TURBULENCE MODIFICATION IN GAS-LIQUID AND SOLID-LIQUID DISPERSED TWO-PHASE PIPE FLOWS

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ABSTRACT

One of the key issues in two-phase turbulence modeling is the turbulence modification due to the interaction between the shear-induced turbulence and the turbulence induced by the dispersed phase. As for the gas-liquid two-phase flows in vertical pipes, Serizawa and Kataoka carried out detailed measurement of turbulence intensity and detected the turbulence modification. Gore and Crowe pointed out that the modification is well correlated with the ratio of a particle diameter to a turbulence length scale (d/l_t). However the modification may depend not only on the length scales but also on the eddy viscosities of shear-induced and particle-induced turbulence. Hosokawa et al. proposed the ratio ϕ of the eddy viscosity induced by the dispersed phase to the shear-induced eddy viscosity and confirmed that measured turbulence modification for gas-solid two-phase flow was well correlated with ϕ.

In this study, we examined whether or not ϕ is also applicable to gas-liquid and solid-liquid two-phase dispersed upflows in vertical pipes. Using the eddy viscosity ratio instead of d/l_t, we obtained much better correlation. The critical point at which no modification occurred was close to $\phi = 1$ irrespective of a type of two-phase dispersed flow. Consequently, we could confirm that the eddy viscosity ratio is a more appropriate parameter for correlating the turbulent modification than the conventional critical parameter d/l_t.

INTRODUCTION

Characteristics of a dispersed two-phase flow such as heat transfer and pressure drop cannot be well predicted without sufficient knowledge of two-phase turbulence. Many experimental studies have therefore been carried out to clarify the two-phase turbulence (Serizawa et al., 1975, Lance and Bataille, 1991). One of the key issues in the two-phase turbulence modeling is the turbulence modification due to the interaction between the shear-induced turbulence and the turbulence induced by the dispersed phase.

As for the turbulence intensities in gas-liquid two-phase flows in vertical pipes, Serizawa and Kataoka (1995) carried out detailed measurement of turbulence intensity and detected the turbulence modification. Gore and Crowe (1989,1991) investigated the turbulence modification caused by the addition of particles in a gas flow, and pointed out that the modification is well correlated with the so-called critical parameter, d/l_t, the ratio of a particle diameter d to a turbulence length scale l_t. They applied this parameter to turbulence modification due to bubbles and drops and confirmed that the parameter is also applicable to gas-liquid dispersed flows. They also reported that the critical parameter refers to only the question of increasing or decreasing the turbulent intensity and does not relate to the magnitude of the change as shown in Fig. 1. The critical parameter can be understood as the ratio of a mixing length of particle/bubble-induced turbulence and that of shear-induced turbulence. However the modification may depend not only on the length scales but also on the eddy viscosities of shear-induced and particle/bubble-induced turbulence. Since the eddy viscosity is one of the most fundamental quantities representing the turbulent characteristics, the ratio ϕ of the eddy viscosity induced by dispersed phases to the shear-induced eddy viscosity can be one of the top-rated candidates for the critical parameter. The magnitude of the eddy viscosity induced by the dispersed phase can be approximately evaluated as the product of the relative velocity u_r and the mean diameter d of the dispersed bubbles, drops or particles. The magnitude of shear-induced eddy viscosity can be evaluated as the product of turbulence length scale l_t and turbulence velocity u'. Hence, the eddy viscosity ratio ϕ can be evaluated as

$$\phi = \frac{u_r d}{u' l_t} \tag{1}$$

To examine whether or not ϕ is an appropriate critical parameter, Hosokawa et al. (1998) measured turbulent

