論文

Cohesive Nature of Ice Particles and Blocking Phenomenon of Ice/Water Slurry

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ABSTRACT

The blocking phenomenon of ice-particle/water mixture flow through pipeline is a problem which must be solved before the engineering application of this flow to cold energy transportation in a district cooling system. In this work, the mechanism of the blocking of ice-particle slurry at a tube orifice is investigated and a criterion for blocking is presented. The cohesive nature of ice particles is shown to cause "compressed plug type blocking" and the compressive yield stress of a particle cluster is presented as a measure for the cohesion strength of ice particles.

Key Words: Blocking, Ice/Water Slurry, District Cooling, Cohesion
キーワード：閉塞，氷水スラリー，地域冷房，付着性

1. INTRODUCTION

A new cold energy transportation system utilizing ice/water mixture flow is under development for the purpose of increasing cold energy density in district cooling systems. Many experiments (Larkin and Young, 1989; Onojima *et al.*, 1991; Kawada *et al.* 2001a; Winters *et al.*, 1991) have been carried out to clarify the flow and heat transfer characteristics of ice/water slurry and to develop devices and instruments for the system. As a result of these works, it is reported that the blocking of pipeline elements such as reducers, valves and distribution manifolds is likely to occur due to compressed ice particle clusters (Winters *et al.*, 1991; Umemura *et al.*, 1986; Shirakashi *et al.*, 1990; Kawada *et al.*, 2001b). This type of blocking is quite different in nature from blocking due to arching or deposition observed in usual solid-particle/water slurry transportation pipelines. It is

guessed that the cohesive nature of ice-particles is the main cause of the blocking of ice/water slurry, since iceparticles in the transporting pipeline cohere with each other due to their cohesion force and form clusters as seen in Fig. 1. These clusters stagnate at an orifice, grow into a rigid plug and lead to the blocking. However, very few works have been carried out so far on the ice particle blocking and no data have been reported on the cohesion force of the ice particles in water to be correlated with this phenomenon.

The specific aim of this work is to clarify the mechanism of the blocking of ice/water slurry flow at an orifice in a pipeline and to

Fig. 1 Cluster in ice/water mixture flow through pipe (Chip ice).

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find a criterion for the occurrence of this phenomenon.

2. TEST PARTICLES

Three kinds of ice-particles with different sizes are used as samples, since the cohesion strength depends strongly on the particle size. Polypropylene beads with size and density comparable with those of the ice-particles are also used for comparison. Photographs of the samples are reproduced in Fig. 2. The mean diameter d_p and density ρ of the samples are:

- (a) Chip ice ($d_p = 10$ mm, $\rho = 917$ kg/m³), made in a common refrigerator.
- (b) Granulated snow ($d_p = 3$ mm, $\rho = 917$ kg/m³), gathered from local spots in winter or made by cracking chip ices, sieved out in either case. The sieve mesh size is 5mm.
- (c) Fresh snow flakes ($d_p = 1$ mm, $\rho = 917$ kg/m³), gathered within 24 hours after they fall on the ground.
- (d) Polypropylene bead ($d_p = 4$ mm, $\rho = 908$ kg/m³). These are used for reference because of its non-cohesiveness.

3. COHESION STRENGTH TEST

In order to estimate the cohesion strength of particles that cause particle clustering in the mixture flow through a pipe as seen in

Fig. 1, a compression test technique is devised in this work. The compressive yield stress is used as a measure of the cohesion strength, because it is too small to be measured by a normal tensile or shearing test. Fig. 3 shows the procedure of the compression test of an ice-particle cylinder. The cylindrical test piece is formed by softly packing the particles in a circular pipe with inner diameter 65 mm and length 65 mm. Then it is submerged in 0°C water and a load w is added abruptly.

In the case of the chip ice, the test piece scatters into particles due to the buoyancy when it is submerged in water. Hence, the yield stress of chip ice can be estimated from the following equations.

$$\sigma_y \leq V_i(\rho_w - \rho_i)g / (\pi d_0^2 / 4) \quad (1)$$

$$V_i = C(\pi d_0^2 / 4) h_0 \quad (2)$$

V_i : substantial volume of ice in a test piece

C : ice packing fraction in volume, = 0.5

ρ_w : density of water, ρ_i : density of ice

In the case of the granulated and fresh snows, the test piece is compressed while its diameter remains unchanged when the load w is smaller than the respective critical values.

Fig. 2 Test particles.

When w is larger than this critical value, the test piece is crushed completely. Fig. 4 shows the relationship between the compression ratio r_h and the compressive stress σ defined by Eqs. (3) and (4). The initial diameter d_0 is used to define the stress σ since the change in diameter is small during the compression.

$$r_h = (h_0 - h) / h_0 \tag{3}$$

$$\sigma = wg / (\pi d_0^2 / 4) \tag{4}$$

h_0 : initial test piece height

Fig. 3 Procedure of the compression test.

Fig. 4 Relationship between compression ratio r_h and compressive stress σ .

h : test piece height after adding the load w
 d_0 : initial test piece diameter

The compressive yield stress σ_y is determined as the value of σ at $r_h = 1$, i.e. the lowest value of σ when the test piece is crushed.

The compressive yield stress of test pieces thus determined are:

- (a) chip ice, $\sigma_y \leq 0.03$ kPa,
- (b) granulated snow, $\sigma_y = 0.7$ kPa,
- (c) fresh snow, $\sigma_y = 1.9$ kPa.

