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Article

Experimental Studies on Hydraulic Lifting of Solid-liquid Two-phase Flow

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Abstract : Experimental studies with 4.3 m and enlarged 30 m in height have been conducted to investigate the flow characteristics of solid-liquid mixture in a lifting pipe and to acquire the design data for sea tests that will be performed in the future. From the results, it was observed that the more the discharged volume fraction and the solid diameter increase, the more the hydraulic gradient increases. Also, the more the diameter of the lifting pipe increases, the smaller the friction loss, and consequently, the less pressure drop and hydraulic gradient. From the enlarged hydraulic pumping experiments, it was shown that the results of the experiments were matched with those of the numerical model previously developed. On the bases of these studies, we plan to conduct further experiments and validate the hydraulic pumping model.

Key words : hydraulic pumping system, manganese nodules, two-phase flow, experiment

1. Introduction

The deep seabed is one of the newest and most rewarding frontiers for mankind in its quest for knowledge and material achievement. Manganese nodules on the ocean floor, in particular, emerge as new alternatives for the exhaustion of mineral resources on land. Metals from manganese nodules are for use in steel, aircraft, military equipment, machinery and cutting tools (Chung 2003). For the development of deep-sea minerals, it demands a totally integrated system, consisting of four different processes, i.e., exploration, mining, transportation and metallurgy. Among these, the mining process can be classified into three categories, including a collecting system, lifting system, and mining ship. The collecting and lifting systems are the most important parts in the commercial mining process.

Lifting technology is crucial to achieve the success of the deep-sea mining project, by which manganese nodules are conveyed from the seafloor to the mining ship and can be classified into the hydraulic pumping system and the air lift system according to the fluid dredging type, the continuous line buckets system of the mechanical type and the modular marine mining automation system. Among the lifting methods, the hydraulic pumping and air lift systems proved technically feasible. In the hydraulic pumping system, solid particles are conveyed with water hydraulically. There are considerable studies on the hydraulic transportation of a two-phase mixture. Newitt *et al.* (1961) carried out an experiment to predict the hydraulic gradients and flow rates of water and solid particles in pipes 1 inch in diameter. Noda *et al.* (1986) derived the settling velocity and drag coefficient of the particle group related to in-situ volume of solids using coal samples. Kitaha *et al.* (1985) dealt with the hydraulic behavior of synthetic nodules and other kinds of solids with grain size up to 42 mm in the vertical pipe. Chung *et al.* (1998) and Sumardi and Chung (1996) presented a two-phase (solid-water) upwardly flowing vertical system with a 1 inch diameter clear PVC pipe to test flow characteristics. Xia *et al.* (1997) studied the basic characteristics of the solid-liquid two-phase flow transport, the prediction and optimization of the hydraulic pumping parameter for the commercial mining system. There have also been studies on the flow behavior of solid particles in a pipe, which are based on the hydrodynamic models (Yoon *et al.* 1998). Sobota *et al.* (2001) investigated the slip velocity between solid and liquid in a vertical pipe through experimentation.

In Korea, Yoon *et al.* (1999) designed and tested an

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apparatus for a two-phase flowing system with 4.3 m in height with a net 3.6 m flow line included to understand the flow characteristics in a vertical pipe. Also, from the results, a model predicting pressure drop in a vertical lifting pipe was developed. However, the enlarged lifting system is inevitable in acquiring enough information for the application of deep-sea. Thus, from the results of the preliminary small-scale experiments and the developed hydraulic pumping model, we designed an enlarged test system on a scale of 30 m. The enlarged hydraulic pumping system has been setup and tested in the lifting test laboratory, which is composed of a lifting pipe 30 m in height and 100 mm in diameter, a lifting pump, circulation pipe, nodule feeder and automatic monitoring and controlling system.

In this study, we will review and explain the small scale and enlarged systems with a scale 30 m in height. Then, the results from the experiments will be compared with the hydraulic pumping model previously developed in order to predict the upward flowing characteristics of the solid-liquid two-phase mixture. These efforts will be a firm foundation for the sea test and finally in the actual mining operation scheduled for testing after 2010.

