New Data on Two-Phase, Two-Component Heat Transfer and Hydrodynamics in a Vertical Tube

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In forced-convective, two-phase, two-component (gas-liquid) flow, experimental data for mean heat-transfer coefficients, pressure drop and flow patterns were taken simultaneously for the flow in a 0.46-in. (1.17-cm) i.d. electrically heated vertical tube using three liquids: water, a glycerine-water solution (58–42% by weight), and silicone liquid (Dow Corning 200, 5 cS viscosity grade) with air as the gas phase. The combination of silicone liquid and the glycerine-water solution provided a set of data, appearing for the first time in the literature, in which the surface tension changed by a factor of 3.4 (being lower for the silicone liquid) with a rough matching of other hydrodynamic properties and a precise matching of the Prandtl number (63 at 25°C). The flow-pattern results showed a significant change in the bubble-slug boundary for the silicone liquid compared with the glycerine-water solution, whereas the total pressure drop for silicone/air in the range of superficial liquid velocity V_{SL} of $0.910 \leqq V_{SL} \leqq 2.26$ ft/s ($0.277 \leqq V_{SL} \leqq 0.690$ m/s) at high gas flow rates showed a sudden drop followed by a subsequent increase. The behavior of the mean heat-transfer coefficient $\bar{h}_{TP}$ for silicone/air in the range $0.260 \leqq V_{SL} \leqq 2.26$ ft/s ($0.080 \leqq V_{SL} \leqq 0.690$ m/s) at high gas flow rates has not been seen with other liquids ($\bar{h}_{TP}$, after a maximum decrease, goes through a minimum, and then increases again).

Nomenclature

A_t = cross-sectional area of the tube
C_p = specific heat at constant pressure
D = inside diameter
$\bar{h}$ = mean heat-transfer coefficient
k = thermal conductivity
$\dot{m}$ = mass flow rate
$\overline{Nu}_{TP}$ = two-phase mean Nusselt number $= \bar{h}_{TP}D/k_L$
Pr_L = liquid Prandtl number $= \mu_L C_{pL}/k_L$
q''_w = heat flux at the wall
Re_{SL} = superficial liquid Reynolds number $= \rho_L V_{SL} D/\mu_L$
$\bar{T}_{\text{Mix}}$ = average bulk temperature of the mixture in the heated test section $= (T_{\text{Mix},i} + T_{\text{Mix},e})/2$
V_{SG} = superficial gas velocity $= \dot{m}_G/\rho_G A_t$
V_{SL} = superficial liquid velocity $= \dot{m}_L/\rho_L A_t$
We_{SL} = superficial liquid Weber number $= \rho_L V_{SL}^2 D/\sigma$
z = distance from the start of the heated test section
α = void fraction
ΔP = pressure drop
μ = viscosity
ρ = density
σ = surface tension

Subscripts

B = bulk
e = exit from heated test section
Exp = experimental
G = gas phase
i = inlet to heated test section
L = liquid phase
Mix = mixture of gas and liquid
Pred = predicted
SG = superficial gas
SL = superficial liquid
TP = two-phase
TPF = two-phase frictional
W = wall

Introduction

COMPREHENSIVE literature reviews on the subject of forced-convective heat transfer (with no evaporation) in two-phase, two-component cocurrent flow in a vertical tube have been conduced by Collier[1] and Michiyoshi.[2] Although a number of experiments (e.g., Groothuis and Hendal,[3] Kudirka et al.,[4] and Ueda and Hanaoka[5]) have been performed involving different liquids and gases, the effect of changing the fluid properties on the heat-transfer coefficients (both local and mean) has not been studied exhaustively. The property receiving the most attention appears to have been the liquid-phase Prandtl number. On the other hand, surface tension and attendant changes in the liquid-phase Weber number have not received much attention. The most relevant contributions are discussed later in the paper.

If one is interested in the effect of surface tension (or Weber number as it appears in the dimensional analysis below) on the various dependent variables, then obviously it would be ideal to have two (or more) liquids whose properties are identical except for the surface tension σ. However, with pure liquids, a precise match of all the other properties excepting σ appeared to be impossible. A dimensional analysis, assuming gravitational forces are unimportant and for a long enough test section, yields for heat transfer

$$\overline{Nu}_{TP} = f\left(Re_{SL}, Pr_L, \frac{V_{SG}}{V_{SL}}, We_{SL}, \frac{\rho_G}{\rho_L}, \frac{\mu_G}{\mu_L}, \frac{k_G}{k_L}, \frac{C_{PG}}{C_{PL}}\right) \tag{1}$$

If the tube wall is wetted, and the liquid layer is thick enough to contain the main resistance to heat transfer, it is expected that, at least to a first approximation, the last three groups in Eq. (1) would be unimportant. Equation (1) would then become

$$\overline{Nu}_{TP} = f\left(Re_{SL}, Pr_L, \frac{V_{SG}}{V_{SL}}, We_{SL}, \frac{\rho_G}{\rho_L}\right) \tag{2}$$

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Consideration of Eq. (2) determined how the liquids were selected and how the data were taken in the present study.

The present investigation was carried out experimentally using three pure liquids: water, a glycerine-water solution (58–42% by weight), and silicone liquid (Dow Corning 200, 5 cS viscosity grade) with air as the gas phase. The water/air data were used to check against the earlier results taken on the same rig by Vijay,[6] Aggour,[7] and Zaidi and Sims.[8] The latter work is of special interest here, as in that study water/air and a surfactant-solution/air were used. The combination of silicone liquid and the 58–42% glycerine-water solution was chosen because of the low surface tension for silicone (19.7 dynes/cm at 25°C), safety aspects, the much higher surface tension for the glycerine-water solution (67 dynes/cm at 25°C), together with a rough matching of the hydrodynamic properties (the ratio of the liquid densities and viscosities were 25 and 80% higher for the glycerine-water solution) and a precise matching of the liquid Prandtl numbers (63 at 25°C).

