertical tubes with some discrepancy with those in horizontal tubes. This, therefore, would affect the heat transfer coefficient. When comparing the work of Chue [10] with that of Abu-Sabe [13], in which very similar dimensions and operating conditions were used but with different orientation, it was found that the ratio h_{TP} / h_{sp} is higher ($\simeq 50\%$) in vertical exchanger than in horizontal exchangers. This is only true at low liquid velocities, while at higher values of liquid velocity almost identical results are observed (Fig. 8).

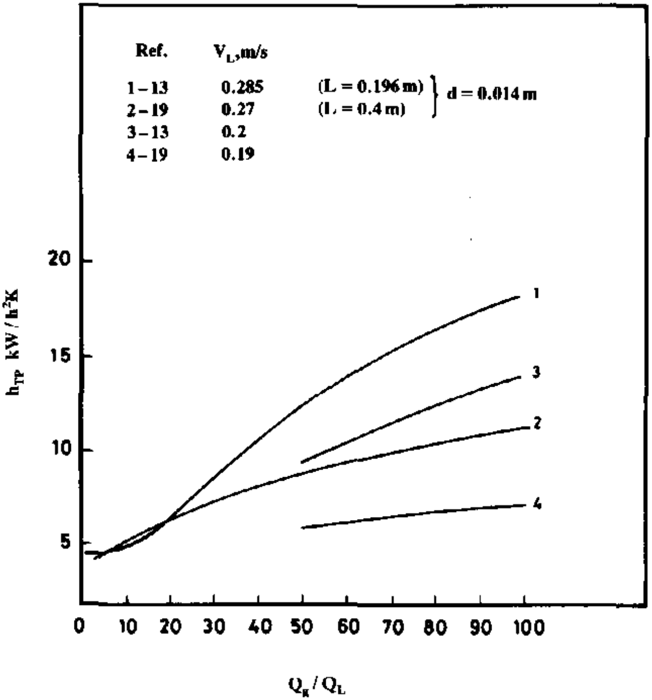

Fig. 7. Effect of exchanger length of the heat transfer coefficient (extracted from the data ov verschoor and that of Groothius).

Presence of calming section prior to the test section

Although this factor seems not significant, Vijay [14] showed that the absence of a calming section appears to influence the heat transfer coefficient at low values of Q_g and Q_L, where the velocity and thermal boundary layer develop simultaneously yielding higher values of h_{TP}. For highly viscous liquids, however, the thermal boundary layer develops very quickly, consequently minimizing the effect of calming section.

Diameter of heat exchanger tube

The effect of exchanger diameter on the heat transfer coefficient in two-phase system is similar to that in single-phase, that is an inverse relationship. This inverse

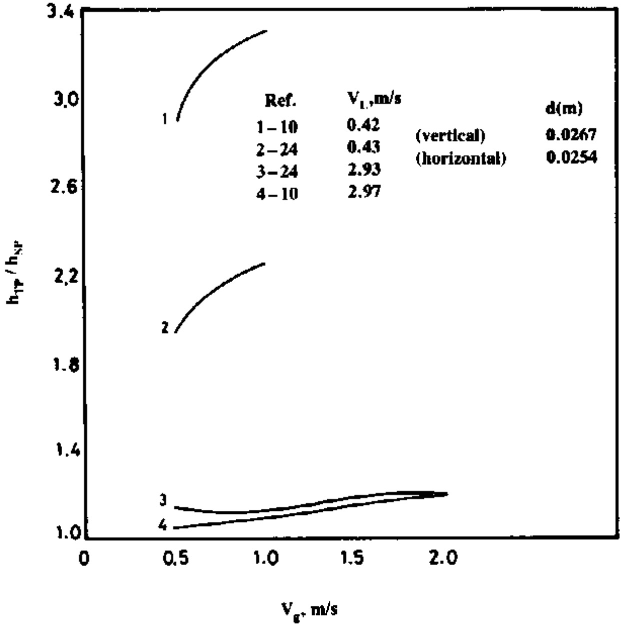

Fig. 8. Effect of heat exchanger orientation.

effect is due to the reduction in velocity with increasing the diameter. Evidence can be provided from comparison of Chue's results [10] with that of Elamvaluthi [15] with similar operation conditions and exchanger length but with different diameter as can be seen in Fig. 9.

Operating conditions

Direction of flow (up or down)

In laminar and transition region for liquid-phase, it is found that the heat transfer coefficient in upflow is generally higher than in downflow [16,17] for the same combination of gas and liquid rates (Fig. 10). This can be explained by the voidage distribution, where higher void fraction near the wall in upweard has been detected [10]. Thjis would result in more enhancement effect with respect to the boundary layer, which is the controlling factor for this situation. Although the results of Chue [10] are for local void fraction, it is a satisfactory evidence for this explanation. In tur-

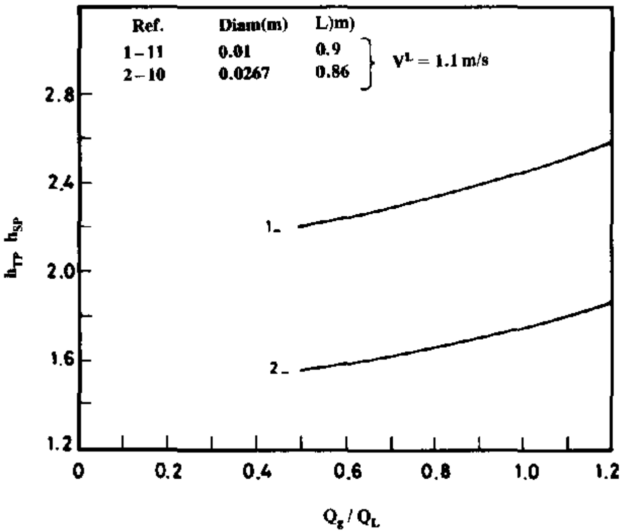

Fig. 9. Effect of exchanger diameter on the heat transfer enhancement (extracted from the data of Chue and that of Elamvaluthi).