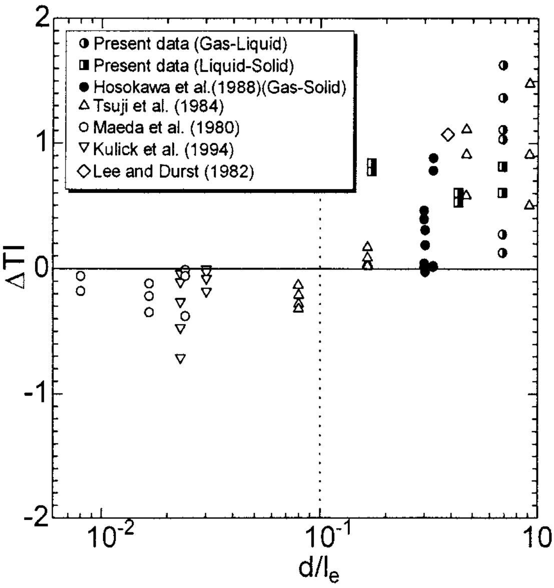

Figure 1: Change in turbulence intensity as function of length scale ratio (Gore and Crowe, 1989).

intensities for gas-solid two-phase flows in a vertical pipe using several particles with different relative velocities, and confirmed that measured turbulence modification was well correlated with ϕ.

In this study, we examined whether or not ϕ is also applicable to gas-liquid and solid-liquid two-phase dispersed upflows in vertical pipes. LDV measurements were carried out to obtain the velocities of continuous phase and solid particles. To examine the effects of ϕ on the turbulence modification, three particles with different diameters were used for solid-liquid two-phase flows and experiments for gas-liquid two-phase flows were carried out under three conditions with different liquid volumetric fluxes.

EDDY VISCOSITY RATIO

The eddy viscosity ratio ϕ can be deduced from the following time-averaged Navier-Stokes equation based on the eddy-viscosity assumption:

$$\frac{\partial \bar{u}_i}{\partial t}+\bar{u}_j\frac{\partial \bar{u}_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i}+\left(\nu+\nu_{TPF}\right)\frac{\partial^2 \bar{u}_j}{\partial x_j^2} \qquad (2)$$

where u is the fluid velocity, P the pressure, ν the kinematic viscosity and ν_{TPF} the eddy viscosity. The ν_{TPF} can be related with the eddy viscosity ν_S of the shear-induced turbulence and the eddy viscosity induced by dispersed phases ν_p. Thus,

$$\nu_{TPF}=f\left(\nu_S,\nu_p,\ldots\right) \qquad (3)$$

The most fundamental dimensionless group deduced from Eq.(3) is

$$\phi=\frac{\nu_p}{\nu_S} \qquad (4)$$

The magnitudes of the two eddy viscosities, ν_S and ν_p, can be approximately evaluated as follows:

$$\nu_S\propto u' l_t,\quad \nu_p\propto u_r d \qquad (5)$$

where u' denotes the fluctuation velocity, l_t the turbulence length scale, u_r the relative velocity and d the diameter of dispersed phase. The following parameter may therefore possess a strong relation with the turbulence modification.

$$\phi\propto\frac{u_r d}{u' l_t} \qquad (6)$$

In the later section, the eddy viscosity ratio will be correlated with a dimensionless change in turbulent intensity, ΔTI, of the present and available experimental data. The change in turbulent intensity is defined by

$$\Delta TI=\frac{\frac{u'_{TPF}}{U_{TPF}}-\frac{u'}{U}}{\frac{u'}{U}} \qquad (7)$$

where u'_{TPF} denotes the RMS of liquid velocity in a two-phase flow, U_{TPF} the mean velocity of the liquid phase in a two-phase flow and U the mean velocity in a single phase flow. The ΔTI would increase with the number density, N_S, of the dispersed phase even if ϕ is constant. Hence, the ΔTI per unit number density, $\Delta TI/N_S$, might be more appropriate than ΔTI as an index of turbulence modification. The number density N_S and the turbulence change per unit number density are defined by