2. Theoretical consideration

The objective of these experiments is to analyze and understand the flow parameters such as phase velocity, in-situ and discharged volume fraction, pressure gradient, and hydraulic gradient of the solid-liquid two-phase mixture in a small vertical tube by measuring the discharged mass flow rate of solid and liquid and the pressure drop as a function of the diameters and volumetric flow rate of solid particles. The following are the basics for the analysis of two-phase mixture flow.

By measuring the discharged solid mass flow rate (W_{SS}) and the discharged liquid mass flow rate (W_{SL}) from the two-phase mixture, the superficial volumetric flowrates of solid particles (Q_{SS}) and liquid (Q_{SL}) can be obtained from Eqs. (1) and (2).

$$Q_{SS} = \frac{W_{SS}}{\rho_L} \tag{1}$$

$$Q_{SL} = \frac{W_{SL}}{\rho_L} \tag{2}$$

where ρ_L and ρ_L are the density of solid particles and liquid respectively. Therefore, the discharged solid volume fraction (C_S) can be expressed as follows:

$$C_S = \frac{Q_{SS}}{(Q_{SS} + Q_{SL})} \tag{3}$$

The superficial solid velocity (V_{SS}) and the superficial liquid velocity (V_{SL}) can also be expressed in terms of a tube cross-sectional area (A).

$$V_{SS} = \frac{Q_{SS}}{A} \tag{4}$$

$$V_{SL} = \frac{Q_{SL}}{A} \tag{5}$$

The average slip velocity (S) between solid and liquid can be expressed as Eq. (6) in terms of the terminal settling velocity of solid particles (V_O) and the in-situ volume fraction of solids, E_S (Govier and Aziz 1972).

$$S = \frac{V_0}{1 - E_S} \tag{6}$$

Under normal turbulent flow conditions, Zuber and Findlay (1965) expressed the terminal settling velocity of the solid (V_O) by using Newton's equation as Eq. (7).

$$V_O = 1.74\left[g\frac{(\rho_S - \rho_L)}{\rho_L}d_s\right]^{\frac{1}{2}} \tag{7}$$

The solid-liquid two-phase mixture velocity (V_M) can be expressed with the flow velocity and in-situ volume fraction of each phase as in Eq. (8).

$$V_M = V_{SS} + V_{SL} = (1 - E_S)V_L + E_S V_S \tag{8}$$

Using this, the average slip velocity between solid and liquid can also be expressed in terms of Eq. (9). The superficial velocity of solid particles and liquid in Eq. (9) can be expressed in terms of Eq. (10):

$$S = V_L - V_S = \frac{V_{SL}}{1 - E_S} - \frac{V_{SS}}{E_S} \tag{9}$$

$$V_{SS} = V_M C_S,\ V_{SL} = V_M(1 - C_S) \tag{10}$$

Eqs. (8) and (10) are substituted into Eq. (9) to obtain the solution for the in-situ volume fraction of solid particles in tube represented as in Eq. (11) including parameters such as E_S, V_M, S and C_S (Newitte *et al.* 1961).

$$E_S = -\left(\frac{V_M - S}{2S}\right) + \left[\left(\frac{V_M - S}{2S}\right)^2 + \frac{V_M C_S}{S}\right]^{\frac{1}{2}} \tag{11}$$

Therefore, the in-situ volume fraction of solid particles and average slip velocity between solid and liquid can be obtained from Eqs. (6) and (11) implicitly. And if the in-situ volume fraction of solid particles is determined, the in-situ velocities of each phase and solid-liquid mixture density can be defined as Eqs. (12), (13) and (14) respectively.

$$V_S = \frac{V_{SS}}{E_S} \tag{12}$$

$$V_L = \frac{V_{SL}}{1 - E_S} \tag{13}$$

$$\rho_M = \rho_S E_S + \rho_L(1 - E_S) \tag{14}$$

The hydraulic gradient (H_M) of the mixture, the important variable in the flow of the two-phase solid-liquid mixture, can be obtained from the Eq. (15).

$$H_M = \frac{\Delta P}{\rho_L g \Delta L} - E_S\left(\frac{\rho_S}{\rho_L} - 1\right), H_T = \frac{\Delta P}{\rho_L g \Delta L} \tag{15}$$

where, ΔP and ΔL denote the pressure drop measured from pressure gauges attached to the upper and lower part of the vertical pipe and the distance between the gauges, respectively. H_M is the frictional hydraulic gradient and H_T is the total hydraulic gradient of the two-phase flow.