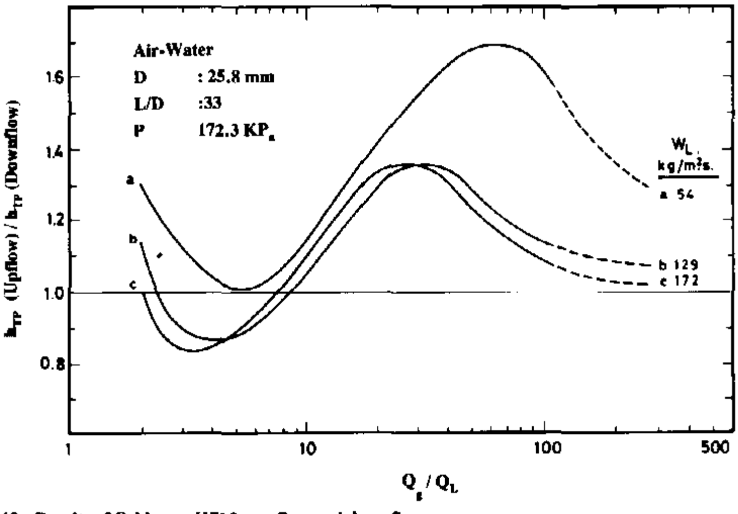

Fig. 10. Results of Oshinowo [17] for upflow and downflow.

bulent flow, Dorrestijin [16] reported similar values for heat transfer coefficient in both upflow and downflow. Meanwhile, Chuc [10] found that in fully turbulent region, the heat transfer coefficient in downflow exceeds that in upflow (Figs 11 and 12).

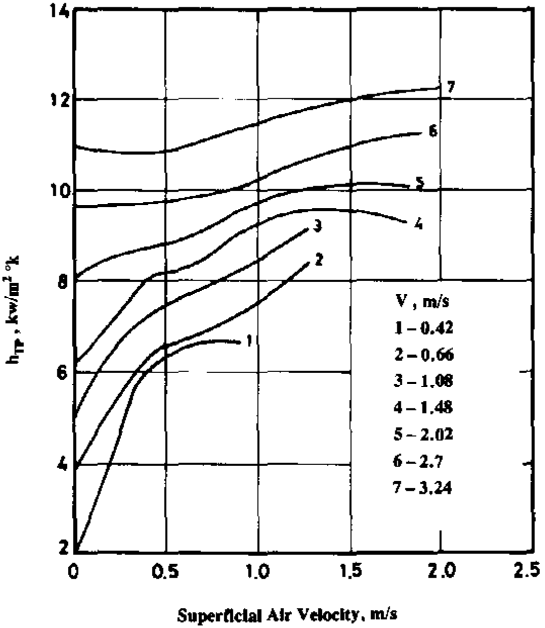

Fig. 11. Chue [10] results for air/water mixture flowing upward.

Chue has related this phenomenon to different flow patterns appearing in up and down flow as a result of higher void fraction reported in downflow than in upflow.

Actually if upflow is applied in fully turbulent region, this would enhance the rise velocity of bubbles and consequently reduces its residence time which means smaller voidage than in downward as measured by Chuc.

Liquid rate

Similar to single-phase, the heat transfer coefficient in two-phase mixture increases with the increase in liquid rate, keeping the gas rate constant [18]. The

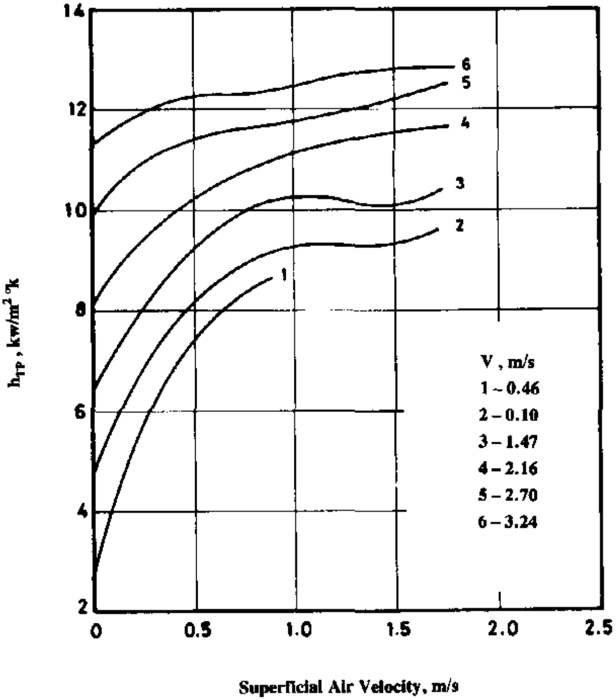

Fig. 12. Chue [10] results for downflow.

degree of dependence of heat transfer coefficient on liquid Reynolds number (corresponding to liquid rate) is not yet as well established as that in single-phase for laminar and turbulent region, where many suggestions for the value of exponent of liquid Reynolds number are available [3,17,19].

Gas flowrate

From the majority of investigators' results it is found that the heat transfer coefficient in the two-phase system increases with the increase in gas rate if the liquid rate is kept constant. Some researchers, however, noticed the presence of a local minimum in heat transfer coefficient for certain values of liquid rates (Figs 1 and 13). Also a maximum value for heat transfer coefficient, beyond which a decrease in the coefficient, has been detected by some investigators [11] (Figs 1 and 17).

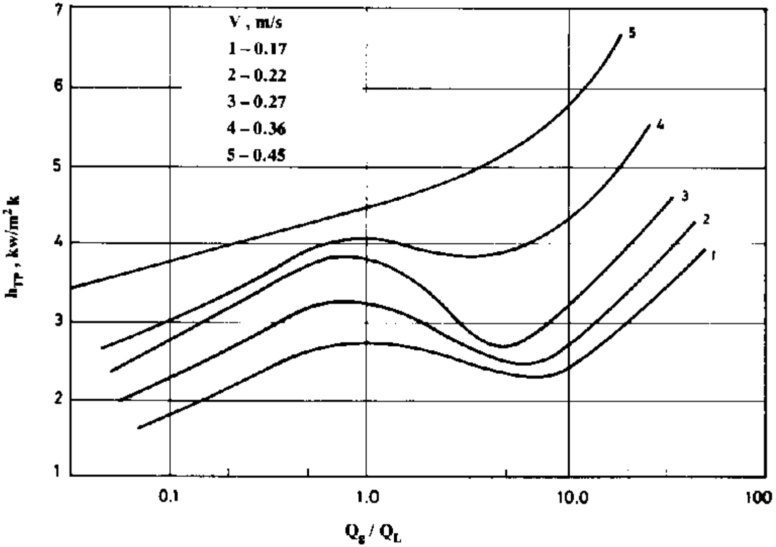

Fig. 13. Data of Kusorotov [18].