$$N_S=\frac{\alpha}{\pi d^3/6} \qquad (8)$$

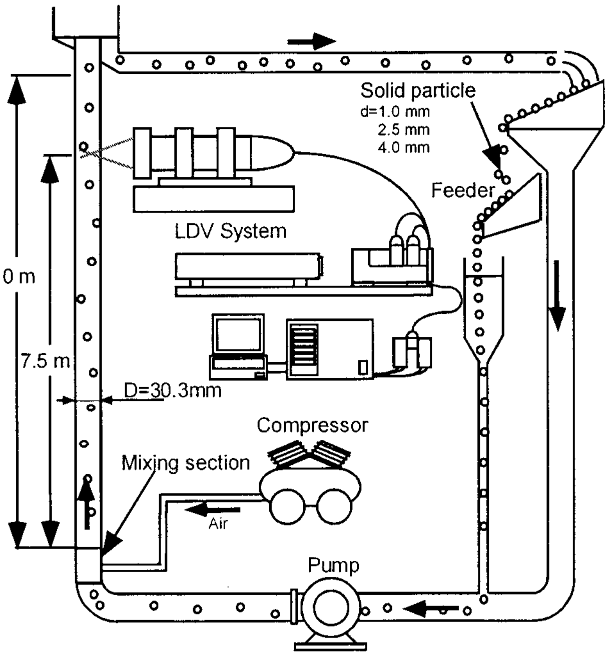

Figure 2: Experimental Apparatus.

$$\frac{\Delta TI}{N_S}=\frac{\pi d^3/6}{\alpha}\left(\frac{\frac{u'_{TPF}}{U_{TPF}}-\frac{u'}{U}}{\frac{u'}{U}}\right) \qquad (9)$$

where α is the phase fraction of the dispersed phase.

EXPERIMENTAL APPARATUS AND CONDITIONS

The experimental apparatus used in the present study is shown in Fig. 2. Water, air and ceramic particles were used as the continuous, gas and solid phases, respectively. Water was supplied from the Mohno pump, and flowed in the upward direction in the vertical pipe made of acrylic resin. The length and the inner diameter of the pipe were 10 *m* and 30 *mm*, respectively. In the case of gas-liquid two-phase flows, air was supplied from the compressor and mixed with water at the mixing section, which located at the inlet of the vertical pipe. For liquid-solid two-phase flows, spherical solid particles were added to the flow using the feeder. The points of measurement located at 7.5 *m* above the bottom of the vertical pipe. Experimental conditions were summarized in Table 1. To examine the effects of shear-induced turbulence and the diameter of dispersed phase on the turbulence modification, experiments of gas-liquid two-phase flows were carried out under three conditions with different liquid volumetric fluxes. Three particles with different diameters were used for solid-liquid two-phase flow experiments. Experiments of gas-liquid two-phase bubbly flows in a vertical pipe, the diameter and length of which were 20 *mm* and 2 *m*, were also carried out to examine the effect of pipe diameter on the turbulence modification.

LDV measurements were carried out to obtain the velocities of liquid and solid phases. An image processing method was used to measure the bubble velocity, void fraction and mean diameter of bubbles. The area-averaged phase fractions in solid-liquid flows were calculated from the area-averaged velocities of liquid and solid phases, and the distributions of local phase fraction were evaluated using the local liquid velocity and the data rate of solid velocity, i.e. particle number per unit time. This phase fraction agreed

Table 1: Experimental conditions.

Gas-Liquid (Air-Water)						
D	J_L	Re	J_G	d	U_T	$< \alpha >$
$30mm$	$0.51m/s$	1.5×10^4	$0.017m/s$	$4.9mm$	$0.28m/s$	2.2×10^{-2}
			$0.023m/s$	$4.9mm$	$0.28m/s$	3.0×10^{-2}
$30mm$	$0.71m/s$	2.1×10^4	$0.017m/s$	$4.8mm$	$0.28m/s$	1.9×10^{-2}
			$0.023m/s$	$4.8mm$	$0.28m/s$	2.7×10^{-2}
$30mm$	$1.01m/s$	3.0×10^4	$0.017m/s$	$4.7mm$	$0.27m/s$	1.5×10^{-2}
			$0.023m/s$	$4.7mm$	$0.27m/s$	2.2×10^{-2}
$20mm$	$0.50m/s$	1.0×10^4	$0.015m/s$	$3.7mm$	$0.24m/s$	1.9×10^{-2}
	$0.90m/s$	1.8×10^4	$0.020m/s$	$3.2mm$	$0.25m/s$	1.9×10^{-2}
Solid-Liquid (Water-Ceramic Particle 3200 kg/m^3)						
D	J_L	Re	J_S	d	U_T	$< \alpha >$
$30mm$	$0.50m/s$	1.5×10^4	$0.004m/s$	$4.0mm$	$0.42m/s$	5.0×10^{-2}
				$2.5mm$	$0.30m/s$	2.0×10^{-2}
				$1.0mm$	$0.21m/s$	1.4×10^{-2}
			$0.002m/s$	$4.0mm$	$0.42m/s$	2.5×10^{-2}
				$2.5mm$	$0.30m/s$	1.0×10^{-2}
				$1.0mm$	$0.21m/s$	0.7×10^{-2}

