Concentration Distribution of Particles in Solid-Liquid Two-Phase Flow Through Vertical Pipe

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Abstract

The concentration distributions of particles were measured in a vertical pipe for both an upward and a doward flow. When the stream Reynolds number was low, the profile for the upward flow was opposite to that for the downward flow. The profiles of the concentration distributions under various conditions were classified into several kinds of modes. They were summarized into a figure by means of the stream Reynolds number and the particle Reynolds number. Two possible forces were suggested in order to explain the general distribution of partices.

1. Introduction

From the point of view of an effective conveying tool, a large number of works has been done about the solid-liquid two phase flow, in which solid particles were suspended and conveyed with a continuous liquid stream. The great majority of the works, however, has dealt with the excess pressure drop due to the presence of solids. However, there are only a few fundamental investigations about the behaviours of a cluster of solid particles[5),9)]. Most of the published works have been concerned with flow in a horizontal pipe, because of its practical importance. However, in order to investigate the behaviour of suspended particles, it is advantageous to study the flow in a vertical pipe, where the gravitational force acting on the particle is parallel to the liquid stream. Newitt et al[6)]. and Toda et al[8)]. photographed a swarm of solid particles in a vertical upward flow, and suggested qualitatively that the solid particles tended to gather near the pipe axis as the liquid velocity increased.

Recently, Toda et al[10)]. measured the radial concentration distribution of particles

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in a vertical pipe as well as in a horizontal one. They pointed out that the distributions were related to the size and the density of the particles as well as the liquid velocity. They further tried to simulate the distribution by means of the Monte Carlo method. Foster et al[3]. performed an interesting experiment in which the radial positions of a sphere suspended in a vertical pipe were measured under various conditions of the velocity and the viscosity of liquid.

In the present study, the radial concentration distribution of particles was measred in a vertical pipe by a fully developed turbulent flow. Previous measrements of the concentration distribution have been confined within only a vertical upward flow. In this work, measrements were made in a vertical downward flow as well as in an upward flow. Some interesting results that could not be deduced from these only in an upward flow were found. The concentration distributions were summarized in a figure, by taking two kinds of Reynolds numbers, Re_t and Re_p, as parameters. Moreover two forces acting on an individual particle were suggested to account for the general concentration distributions obtained.

2. Experimental apparatus and procedure

The experimental apparatus used is shown diagrammatically in Fig. 1. The

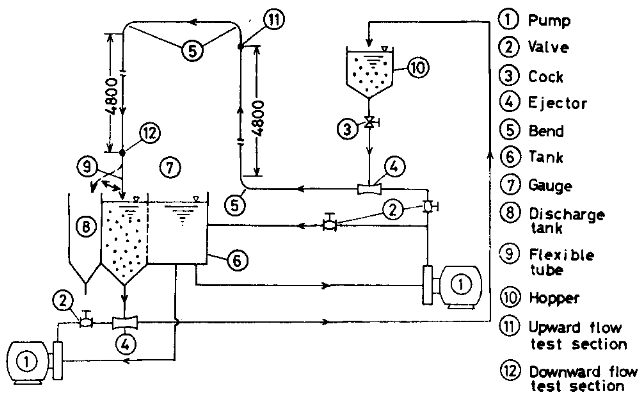


Fig. 1. Schematic diagram of experimental apparatus

solid particles with liquid were fed from a hopper and conveyed through a pipe. The liquid from the test line was discharged into a tank, and the particles were returned to the hopper. The test line consisted of 52 mm I. D. transparent polyacrylate pipe. The concentration distributions of particles were obtained by taking photographs at 4.8 m above the bend in the upward flow and 4.8 m below in the downward flow. At each test section, a $100\times100\times130$ water box made of transparent polyacrylate plates was attached to prevent any lens effect. In order to take synchroflash photographs of particles, a xenon flash-tube was used as a light source, as shown in Fig. 2. The light, which was made parallel, entered the pipe through a slit of 4 mm in width. The picture was divided radially into eleven equally spaced sections. By counting the number of particles in each section, the distributions of particles were obtained. The total number of the particles picked up in one experiment amounted to between 500 to 1500. The physical properties of the particles used are summarized in Table 1.