Considering again Eq. (2), having the same Re_{SL}, Pr_L, V_{SG}/V_{SL}, and roughly the same ρ_G/ρ_L, differences in $\overline{Nu}_{TP}$ could be basically attributed to differences in We_{SL} through changing the surface tension [for conditions, of course, where Eq. (2) would be valid]. Even if the assumption regarding the last three groups in Eq. (1) does not hold over the full range of data taken, the present work reports new data for two liquid-gas combinations where measurements of the heat-transfer coefficients, total pressure drop, and flow-pattern observations were taken simultaneously in this systematic way.

Experimental Apparatus and Procedure

Apparatus

The experimental apparatus (a schematic diagram is shown in Fig. 1), essentially the same as that of Vijay[6] and Vijay Sims[9] with some modifications on the instrumentation side, consisted primarily of the following: 1) liquid-flow circuitry including a positive-displacement pump, a heat exchanger, and flow meters, 2) an airflow system including a compressor and flow meters, 3) a gas-liquid mixing chamber in which the air was blown radially inwards into the liquid flowing vertically upwards, 4) a calming-length tube of 0.46-in. or 11.7-mm i.d. with a length of 5.0 ft or 1.542 m, 5) a 2.0-ft or 610-mm long × 0.46-in. or 11.7-mm i.d. × 0.020-in. or 0.51-mm thick, type 304 stainless steel test-section tube electrically heated using ac power with the tube as a resistor; the heated tube was surrounded by a guard heater made of a split copper tube with upper and lower sections, these sections being heated independently by two dc power supplies; copper-constantan AWG # 36, 0.005-in. (0.0127-mm) diam thermocouples were located on the outside surface of the heated section for measuring the wall temperature, and copper-constantan AWG # 30, 0.010-in. (0.254-mm) diam thermocouples were located on the inside surface of the guard heater for measuring the inside guard heater wall temperature, 6) a transparent section, of the same inside diameter as that of the heated tube and 1-ft (30.5-cm) long, located directly on top of the heated section, and 7) a gas-liquid separator where the liquid was separated for recirculation in the loop.

Temperature measurements, using thermocouples, were taken for the heated-section outer wall, the inner wall of the guard heaters, the fluid at the inlet and outlet of the mixer, and the outlet of the visualization section. For obtaining length-mean heat-transfer coefficients, local temperatures at seven elevations were used (each with four thermocouples around the circumference, and so giving a mean temperature at each elevation); these elevations in terms of z/D, as measured from the lower bus bar, were 4.35, 9.78, 16.3, 23.9, 35.9, 45.7, and 48.9. The thermocouple emf's were recorded by any one or a combination of 1) a 60-channel Fluke data logger with a scanning speed of 15 channels per second, 2) a digital voltmeter (DVM), 3) a two-pen strip-chart recorder. The local heat flux was calculated knowing the tube resistivity and the current flowing through the tube.

The total pressure drop across the test section was measured by means of three Rosemount differential pressure transmitters covering a range of readings from −25 to 750 in. (−0.635 to 19.05 m) of water, and a fourth gage-pressure transmitter to measure the gage pressure at the inlet to the heated section (its range was from 0 to 100 psig, or 0 to 690 kPa). The distance between the pressure taps was 24.5 in. (62.4 cm). The flow patterns were observed and photographed through the acrylic transparent visualization section, using an EG&G Microflash electronic flash unit (duration ~ 0.5 μs) with the driver unit producing a 2-KV pulse to trigger the flash.

Some of the liquid properties were measured in the laboratory to check against tabulated values; these properties were the liquid viscosity and surface tension (using a Fisher 215 Autotensionmat Surface Tension Analyzer for the latter). Calibration of the instrumentation is described in Rezkallah[10] and Vijay.[6]

Procedure

The main independent variables were the air and liquid flow rates and liquid used. The dependent variables reported in the present study are the heat-transfer coefficient, total pressure drop, and flow patterns. The preparation of tests and the method for acquisition of the data are explained in detail in Rezkallah.[10] Before taking any set of data, steady-state conditions were first achieved through continuous monitoring and

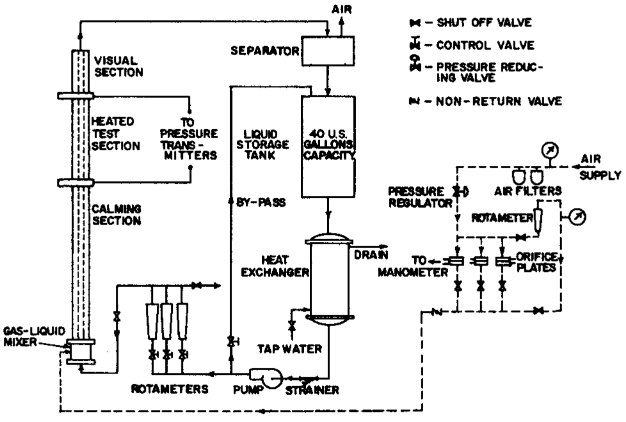

Fig. 1 Schematic of the two-phase apparatus.