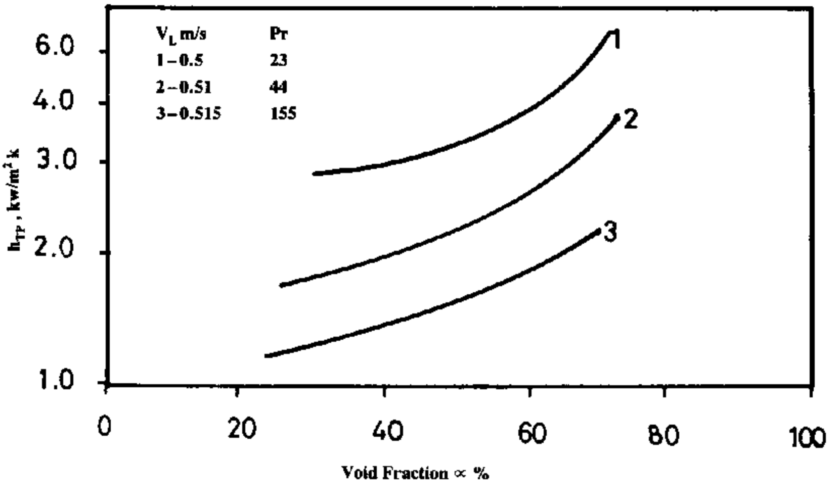

Fig. 14. Data of Ueda [20] showing effect of liquid viscosity.

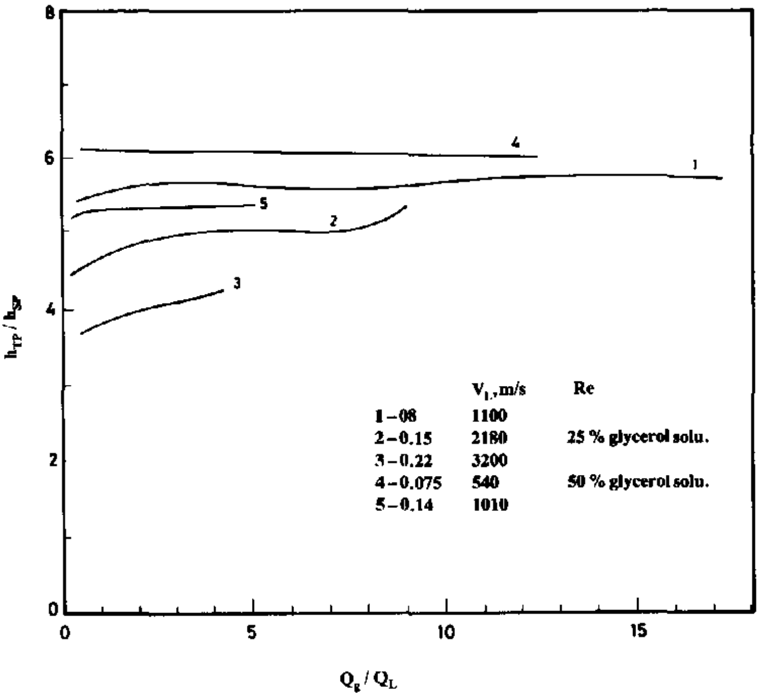

Fig. 15. Alahmad [4] data for viscous liquids.

While a small amount of gas injected has increased the heat transfer coefficient tremendously, much more quantity of gas is needed to keep continuous increase in heat transfer coefficient [4] especially at high liquid rate (Figs 4,6 and 12).

Liquid physical properties

The physical properties of liquid are believed to be dominant in determining the two-phase heat transfer coefficient because of its higher thermal properties. However, the liquid viscosity is the only property which has received extensive study concerning its influence on the heat transfer process.

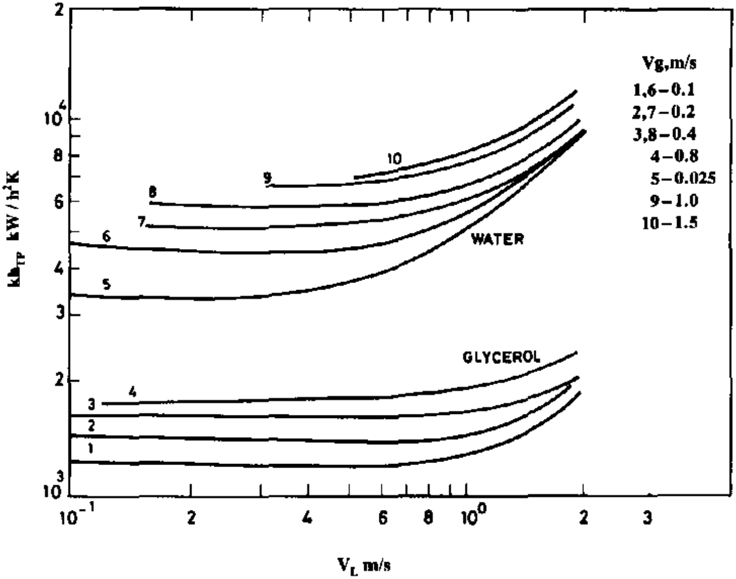

Fig. 16. Data of Domanski [21] showing effect of liquid rate.

Similar to single-phase, the heat transfer coefficient in two-phase mixture decreases with the increase in liquid viscosity as reported by some investigators [4,15,20] (Fig. 14). The two-phase heat transfer coefficient in viscous liquids follows similar trend to that of non-viscous liquids, but to lesser extent, and the enhancement in heat transfer is most pronounced at the lowest liquid rate and highest viscosity (see Figs. 15 and 16). The effect of increasing gas rate was, generally, not significant on the heat transfer coefficient [4].

Gas properties

Gas physical properties effect on two-phase heat transfer coefficient have received very little attention in the literature. This almost certainly is due to the less pronounced effects of the gas properties upon the heat transfer coefficient (being very low) compared with the effects of liquid properties.