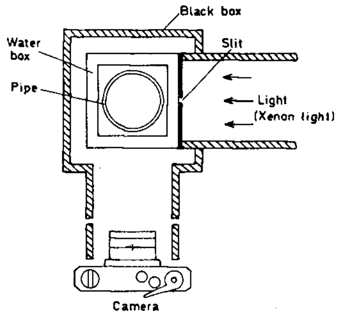


Fig. 2. Test section

Table. 1. Physical properties of particles

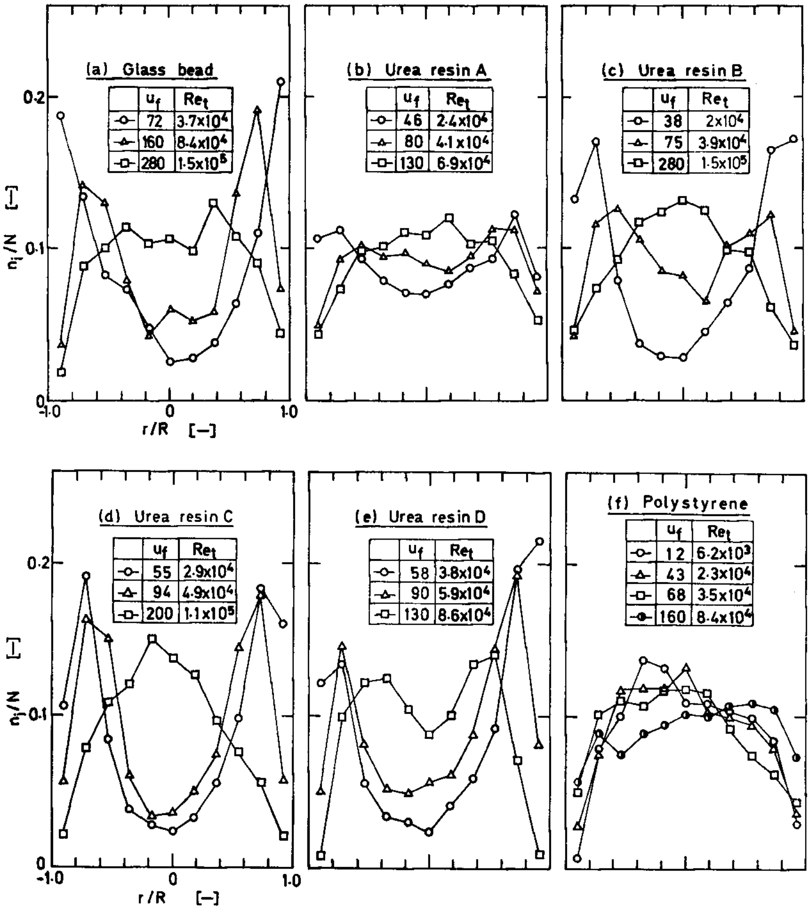
Material	Density : ρ_p [g/cm^3]	Diameter : d_p [cm]	Standard deviation of diameter [cm]	Terminal velocity : u_p (calculated) [cm/sec]
glass bead	2.47	0.187	0.0083	31.7
urea resin A		0.147	0.00330	10.8
urea resin B	1.47	0.188	0.00248	14.7
urea resin C		0.313	0.0060	20.4
urea resin D		0.409	0.0070	29.0
polystyrene	1.03	0.184	0.0101	2.35

3. Results and discussion

3.1. Concentration distribution of particles

The experimental results of the distribution of particles for the vertical upward flow are shown in Figs. 3(a)−(f). In these figures, the ordinate denotes the ratio of the number of pariticles in the i-th section to the total number of them. In Figs. 3(a)−(e), it is found that the concentration profiles for the glass beads and the urea resin particles, both of which have large specific density, vary significantly with the liquid velocity. When the liquid velocity is low, the concentration becomes extremely high near the pipe wall, and decreases monotonously towards the pipe axis. As the liquid velocity increases, the concentration adjacent to the wall decreases rapidly. Then it is seen that the concentration becomes maximum at a certin point between the axis and the wall of the pipe. As the liquid velocity increases, the position of the maximum shifts toward the pipe axis and the particles tend to be distributed uniformly throughout the cross section of the pipe except near the pipe wall.