Table 1 Range of variables in the present study

Variable	Water/air	Glycerine-water/air	Silicone/air
V_{SL} ft/s (m/s)	0.185–34.7 (0.056–10.6)	0.073–24.2 (0.022–7.38)	0.073–30.2 (0.022–9.20)
V_{SG} ft/s (m/s)	1.08–425 (0.329–129)	0.190–344 (0.058–105)	0.170–364 (0.052–111)
$\bar{T}_{\rm Mix}$ °F (°C)	66.0–88.3 (18.9–31.3)	70.1–87.3 (21.2–30.7)	66.4–82.1 (19.1–27.8)
Re_{SL}	845–1.27 × 10^5	42–1.3 × 10^4	51–2.07 × 10^4
Re_{SG}	318–1.35 × 10^5	68–12 × 10^5	52–1.15 × 10^5
Pr_L	5.4–7.2	42.4–65.8	61.0–72.3
We_{SL}	0.525– 1.8 × 10^4	0.095– 1.02 × 10^4	0.073– 1.27 × 10^4

controlling of the liquid inlet temperature to the mixer, the wall temperature at six elevations along the heated tube (two at each end and two at the middle), and the power supply to the test section and the guard heaters. Steady-state conditions were deemed to prevail when the difference between the readings (for both wall and bulk temperatures) of two successive sets of recorded emf's was within ±0.2°F (±0.1°C) in 7 min. The voltage supply to the guard heaters was controlled so as to achieve approximately a zero-temperature-gradient boundary condition at the outer wall of the test section. Deviations from this condition and the subsequent (very small) influence on the calculated heat-transfer coefficients are discussed in Vijay.[6]

During the course of the experiments, it was attempted to maintain a reasonably constant temperature difference between the inside wall temperature and the bulk temperature of the two-phase mixture. The spread in $(T_W - T_B)$ for the entire series of tests was approximately 15 ± 7°F (8.3 ± 3.9°C). The data were taken by fixing V_{SL} and changing V_{SG}. The range of variables covered in the present study is given in Table 1.

The estimated errors in V_{SL} and V_{SG} over the total range given above were from 5.8 to 7.3% (for V_{SL}) and from 3.8 to 7.5% (for V_{SG}). The error in ΔP_{tot} was from 0.5 to 5%, whereas for the majority of the data, the error in the mean heat-transfer coefficient was estimated to be less than 10%.

Discussion of Results

Flow Patterns

Because flow patterns can influence heat transfer and pressure drop in two-phase systems, they were observed and photographed in the present investigation. The heat-transfer and pressure-drop results are discussed in terms of flow patterns; the symbols appearing beside the data points on the figures refer to the flow pattern (or flow-pattern transitions) observed. The basic flow patterns observed were bubble "B," slug "S," churn "C," annular "A," and froth "F" flows. Any flow pattern configuration that had the elements of two basic flow patterns was classified as a transition between those two flow patterns. The annular-mist transition "A-M" was also observed in the present work, though mist flow itself was not observed. A description of the flow patterns is given in Rezkallah[10] and in Zaidi and Sims.[8]

The various flow patterns observed in the present study are presented in Figs. 2 and 3 on dimensional coordinates of V_{SL} against V_{SG}. The cross-hatching indicates the boundaries between the flow-pattern regions. Comparing the transition boundaries shown on Figs. 2 and 3 for both data sets, though not plotted together on the same map, would lead to the following observations with regard to the changes that took place in the silicone/air boundaries compared with the glycerine-water/air boundaries: The bubble-slug boundary moved in such a way that part of the region formerly occupied by slug flow was replaced by bubble flow; this was the most significant change noted, but with the present state of knowledge it is difficult to interpret the change in terms of physical mechanisms. Small changes took place with the slug-churn, churn-annular and annular-mist boundaries, which appeared to move slightly toward the left on the map, so that annular flow and the annular-mist transition were observed earlier (in terms of V_{SG} at the same V_{SL}) with silicone/air.

Pressure Drop

Total-pressure-drop measurements ΔP_{tot} across the test section were taken during the present study; these results are shown in Figs. 4–7 for water/air, glycerine-water/air, and silicone/air, respectively. At very low liquid and gas flow rates for the glycerine-water/air data, the readings of ΔP_{tot} gave negative values. For such cases (11 data points at V_{SL} = 0.073 ft/s or 0.022 m/s, three data points at V_{SL} = 0.144 ft/s or 0.044 m/s, and one point at V_{SL} = 0.380 ft/s or 0.116 m/s), the data were excluded from Fig. 5.

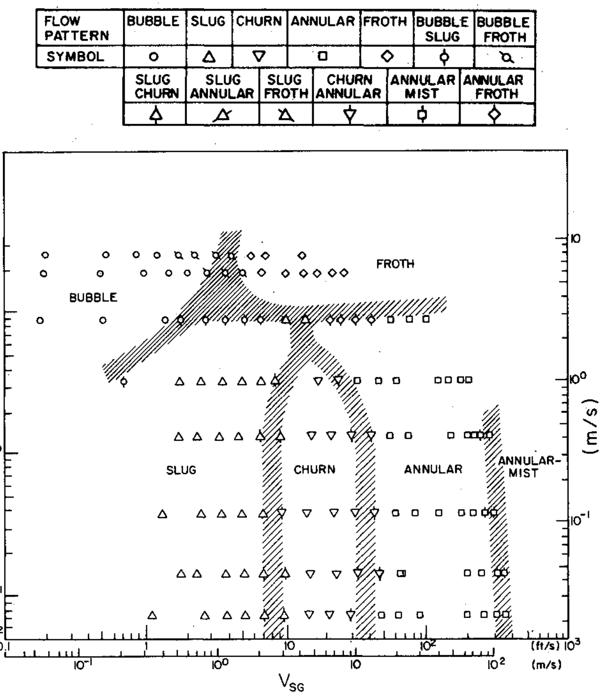

Fig. 2 Glycerine-water/air flow-pattern results.

