Characteristics of movement of solid particle in snow-water mixtures

Mikio SASAKI

1 Hachinohe Institute of Technology
88-1 Ohbiraki, Myo, Hachinohe 031-8501, Japan
Tel: +81-0178-25-8074 Fax: +81-0178-25-0722
msasaki@hi-tech.ac.jp

Abstract. In the present study, experimental observations for the movement of solid particles in the solid-water mixture flow were carried out in the horizontal pipe with a high-speed camera. When flow is slow, the picture was taken at 1000 scenes per second, and when flow is fast, the flow observation catches the solid particle very clearly at 4000 scenes per second. From the flow observation of the solid-water multi-phase flow that the solid specific gravity is near that of the transportation fluid, the change of the solid particle position and the speed change of the solid particle were shown in the present study. Within the scope of the present study, the following conclusions were derived. The solid particle flows with moving up and down. The change of the speed is large. The speeds in the lower layer and upper layer are both great fluctuations because the change of the speed near the wall is large. On the other hand, the vicinity of the solid particle in the middle layer of the pipe fluctuates a little and a steady speed continues. The solid particle near the wall rotates greatly, however, the solid particle in the middle layer of the pipe shows a small rotation. The rotation means that the flow of the mixtures is not Bingham flow..

1. INTRODUCTION

In this experimental study, polystyrene particles are used. The density of solid is nearly equal to that of the carrier fluid, namely, water. Using the particles with the density near 1, we have got good observations in the high degree of exactness for the snow-water mixture flows. Solid particles with the specific gravity lower than 1 are chosen to imitate the pure snow masses. On the other hand, solid particles with the specific gravity denser than water are taken to observe the behavior of snow masses including sand or mud.

Heavy snowfall occurs in the north districts in Japan. To remove snow, snow drains are utilized by townspeople in the north cities. The snow drains are constructed along streets, and used as a hydraulic conveyor for removing snow from the urban area to a river. Recently, the number of cities utilizing the snow drain has increased greatly, and many more cities are planning to build new snow drains. However, there are many locations where such snow drains are not feasible due to lack of adequate slope to the road. If the end of the snow drain is lower than a river, snow conveyed by the drain is not transported by water flow from to a river. Nowadays, a snow drain system with pipeline in final transportation has been investigated to pump up the mixtures from the snow drain to a river when the end of the snow drain is lower than a river. Then, the water slurries of snow in pipe are of considerable importance in final transportation in the snow drain system.

The solid-liquid multi-phase flow is observed with the high-speed camera. The observation is to examine the rotation behavior characteristic of the solid particle. In this experiment, the pipeline was
used, and the diameter of the pipe is 5 cm, the specific gravity of the solid particle is 1.06.

2. EXPERIMENTAL EQUIPMENT

The equipment in the present experiment is shown in Figure 1. The test section, which is 13 meters in long, is made of transparent acrylic pipe with the diameter, \( d = 49.7 \text{ mm} \). A part of the pipe goes through a quadrilateral water jacket. Within the jacket, visual observations for the behavior of the slid particles can be made with a high-speed video camera.

**Table 1.** Experimental conditions.

| Diameter of polystyrene particle, \( d_s \) (mm) | 3.09 |
| Specific gravity of solid particle, \( S \) (-) | 1.04 |
| Mean velocity, \( v \) (m/s) | 0.5, 1.0, 1.5, 2.0 and 2.5 |
| Reynolds number, \( Re \) (-) | From 25700 to 128500 |
| Solid concentration, \( C_v \) (-) | 0.025 and 0.05 |

The diameter and the specific gravity of the polystyrene particles are 3.09 mm and 1.04. In this present experiment, mean velocity and Reynolds number and the solid concentration by volume are in the ranges from 0.5 to 2.5 m/s, from 25700 to 128500, respectively. The solid concentrations, \( C_v \) are 0.025 and 0.05, where \( C_v = V_s/Q \), where \( V_s \) is the flow rate of solid particles and \( Q \) is the flow rate of the mixtures. Table 1 shows the experimental conditions in this study. In Table 1,
Reynolds number, \( \text{Re} \), is defined by \( \text{Re} = \frac{\nu d}{\nu_w} \), where \( \nu \) is the mean velocity and \( \nu_w \) is the kinematic viscosity of water.

In general, it is better to set the solid pump at the beginning of the pipeline. When the slurry pump is set at the start station in the snow-water mixture flows, the pump crushes snow blocks into much smaller ones. Hence, the snow-water mixture flows become similar to polystyrene solid-water mixtures.

When the velocity is higher than 0.5 m/s, the snow blocks are flowing down individually without combining together. In the present experiment, there is no combine by meltdown of the snow blocks in the mixtures as long as the snow blocks are flowing through the pipe with a speed beyond 0.5 m/s. The results of observations in the present study are available for snow-water mixtures.