well with the local phase fraction measured by the image processing method. The eddy viscosity ratio defined by Eq. (6) includes the turbulence length scale l_t in a single phase flow. Since l_t is an unknown parameter, a model or empirical correlation has been used to evaluate l_t. In the present study, high data rate measurements were performed. Hence the length scale was directly evaluated from the measured time series data of continuous phase velocities using the following equation:

$$l_t = \int_0^\infty g(\tau)\,d\tau \qquad (10)$$

$$g(\tau) = \frac{1}{\overline{u'^2}} \lim_{N\to\infty} \frac{1}{N} \int_0^N \overline{u'(t)\,u'(t+\tau)}dt \qquad (11)$$

where $g(\tau)$ is the autocorrelation function of fluctuating velocity and N the sample number (N=16384). The turbulence length scale evaluated with Eqs.(10) and (11) and measured fluctuating velocities of a single phase flow was compared with Hutchinson's data (1971). The result is shown in Fig. 3. The trend of the profile of Hutchinson's length scale is similar to that of the present data. Their values were however smaller than the present data. Since the measured tendency agreed with the Hutchinson's data, the measured length scale was used to evaluate the eddy viscosity ratio.

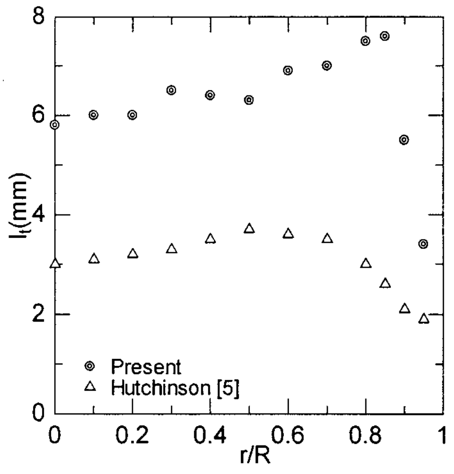

Figure 3: Measured turbulence length scale.

RESULTS AND DISCUSSION

Mean velocity and turbulence intensity

The measured liquid velocities U and the RMS values u' normalized by the bulk velocities $< U >$ for gas-liquid two-phase flows in 30-mm-dia. pipe are shown in Fig. 4. The liquid velocity is accelerated due to the presence of bubbles, especially in the near wall region. The turbulence also enhances due to the presence of bubbles and the augmentation is larger in the core region than in the near wall region. As a result, the turbulence distributions become flat in gas-liquid two-phase flow whereas the void distributions take wall peaking profiles. The ΔTI and $\Delta TI/N_S$ are much larger in the core region than in the near wall region as shown in Fig 5. The ΔTI and $\Delta TI/N_S$ increase with decreasing the liquid volumetric flux, i.e. decreasing the intensity of shear-induced turbulence, whereas they little depend on the gas volumetric flux. Since the bubble sizes and relative velocities between two phases are almost constant in the present experimental conditions for gas-liquid flows, the eddy viscosity ratio increases with decreasing the shear-induced turbulence. This result indicates that $\Delta TI/N_S$ increases with the eddy viscosity ratio ϕ.