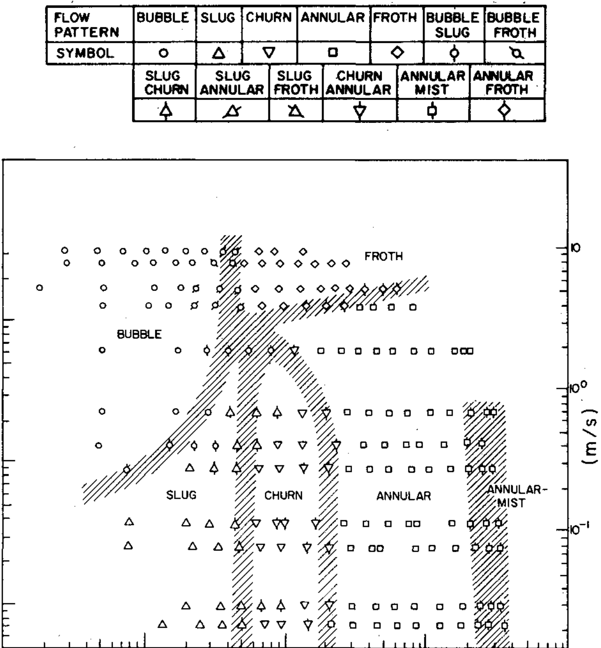

Fig. 3 Silicone/air flow-pattern results.

The existence of local minima and maxima in the pressure-drop curves for constant liquid flow has been observed and reported by other investigators (e.g., Govier et al.[11] and Owen et al.[12]). This behavior took place in the lower gas-flow-rate region and was associated with a variety of flow patterns and transitions including slug, slug-churn, churn, and churn-annular. However, with the silicone/air system, at V_{SL} = 0.910, 1.30, and 2.26 ft/s (0.277, 0.399, and 0.690 m/s), the increase of ΔP_{tot} with further increase in $\dot{m}_G$ was not continuous. At these liquid superficial velocities, a sudden drop in ΔP_{tot} occurred (less dramatic for V_{SL} = 0.910 ft/s or 0.277 m/s) reaching a minimum at $V_{SG} \approx 200$ ft/s (≈ 60 m/s), and was followed again by a monotonic rise. Owen et al.[12] reported similar results for water/air at water superficial velocities of 0.975 and 1.31 ft/s (0.297 and 0.399 m/s) in the range of V_{SG} from 30 to 210 ft/s (9 to 64 m/s), approximately. They suggested that what takes place in those regions is the result of two competing processes that occur as the gas flow rate increases in annular flow. The first is a tendency to increase the interfacial shear stress as $\dot{m}_G$ increases, analogous to the behavior in single-phase flow. The second process is the rapid decrease of the amount of liquid in the film (and hence the film thickness), resulting in a reduction in wave activity on the interface and a consequent reduction in the interfacial friction factor. The authors[12] suggested that the decrease in ΔP_{tot} occurs when the second of these processes becomes dominant. Ultimately, when nearly all of the film has been entrained away, the first process again prevails, and ΔP_{tot} increases with further increase in $\dot{m}_G$. This explanation of the pressure-drop behavior in the annular-flow region seems reasonable to explain the results obtained in the present study with silicone/air in the range of liquid velocities given earlier, and also at higher flow rates (where the first process again becomes dominant). However, this behavior was not observed with the present water/air data (these data were taken at different liquid velocities than those of Owen et al.[12]), and also was not reported in the earlier work of Vijay,[6] Aggour,[7] and Zaidi and Sims.[8] This observation requires more investigation in the future. It should be mentioned that with the silicone/air data, the steep rise in ΔP_{tot} (following the drop) occurred at the annular-mist transition in the present work. In connection with the pressure-drop results, and particularly with regard to the frictional-pressure-drop component, a detailed study is in progress using the present and other data in the recent literature.

Heat Transfer

The mean heat-transfer coefficients were obtained by length-mean integration of the local values measured at seven elevations along the test section. Figure 8 shows the single-phase mean heat-transfer results against the correlations of Sieder and Tate in laminar and turbulent flows. Excellent agreement was obtained with the correlations over the entire range of Re_{SL}, including the transition region ($2000 < Re_{SL} \gtrsim 10^4$). The overall algebraic and rms deviations for the total data set were -13.0% and 16.1% for laminar flow, and 0.93% and 10.5% for turbulent flow, respectively.

The two-phase mean heat-transfer coefficients shown on Figs. 9–12 are plotted as a function of V_{SG} with V_{SL} as a parameter. From an examination of these figures, the following observations can be made:

1) As with other studies, it can be seen that $\bar{h}_{TP}$ generally (but see point 3 below) increases with increasing gas flow rate,

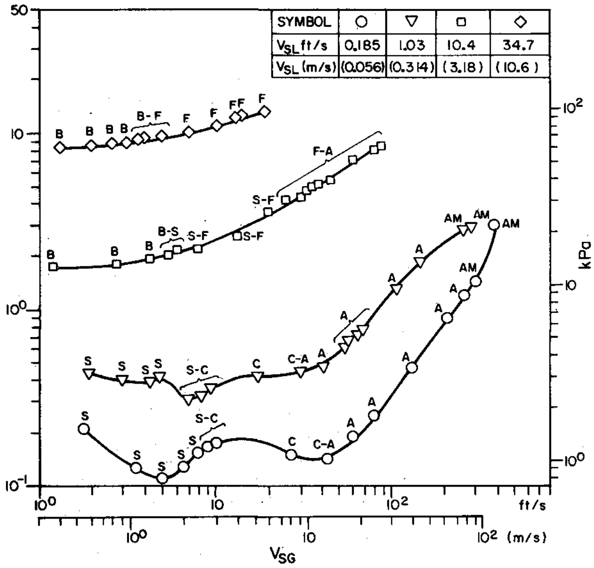

Fig. 4 Water/air total-pressure-drop results.