Aggour [22] was the only investigator who had studied the effect of gas properties on the heat transfer coefficient. He observed that the density of gas is effective

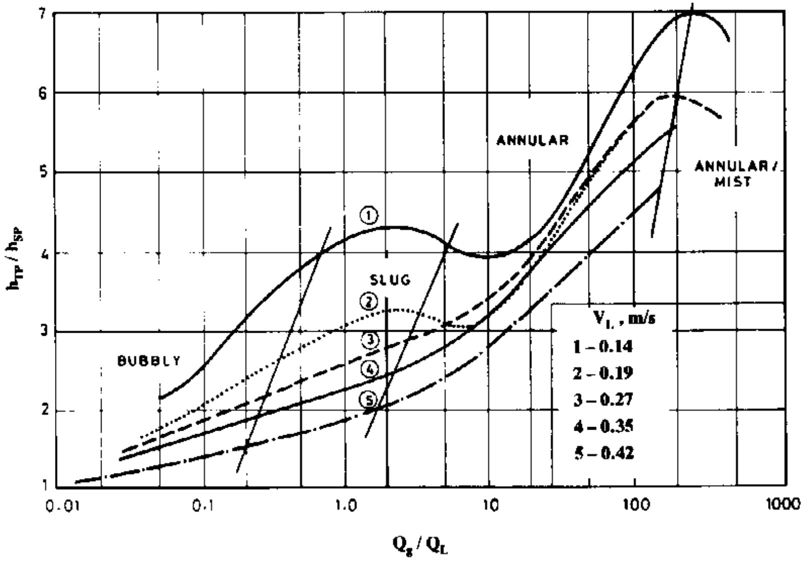

Fig. 17. Data of Verschoor and Stemerding [12].

only at low liquid rate associated with high gas rate and the relationship between the gas density and heat transfer coefficient was found to be proportional. No explanation was given by Aggour for this enhancement in heat transfer as a result of higher gas density. Actually for high gas rate associated with low liquid rate, the gas with higher density might have higher enhancement power on heat transfer not only due to pressure drop increase but also to its higher energy content per unit volume which would produce more turbulence in the system resulting possibly in thinning of liquid film.

Chemical composition of the gas-phase

As a result of heat added to flowing gas-liquid mixture, vaporization will occur from the liquid-phase to the gaseous phase resulting in two-component mixture in the gas-phase. The system is not pure heat transfer problem but it is the reflection of mass transfer limitation. Therefore, whether the gas-phase is wet or dry is important because a considerable amount of heat will transfer to the dry gas in the form of latent heat in the course of the saturation of the gas. This would affect the calculation of heat transfer coefficient unless the heat transfer taken up from liquid (mostly water) is included in the heat load. Both Ueda (20) and Alahmad [4] have reported the maximum heat gained by air in the form of latent heat as 5% and 1.5% respectively of the total heat load for the range of variables covered by them.

Flow Pattern and Heat Transfer

The flow pattern depends on many factors (basically those mentioned before as factors affecting heat transfer). Therefore it cannot be mentioned as an independent factor affecting heat transfer. It is actually a major (dependent) factor because many investigators related or described their heat transfer data according to different flow regimes.

It is worth mentioning here before describing investigators' remarks according to flow patterns that some problems exist when dealing with flow pattern. Those are basically: (A) Difficulty in identifying and classifying flow pattern, (B) Instability of the pattern itself; (C). Change in the flow pattern from inlet to outlet of the tube (when enough calming section is not available); (D). No single satisfactory flow pattern map for isothermal mixtures is present; (E). The heat addition would affect gas density resulting in different flow pattern. Even though the effect is not significant, it can not be ignored especially when high heat flux is added, and (F). Various degrees of low stratification in horizontal pipes complicate the flow pattern even further, suggesting different treatment of heat data due to different flow patterns produced.

The relationship between heat transfer and flow pattern is quite significant. The change in the slope of heat transfer coefficient is basically due to the change in flow pattern [3,4,5,7,8,10,17,20] (Fig. 17). Therefore a brief review of the major observations of the effects of flow pattern on heat transfer as given in literature is discussed below.

1. Maximum in heat transfer coefficient was detected at transition between annular and mist flow as reported by some investigators [12] (Fig. 18). This suggests that the highly turbulent motion of gas-liquid mixture with increasing amount of gas caused randomly distributed gas (air) spots to appear on the wall and thereby decreasing the heat transfer rate beyond the maximum [19].

2. In the transition region between slug and annular flow pattern, some investigators reported a local minimum in heat transfer coefficient (Figs 13 and 17). Chue [10], for instance, reported that this is true only in laminar and transition region, while in turbulent flow a monotonical increase is observed. The results of Verschoor and Stemerding [12] also shows the same observation but at $Re_L < 4000$ (basically laminar and part of transitioin).

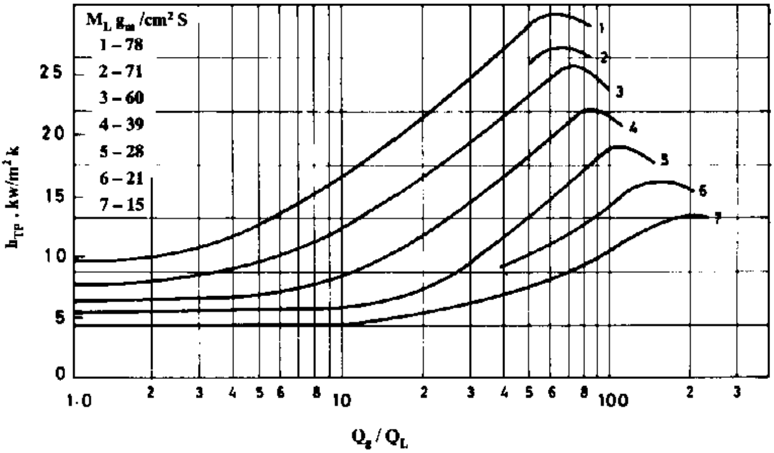

Fig. 18. Data of Croothivs and Hend [11].

The results of Kudirka [3] also shows a local minimum at $Re_L = 5500$ for water, which is believed to be in transition region from slug to annular flow pattern.