For liquid-solid two-phase flow, the liquid velocity is accelerated, especially in the core region as shown in Fig. 6. The turbulence also enhances due to the presence of particles and ΔTI is more or less uniform over the cross section as shown in Fig. 7 whereas it is not uniform for gas-liquid two-phase flow. On the other hand, the $\Delta TI/N_S$ shown in Fig. 7 indicates large turbulence augmentation in the core region. The $\Delta TI/N_S$ depends on the particle diameter and little depends on solid volumetric flux. The increase with the particle diameter implies that $\Delta TI/N_S$ increases with the length scale of turbulence induced by the dispersed phase. Since the liquid volumetric flux is kept constant under the

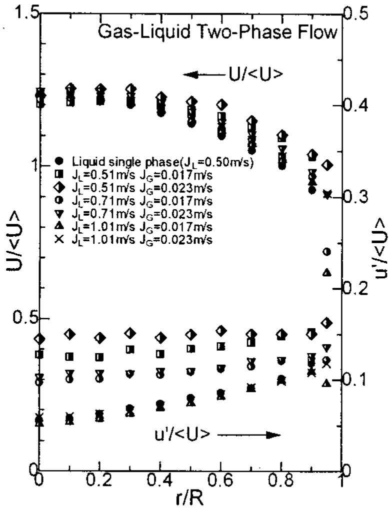

Figure 4: Mean velocity and RMS in gas-liquid flow.

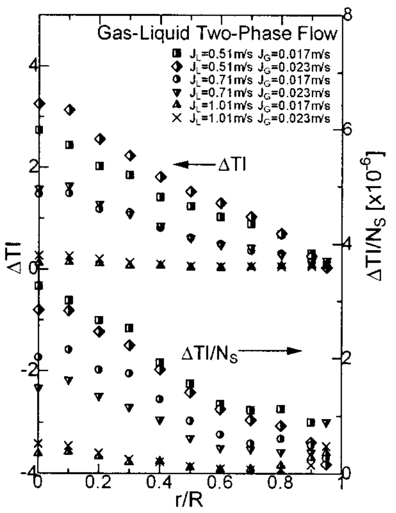

Figure 5: Turbulence modification in gas-liquid flow.

present experimental conditions for liquid-solid flows, the eddy viscosity ratio ϕ increases with the particle diameter. Therefore, the increase in ϕ corresponds to the increase in $\Delta TI/N_S$.

Correlation between eddy viscosity ratio and turbulence modification

The $\Delta TI/N_S$ is shown in Fig. 8 against the Gore & Crowe's critical parameter. There is a large scatter in Fig. 8 and very low turbulence augmentations are observed even in the range of $d/l_t > 1$. Using the eddy viscosity ratio ϕ, we obtain much better correlation as shown in Fig. 9. The critical point at which no modification occurs is close to $\phi = 1$ irrespective of a type of two-phase dispersed flow. The eddy viscosity ratio defined by Eq.(1) is therefore a more appropriate parameter for correlating the turbulent modification not only for gas-solid flows but also for gas-liquid and liquid-solid flows than d/l_t.

The correlations between $\Delta TI/N_S$ and ϕ of the gas-

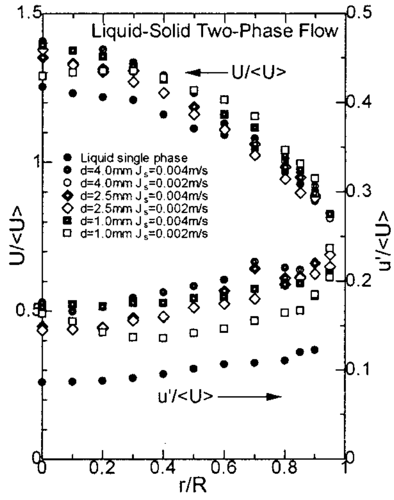

Figure 6: Mean velocity and RMS in liquid-solid flow.