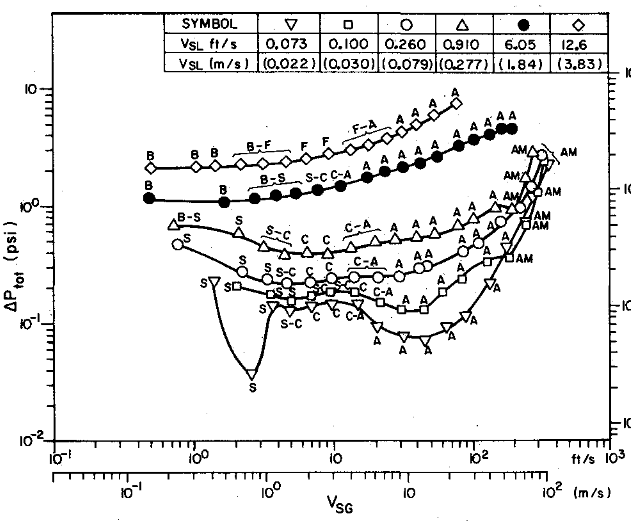

Fig. 6 Silicone/air total-pressure-drop results.

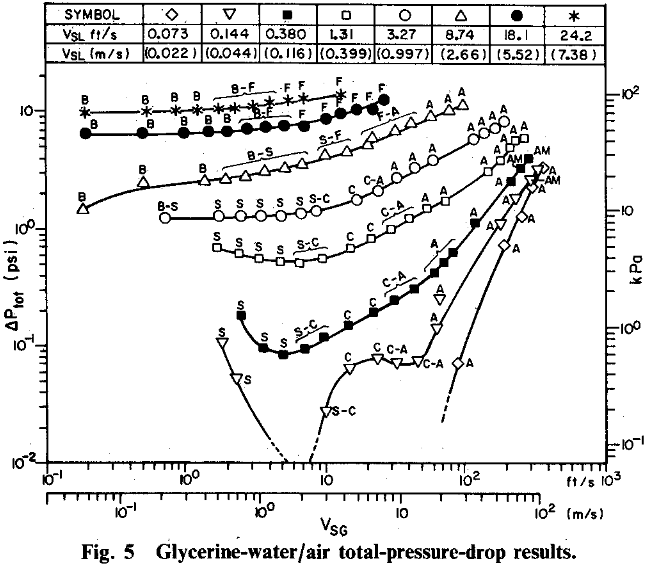

Fig. 5 Glycerine-water/air total-pressure-drop results.

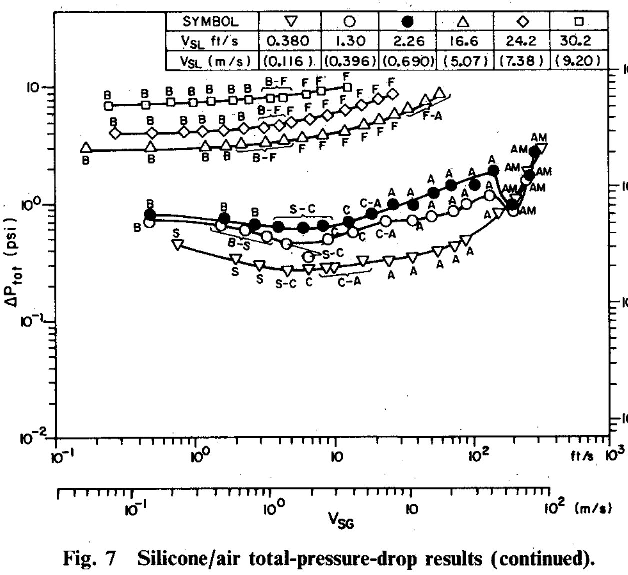

Fig. 7 Silicone/air total-pressure-drop results (continued).

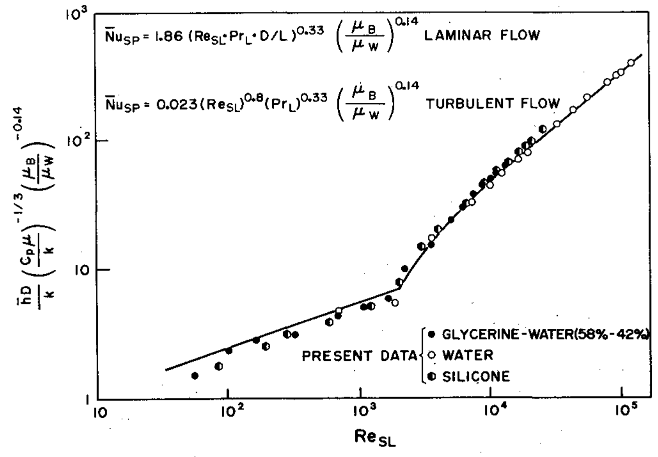

Fig. 8 Comparison between present single-phase heat-transfer results and the Sieder-Tate correlation.

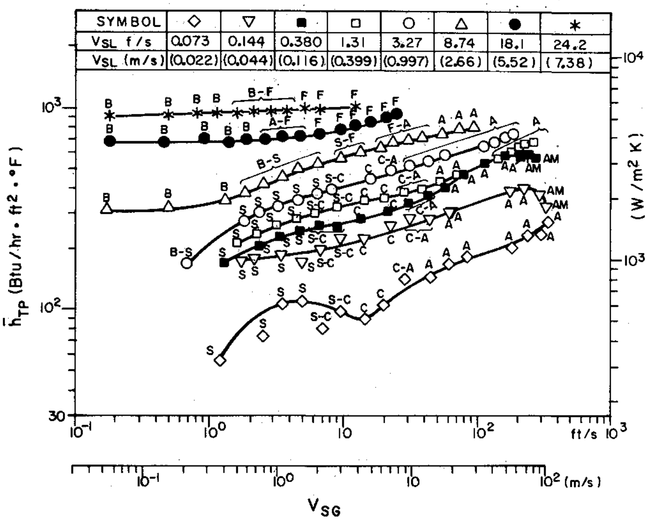

Fig. 10 Glycerine-water/air heat-transfer results.

