Development of Simulation Tool for the Prediction of Large Particles Transport in Liquid Flow

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During the extraction of mineral resources, mixtures of water and rocks are often used to transport large quantities of ore. The pressure losses in a pipeline conveying this kind of mixtures change continuously due to the large variations of the size, density and concentration of the rocks transported. Therefore, continuous operation at a constant flow is often challenging. Mitsubishi Heavy Industries, Ltd. (MHI) developed a solid and liquid multiphase flow simulator that evaluates the unsteady motion of particles. The predictions are compared with the measurements effectuated during a subsea mining test, showing a remarkable agreement. This confirms that this simulator can be applied to quantitatively evaluate the risk of unplanned outages.

1. Introduction

The continuous and mass conveyance of solid particles is widely used in various industrial fields. For example, coal fired power plants use conveyer belts or air flow to constantly inject coal to be used as fuel and evacuate the ashes contained in the exhaust gases. On the other hand, in the field of mineral resources heavier particles are transported at higher speeds. Therefore, specifically designed pumps are used to transport mined ore in a water flow. The friction of the liquid and the solid particles on the walls of the pipeline reduces the pressure of the flow. Therefore, it is necessary to use a pump to overcome this pressure loss and ensure the desired flow rate of liquid and particles. Unless the temporal and spatial distribution of the solid particles in the pipeline can be accurately determined, the pump pressure necessary to maintain continuous operation cannot be calculated. The pressure loss is highly affected by the particles size, concentration and density. Moreover, if the particles are large and the liquid and solids cannot be handled as homogeneous media, the actual spatial distribution of particles in the tubes also plays an important role. To address these issues MHI developed the Solid and Liquid Multiphase Flow Simulator which estimates the instantaneous motion of large solid particles in a conveying system, their position and the generated pressure losses. The computation results have been compared with the measurements obtained during a continuous subsea mining test to verify the accuracy of the simulator. In this report, an outline of the simulator and the future perspectives are described.

2. Outline of solid and liquid multiphase flow simulator

2.1 Calculation model

MHI has promoted the generalization and expansion of the existing solid and liquid flow models in order to apply it to various pipeline configurations (kinds of pipes, lengths of pipelines, pump layouts, etc.) and various solid particles (particle size/density).

The important point in solid and liquid transport is to accurately predict the instantaneous spatial distribution of solid particles, which in turn necessitates a precise estimation of the moving speed of the particles in the carrying fluid. The forces acting on a single solid particle within a moving fluid are the buoyant and drag forces from the fluid, and the weight of the particle itself, as

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shown in **Figure 1**. In a vertical pipe with fast enough upward flow the resultant of buoyant and drag forces is much larger than the weight, therefore solid particles are carried in the fluid direction (upward). Moreover, if large quantities of solid particles are present in the pipe, the collisions between them create additional forces, and the very presence of particles modifies the flow field. Several experimental investigations have been performed to establish models that can predict this complex coupling phenomena, especially in simplified conditions. Masanobu, et al.[1] conducted f tests in which particles with various shapes and sizes were transported by water in a pipeline with given inclination angle, and proposed a model for calculating the liquid and solids speeds and the pipeline pressure loss, in case of steady state operations.

In our solid and liquid flow simulator the model proposed by Masanobu et al. is improved to take into account not only the steady state operation (constant inlet concentration) but also unsteady conditions where the concentration of solids at the inlet of the system is continuously changed.