4. BLOCKING IN PIPELINE-ELEMENT TEST DEVICE

4.1. Experimental Apparatus and Methods

In order to clarify the blocking mechanism at a pipeline-element isolated from a pump-pipeline system, the pipeline-element test apparatus as shown in Fig. 5 was devised and used to investigate blocking at a tube orifice. Fig. 6 shows the details of the test section. Before a test run, test particles are weighed and put into the test section uniformly along the pipe axis. The ice-particle/water mixture filling the transparent test section set in this way is driven out through the test orifice by a piston-cylinder unit. The blocking process is observed and recorded by video. Pressures p_1 and p_2 at the locations in Fig. 6 and the volumetric ice fraction C upstream from the orifice are detected (Kitahara, *et al.*, 1993). Electrodes for ice fraction measurement are attached at position A. These electrodes are

Fig. 5 Schematic diagram of apparatus.

particles in water is considered to be a governing factor for the compressed plug type blocking, the ratio of the maximum orifice diameter for blocking to the particle size is plotted against the compressive yield stress in Fig. 8. It shows that the higher the yield stress is, the larger is the maximum orifice diameter relative to the particle size for the occurrence of blocking. This result suggests that the cohesive nature estimated by σ_y can be a measure of the blocking.

The criterion for blocking obtained through the pipeline-element test is presented in Fig. 9 as a curve on the u - C_o plane. In Fig. 9(a), blocking occurs when the initial fraction C_o is higher than a certain value

independent of the velocity u . For granulated snow, Fig. 9(b), at a velocity u lower than a certain value, stagnation of the particle cluster occurs for the lowest value of C_o . Since the stagnation may lead to blocking if the orifice is installed in a pipeline for cold energy transportation, this velocity is taken as the threshold for the non-blocking condition. In the case of fresh snow, the threshold value of u is higher as seen by comparing Fig. 9(b) and (c).

Fig.10 shows the typical behavior of ice fraction and pressure difference at the orifice for each slurry when the blocking occurs. For chip ice, Fig.10(a), the particle fraction C increases steeply and soon attains a constant value nearly equal to that of the natural packing. Since the gaps among the coarse particles permit water flow through them with small resistance, the pressure difference through the cluster is small. For granulated snow, Fig. 10(b), the profile of fraction is similar to that of the chip ice. Because of the small size of particles, the pressure difference increases as a compressed plug is growing at the orifice. For fresh snow, Fig. 10(c), because of the softness of the particles, the fraction C increases gradually after a small snow particle cluster is stagnated at the ori-

Fig. 8 Blocking diameter ratio vs compressive yield stress.

Fig. 9 Blocking condition in test tube.

Fig. 10 Particle fraction and pressure difference ($u = 0.11$ m/s).

Fig. 11 Cluster of fresh snow.

fice until a plug-like particle cluster filling the pipe is formed. Since a water path or channel is formed through the cluster of fresh snow, as seen in Fig. 11, the pressure difference in Fig. 10(c) is small. However in a real pump-pipeline system the pressure difference must be large, because the particles are supplied continuously and a water path is prevented from growing.

5. BLOCKING IN THE PIPELINE

The orifices used in the pipeline-element test were inserted into a pipeline of a slurry transportation system, and blocking was examined by lowering the velocity u while

Fig. 12 Pipeline diagram.

keeping C constant.

Fig. 12 shows the schematic diagram of the pipeline system for the experiment. The test section is made of transparent acrylic or PVC pipe with an inner diameter of 50 mm and has sufficient length upstream (more than 10 m). The test particles and water are mixed in the mixing tank and driven into the pipeline by a vortex pump. Then the particle fraction is regulated at an arbitrary desired value by the fraction regulator. (Shirakashi *et al.*, 1990.)

The results for the fresh snow are compared with those of the pipeline-element test in Fig. 13. The criterion curve by the latter is seen to present the condition for the occurrence of blocking of the ice/water slurry in a pump-pipeline system.

Fig. 13 Comparison of blocking conditions in pipeline and in the pipeline-element test apparatus, for fresh snow.

6. SUMMARY

The blocking mechanism of an ice-particle/ water mixture at a tube orifice isolated from a pipeline is investigated using an apparatus specifically devised for the purpose. The same orifices are inserted in a pump-pipeline system and the threshold values of the velocity and the ice fraction for blocking are investigated. The conclusions are summarized as follows.

(1) Blocking of the chip-ice slurry and polypropylene beads slurry occurs due to arching. In this case, the governing factor of blocking is the ratio of particle size to the orifice diameter. Blocking of both granulated snow slurry and fresh snow slurry is caused by a compressed ice-particle cluster like a plug formed upstream of the orifice. The main cause of this compressed plug type blocking is the cohesive nature of ice-particles. The flow velocity and the ice fraction are the dominant parameters for the occurrence of

blocking.

(2) For a fixed ice fraction, compressed plug type blocking occurs when the velocity u is lower than a critical value u_c . The yield stress of an ice-particle cylinder obtained through the compression test correlates well with the tendency for blocking.

(3) The critical velocities for the blocking of fresh snow slurry at the orifice in the pump-pipeline system correlated with the criterion curve obtained through the element test.

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氷の付着性と氷水スラリーの閉塞現象

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要 旨

パイプラインにおける氷水混相流の閉塞現象は地域冷房システムにおける冷熱輸送に氷水を利用しようとするとき解決しておかなければならない重要な問題である。

本研究においては、管路中のオリフィスでの氷粒子の閉塞の機構を探求し、閉塞に関する一つの基準を提案した。また、氷粒子の付着性が“圧密型閉塞”の原因であり、粒子塊の圧縮降伏応力が氷粒子の付着強度の指標であることを示した。

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