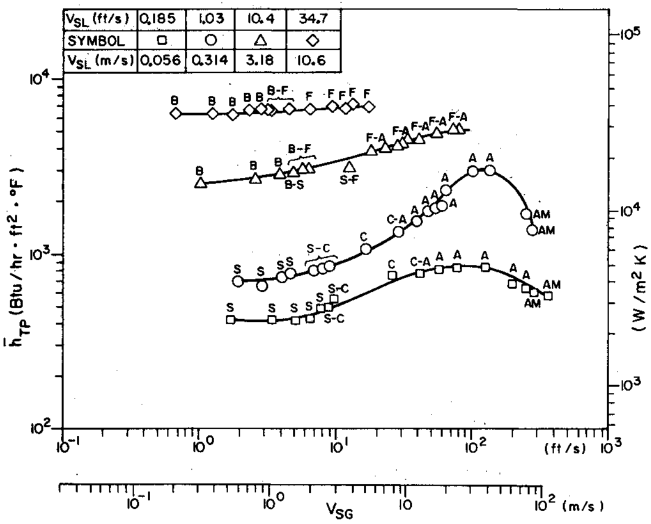

Fig. 9 Water/air heat-transfer results.

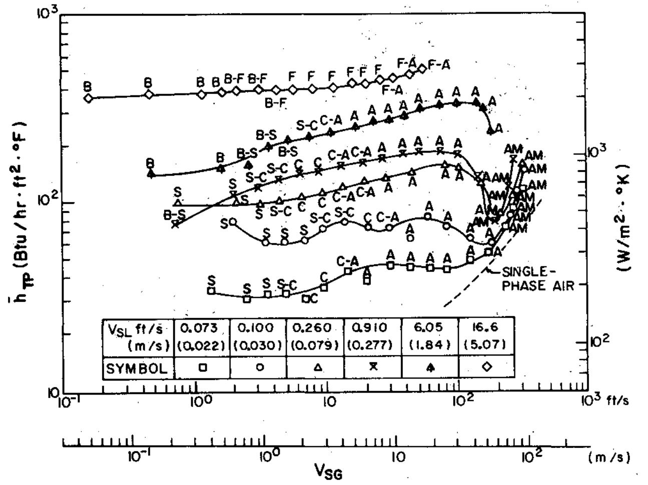

Fig. 11 Silicone/air heat-transfer results.

and that the effect of the gas-phase flow rate in increasing $\bar{h}_{TP}$ is more pronounced at low liquid flow rates ($V_{SL} \leq 1.3$ ft/s or 0.4 m/s). Also, $\bar{h}_{TP}$ generally increases with increasing V_{SL} for a fixed V_{SG}.

2) In the liquid superficial velocity range between 0.10 and 2.26 ft/s (0.030 and 0.690 m/s), an unmistakable maximum in $\bar{h}_{TP}$ is observed with water/air and silicone/air data and some glycerine-water/air data.

3) For the silicone/air data at low-to-medium V_{SL} ($0.260 \leq V_{SL} \leq 2.26$ ft/s or $0.080 \leq V_{SL} \leq 0.690$ m/s), the behavior of $\bar{h}_{TP}$ at high gas flow rates differs from that seen with other liquids. Initially, as with other liquids, for any liquid velocity within this range, $\bar{h}_{TP}$ increases with an increase in V_{SG} until it reaches a maximum at superficial gas velocities of approximately 70 to 110 ft/s (20 to 40 m/s) in the annular-flow region. At yet higher gas velocities, $\bar{h}_{TP}$ decreases, reaching a minimum at $V_{SG} \cong 200$ ft/s (60 m/s), after which $\bar{h}_{TP}$ increases again.

Considering all liquids, one might reason beginning with the proposal of Groothuis and Hendal.[3] After the maximum in the heat-transfer coefficient is reached, the liquid film on the wall begins to become thin enough such that the gas-phase properties begin to become important. As the gas flow rate increases, the film becomes thinner, and possibly dry spots develop on the tube wall, and $\bar{h}_{TP}$ decreases with increasing V_{SG}. With a very thin, or practically nonexistent film on the wall, $\bar{h}_{TP}$ increases again with increasing V_{SG} in a manner analogous to a single-phase flow. It is expected that for otherwise fixed conditions, with the silicone liquid (low surface tension) the films are thinner and conditions generally more developed along the progression described.

Figures 13 and 14 show a comparison of the mean Nusselt number for the two sets of data (glycerine-water/air and silicone/air) at the same Re_{SL}. From this comparison, it can be seen that in the range $Re_{SL} < 2000$, $\overline{Nu}_{TP}$ was higher for the silicone/air data up to the maximum in $\overline{Nu}_{TP}$, after which the data cross. At $Re_{SL} > 2000$, the silicone/air data were 10–40% higher than those for the glycerine-water/air for the entire range of the gas flow rates. No special correlation was found between the observed change in $\overline{Nu}_{TP}$ (from one liquid/air combination to the other) and the expansion of the bubble-flow regime, although such a relation has been observed in the surfactant/air data of Zaidi and Sims,[8] as discussed below.

