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Development of a snow-fraction meter based on the conductometric method

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ABSTRACT. Hydraulic conveying of snow is one of the most promising techniques for snow removal from an urban area. The method for measuring the fraction of snow in a snow–water mixture flowing in a pipe is a key technique for its practical application. A new method based on the conductometric method has been developed in this study. The method was tested using a prototype snow-fraction meter in a testing apparatus and a closed pipeline system. This type of meter has the advantage of in situ measurement of a wide fraction range from zero up to packed value. The meter is capable of quick response, independent of flow velocity or snow properties and nonintrustive in flow. This paper describes the application of techniques for the development of the meter and the test results. This new method is expected to be useful for hydraulic conveying of ice particles or ice cubes, a new technology in the air-conditioning field.

INTRODUCTION

Hydraulic conveying of snow by mixing snow with water and pumping through pipelines is a useful method for removing snow from an urban area (Umemura and Shirakashi, 1989). A method to measure the fraction of snow in snow–water mixture flowing in a pipe is a key technique for its practical application. Calorimetric, hydraulic-gradient, stirring-torque and centrifugal-separation methods have been used in the past (Shirakashi, 1988), but the conventional methods are generally cumbersome. A desirable snow-fraction meter would have real time measurement, be independent of flow velocity or snow properties, be non intrusive in the flow and have high accuracy.

We have developed a new snow-fraction meter based on the electrical conductance of a snow–water mixture for practical use to satisfy the conditions stated above. The basic principle is that the apparent resistivity of a mixture of a solid phase dispersed in a liquid depends upon the resistivities of the two pure phases and on their volume fraction. Maxwell (1954) has expressed the relationship as

$$\frac{\rho}{\rho_1} = \frac{1+\beta f}{1-2\beta f}\,, \tag{1}$$

where ρ is the resistivity of the mixture, ρ_1 is the resistivity of the liquid phase, f is the volume fraction of the dispersed phase, and β is given by

$$\beta = \frac{\alpha - 1}{2\alpha + 1}\,, \tag{2}$$

where ρ_2 is the resistivity of the solid particle and α is ρ_2/ρ_1.

We applied the Maxwell relationship to a snow–water mixture, where water has a known conductivity due to ions in the water. Particles of snow or ice have little conductivity due to an absence of free electrons or drifting ions. In practice, snow or ice particles can be regarded as nonconducting materials. In this case, the Maxwell relation can be reduced to

$$\frac{\rho}{\rho_1} = \frac{1+0.5f}{1-f} \tag{3}$$

for $\alpha \doteqdot \infty$ and $\beta \doteqdot 0.5$. Equation (3) shows that we can get the fraction value f, if we know the value of ρ/ρ_1 or the relative resistivity by resistance measurement. The Maxwell relation (Equation (3)) is very simple and attractive for practical purposes, but precise experimental measurements are required to evaluate its use in practical applications. By using a prototype fraction meter, we have obtained a relationship between f and ρ/ρ_1.

APPLICATION OF TECHNIQUES

Equation (3) indicates that a good snow-fraction meter is possible, but until now we have not had a meter which

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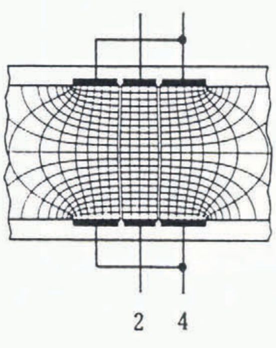
would meet the stated requirements. By systematically applying the techniques explained below, we have developed a practical method for measuring the snow-fraction in a snow–water mixture.

The resistivity of a liquid is sensitive to changes in its temperature and the concentration of electrolytes. We will be able to obtain a more accurate value of ρ/ρ_1 by simultaneous separate measurement of resistances for both ρ and ρ_1. This may avoid introducing errors which may occur in confluences and in melting regions within the flow. Therefore, we provided a pair of resistance meter units in the prototype snow-fraction meter: one is for the measurement of the snow–water mixture and the other is for pure water nearby.

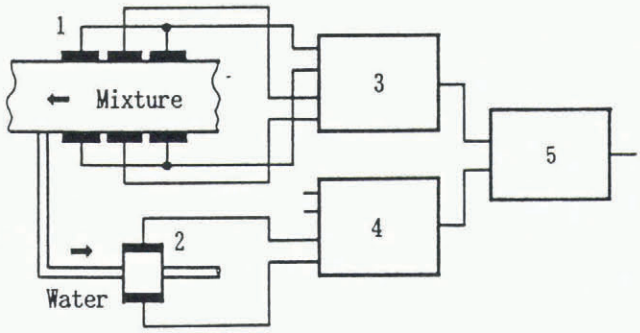
We used the alternating-current method for measuring resistance to avoid polarization effects. The AC current is small, ranging from $10\,\mu$A to $10\,$mA. A synchronized rectifier was included to minimize the influence of the capacitance's change on the electrode. Active shielding for the cables connecting electrodes with resistance-meter units was also provided.