3. Hydraulic lifting experiments

In order to analyze the flow characteristics of the solid-liquid two-phase mixture and validate the hydraulic pumping model which depicts the solid-liquid flow, preliminary hydraulic pumping experiments and the enlarged scale experiment have been conducted.

Small scale experiments with 4.3 m height scale

A small-scale experimental apparatus illustrated in Fig. 1 was devised and constructed for the overall experiment and analysis of the flow characteristics of the two-phase solid-liquid mixture. It is an open circulating flow experimental apparatus with a vertical height of 4.3 m and a vertical length of 3.64 m. A transparent acryl pipe is used for the vertical tube with an internal diameter of 20 and 30 mm to observe the movement of the solid particles. This experimental system consists of a vertical tube, a partible feeder, an overflow tank and a lifting pump. The input mass rate of solid particles is controlled by regulating the screw feeder RPM. The water level in the apparatus is maintained by regulating the level of an overflow tank. After the whole system is installed, the lifting pump characteristics are estimated through tests using tap water. Firstly, the two-phase mixture of solid particles and water flows upward through the vertical tube by means of an experimental 3-hp centrifugal pump connected to the inverter in the control box. The inverter regulating the RPMs of the lifting pump controls the input flow rate of the solid-liquid mixture and then the mixture passes through the digital differential pressure gauge and the electomagnetic flowmeter. The pressure taps of the DP gauge are installed 2.5 m apart at the upper and lower ends of the tube to measure the pressure drop of the two-phase mixture and the flowmeter. The discharged solid and water are measured by load cells. The water pump supplies water from the water supply tank to the water reservoir in order to complement the water outflowing from the water reservoir.

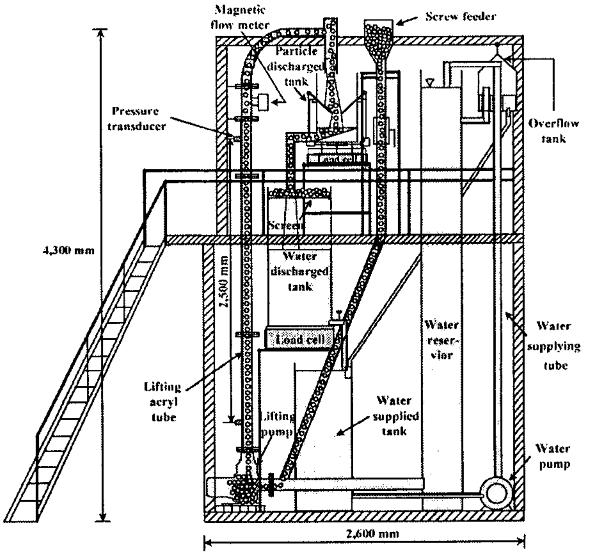

Fig. 1. Schematic view of two-phase flow experimental system with a scale 4.3 m in height.

The water used in this study is tap water with salt, which was made by mixing water and salt at the weight ratio of 966:34. The solid particles are spherical alumina balls of 3 types with the particle diameters of 2, 3, and 5 mm and densities of 3,698, 3,617, and 3,657 kg/m^3 in order to analyze the effects of ball diameter.

Hydraulic lifting system with a scale 30 m in height

The experimental setup for the present study is similar to that of the previous small-scale two-phase flow apparatus. A schematic diagram of the hydraulic pumping system, which is designed to simulate the lifting process for deep-sea manganese nodules, is shown in Fig. 2. The diameter of the vertical pipe is 100 mm and designed to ensure the possibility of complete flow movement 23.6 m in height, where the measurement interval is 15.5 m with a pressure gauge. A transparent acryl pipe of 1 m in height is attached