Meanwhile the results of Vijay [14] in vertical tube shows a local minimum in froth flow (transition region from slug to annular). The results, however, were correlated regardless of flow pattern with reasonable accuracy and a better representation of data would be possible if a separate correlation is used for each pattern.

In contrast with others' findings, Johnson's [13] results in horizontal tube shows a maximum in heat transfer coefficient at transition from slug to annular regime.

3. The results of Kosorotov [18] show a decrease in heat transfer coefficient corresponding to transition from bubble to slug flow at $Re_L < 3300$ (basically laminar) (Fig. 13).

4. Fedotkin [23] treated his experimental heat data according to flow pattern, suggesting different correlation for each pattern. Although this seems reasonable, it is still not favourable because of the difficulty in identifying the flow pattern, also the transition region will be difficult to deal with [24].

5. Oshinowo [17] who reported different heat transfer coefficient between up flow and downflow has attributed this to different flow patterns occurring between the two directions as can be seen in Figs 19 and 20.

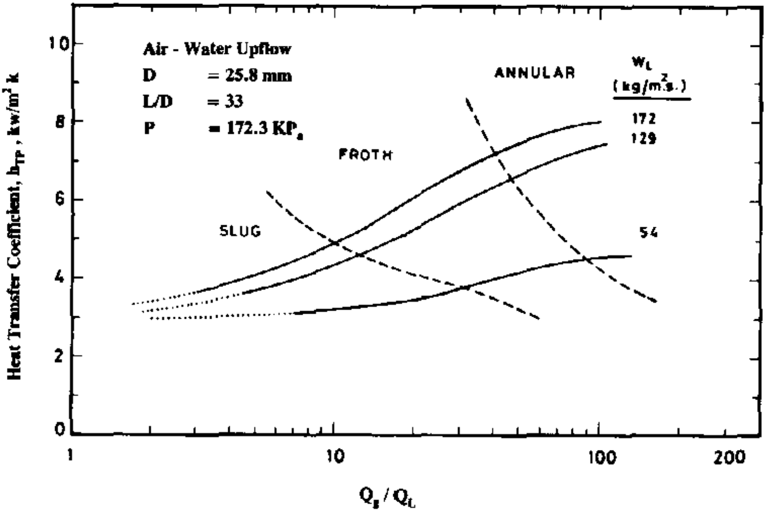

Fig. 19. Data of Oshinowo [17] for upflow.

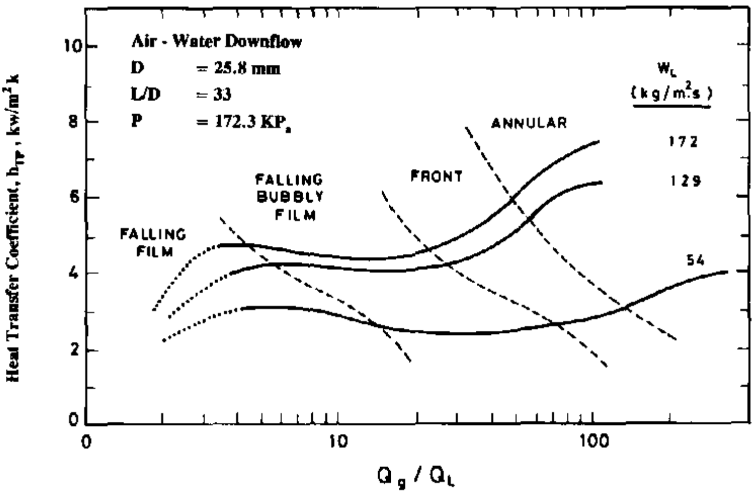

Fig. 20. Data of Oshinowo [17] for downflow.

Although flow pattern maps are available in literature, [25,26] there is a need to recommend a definite criteria for determination of flow patterns in non isothermal conditions of the two-phase system.

Hydrodynamic Classification of Two-phase Heat Transfer Data

Single-phase convective heat transfer can be easily treated as laminar, transition or turbulent flow. This is not the case in two-phase mixture, where four combinations could be present with ignorance of transition region and regardless of flow pattern. Lockhart and Martenlli [27], for instance, have suggested in their study of pressure drop in gas-liquid mixtures four combinations based on the individual flow (laminar or turbulent) of each phase.

Classification of two-phase two-component system is a difficult task because of the complexity of the mixture resulting from numerous factors affecting the system. It is important here to discuss this subject in order to describe and treat the heat transfer data correctly.

In spite of its importance, no analysis in literature was found except the general brief overview done by Kudirka [28] in early days. Collier [9] and Mishiyoshi [8] have classified simply the works done according to the four distinct flow regimes (bubble, slug, annular, mist).

In Table 1, some suggestions for the classification are given. It is always advisable to separate heat transfer in horizontal tubes from that in vertical tubes because of its significant effect on flow pattern [3,4].

Classifications based on reynolds number

Classification I

This classification is originally suggested by Lockhart and Martenlli [27] in order to correlate the pressure drop in two-phase mixtures. Although this classification seems simple it lacks a full description of the mixture. Also the effect of transition region for the gas-phase and the liquid phase is ignored.

Classification II

This classification is simply a development of that of single-phase. Although this approach seems attractive, is not easy to define the two-phase mixture Reynolds number. In literature some investigators have suggested to be the additive of the gas and liquid Reynolds number [15,23]. Others have suggested liquid Reynolds number based on actual velocity to be that of mixture [19,29]. It should be noted here that the

Table 1.

Classification I

- Laminar/Turbulent (gas / liquid)
- Laminar/Laminar (gas / liquid)
- Turbulent/Laminar (gas / liquid)
- Turbulent/Turbulent (gas / liquid)

Classification II

- Laminar mixture
- Transition mixture
- Turbulent mixture

Classification III

- Bubble flow
- Slug flow
- Annular flow
- Mist flow

Classification IV

- Bubble flow
  - Laminar liquid
  - Turbulent liquid
- Slug flow
  - Laminar liquid
  - Turbulent liquid
- Annular flow
  - Laminar liquid
  - Turbulent liquid
- Mist flow
  - Laminar gas
  - Turbulent gas

Classification V

- Continuous liquid (+ < 0.4)
  - Laminar liquid
  - Turubulent liquid
- Transition zone (0.4 <   < 0.6)
  - Laminar liquid
  - Turbulent liquid
- Continuous gas (> 0.6)
  - Laminar gas
  - Turbulent gas

transition region is difficult to deal with in single-phase, therefore it is expected to be even more difficult in the two-phase flow. Until accurate definition of mixture Reynolds number is found, it is advisable to refer to individual Reynolds numbers of the phases and to combine the transition region with the laminar region where almost the same heat transfer trend has been detected by some investigators [15,29].