3. SOLID PARTICLE VELOCITY

Figures 2(a), 2(b) and 2(c) show an example of the observations with the high speed camera for the solid particle at solid concentration \( \text{Cv} = 2.5\% \). The solid particle moves quick in order of (a), (b), and (c), that is, the mean velocities are 0.6, 1.5 and 2.5 m/s in the figures. Figure 2(a) is showing that solid particles are flowing in the lower part of the pipe. The reason for the movement of a particle that is heavier than the fluid is that the particle flows in the lower layer of the pipeline because the shear stress working on the solid particle is small as the flow velocity becomes lower. Figure 2(b) shows the movement of solid particles that are heavier than the fluid. As shown Figure 2(b), the solid particle extends to the entire pipe section and flows when the mean flow velocity becomes 1.5 m/s. Figure 2(c) shows that solid particles that are heavier than the fluid move to the upper layer of the pipe and extend to the entire pipe section and are flowing down in the entire pipe without the distinctions of upper layer and lower layer as the average velocity becomes 2.0 m/s. This means that the shear stress working on the solid particle is growing enough, as the mean velocity becomes higher. The shear stress is caused by the speed difference between the solid particle and the fluid particle. As the mean flow velocity grows, this speed difference, that is, slipping velocity becomes high. Of course, there is a speed difference between the solid particle and the fluid particle in the flow of a low-speed region like case 2. The velocity difference is small also in the low-speed region though the slipping velocity exists. It doesn’t make a large shear stress that the solid particle defies gravity to flow up. As shown in the figures, the solid particle extends to the entire pipe as flow velocity becomes higher.

Figure 2(a). Observations for solid particle in Case 1, mean velocity, \( \nu = 0.6 \) m/s, solid concentration, \( \text{Cv} = 0.025 \). The flow is from the right to left.
When the solid specific gravity is larger than the specific gravity of the transportation fluid, when flow velocity is small, the solid particle flows accumulating in the lower layer, the distortion of the speed distribution grows, and the energy loss grows. When the solid specific gravity becomes smaller than one, the solid particle accumulates in the upper layer in the low-speed region. As the mean velocity becomes large, the solid particle extends to the entire pipe section because the speed difference between the solid particle and the fluid particle grows, and the shearing force grows.
Figure 3(a) Movement of solid particle in upper layer along pipe direction

Figure 3(b) Movement of solid particle in middle layer along pipe direction

Figure 3(c) Movement of solid particle in lower layer along pipe direction

Figure 3. Movement of solid particle in the upper, middle and lower layers in Case 1, mean velocity, \( v = 0.6 \text{ m/s} \), solid concentration, \( C_v = 0.025 \)
Figure 4(a). Velocity of solid particle in upper layer along pipe

Figure 4(b). Velocity of solid particle in middle layer along pipe

Figure 4(c). Velocity of solid particle in lower layer along pipe

Figure 4. Observation of solid particle velocity in Case 8, mean velocity, \( v = 2.0 \text{ m/s} \), solid concentration, \( C_v = 0.025 \)

Figure 3 shows an example of the result of examining the vertical movement of the solid particle. The solid particle flows with repeating the vertical movement in the solid size scale that becomes 0.06
in the value of the vertical axis because the pipe diameter d is 50mm and the size of solid particle ds is 3mm. As shown figure 3(a), the solid particle moves from 0.778 to 0.772 in a perpendicular direction while it moves horizontally by 15mm. This becomes a perpendicular distance 0.3 mm. Therefore, the figure 3(a) shows that the solid particle flows down horizontally little moving in a perpendicular direction in the upper layer in the pipeline. On the other hand, the solid particle moves from 0.426 to 0.407 in a perpendicular direction in the middle layer while it moves horizontally by 15 mm as shown in Figure 3(b) and this distance is 0.5mm. The movement of a perpendicular direction of the solid particle in the middle layer is larger than the one of the solid particle in the upper layer. And, a perpendicular movement of the solid particle is small in the lower layer as shown in Figure 3(c) as well as the upper layer. The solid particle in the lower layer moves by the same degree of the distance as the upper layer. The difference of the movement of the perpendicular distance means the difference of the force to act on the solid particle, the force on the solid particle becomes small in the middle layer and the force is strong near the upper and lower layers. The nearer to the wall the solid particle goes, the stronger the force acting on the solid particle. This force is the shear stress caused from the speed difference between the solid particle and the transportation fluid.