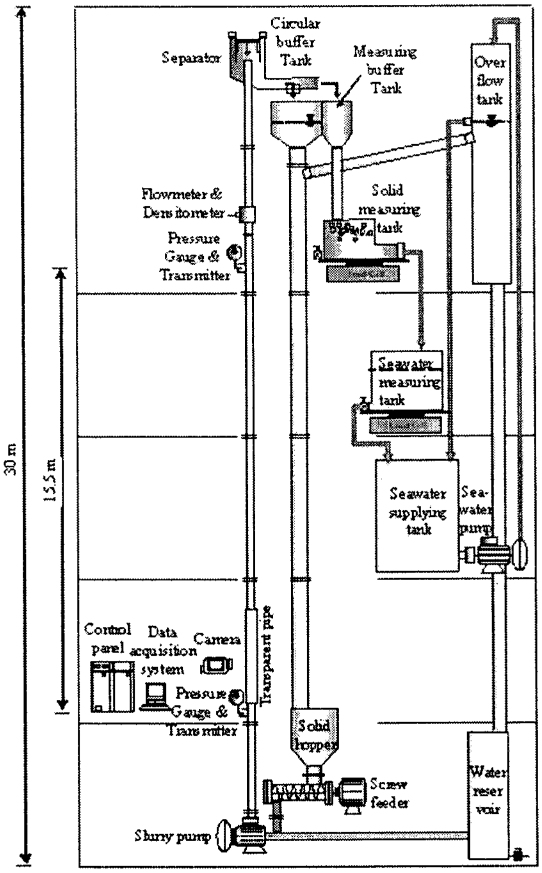

Fig. 2. Hydraulic lifting system with a scale 30 m in height.

to the lifting pipe in the second floor so that we can watch the flow pattern of the solid-liquid two-phase mixture. Solid-water mixture is pumped vertically upward through the pipe by means of a centrifugal pump. The slurry mixture passes through the flowmeter combined with a radioactive densitometer and digital and analog pressure gauge. Also, the weight of solid and water are measured by load cells. The framework of the test system can be divided into 4 parts: (1) the lifting part of the nodule feeder, a vertical lifting pipe and lifting pump, (2) the storage part of a separator and a buffer tank which stores the transferred water and solid particles temporarily, (3) the measuring and controlling apparatus of a flowmeter with densitometer, pressure gauges, computer data acquisition and controlling system, and so on, (4) the circulation part of an overflow tank, which maintains the water level in a pipe, a sea water pump and a sea water feeder which recirculates fluids after measurement, and a conveyer system which circulates the solid particles into the circulation buffer tank.

For these experiments, a 50-hp centrifugal slurry pump with a 4-inch outlet was selected. The total head at 2.4 m^3/min is 45 m and the efficiency of the pump shows about 60%. The pump RPM can be controlled by inverter. Synthetic nodules used in this study were manufactured with fly ash. The shape and density of artificial manganese nodules shows macroscopic shape index (δ, roundness) $1.0 > \delta > 0.75$, microscopic shape index (ζ, flatness of the surface) $1.0 > \zeta > 0.83$ and the average density 2,140 kg/m^3. Synthetic nodules stored in the nodule hopper are fed to the slurry pump by a screw feeder at variable speeds. Two screw feeders of 300 mm interval between screws and 400 mm of inner diameter are installed to guarantee to supply nodules with enough means to meet the level to simulate the deep sea lifting system. Supplying speed can be controlled by changing the RPM of the motor connected to the screw feeder.

For the measurement of solid-water mass flowrates, the DeltaMass flowmeter of Advanced Flow Technology Company is used. The flowmeter combines a DeltaForce magnetic flowmeter and a low level gamma ray density sensor in one package in a pipe of 4 inches. The densitometer incorporates ultra sensitive scintillation detectors which allow slurry density to be measured with the typical accuracy of a span of ±0.5%. The measured mass flowrates of solid and water are compared with the weight by the load cells and a calibrated instrument.

Experimental procedure

The experimental procedures can be summarized in the following way: Firstly, let the lifting pipe be filled with water so that the water head can be situated at the top of the pipe. This means the experimental environments are similar to that of the sea water level. Then, preliminary experiments to understand the characteristics of a lifting pump are performed. Mass flow rate and velocity according to the pump's RPMs are measured using only water to express the linear relationship and understand the pump characteristics. Thirdly, the relationship between feeder revolution and input volume are estimated. Experimental parameters are the input volume fraction of particles and pump revolution and the measured variables consist of pressure drop, and the superficial mass flow rate of solid and liquid. The calculated variables consist of the discharged volume fraction, in-situ volume fraction, in-situ velocity of each phase, pressure gradient and hydraulic gradient.