Classifications based on flow patter

Classification III

This classification is simple because of the limited number of flow categories.

Classification IV

This is identical to the previous one but with more branches showing all possibilities of the mixture. Although this classification is most descriptive it is not practical due to numerous number of branches associated with. The difficulties encountered in with the use of both classification III and IV are mainly the flow pattern determination and the absence of the transition regions.

Classifications based on void fraction (Classification V)

This classification seems most reasonable. The use of void fraction is practical because it is easily determined both theoretically and experimentally.

Three different distinct regions according to the voidage are adopted in order to explain the heat transfer trend in two-phase mixture and the development in heat transfer coefficient as a result of the continuous gas addition.

Region I

The liquid is the continuous phase, and the void fraction is approximately less than 0.4. From exploration of some investigators' data, it is found that the increase in heat transfer coefficient is basically due to eddy mechanism of the flow by the gas bubbles. At this stage the flow pattern is basically bubbly.

Region II

At this stage the gas is the continuous phase ($\alpha > 0.6$) and the liquid is basically on the was of the tube forming a film. The flow pattern is basically annular and will turn to mist flow as the gas volume is increased. The heat transfer coefficient will increase here as a result of liquid film thinning and it will continue increasing with the more thinning of the liquid film as a result of the increase in gas rate. When the flow turns to mist flow, i.e. dry wall, because of the disapperance of the liquid film, the heat transfer coefficient will decrease because the liquid film is better heat transfer medium. The decrease in the coefficient will continue with the increase in gas voidage until single-phase gas is present, with heat transfer coefficient is approximately less than that of single-phase liquid originally present (Figs. 17 and 18).

Region III

In this region no clear continuous phase is present ($0.4 < \alpha < 0.6$) where each phase is forming almost half of the tube volume and non of them is controlling.

The flow pattern at this stage is basically churn flow and partly slug flow and perhaps the beginning of annular flow.

The heat transfer trend here is not settled because this is basically a transition region from bubble to annular flow, where these two regions are hydrodynamically settled. In churn flow a decrease in heat transfer coefficient is expected because the presence of large quantities of gas in the bulk of the tube with undefined shape will result in gas dead pockets that would temporary prohibit the heat transfer to the mixture.

If slug flow is present, the enhancement in heat transfer coefficient will depend on the type and shape of the slugs present. For very long gas slugs almost annular type of flow is present with liquid film thinning, resulting in enhancement in heat transfer rate. While for short small slugs a decrease in heat transfer coefficient is found (Fig. 21) at low liquid rates which is ascribed to the resistance added by the gas phase to the original resistance of liquid phase while at high liquid rates, a continuous increase in heat transfer coefficient is detected [7,12]. It is worth mentioning here that Ueda [20] himself did not give explanation for such decrease in heat transfer coefficient.

Correlations of Two-phase Two-component Heat Transfer Coefficient

Correlations available in literature can be divided into two sets based on the method of predicting the heat transfer coefficient for the two-phase mixture. The first set is in the form of dimensionless correlations similar to those of single-phase with modification to account for gas-phase presence (Table 2).

Those correlations are limited to each investigators' data where large variation is observed in experimental set up and operation conditions between investigators' work (Table 3).

Meanwhile Katsuhara [6] suggested a dimensionless correlation for prediction of two-phase heat transfer coefficient in the form of

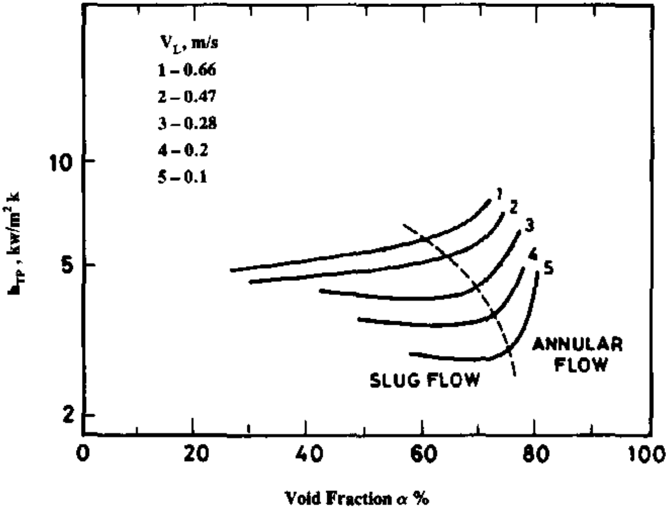

Fig. 21. Data of Ueda [20] for air/water mixture.

$$Nu_{TP} = \frac{h_{TP}}{k_m} = C\,K^{-0.5m}\,[Re_m(1-\alpha)^{0.5}]^m\,Pr_m^n$$

where n,m,c are constants, based on experimental data.

K : a parameter based on flow pattern

$$Re_m : u_m\,(d/v_m), \qquad u_m = (m_L + m_g)/\rho_m A_t$$

Pr_m, k_m and v_m are functions of individual gas and liquid values such that

$$(Prop)_m = \left(\alpha\frac{\rho_g}{\rho_m}\right)(Prop)_g + (1-\alpha)\frac{\rho_L}{\rho_m}(Prop)_L$$

$$\rho_m = \alpha\,\rho_g + (1-\alpha)\,\rho_L$$

When applying his own data, Katsuhara found that

$$Nu_{TP} = 8.7\ Re_m^{0.25}\,(1-\alpha)^{0.125}\,Pr_m^{0.4}$$

This is the only correlation to the authors' knowledge which considered the physical properties of the mixture rather than the individual properties of each phase (as in