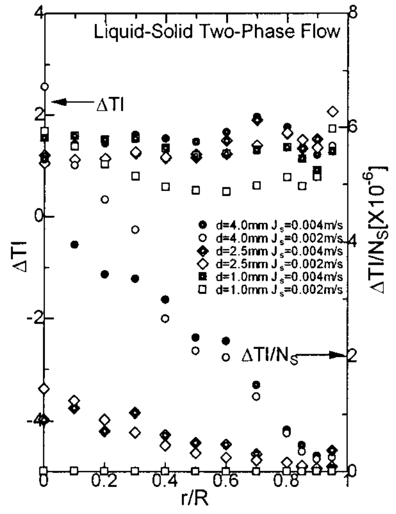

Figure 7: Turbulence modification in liquid-solid flow.

liquid and liquid-solid two-phase flows are compared with that of the gas-solid two-phase flow (Hosokawa et al., 1998) in Fig.10. The gradient of the correlation for the gas-solid dispersed flow is much smaller than that for the liquid-solid and gas-liquid dispersed two-phase flows. This indicates that the magnitude of turbulence modification depends on the fluid properties of the continuous phase. The most important fluid property for the turbulence dissipation would be the kinematic viscosity of continuous phase. High kinematic viscosity induces high dissipation rate, and therefore, the larger kinetic energy might be required to increase the turbulence intensity. Hence the $\Delta TI/N_S$ is multiplied by the ratio of the kinematic viscosity of continuous phase to the kinematic viscosity of water as a reference fluid (ν/ν_{water}). The correlations between $\nu/\nu_{water}\Delta TI/N_S$ and ϕ are shown in Fig. 11. The $\nu/\nu_{water}\Delta TI/N_S$ is well correlated with ϕ irrespective of a type of two-phase flow. Although further experiments with different fluid properties of continuous phase are required to verify the applicability of $\nu/\nu_{water}\Delta TI/N_S$

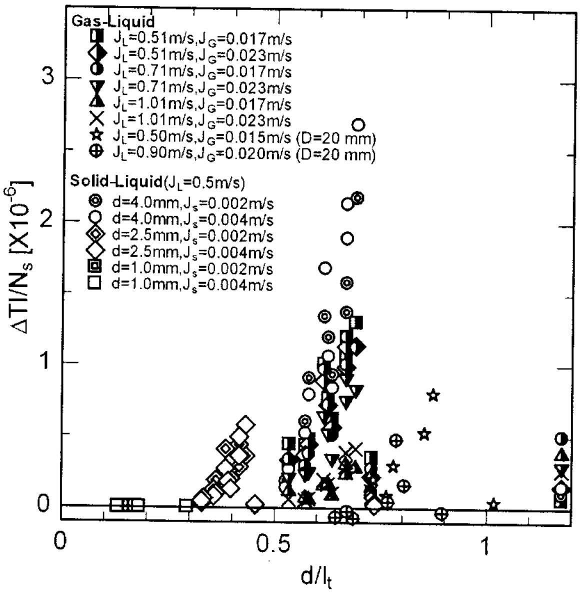

Figure 8: Correlation between critical parameter and turbulence augmentation per unit number density.

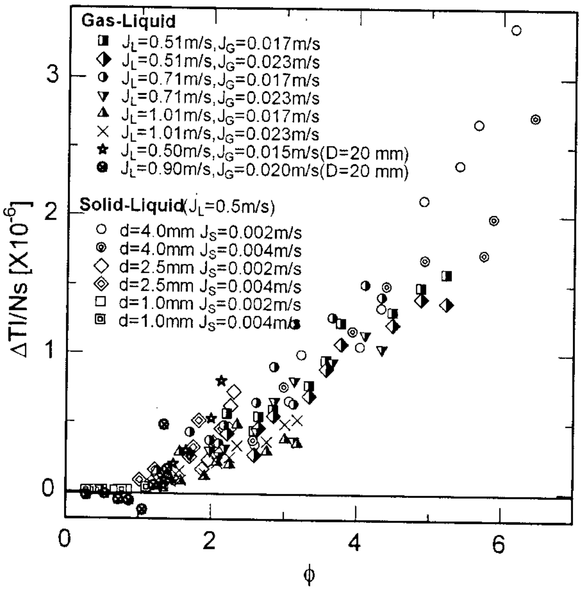

Figure 9: Correlation between eddy viscosity ratio and turbulence augmentation per unit number density.

to various two-phase flows, we could confirmed that ϕ is an appropriate parameter for correlating the turbulent modification in air-water, water-solid and air-solid two-phase flows in vertical pipes.