On the other hand, for the polystyrene particle which has a slightly larger den-



Fg. 3. Concentration distribution of particles in upward flow

sity than the liquid, it is seen that at the slow liquid velocity the concentration near the wall is low, but increases toward the pipe axis, as illustrated in Fig. 3(f). The concentration profiles in the upward flow, mentioned above, are similar to the results obtained by Toda et al[10].

In Figs. 4(a) – (f), there are shown the distributions of particles for the vertically downward flow in the pipe. It is found that the heavy particles, such as glass beads and urea resin particles, tend to gather near the center of the pipe at a low liquid velocity. Such distributions are completely contrary to those for an upward flow under the same liquid velocity. With an increase of the liquid velocity, the concentration near the pipe axis decreases gradually and the one near the wall increases. On the contrary, as shown in Fig. 4(f), for the polystyrene particle, the concentration near the wall seems to be somewhat high at a small liquid velocity, though the

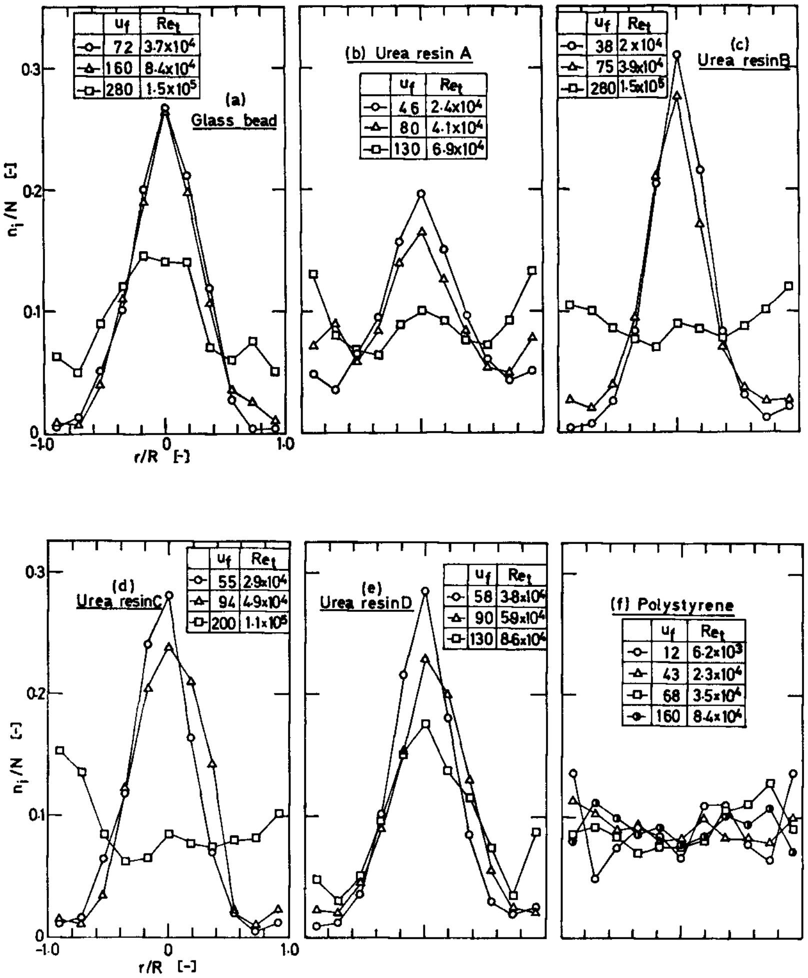


Fig. 4. Concentration distribution of particles in downward flow

scattering of data is compartively large. This concentration distribution is also contrary to the one under a similar liquid velocity for an upward flow. Further, it is worth noting that in a downward flow, the concentration of heavy particles near the wall has a tendency to rise gradually as the liquid velocity increases, though in an upward flow the concentration there reduces.

Figs. 5(a) and (b) show the effect of the specific density of particles on the concentration distribution for an upward and a downward flow, respectively. It is clear that the concentration distribution depends strongly on the density of particles, especially when the liquid velocity is small.