Table 2. Summary of previous investigators' results

Author	Test section	Orientation and direction	d mm	L/d	q KW/m²	Fluids	M_L kg/m².s	Q_g/Q_L	Re_L	Flow Pattern	h_{TP} KW/m².K	h_{TP}/h_{sp}	Remarks
Verschoor [12]	Steam heated	Vertical up	14.0	28	–	Air/water	140–446	0.1–200	$(64–192)10^3$	B,S,A	2.3–12.5	1.1–6.8	
Gose [1]	Elec. heated	Vertical up	22.2	6.9	–	N_2/water	44–940	–10.2	750–20500	–	2.3–5.3		
Groothuis [12]	Steam heated	Vertical up	14.0	14	–	Air/water Air/oil	200–800 220–420	1–20 1–40	> 5000	B,S,A	1–7	1.8–6.2 4.1–10.9	
Knott [5]	Elec. heated	Vertical up	13.0	118	–	N_2/oil	54/1400	0.1–100	7–162	B	–	1.0–6.7	
Kosorotor [18]	Elec. heated	Horizontal	6	167	45–50	Air/water	170–450	0.05–50	$(2.2–4.9)10^3$	B,S,A	1.8–6.4	1.5–3.0	
Kudirka [3]	Elec. heated	Vertical up	15.9	14	–	Air/water air/eth. glycol	305–2750 344–1526	0.16–75 0.25–75	$(5.5–48)10^3$ 380–1700	 B,S,A	8.8–17.6 8.8–17.6	1.1–6.25 1.08–6.84	
Dorresteijn [16]	Elec. heated	Vertical up/down	70	16		Air/oil	20–2460	–4500	290–67300	B,S,A	0.5–1.6		
Fedotkin [23]		Vertical	10,21.5, 30			Air/liq. ($\mu_L = (0.3–28)10^{-6}$m²/s)				B,S,A,M			
Chu [10]	Elec. heated	Vertical up/down	26.7	34	55	Air/water	416–3211	0.12–2.14	$(16–123)10^3$	B,S,A	6–12.7	0.96–3.07	
Elamvaluthi [15]	Elec. heated		10	86		Air/water glycerin H_2O/Fe,He	300-1600 200-1500	0.3–2.5 0.6–4.6	$(180–1.3)10^5$ 300–16500	B,S,A B,S		 1.2–4.7	

Table 2. *Continued...*

Author	Test section	Orientation and direction	d mm	L/d	q KW/m^2	Fluids	M_L $kg/m^2.s$	Q_g/Q_L	Re_L	Flow Pattern	h_{TP} $KW/m^2.K$	h_{TP}/h_{sp}	Remarks
Vijay [14]	Elec.		11.7	52		Air/water glycerin H_2O/Fe.Hc	0.013-	$(180\text{-}1.3)10^3$ 5200	B,S,A	C,M			
Oshinowo [17]	Elec. heated	Vertical up/down	25.8	33		Air/water	54–172	2–220	1700–5600	B,S,A	3–8		
Ravipudi [19]		Vertical up/down	19.1	79.8		Air/water	305–2448	1–100	8554–89626			1.01–3.18	
Ueda [20]	Elec. heated		51	1.96	$3.5x10^3$ $-5.6x10^4$	Air/water		0.3–100		B.A		1.6–8.0	
Martin [30]	Elec. heated	Horizontal channel	13.7 6.5			Air/water			7800–13500				
Mishiyoshi [31]	Elec. heated	Vertical annulus	equiv.	75	11–44	Air/water			15400–52000	B,S		1.0–3.0	

Table 3. Dimensionless correlations for two-phase heat transfer coefficient

$$Nu_{TP} = a\, Re_m^b\ (\mu_g/\mu)^c\ (Q_g/Q_L)^d\ Pr_L^{0.33}\ (\mu_b/\mu_w)_L^{0.14}\ W$$

Investigator	Re_m	a	b	c	d	W	Remarks
Kodirka [3]	Re_L	125	0.25	0.6	1.125	1.0	The effect of gas phase presence is considered as the ratio of its rate to that of liquid, while the mixture Reynolds number is defined as that of the liquid.
Ravipudi [19]	Re_L	0.56	0.6	0.2	0.3	1.0	
Oshinowo [17]	Re_L	0.86	0.6	0.2	0.26	1.0 (up flow)	
		1.20	0.6	0.2	0.1	1.0 (down flow)	
Elamvaluthi [15]	$Re_L + Re_g$	0.5	0.7	0.25	0.0	1.0	A new definition for mixture Reynolds number is suggested here, i.e. additive of individual gas and liquid Reynolds numbers. This seems over simplification of the problem because the effect of Re_g is definitly not the same order as that of Re_L.
Fedotkin [23]	$Re_L + Re_g$	function of diam. and pattern		0.25	0.0	1.0	
Goothius [11]	$Re_L + Re_g$	0.029	0.87	0.0	0.0	1.0 (air/water)	
		2.6	0.39	0.0	0.0	1.0 (air/gas oil)	
Kosorotov [18]	$Re_L + Re_g$	0.065	0.69	0.0	0.0	1.0	
Lunde [29]	$Re_L/1-\alpha$	0.022	0.8	0.0	0.0	(Pa/P) 0.17	Mixture Reynolds number is defined here as that of liquid but based on the actual liquid velocity rather than the superficial velocity. Although the liquid is the main heat transfer medium in many flow regimes and the gas phase effect is mostly in mixing, turbulence and velocity increase action, still significant effect might be detected due to gas/liquid interaction where gas properties cannot be ignored.
Chue [10]	$Re_L/1-\alpha$	0.45	0.55	0.0	0.0	(Pa/P) 0.17	

second group in Table 2). The definitions of Nu, Re and Pr numbers of the two-phase system are attractive because this seems more realistic in describing the system. When mixture physical properties are correctly identified, this will lead to better correlations of the heat transfer data of such complex mixture. Although this correlation seems most promising one in the literature, however the values of the constants depend mainly on their experimental ranges and hence cannot be generalized.

The second trend in correlating the two-phase heat transfer coefficient is in the form of enhancement over that of single-phase liquid (h_{TP} / h_{sP}). This form is superior in reducing the effect of each investigator's experimental set up and operational conditions (Table 4). Those correlations mostly based on experimental data for limited range of variable covered by each investigator and non has suggested a general one which could be successful in predicting other's data.