In both experiments for small and enlarged systems, the discharged weight of water and solids were measured by load cells, but we also used the flowmeter combined with a radioactive densitometer for measuring mass flowrates in the enlarged system.

4. Results and discussion

This study has been performed to develop the lifting technology of deep-sea manganese nodules deposited in seabeds. On the basis of the previous section, small scale and enlarged systems were built and a lot of experiments have been conducted according to changes in pipe diameter, solid particle diameter, solid volume fraction of solid particles, and so on.

Small scale experiments with a scale 4.3 m in height

At first, the pressure drops according to variations in solid diameter, investigated as illustrated in Fig. 3. When the solid particles 3 and 5 mm in diameter flow in the tube, the pressure drop increases compared with those 2 mm diameter. This is because the pressure fluctuation is relative to total pressure drop in low velocity increases as opposed to those at high velocity. In this study, experiments less than 2.5 m/s in velocity could not be obtained for the prevention of the pump blockade.

The pressure drops to analyze the effect of tube diameter changes were measured. As illustrated in Fig. 4, the larger the tube diameter, the smaller the friction loss, and consequently, the less pressure drop and hydraulic gradient were shown. Also, in terms of similar flow velocity, pressure drop increases according to the increase in the discharged volume concentration of solid particles. This is because hydrostatic pressure and friction loss increase when the supply of solid particles increases.

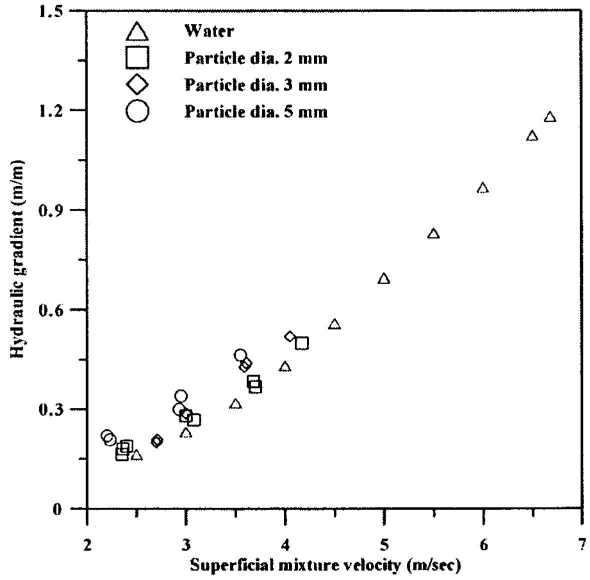

Fig. 3. Hydraulic gradient for water-alumina particles in a 30 mm pipe (solid volume fraction 1.5-2.0%).

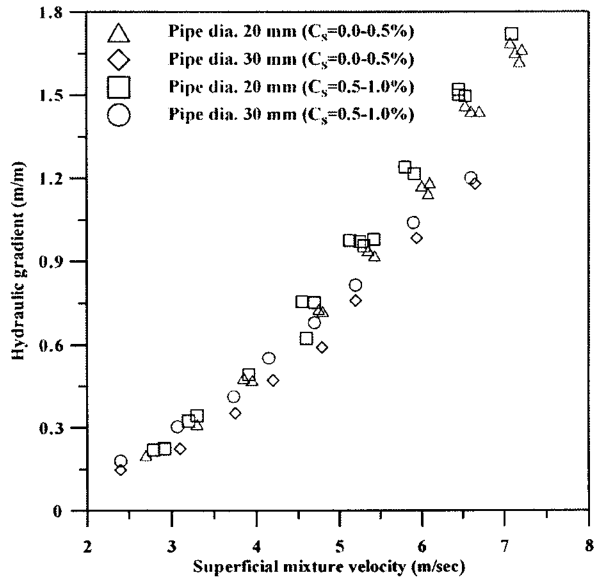

Fig. 4. Hydraulic gradient for water-alumina particles according to the discharged volume fraction of the solid (particle dia. 2 mm).