Zaidi and Sims,[8] in their study using surfactant-solution/air and water/air mixtures, reported that when a surfactant was added to water, it produced very little effect on $\bar{h}_{TP}$, and that the tendency was for $\bar{h}_{TP}$ to be lower for the surfactant solution by 2–20% over the range of V_{SG} where effects were observed. These differences were believed to be significant where changes in the flow patterns were observed. Also, Ravipudi and Godbold[13] used a toluene/air mixture in their

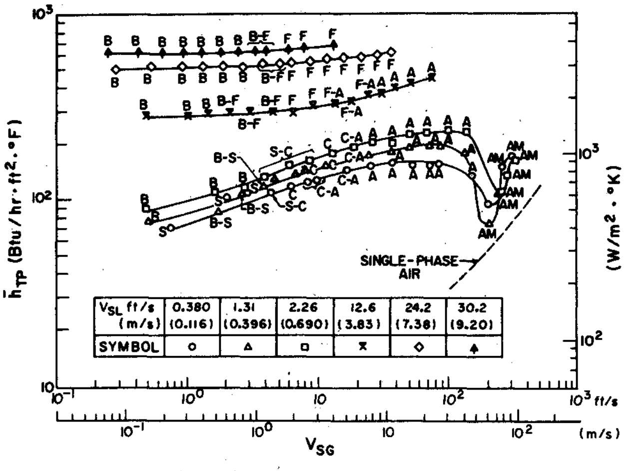

Fig. 12 Silicone/air heat-transfer results (continued).

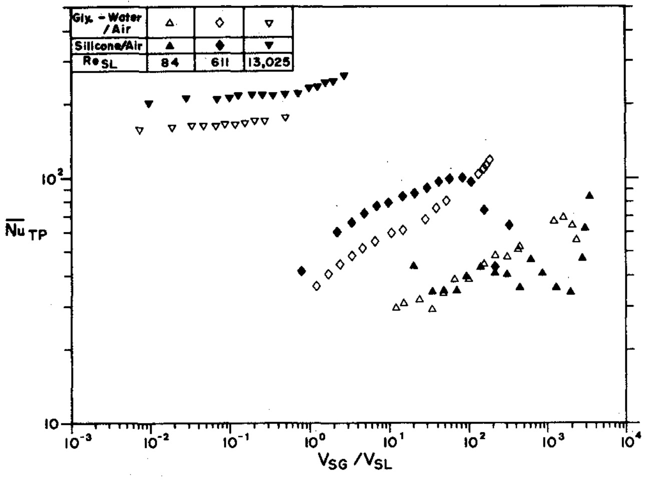

Fig. 13 Comparison between the glycerine-water/air and silicone/air heat-transfer results.

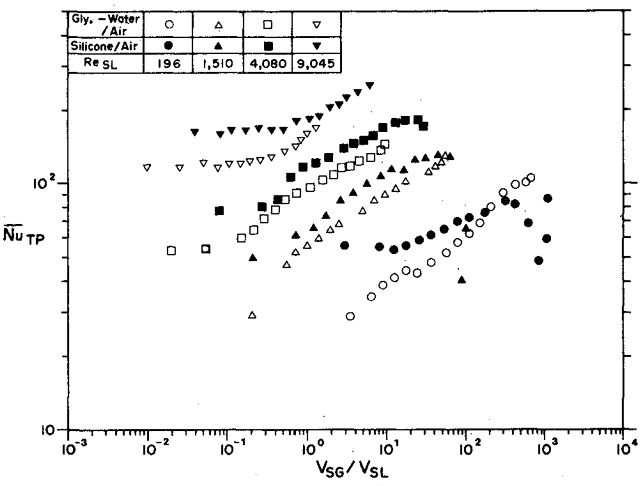

Fig. 14 Comparison between the glycerine-water/air and silicone/air heat-transfer results (continued).

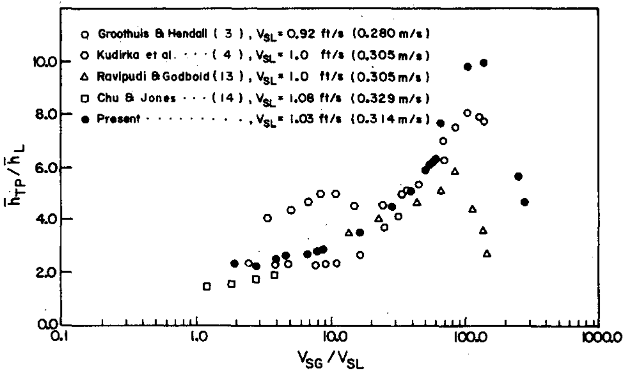

Fig. 15 Comparison of present water/air heat-transfer data with some existing literature data.

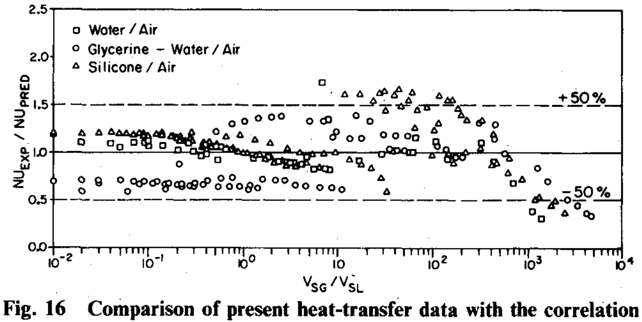

Fig. 16 Comparison of present heat-transfer data with the correlation of Vijay et al.[15]

study (the surface tension of toluene is ~28 dynes/cm at 25°C). A comparison between their water/air and toluene/air data at approximately the same liquid Reynolds number (16,000), in terms of the mean Nusselt number against V_{SG}/V_{SL}, showed there was essentially no change in $\overline{Nu}_{TP}$ for the same V_{SG}/V_{SL}. These previous two investigations were carried out using liquids with different liquid properties, such as lower Prandtl number, than those used in the present study.