Major deficiency in those correlations is the absence of the effect of the liquid rate, where experimental evidence showed definite trends of heat transfer enhancement for definite liquid rates [4,14]. Also the mixture properties are completely ignored while if considered a better prediction is expected.

Meanwhile, Drucker [33] did a theoretical analysis of heat transfer enhancement as a function of void fraction and found that:

$$h_r = 1 + 25 \left(\frac{\alpha\, Gr_c}{Re_c^2}\right)^{0.5}$$

where C : continuous phase = liquid ($\alpha < 0.4$)

The correlation was successful in predicting data collected from literature for wide range of liquid Reynolds number [$(2 - 150) \times 10^3$] and up to vodage of 0.4

The correlation is also suggested for higher voidage ($\alpha < 0.4$), where the gas is the continuous phase and the liquid is the dispersed phase but it is not tested in this range. A transition region is expected where no continuous phase, for voidage between 0.4 and 0.6 and both phases are effecting which needs different treatment of the system.

The correlation seems most promising for heat transfer enhancement prediction because both Gr and Re numbers have been considered in the correlation and are believed to have significant effect on the heat transfer enhancement.

The correlation, however, is developed from air/water data. If viscous liquids are used (high Pr), Drucked stated that with the uncertainty of the available data the enhancement (h_{TP}/h_{sP}) is idependent of Pr number. This is susbisions because evi-

Table 4.

Investigator	$h_r\,(h_{TP}/h_{SP})$	Remarks
Collier [9] & Aggour [22]	$(1/1-\alpha)^a$ a = 0.33 (laminar liquid) = 0.8 (turbulent liquid)	The correlation is limited to basically bubble flow and frequently to slug flow, where enhancement is due to increase in liquid velocity. An additional enhancement which must be considered at low liquid Reynold number corresponding to the viscous and transition region is completely ignored.
Shah [24] Knott [5]	$(1+Q_g/Q_L)^a$ a = 0.25 (Shah) = 0.33 (Knott)	It is limited to very low liquid Reynolds number ($Re_L < 170$)
Martin [30]	$1+0.64\,(Q_g/Q_L)^{0.5}$	It is restricted to special geometry (horizontal duct with exclusion of stratified and froth flow ($Re_L < 14000$)
Vijay [14]	$(\Delta P_{TPF}/\Delta P_{sp})^n$ n : depends slightly of flow pattern with average value of 0.454	Almost no dependence on liquid Reynolds and Prandtl numbers. It does not apply to annular-mist transition region and does not work well for slug and slug-annular transition flow with low frictional pressure drop
Mishiyoshi [32]	$1+a\,X_{tt}^b$ a,b varies for premixing of gas with liquid and gas injection through the heated surface X_{tt} : Lockhart-Martenll Modulus	The scheme is identical to two-phase single-component mixture (boiling)

dence from literature [3,4,11,15] (Fig. 15) shows that higher enhancement in heat transfer coefficient is achieved for higher Prandtl number. Although the effect of Prandtl number is not significant, it cannot be ignored. If Drucker correlation is corrected to include Pr number it will definily be the best correlation which can be generally applied.

Conclusions

1. Significant enhancement in heat transfer can occur as a result of gas addition to flowing liquid-phase.

2. The enhancement in heat transfer is mainly due to reduction in boundary sublayer thickness; increase in liquid velocity and the increase in turbulence and mixing action in the main stream, as a result of gas addition.

3. Classification of two-phase system data is significant but it is not easy. Two distinguished classifications have been found in literature; the first is based on flow pattern and the second on Reynolds number (either that of the mixture or of the individuals). A new classification based on the void fraction has been recommended which is believed to overcome the difficulties encountered in the use of the previous ones.

4. The void fraction (gas holdup) is a significant parameter for understanding the enhancement mechanism of heat transfer in two-phase mixture.

5. Heat transfer is strongly related to flow patterns which evolve under different flow conditions of both gas and liquid phases.

6. Until a full understanding of the two-phase system is achieved, it is too early to make strong comparison between investigator's results.

7. Range of variables covered by different investigators is limited. Basically gas and liquid rates are the major parameters studied extensively in literature.

8. Available correlations of the mixture heat transfer coefficient lacks satisfaction in precise prediction of the system.

Recommendations

1. Flow pattern studies and hydrodynamics of two-phase have to be given more attention in future work to simulate the understanding of the heat transfer mechanism.

2. The void fraction (gas holdup) approach needs further study as it is promising and can help in understanding and simplifying the two-phase heat transfer problem.

3. The measurement of transport properties of gas/liquid mixture as a system by itself using suitable techniques is highly recommended.

4. Precise specifications of experimental design and operating conditions have to be given more attention and to be mentioned in any published work.

5. Factors affecting the heat transfer enhancement should be studied carefully using the same apparatus, to minimize the errors expected from side parameters, in order to get comprehensive understanding of the effect of each individual factor investigated.

6. There is an urgent need for more reliable design correlations for the two-phase system.

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تحليل عمليات انتقال الحرارة في المخاليط
ثنائية الطور ثنائية المكوّنات

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(استُلم في ١٣/٦/١٩٩٠م؛ قُبل للنشر في ٦/١٠/١٩٩١م)

ملخص البحث. تشتمل الدراسة الحالية على تحليل عمليات انتقال الحرارة في المخاليط ثنائية الطور (غاز وسائل) ثنائية المكوّنات.

ولقد درس أثر وجود الغاز على عمليات انتقال الحرارة في السوائل الجارية. ولقد حللت الآلية كيما تساعد في فهم أسباب التحسين الملحوظة كنتيجة لوجود الغاز مصاحبًا للسائل.

ولقد استقصيت العوامل المؤثرة على انتقال الحرارة سواءً المتعلقة بالتصميم أو طريقة العمل.

وبيّنت الدراسة أهمية أشكال السريان وأثرها على عمليات انتقال الحرارة ولقد سبرت التقسيمات المحتملة للخليط، وأقترح نموذج عملي بسيط ومناسب مبني على نسبة الفراغات في الخليط.

وأيضا استقصيت المعادلات المختلفة لعمليات انتقال الحرارة في الخليط مع توصيات للأنسب منها والأصلح للاستخدام.

وختمت الدراسة بأهم الاستنتاجات وكذلك الاقتراحات للدراسات المستقبلية.