A pair of electrodes, "main electrodes", are attached face-to-face to the inner walls of a flow pipe so that they can measure the resistance of the mixture between them. In addition to the main electrodes, we introduced the use of "auxiliary electrodes" on either side of each main electrode (Fig. 1). The two auxiliary electrodes placed on the sides of each of the main electrodes are always supplied with the same potential as the main electrode between them. Such an arrangement of electrodes gives three major advantages. First, these auxiliary electrodes work to keep the potential gradient or the current density between the main electrodes uniform to give an accurate measurement independent of the course of the snow particles passing between the main electrodes. The auxiliary electrodes differ from the commonly used guard electrodes in usage and function. Second, if necessary, such a set of electrodes can give higher spatial resolution in the direction of the pipe axis with narrower main electrodes. Third, the auxiliary electrodes can prevent stray grounding or current leakage from the main electrodes to the pipe walls of conductive materials (Nimura and others, 1988).



1, 2 Main Electrode
3, 4 Auxiliary Electrode

Fig. 1. Application of "auxiliary electrodes". The electrodes work to keep the potential gradient or the current density uniform between the main electrodes.



1 Electrodes for Mixture
2 Electrodes for Water
3, 4 Resistance Meter Unit
5 Data Processing Unit

Fig. 2. Experimental setup for the measurement of snow fraction. The meter measures the resistances of the mixture and the pure water simultaneously.

DIAGRAM OF FRACTION METER

We constructed a prototype of the fraction meter applying the techniques described above. Experiments were conducted in duct sections containing electrodes. The experimental setup is shown in Figure 2. The auxiliary electrodes will be effective in the flow ducts for the snow–water mixture. The meter is composed of three units: two resistance-meter units and a data-processing unit. Each resistance-meter unit has four measuring ranges, $0.2\,\mathrm{k\Omega}$, $2\,\mathrm{k\Omega}$, $20\,\mathrm{k\Omega}$ and $200\,\mathrm{k\Omega}$, for full scale. The data-processing unit receives signal voltages proportional to the resistance values from the above units, calculates the fraction value and indicates it directly. The output of the meter can be sent to a controller for automatic fraction controlling or to a data recorder. Here the calculation base for the value ρ/ρ_1 is given by

$$\frac{\rho}{\rho_1} = \frac{[R_\mathrm{M}/C_\mathrm{M}]}{[R_\mathrm{W}/C_\mathrm{W}]} = \frac{[R_\mathrm{M}/(R_\mathrm{M0}/\rho_0)]}{[R_\mathrm{W}/(R_\mathrm{W0}/\rho_0)]} = \left(\frac{R_\mathrm{W0}}{R_\mathrm{M0}}\right)\left(\frac{R_\mathrm{M}}{R_\mathrm{W}}\right). \tag{4}$$

In Equation (4), R is resistance and C is cell constant. The subscripts M and W indicate the electrode values for mixture and for water, respectively. The subscript 0 indicates the values for pure water.

Using this method, we do not need individual calculations for ρ and ρ_1 from the measured resistances and the cell constants. Instead we measure R_W0 and R_M0 once in the initial setting on the data-processing unit before an operation. This simplification enables us to obtain accurate and stable measurements while avoiding troublesome estimation for cell constants. The data-processing unit can be easily replaced by a computer for more advanced utility.

TESTS OF NEW METHOD AND RESULTS

We carried out three stages of tests. First, we obtained experimentally the relation between ρ/ρ_1 and f by

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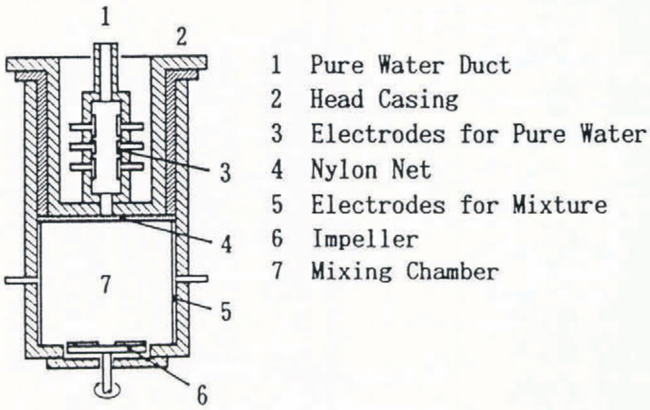