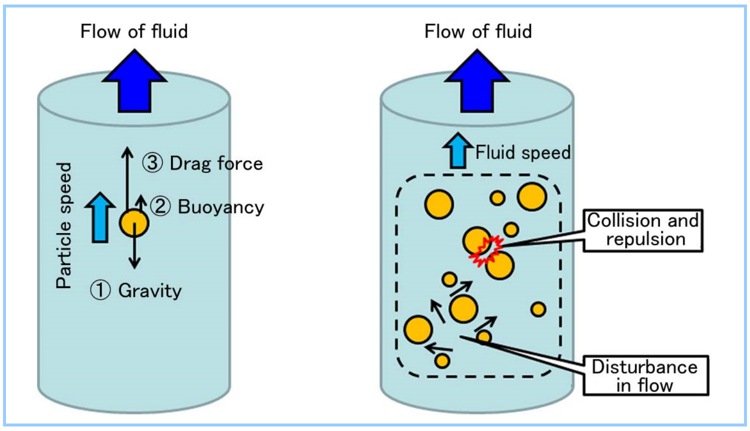

Figure 1 Balance of forces on solid particles carried in fluid

2.2 Features of the simulator and the calculation method

The calculation flow can be seen in **Figure 2**. First, the whole extraction system (rigid and flexible pipes, vales, pumps) is discretized into elements. The boundary conditions are the inlet end and outlet pressures and the inlet solid concentration (time dependent). At each time step, the speed concentration and pressure distribution of solid particles in the whole pipeline are calculated. The particles are then advanced according to their velocity, and the calculation is repeated in the next time step. The control logic of the pump is also simulated, as the rotational velocity is changed to maintain a target flow rate.

Flexible hoses shape changes according to the flow speed and the concentration of solids in the pipe, and in turn it influences the velocity at which the particles move, hence the distribution. This coupled influence is considered in the simulator. Moreover, when considering the submarine resources mining, the force applied to a pipeline by the currents and the buoyancy of the floaters can also be considered.

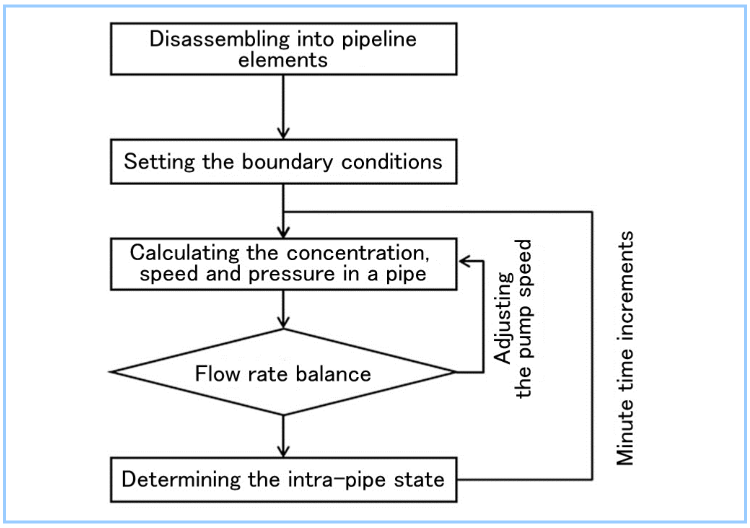

Figure 2 Calculation diagram of the multiphase flow simulator

3. Example of calculation

3.1 Setup of test for continuous ore extraction from seafloor hydrothermal deposits

For the purpose of verifying the accuracy of the simulator, a long-distance conveyance test for large particles was conducted during the period from August to September 2017 by the industrial consortium, which MHI represents, under commission from Japan Oil, Gas and Metals National Corporation (JOGMEC). The world's first test for continuous ore rising from seafloor hydrothermal deposits[2] was conducted (**Figure 3**). In this test, ore that was excavated and crushed on the sea floor at a depth of 1600m was continuously transported by seawater to the surface. MHI was in charge of defining stable operating conditions and developing the overall system control logic using this simulator, as well as conceiving and developing the ore collecting machine and submerged pump.

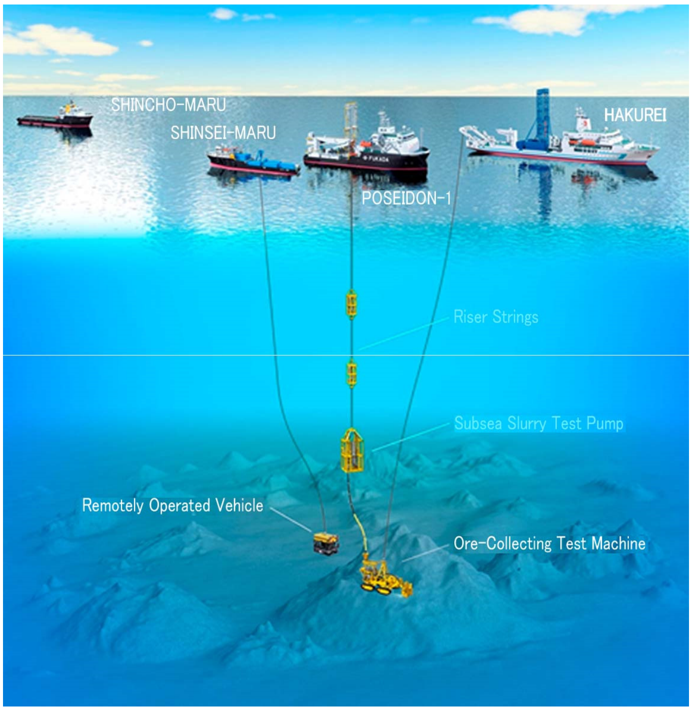

Figure 3 Image of the system configuration for the test for continuous ore rising from seafloor hydrothermal deposits