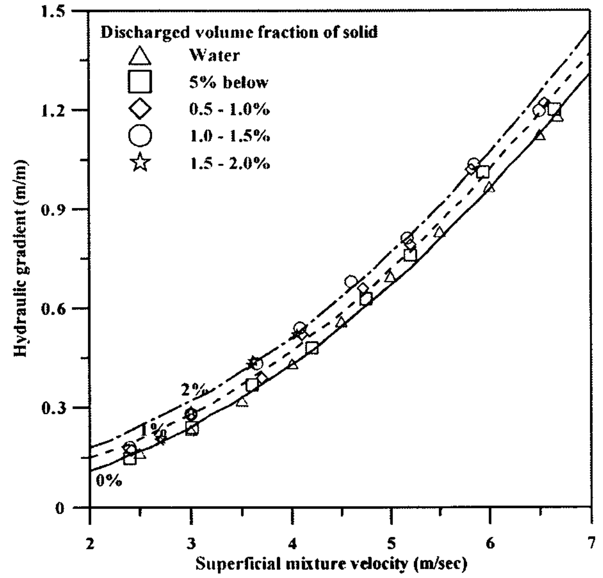

Fig. 5. Comparison of hydraulic gradients comparing experimental and computational results in a 30 mm pipe (particle dia. 3 mm).

From the whole data, it is consistently observed that the hydraulic gradient increase gradually according to the increase of the discharged volume fraction of solid particles. For higher volume fraction of solid particles, the velocity of solid-liquid two-phase mixture should be increased due to the increase of the additional fraction loss between the tube wall and solids.

Fig. 5 shows the experimental and numerical results for the hydraulic gradient respectively when the spherical alumina particles are present in a tube of 20 mm diameter. As illustrated in the figure, the measured pressure drop is relatively similar to the numerical model.

Hydraulic lifting system with a scale 30 m in height

On the basis of the above, the experimental variables consist of the injection volume fraction and flow velocity of the artificial nodules in the vertical pipe. The measuring variables consist of pressure drop, superficial volume flow ratio, and mass flow ratio of the solid and fluid, and the flow ratio and density of the mixture. The calculated variables are discharged volume fraction, volume fraction in the pipe, pressure gradient, and hydraulic gradient. The experimental results have been compared with the prediction model (Yoon *et al.* 1998) previously developed.

As a preliminary test before two-phase experiments, experiments on the hydraulic gradient of clear water have been carried out. The predicted hydraulic gradient of the solid line and experimental results versus fluid velocity were presented in Fig. 6. As shown in the figure, the hydraulic gradient in this study shows the almost identical tendency to agree with the prediction of the model.

The experiments for the hydraulic gradient of the two-phase mixture have been carried out with synthetic nodules 20 mm in diameter. We have performed the experiments on solids with a slurry concentration up to 10%. Fig. 7 shows that the total hydraulic gradient increases with the increase in the solid fraction. The experimental results were lower than the predicted values of the solid line. However, we are not confident of the tendency and further investigations are needed. Also, it was demonstrated that the effect of the friction loss of the mixture flow was reduced, because solid particles moved to the center of the pipe in the case of higher fluid velocity. In the region of higher velocity, it was shown that the frictional loss of single phase flow would be substituted for the hydraulic gradient of a two-phase mixture flow in a vertical pipe.

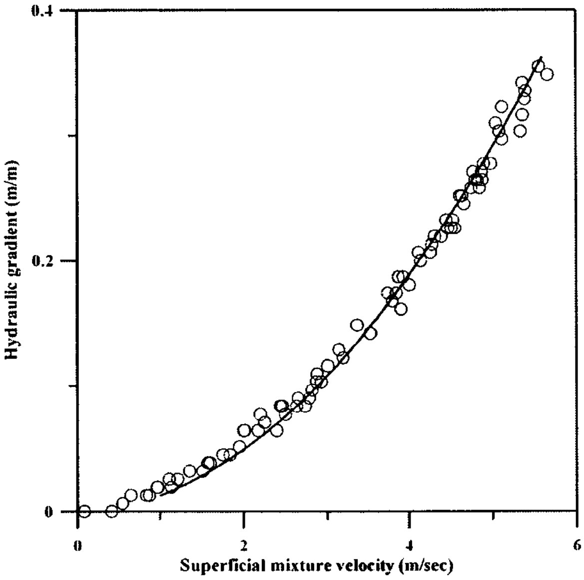

Fig. 6. Hydraulic gradient as a function of the velocity of clear water flow.