Fig. 3. Testing apparatus for resistance measurement. The apparatus has a mixing chamber and a pure-water duct on the head casing.

measuring resistances in the mixture and pure water, varying the value of f by testing apparatus shown in Figure 3. The apparatus, made of acrylic plate, is composed of a 150 mm^3 mixing chamber which has a stirring impeller, driven by a variable-speed electric motor, at the bottom and a double-sleeved head casing to be inserted into the upper half of the chamber. The head casing has a water duct on it to measure the resistance of the pure water displaced by the insertion. The mixing chamber has only a pair of main electrodes, 150 mm^2, on the inner wall. The chamber does not need the auxiliary electrodes, since the shape of the mixture would not change, but the auxiliary electrodes were included inside the pure water duct. Some solid particles tested are listed in Table 1 for examples.

Measurements were made over the full range of fraction values from 0 to about $f = 0.6$. As each density in Table 1 is close to that of water, the solid particles mixed well with water in the mixing chamber. As for the granular snow, the insertion of the head casing into the chamber required increased force above $f = 0.45$ and measurements were limited. The ice cubes were made by a home ice-maker. The experiments with snow and ice were carried out in the thermostatic chamber kept at 0°C to avoid melting. The resistance data measured were processed according to Equation (4) for the value of ρ/ρ_1. The experimental results are shown in Figure 4. All the experimental points lie on a common curve independent

Table 1. Solid particles tested for resistance measurement

Particle	*Size* mm	*Density* g cm^{-3}
ABS resin bead	3 (dia.)	1.052
Rubber ball	47 (dia.)	0.917
Granular snow	–	–
Ice cube	25 × 30 × 30	0.916

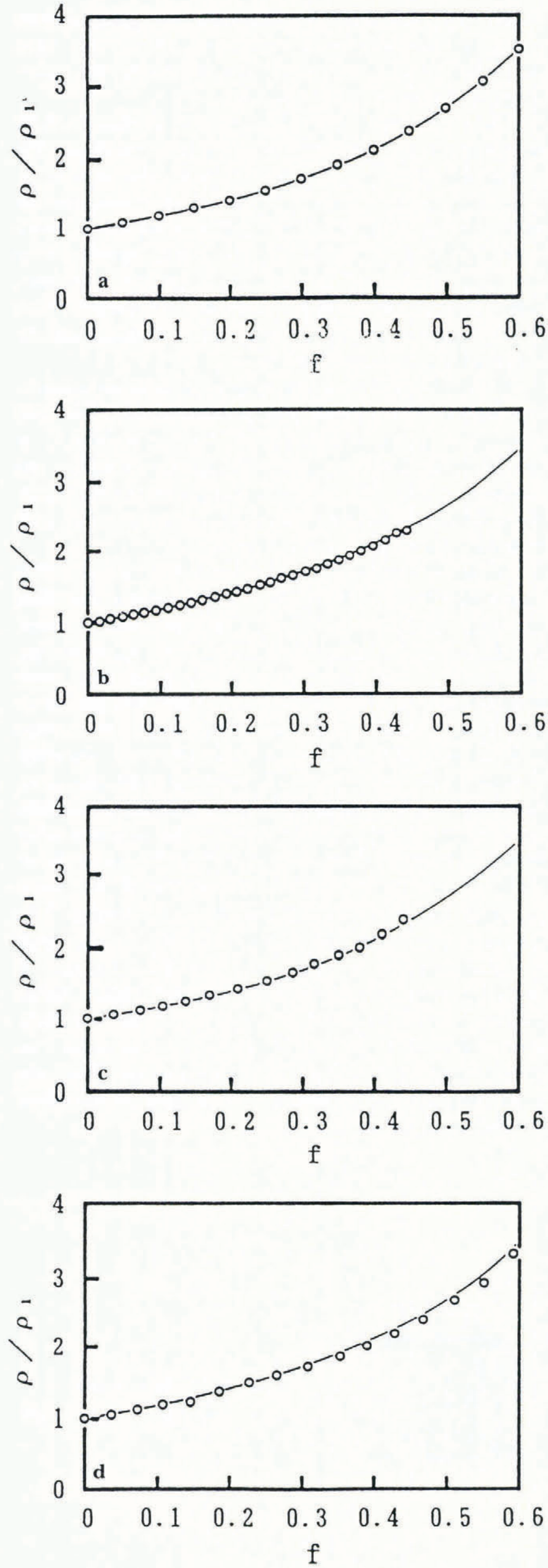

Fig. 4. Relative resistivity, ρ/ρ_1, vs volume fraction, f. The curve is authors' relation. a, ABS resin bead; b, rubber ball; c, granular snow; d, ice cube.