Comparisons of the Data

The present data for water/air at $V_{SL} = 1.03$ ft/s (0.314 m/s) were compared with those of Groothuis and Hendal,[3] Kudirka et al.,[4] Ravipudi and Godbold,[13] and Chu and Jones[14] at approximately the same water velocity. This comparison is given in Fig. 15, which shows good agreement with the literature data over the total range of V_{SG}/V_{SL}, except for a few data of Kudirka et al.[4] (which fell above the present data) and also a few data beyond the maximum in $\bar{h}_{TP}$.

The present data were also compared against some of the existing correlations in the literature for predicting the mean heat-transfer coefficients in two-phase, two-component flow in vertical tubes. Good agreement was obtained with the correlations of Vijay et al.[15], Ravipudi and Godbold,[13] and what might be called the "liquid-acceleration model."

The comparison with the correlation of Vijay et al.[15] (Fig. 16), was done using the exponent $n = 0.451$ in their equation, given by

$$\frac{\bar{h}_{TP}}{\bar{h}_L} = \left(\frac{\Delta P_{TPF}}{\Delta P_L}\right)^n \tag{3}$$

where $\bar{h}_L$ and ΔP_L are the single-phase liquid heat-transfer coefficient and frictional pressure drop, respectively, and ΔP_{TPF} is the two-phase frictional pressure drop. The frictional pressure drop was calculated from the measured total pressure drop using the void fraction correlation of Chisholm[16] in the same manner as in Vijay et al.[15] This exponent was suggested when considering all of the flow patterns and transitions together, and it gave an overall rms deviation of 29.3%. However, when the comparisons were done for each flow pattern using the appropriate exponent given by the authors,[15] and overall rms deviation was 25%. Equation (3) does not apply to data in the annular-mist transition, and also to data with frictional pressure drop gradients below approx-

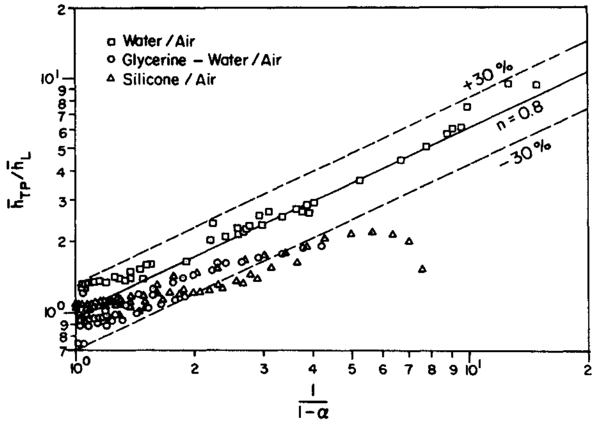

Fig. 17 Comparison of present heat-transfer data with the liquid-acceleration model.

imately 0.05 psi/ft (1000 Pa/m). The few data points that fell outside the range ±50% have pressure gradients very close to this criterion.

The correlation of Ravipudi and Godbold,[13] given by

$$\overline{Nu}_{TP} = 0.56\left(\frac{V_{SG}}{V_{SL}}\right)^{0.3}\left(\frac{\mu_G}{\mu_L}\right)^{0.2}(Re_{SL})^{0.6}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14} \qquad (4)$$

was used in the range $8554 < Re_{SL} < 89{,}626$ and $1 < V_{SG}/V_{SL} < 90$, as covered by the original authors. The correlation predicted very well the data points that fell within this range (a total of 18 data points) giving an rms deviation of 20.6%. The comparison with the liquid-acceleration model is given in Fig. 17. The equation describing this model is

$$\frac{\bar{h}_{TP}}{\bar{h}_L} = \left(\frac{1}{1-\alpha}\right)^{0.8} \qquad (5)$$

where α is the void fraction (calculated from the Chisholm[16] correlation here). This model was used with the experimental data in the turbulent flow region ($Re_{SL} > 2000$) with the exponent $n = 0.8$, being the most common exponent used in the single-phase correlations. The agreement was such that the overall algebraic and rms deviations were −8.8 and 20.4%, respectively. However, there was a slight tendency to overpredict the mean heat-transfer coefficients for the glycerine-water/air and silicone/air data. No annular-mist data were used in this comparison.

Conclusions

1) New data for two liquids were reported for mean heat-transfer coefficients, total pressure drop, and flow patterns. The combination of glycerine-water (58–42%)/air and silicone/air provided a new set of data in which the surface tension changed by a factor of 3.4 (being higher for the first liquid) with a rough matching of other hydrodynamic properties and a precise matching of Pr_L.

2) Flow-pattern results of the two liquids showed a significant change in the bubble-slug boundary for silicone/air compared with glycerine water/air, which moved considerably expanding the bubble-flow region. Only small changes were observed with the other boundaries.

3) The pressure-drop results for silicone/air, in the range of $0.910 \leqq V_{SL} \leqq 2.26$ ft/s ($0.277 \leqq V_{SL} \leqq 0.690$ m/s), showed a sudden drop in ΔP_{tot} followed by an increase at high gas superficial velocities. A discussion of this behavior is given in the paper.

4) The behavior of the mean heat-transfer coefficients for the silicone/air at low-to-medium liquid flow rates and high gas flow rates has not been reported with other liquids ($\bar{h}_{TP}$, after a maximum decreases, goes through a minimum, and then increases again); a possible explanation is presented in the paper. Also, at a fixed Re_{SL} in the range of $Re_{SL} < 2000$, $\overline{Nu}_{TP}$ was higher for the silicone/air data up to the maximum in $\overline{Nu}_{TP}$, after which the data cross. At $Re_{SL} > 2000$, the silicone/air data were 10–40% higher than those for glycerine-water/air for the entire range of V_{SG}/V_{SL}.

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