Figure 4 shows an example of the result of observing the speed of the solid particle in the upper, middle and lower layers, where the horizontal axis of figure is a distance taken in the direction of the flow. As shown in the figure, the speed of the solid particle changes in the direction of the flow. As shown in Figure 4(a), the speed change is caused in 8 cm/s in the upper layer, however, as shown in Figure 4(b), the speed changes in a range of 5 cm/s in the middle layer. As well as the upper layer, the speed change is caused in a range of 15 cm/s. Thus, the speed change is growing in the upper and lower layers more than the middle layer. The difference of the width of the speed change between the middle layer and wall layer is due to the gradient of the velocity distribution in the direction of the pipe section. As shown in Figure 4, there is the cycle in the speed change. As the solid particle moves by 1 cm, the cycle is one in the middle layer and the cycle comes to two in the upper and lower layers.

Figure 5 shows the velocity distribution in the lower mean velocity. As shown in the figure, the distortion of the velocity distribution causes a little because the solid concentration is small. In this
case, the energy loss of the mixtures becomes small due to the small solid concentration. Because the solid particle flows with accumulating in the lower layer in a low-velocity region (See Figure 2(a)), the velocity of the solid particle is relatively low. On the other hand, the velocity of the solid particle in the upper layer has quickened comparatively because most upper layers are liquid layers. As shown in Figure 5, the velocity distribution doesn’t become symmetry for the centre of the pipe, and the maximum value of flow velocity is caused within the range of 0.6-0.7 of the vertical axis in the figure.

4. ROTATION OF SOLID PARTICLE

Fig.6 shows the result of the rotational angle speed of the solid particle in the low mean velocity. In the figure, y is the distance from the pipe bed to the top of the pipe. The horizontal axis is a rotation angle of the solid particle per 10 cm. The rotation angle shows the rotation of the solid particle as the solid particle moves by 10 cm. It is observed by using the present high-speed camera. As shown in the figure, the solid particle near the wall rotates greatly compared with the solid particle in the middle layer. The solid particle’s rotating shows that the flow of this solid-water mixture flow is not the Bingham flow but the Dilatant flow. Then, It will be necessary to show the velocity distribution of the solid-water mixture flow shown in Figure 6 by the Dilatant flow.

Figure 6 Rotation of solid particle per horizontal distance, 10 cm along the pipe in low-speed region

3. CONCLUSIONS

In the present study, experimental observations for the energy losses were carried out in the solid-water mixture flows. Within the scope of the present study, the following conclusions were derived:

(1) The solid particle flows with moving up and down. The movement of a perpendicular direction of the solid particle in the middle layer is larger than the one of the solid particle in the upper layer. The difference of the movement of the perpendicular distance is due to the difference of the force to act on the solid particle, the force on the solid particle becomes small in the middle layer and the force is strong near the upper and lower layers.

(2) The change of the speed is large. The speeds in the lower layer and upper layer are both great fluctuations because the change of the speed near the wall is large. On the other hand, the vicinity of the solid particle in the middle layer fluctuates a little and a steady speed continues.

(3) The solid particle near the wall rotates greatly, however, the solid particle in the middle layer shows a small rotation. The rotation means that the flow of the mixtures is not Bingham flow but Dilatant flow.
NOMENCLATURE

d  = diameter
Re  = Reynolds number
v  = velocity
vw  = kinematic viscosity of water
ds  = Diameter of polystyrene particle
S  = Specific gravity of solid particle
Cv  = Solid concentration
Fr  = Froude number
f*  = friction factor
f  = wall friction coefficients
fw  = wall friction coefficients
I  = hydraulic gradient
m  = proportion coefficient
A and B  = coefficients which change depending on the specific gravity
S  = specific gravity
φ  = function

REFERENCES

(1) Kawashima T., Sasaki M. and Takahashi H. (1993) : Experimental study of snow-water mixture flows in horizontal pipes, Hydrotransport 12, pp.525-533.
(2) Mikio Sasaki, Toshio Kawashima and Hiroshi Takahashi (1992): Flow characteristics of snow-water mixture flows in horizontal pipes, Proceedings of 2nd International conference of Snow Engineering, pp.301-312.
(3) Mikio Sasaki, Toshio Kawashima and Hiroshi Takahashi (1995): slip velocities of solid-liquid mixture flows in horizontal pipe, Two-Phase Flow Modelling and Experimentation, pp.1035-1039.
(4) Mikio Sasaki and Takahiro Takeuchi (1999): Eddy viscosity of solid-liquid flow with nearly equal density in horizontal pipe, Hydrotransport 14, pp.359-370.
(5) Mikio Sasaki and Takahiro Takeuchi and Hiroshi Takahashi (2001): Coefficients of wall friction in snow-water mixture, The CD-ROM Proceedings of the ICMF-2001, the 4th International Conference on Multiphase, Session AM, No264, 2001.