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Table 2. Example data and procedure for empirical formula

	AUTHORS				MAXWELL		$\frac{(\rho/\rho_1)_{AUTHORS}-1}{(\rho/\rho_1)_{MAXWELL}-1}$
f	R_W Ω	R_M Ω	ρ/ρ_1	ρ/ρ_1-1	ρ/ρ_1	ρ/ρ_1-1	
0	402	46.2	1.00	0.00	1.000	0.000	–
0.05	401	49.9	1.08	0.08	1.078	0.078	1.02
0.10	400	54.1	1.18	0.18	1.166	0.166	1.08
0.15	399	58.8	1.28	0.28	1.264	0.264	1.06
0.20	398	64.0	1.40	0.40	1.375	0.375	1.06
0.25	398	70.5	1.54	0.54	1.500	0.500	1.08
0.30	397	77.7	1.70	0.70	1.642	0.642	1.09
0.35	397	86.2	1.89	0.89	1.807	0.807	1.10
0.40	396	96.0	2.11	1.11	2.000	1.000	1.11
0.45	395	107.5	2.37	1.37	2.227	1.227	1.11
0.50	394	121.1	2.67	1.67	2.500	1.500	1.11
0.55	393	137.4	3.04	2.04	2.833	1.833	1.11
0.60	392	157.6	3.50	2.50	3.250	2.250	1.11

of particle size. From the results we have determined an empirical formula for the relation between f and ρ/ρ_1 (Equation (5)) by curve fitting:

$$\frac{\rho}{\rho_1}=1.11\left[\frac{1+0.5f}{1-f}-1\right]+1 \quad \text{or} \quad f=\frac{\rho/\rho_1-1}{\rho/\rho_1+0.665}\,. \tag{5}$$

As indicated by Equation (5), our experimental results diverge from the Maxwell relation with increased f within the range tested. Example data with ABS resin beads is given in tabular form in Table 2 for better understanding of the data processing and the relationships developed. In the table, $(\rho/\rho_1)_{AUTHORS}$ is calculated according to Equation (4) and $(\rho/\rho_1)_{MAXWELL}$ is obtained from Equation (3). The relationship, Equation (5), was determined by investigating the difference between the author's results and the values from Maxwell's equation.

Second, we tested the operation of the whole system of the fraction meter after adjusting the calculating functions of the data-processing unit following Equation (5) for f. The major functions are linearization, offsetting and spanning. Results are shown in Figure 5 for granular snow and ice cubes. Here f_A is the actual fraction. The results show that the fraction meter works very well over the full range.

Lastly, we applied the fraction meter to a closed-pipeline system for laboratory testing, providing other "electrode-duct-sections" to fit the pipe ducts. The flanged type of "electrode-duct-section" is illustrated in Figure 6. A small amount of water was extracted for resistance measurement through a #100 mesh filter from the main flow by pressure inside the pipeline or pumping. The indicated values of f are compared with that