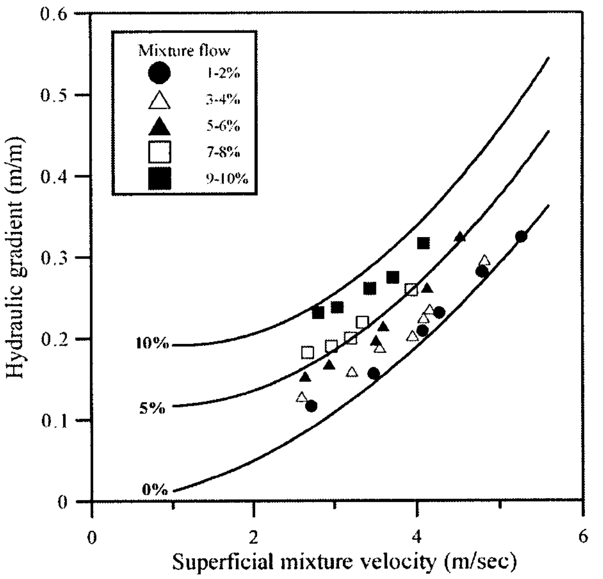

Fig. 7. Total hydraulic gradient as a function of mixture velocity.

On-land lifting experiments on a scale of 30 m were performed to verify the numerical hydraulic pumping model based on the results of the small scale experiments and to investigate the problems that can occur in sea tests. As a preliminary test before two-phase experiments, experiments on the hydraulic gradient of clear water have been carried out. From the results, it was found that the hydraulic gradient in this study shows an almost identical tendency with that of the predicted values. On the other hand, the experimental hydraulic gradient of the two-phase mixture is slightly different from the results of the numerical model. But further experiments are needed for verifying and determining the range of the higher solid volume fraction based on the present studies.

If we suddenly turn off the pump or close the valve, the water at the front is brought to an immediate halt and this requires an impulsive pressure rise, namely, that of a water hammer. We have experienced the blows of a hammer that created damaging pressure spikes, leading to blown pressure gauges, seals and gaskets. From additional investigation for the lifting system, it was predicted that the effects of a water hammer could be diminished by the length of the pipe and surrounding sea-water. However, we have to pay attention to the phenomena and it is thought that a UPS and by-pass valve to avoid the use of a water hammer.

5. Conclusions

Flow experimental systems with an overall vertical height 4.3 m and 30 m were designed and constructed to analyze the factors influencing the flow characteristics of a two-phase solid-liquid mixture in the vertical pipe. From the experiments, the following conclusions were reached:

1. Pressure drop and hydraulic gradient increase according to the discharged volume fraction of the solid particle increases. For higher volume fraction of solid particles, the velocity of a solid-liquid two-phase mixture should be increased due to the increase of the additional friction loss between the tube wall and mixture.
2. It was confirmed that the settling velocity of a solid particle in a vertical pipe increases and also pressure drop increases when the size of the particles increases. Also, it was observed that the accumulation of solid particles in a vertical pipe was closely related to their settling velocity.
3. In the case of a single-phase flow test, it was found that the calculated hydraulic gradient in this study shows an almost identical tendency with that of the experimental values.
4. From the experiments for hydraulic gradient of the two-phase mixture in the enlarged hydraulic pumping system, it was shown that the hydraulic gradient increases with the increase of the solid fraction and the solid particles moved to the center of the pipe in the case of high fluid velocity, thus the effects of friction loss on the mixture flow was reduced.
5. In the process of the present experiments, we have experienced the blows of a hammer that created damaging pressure spikes, leading to blown pressure gauges, seals and gaskets. So we have to investigate the effects of a water hammer in the lifting system to prevent damage.

So far, the experimental studies on the two-phase flow have been performed on only 10% in the steady state condition by volume. Thus, further research on the higher solid volume and the transient flowing experiments will be continued based on the present experiences.

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