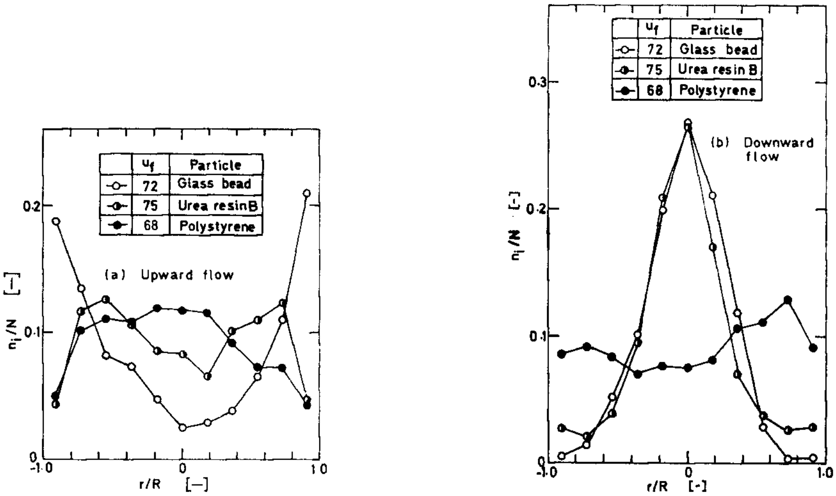


Fig. 5. Effect of particle density on concentration distribution

3.2. Chart of particle concentration profiles

As seen in Figs. 3 and 4, the concentration distribution varies very complicatedly with the particle dimension, its density and the liquid velocity. The profiles under the various conditions are summarized in Fig. 6, where the patterns of the concentration distribution are classified by means of the particle Reynolds number Re_p and the stream Reynolds number Re_t. The codes used in the figure correspond to the mode of the distribution curve diagrammatically illustrated in Fig. 7. The parts marked by asterisks are the present experimental results. In the figure are also

		upward flow			downward flow		
Re_p \ Re_t		laminar	turbulent		laminar	turbulent	
			5×10^3-5×10^4	-10^5		5×10^3-5×10^4	-10^5
Stokes		AXIS [4]	(AXIS / UNIF)	(UNIF)	WALL [4]	(WALL / UNIF)	(UNIF)
Allen	10	AXIS [4]	(AXIS / UNIF)	(UNIF)	WALL [4]	(WALL / UNIF)	(UNIF)
	50	(AXIS)	AXIS* [10]	UNIF* [10]	(WALL)	WALL*	UNIF*
Re_{pn}							
Allen	150	(WALL)	U-RING* [10]	UNIF* [10]	(AXIS)	AXIS*	D-RING*
	500	(WALL)	WALL* [10] U-RING	U-RING* [10] UNIF	(AXIS)	AXIS*	AXIS* D-RING
Newton		(WALL)	WALL*	WALL* U-RING	(AXIS)	AXIS*	AXIS*

Fig. 6. Chart of concentration distribution

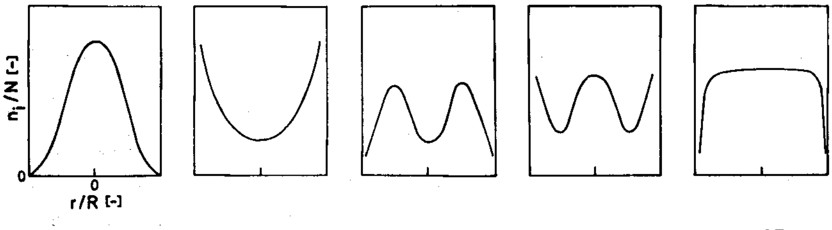


Fig. 7. Modes of concentration distribution

shown the observations by Toda et al[10] and Matsunobu[4]. On the basis of these results, the distributions of the remaining portions in the figure are presumed, and they are set in parentheses. From the figure, it can be recognized at a glance how the concentration distribution changes with the physical properties of particles and the liquid velocity. Thus, the following considerations are performed.