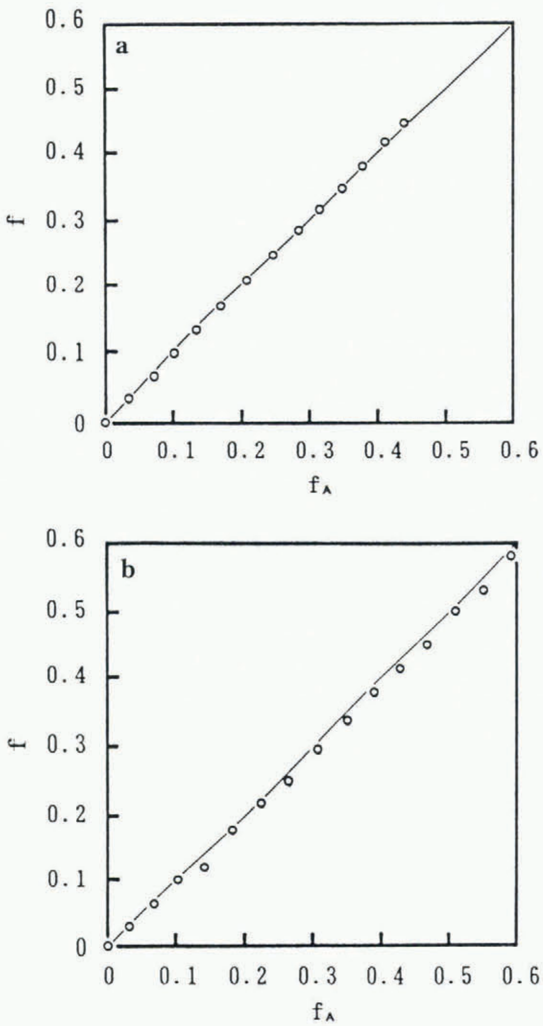

Fig. 5. Indicated fraction, f, vs actual fraction, f_A, by testing. a, granular snow; b, ice cube.

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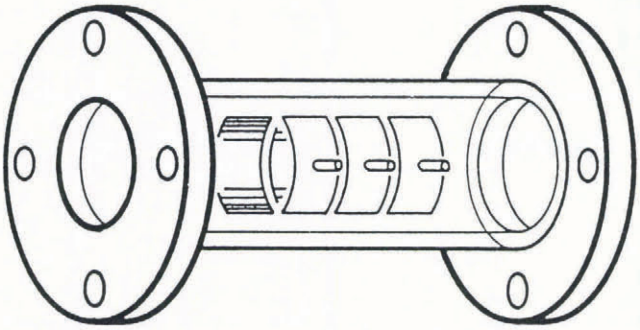

Fig. 6. An electrode-duct-section for pipeline system. Electrode pairs are fitted opposite each other in the duct.

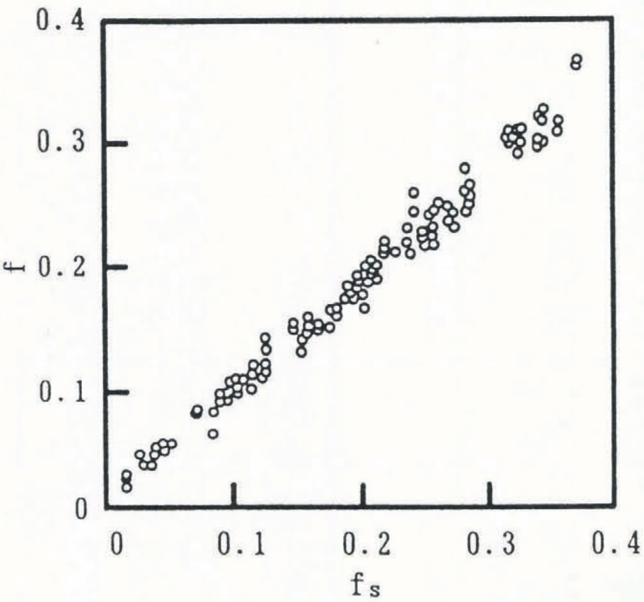

Fig. 7. Indicated fraction, f, vs sampled fraction, f_s, by a pipeline system on snow–water mixture.

obtained from the sampling method, f_s, in Figure 7. The tests were carried out by mixing an amount of snow into the pipeline by a mixing tank. The values, f_s, were obtained by sampling by changing the pipeline flow into a bucket for a short time and centrifugal separation of the sample. The test conditions are presented in Table 3.

The "electrode-duct-section" of 50 mm diameter was attached in a vertical position and the 80 mm diameter section was attached horizontally in the pipeline. Experimental results showed that there was no effect of snow properties, direction of "electrode-duct-section" or flow velocity within the range tested. Although the points are scattered a little in Figure 7, the meter is confirmed to work well.

Table 3. Test conditions for "electrode-duct-section" at 0°C

	Diameter of electrode duct	
	50 mm	80 mm
Snow property	fresh snow	granular snow
Direction of electrode duct	vertical	horizontal
Flow velocity ($m\,s^{-1}$)	0.48–6.22	0.19–2.43

CONCLUSIONS

A new method for measuring the snow-fraction in a snow–water mixture has been developed. The prototype of the fraction meter was found to give precise measurements of resistance. The relation between the increase in the relative resistivity of the mixture, ρ/ρ_1, and the snow-fraction value, f, was obtained experimentally over a wide range. Laboratory measurements were made using a testing apparatus and a closed-pipeline system. The experimental results presented here show that the prototype of the snow-fraction meter is practical. The new method and the relation between ρ/ρ_1 and f described here may lead to the practical application of hydraulic conveying of snow or ice.

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The accuracy of references in the text and in this list is the responsibility of the authors, to whom queries should be addressed.