For comparison with available experimental data, ΔTI was integrated over the cross-sectional area of the pipe, and the area-averaged change in turbulent intensity $< \Delta TI >$ was defined by

$$< \Delta TI > = \frac{\int_0^R 2\pi r \frac{u'_{TPF}}{U_{TPF}} dr - \int_0^R 2\pi r \frac{u'_S}{U_S} dr}{\int_0^R 2\pi r \frac{u'_S}{U_S} dr} \qquad (12)$$

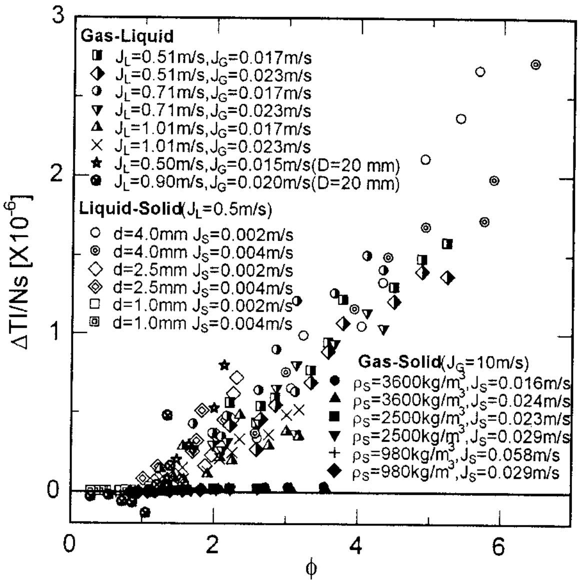

Figure 10: Correlation between $\Delta TI/N_S$ and ϕ of gas-liquid, liquid-solid and gas-solid two-phase flow.

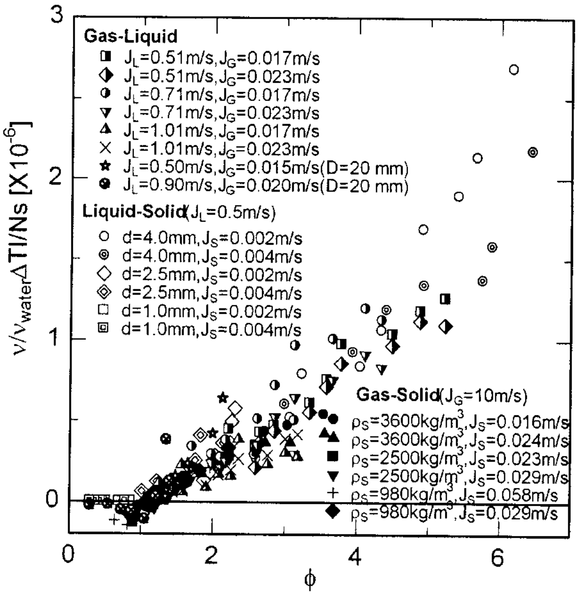

Figure 11: Correlation between $\nu/\nu_{water}\Delta TI/N_S$ and ϕ of gas-liquid, liquid-solid and gas-solid two-phase flow.

Since the diameter of the dispersed phase is more or less uniform over the cross-sectional area, the area-averaged number density of the dispersed phase $< N_S >$ was evaluated by using the area-averaged phase fraction $< \alpha >$:

$$< N_S > = \frac{6 < \alpha >}{\pi d^3} \qquad (13)$$

The area-averaged relative velocity $< u_r >$ and the area-averaged RMS value $< u' >$ in a single phase flow were used to evaluate the area-averaged eddy viscosity ratio. The integrated turbulence length scale in a single phase flow however is an unknown parameter. Hutchinson et al. (1971) suggested that the ratio of the local length scale to the pipe radius is constant across the pipe diameter under the conditions of $5.0 \times 10^4 < Re < 5.0 \times 10^5$, where Re is the flow Reynolds number. From the measured turbulence length scale shown in Fig. 3, the turbulence length scale was roughly 6 *mm*, i.e. $0.2 \times D$. We therefore selected $0.2 \times D$ as the area-averaged turbulence length scale of the single phase flow. Thus, the area-averaged eddy viscosity ratio was defined by