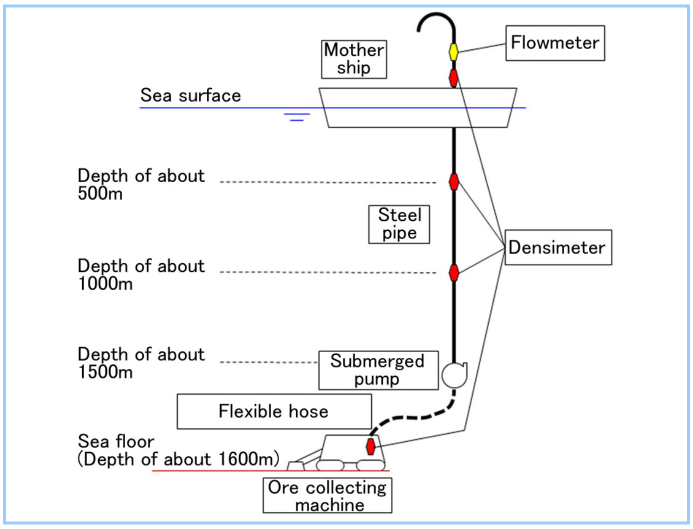

Figure 4 Conceptual diagram for the system for rising ore from seafloor hydrothermal deposits

The structure of the ore rising system adopted in this test is presented in **Figure 4**. A submerged pump is suspended by steel pipes at about 1,500m below the sea surface from the mother ship, and is connected to the ore collecting machine (on the sea floor at a depth of about 1,600m) through a flexible hose. Densimeters, pressure gauges and flowmeters were set at several points to monitor the operating state, and the speed of the submerged pump is controlled by feedback so that the flow rate is kept constant during the test. Thus, ore was stably and continuously raised. The design flow velocity used is 4m/s, therefore it takes about 7 minutes before the ore collected from the sea floor reaches the ship. The amount of ore collected (the inlet in the system) may depend on the operating state of the collecting machine and the state of the ore deposit. Therefore, as described in the previous section, the temporal change of the concentration must be taken into account by the simulator.

3.2 Calculation results

The density measured in the ore collecting machine is used as input for the calculation. The predicted flow rate and density were compared with the measurements were available, to evaluate the accuracy.

Figure 5 illustrates the comparison between the calculated density and the test results at each measurement location as a function of the elapsed time from the start of operations. The passage of ore is detected as an increase in density. Very good agreement is observed between the prediction and the measurements, not only in the prediction of the time required to reach the various measurements locations but also in the changes of the rock distribution due to the transport. However, analysis noticeable difference is observed in the prediction of the propagation of the front of the rocks, especially at the topside: the model predicts rocks velocity at the front that is around 3% lower than the measured one. This is mainly due to the lack of precise models and measurements of the velocity of particles at the front of a group (as opposed to particles in a homogeneous mixture of rocks and water). Notwithstanding this difference, the behavior of the overall system was accurately predicted.

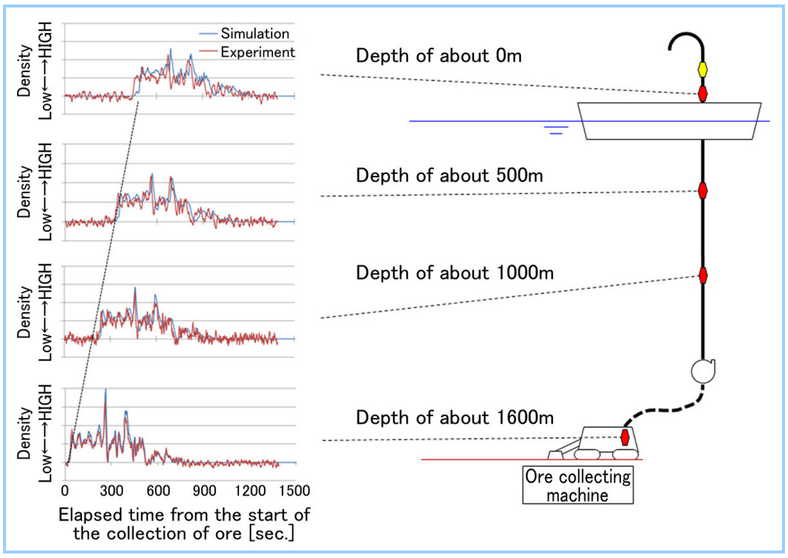

Figure 5 Comparison of the measured and predicted density as a function of the time, at four locations along the piping system