3.3. Neutral particle Reynolds number

It is noticed from Fig. 6 that, when the liquid stream is relatively low turbulent, the concentration profile alters at some value of Re_p from a convex to a concave form in an upward flow, as Re_p increases, and vice versa in a downward flow. Let's call this value of Re_p as "neutral particle Reynolds number, Re_{pn}". The value seems to lie between 50 and 150. This interesting phenomenon can also be presumed from the experiment by Foster et al.[3], where the value of Re_{pn} was between 40 and 150 in an upward flow. Fig. 6 shows that Re_{pn} of nearly the same value also exists in a downward flow.

3.4. Considerations of kinetics on particle distribution

It is an important matter to show under what kinetic models these distributions may be elucidated generally.

Some attempts[1,10] have been tried to explain the concentration distributions based only on the particle eddy diffusivity. However, such computation results can not fully interpret the complicated distributions in Fig. 6, except the "UNIF"-distribution at the large Re_t. Therefore, it is necessary to assume other causes in addition to the particle eddy diffusivity. The following three actions were assumed to explain qualitatively the distributions.

1) Force due to velocity gradient of liquid: Because of the velocity gradient of the liquid near the wall, it is possible to assume some force acting on the particles suspended there.

Saffman[7] estimated analytically a lift force acting on a sphere placed in a uniform sheared creeping flow, as follows.

$$F_s = 81.2\mu(d_p/2)^2 u_p (du_{fr}/dy/\nu)^{\frac{1}{2}} \quad \cdots\cdots\cdots\cdots (1)$$

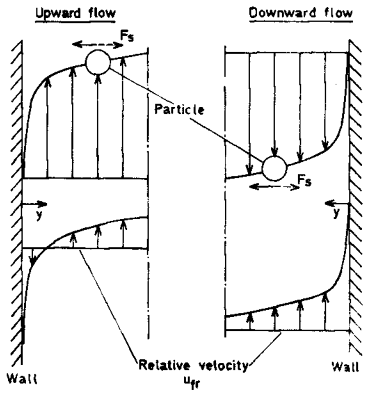


Fig. 8. Velocity distribution of fluid relative to particle

When $du_{fr}/dy > 0$, the force F_s is in positive y-direction, and vice versa. If $\rho_p > \rho_f$, the relative liquid velocity profiles u_{fr} are represented as sketched in Fig. 8, so that the force F_s exerts on the sphere in the positive y-direction for an upward flow and in the opposite direction for a downward flow. Therefore, the concentration distributions in Fig. 6, when the flow in the pipe is laminar and Re_p is in the Stokes region, can be explained reasonably by Saffman's force.

Furthermore, the polystyrene particles, of which Re_p is comparatively small ($\sim$40), seem to be distributed under the effect of this Saffman's force, when $Re_t \leqq 5\times10^3$. However, as Re_p becomes larger than Re_{pn}, the profile of the concentration changes to become opposite to that for $Re_p > Re_{pn}$. Therefore, it is impossible to explain the profile by Saffman's force. Hence, in order to explain reasonably these profiles in the region $Re_p > Re_{pn}$, a force must be postulated which acts on the particle in the opposite direction to Saffman's force as shown in Fig. 8 by a solid line, though there are no physical bases for this force as yet.

2) Contribution of anisotropy of the turbulent flow field near the wall to particle motion: As Re_t becomes larger, the actions due to the turbulence of the liquid becomes effective. One of them is the so-called particle eddy diffusivity. The other is due to the anisotropy of the turbulence in the liquid stream. The "bursting" is a result of the anisotropy, which Corino and Brodkey[2] recently found to play a significant role in the production of turbulence in the pipe. According to their research, the bursting phenomenon is composed of several factors. Among them, the ejection and the sweep are thought to influence the behaviour of the particles near the wall. The ejection itself is a rapid and abrupt movement of fluid, outward from the wall region. On the other hand, the sweep is of a larger scale and a slower movement of fluid toward the wall. When a heavy particle, the dimension

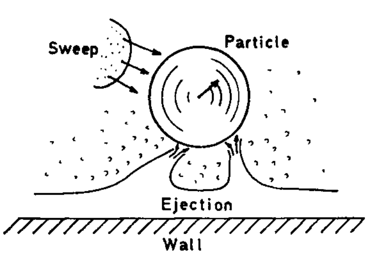


Fig. 9. Effect of "bursting" on particle

of which is larger than the scale of both ejection and sweep, exists near the wall as shown in Fig. 9, it receives the force by the impaction of the fluid lumps by the ejection and the sweep.