$$< \phi > = \frac{< u_r > d}{0.2 < u' > D} \qquad (14)$$

As shown in Fig. 12, all the measured data are well correlated with $< \phi >$. The scatter of the data is smaller and the critical point is clearer than the correlation based on d/l_t shown in Fig. 1. We therefore confirm that $< \phi >$ is an appropriate parameter for evaluating the area-averaged turbulence modification in gas-liquid, liquid-solid and gas-solid two-phase dispersed flows in vertical pipes.

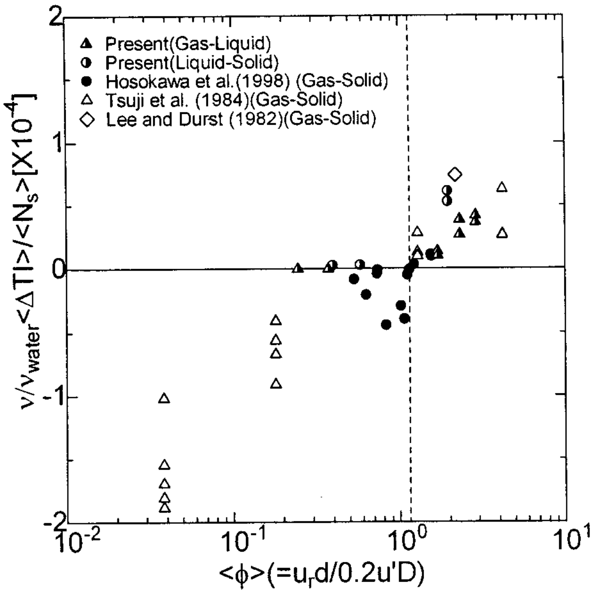

Figure 12: Correlation between area-averaged eddy viscosity ratio and turbulence augmentation per unit number density.

CONCLUSIONS

In order to examine whether or not the eddy viscosity ratio ϕ is applicable to gas-liquid and solid-liquid two-phase dispersed upflows in vertical pipes, velocities of continuous phase and dispersed phases were measured by LDV and an image processing method. Using the eddy viscosity ratio ϕ, we could obtain much better correlation between ϕ and change in turbulence intensity per unit number density of dispersed phases $\Delta TI/N_S$ than the correlation between d/l_t and ΔTI. The critical point at which no modification occurred was close to $\phi = 1$ irrespective of a type of two-phase dispersed flow. The area-averaged eddy viscosity ratio also well correlated with area-averaged turbulence augmentations measured in various two-phase flows. Consequently, we could confirm that the eddy viscosity ratio is a more appropriate parameter for correlating the turbulent modification not only for gas-solid two-phase flows but also for gas-liquid and liquid-solid two-phase flows than the conventional critical parameter d/l_t.

NOMENCLATURE

D: Pipe diameter [m]
N_S: Number density of dispersed phase
P: Pressure [Pa]
R: Pipe radius [m]
Re: Reynolds number [-]
U: Mean velocity [m/s]
U_T: Terminal velocity in stagnant water [m/s]
d: Diameter of dispersed phase [m]
$g(\tau)$: Autocorrelation function [-]
J_G: Gas volumetric flux [m/s]
J_L: Liquid volumetric flux [m/s]
J_S: Solid volumetric flux [m/s]
l_t: Turbulence length scale [m]
r: Radius [m]
u': Turbulence velocity [m/s]
u_r: Relative velocity between two phases [m/s]
ΔTI: Turbulence augmentation [-]
α: Phase fraction of dispersed phase [-]
ϕ: Eddy viscosity ratio [-]
ν: Viscosity [m^2/s]
ν_p: Eddy viscosity induced by dispersed phase [m^2/s]
ρ: Fluid density [kg/m^3]

Subscript

TPF: Two-phase flow

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