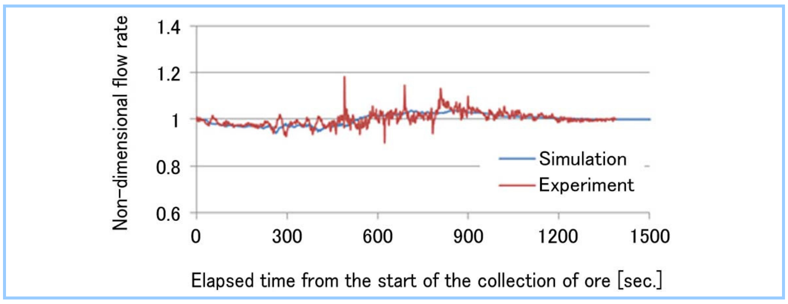

Figure 6 Comparison between the actual measured value and the simulation results for flow rate

Figure 6 compares the measured and predicted flow rate (dimensionless as a ratio of the design flow rate). In the test, an electromagnetic flowmeter was used for the measurement of the flow rate. It can be seen that the test results, measured by an electromagnetic flow meter, show a very large level of noise when rocks are present in the measured flow. This effect is thought to be solely to due to the passage of ore in the vicinity of the electromagnetic sensor, and not to the any instability in the flow velocity. Therefore, although this high frequency noise is not predicted by the calculation, the general flow rate change trend agrees well with the test results.

Complete blockage of a pipeline is the biggest thread to the conveyance system. This phenomenon is very complex and is some cases casual: it can be due to a particularly large rock, or its orientation, parameters that the simulator does not take into account. However, the simulator can be used to predict the distribution of solid concentration and flow rate, thus the blockage risk can be evaluated referring those value to known blockage conditions (determined experimentally).This allows quantitative evaluation of the risk of unplanned outage due to blockage, and the optimization of the production conditions in consideration of this risk (**Figure 7**).

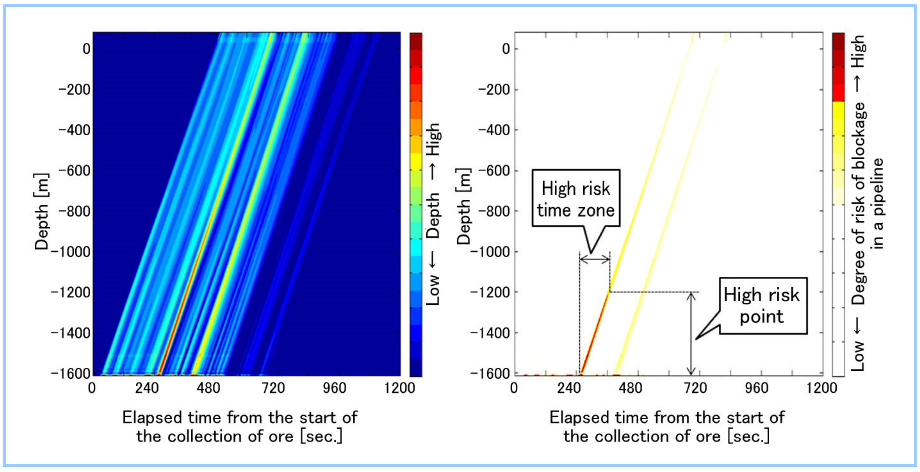

Figure 7 Temporal and spatial distribution of solid concentration and example of representation of the blockage risk

4. Conclusion

It has been confirmed that the developed solid and liquid flow simulator is able to accurately reproduce the long-distance continuous conveyance of solid and liquid multiphase flow. It also enables the evaluation of the overall solid conveying system behavior and the tolerance to unplanned outage risk, and it is expected to be used for the improvement of productivity in the resources mining field.

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