The force given to a particle at rest by the former is greater than that by the latter, because the force is assumed approximately to be proportional to the square of the velocity. As a result, a shift force acts on the particle toward the pipe axis. Under this consideration, it seems to be reasonable that the concentration of the heavy particles near the wall decreases with the increase of Re_t. However, if the particle under consideration is light, the effect of bursting does not show apparently in the concentration distribution. This is because the particle ejected from the wall region is easily mixed by the turbulence of the liquid stream.

3) Particle eddy diffusivity: The particle eddy diffusivity seems to be closely related to that of the fluid in a two-phase flow. Its value is considered to increase with a rise of the liquid velocity. Hence, as Re_t increases, the effect of the particle eddy diffusivity also increases, and the profile of the concentration tends to be smoothed over the cross section of the pipe.

3.5. Qualitative interpretations of the particle distributions

Let's consider how the chart of the concentration distribution shown in Fig. 6 is interpreted in terms of the combination of the three actions mentioned above.

When $Re_p < Re_{pn}$ and the flow in the pipe is laminar or weakly turbulent, Saffman's force plays a significant role in the particle distribution which shows the mode of "AXIS" for an upward flow and "WALL" for a downward flow. As Re_t increases, the particle eddy diffusivity becomes larger and the particles tend to be distributed uniformly over the cross section of the pipe.

When $Re_p > Re_{pn}$ and the flow in the pipe is weakly turbulent, the hypothetical force mentioned above would work effectively on the particles in the opposite direction of Saffman's force. Then the profile becomes "WALL" in an upward flow and "AXIS" in a downward flow, respectively. As Re_t becomes larger, the bursting effect begins to exert its influence. Because it gives a radially outward force to the particles, the concentration near the wall decreases. As a result, the profile for an upward flow shows the mode of "U-RING". If Re_t becomes still larger, the concentration near the pipe axis decreases, because of the mixing effect by the particle eddy diffusivity.

Thus, the three actions mentioned above are effective for explaining the distribution of particles under the various conditions, except for the case in which the concentration near the wall rises gradually with the increase of Re_t in a downward flow ($Re_p > Re_{pn}$). This exception may be caused by missing some other forces acting on the particles.

All the patterns of the concentration distributions could not be explained completely even though these three actions were taken into consideration. At present, the functional formulae of these actions have not been obtained at all. Qualitative and also quantitative studies on them are indispensable to know the behaviour of the particles, and are the subject for a future work.

4. Conclusion

(1) The concentration distributions of particles in a vertical pipe were measured. The profiles in an upward flow were opposite to those in a downward flow, when Re_t was not so large.

(2) For both upward and downward flows, the patterns of the particle concentration distribution for $Re_p < Re_{pn}$ showed the opposite to those for $Re_p > Re_{pn}$.

(3) All the experimental results of the concentration distributions could be classified by taking Re_t and Re_p as parameters.

(4) Some considerations on the kineties of particle distribution were described.

Nomenclature

d_p	; particle diameter	[cm]
n_i	; number of particles in i-th section	[−]
N	; total number of particles	[−]
r	; radial distance	[cm]
R	; radius of pipe	[cm]
Re_p	; particle Reynolds number $(d_p u_p/\nu)$	[−]
Re_{pn}	; neutral particle Reynolds number	[−]
Re_t	; stream Reynolds number $(2Ru_f/\nu)$	[−]
u_f	; liquid velocity	[cm/sec]
u_{fr}	; liquid velocity relative to particle	[cm/sec]
u_p	; terminal velocity of particle	[cm/sec]
y	; distance from pipe wall	[cm]
ρ_f	; fluid density	[g/cm^3]
ρ_p	; particle density	[g/cm^3]
ν	; kinetic viscosity of liquid	[cm^2/sec]

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