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VELOCITY AND ANGLE DISTRIBUTIONS OF DRIFTING SNOW PARTICLES NEAR THE LOOSE SNOW SURFACE

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Abstract: Drifting snow experiments in a cold wind tunnel were conducted to investigate impact and ejection velocities and angles of snow particles as functions of friction velocity from 0.15 to 0.39 m/s. Disintegrated particles of natural compact snow were used. Trajectories of snow particles were illuminated with a laser sheet cut with a rotary shutter and were recorded with a video camera system.

Both average impact and ejection velocities increased with the friction velocity. However, average impact and ejection angles decreased. Standard deviations of the ejection angles were larger than those of the impact angles. Average horizontal components of both the impact and ejection velocities increased with the friction velocity, while average vertical components did not change much. In general, faster particles had smaller impact angles and slower particles had larger angles. The ratio of the average ejection velocity to the average impact velocity, that is the restitution coefficient, increased with the friction velocity. The vertical restitution coefficient ranged from 1.5 to 2.3, showing the increase of vertical ejection velocity at each impact.

The results were discussed in comparison with those of previous studies including sand particles, and it was concluded that the overall characteristics of a loose snow surface at impact are similar to those of a sand surface in spite of different materials.

1. Introduction

When the wind stress acting on the snow surface exceeds a threshold, snow particles begin to move in short hops (the aerodynamic entrainment process). Particles striking on the snow surface usually rebound successively and sometimes even splash other particles (the splash process). These drifting particles are produced by the following three modes: entrainment by wind, rebounding after the collision, and newly splashing from the snow surface. Velocities and angles of snow particles at these three modes are crucial elements for understanding the transport rate of the snow particles, the structure of snow drifting, and other features of snow movement.

Although many investigators have carried out not only splash experiments of snow (ARAOKA and MAENO, 1981; KOSUGI *et al.*, 1995) and sand (WILLETTS and RICE, 1985; NALPANIS *et al.*, 1993) but also aerodynamic entrainment experiments (WILLETTS *et al.*, 1991), there remain uncertainties about the detailed interaction between the loose surface and the drifting particles.

The purpose of this paper is to measure velocities and angles of individual snow particles near the loose snow surface as functions of friction velocity and to try to obtain a more realistic picture of the particle motion near the surface.

2. Wind Tunnel Experiment

Motions of drifting snow particles were observed in a return-flow wind tunnel with a working section 8 m in length, 0.5 m in width and 0.5 m in height (Fig. 1). It was located in a large cold room, and the room temperature was maintained at $-15°C$. The temperature was chosen to avoid sintering between snow particles.

Disintegrated particles of natural compact snow, the average diameter of which was 0.36 mm with a standard deviation of 0.14 mm (Fig. 2), were scattered uniformly on the tunnel floor. The thickness of the snow bed was 25 mm and its surface was formed as smooth as possible. At each wind velocity steady drifting snow was produced by seeding a small number of particles from the bottom at the windward end. However, at the weakest wind velocity (4.0 m/s) in our experiments, additional seeding of particles from above was necessary; this led to an alteration of the wind structure as stated later.

Wind velocities were measured at 5 cm above the snow surface with an ultrasonic anemometer, and friction velocities were estimated by the eddy-correlation method, $u_* =$ 0.15, 0.23, 0.30 and 0.39 m/s for the central wind velocities (25 cm above the snow surface) of 4.0, 6.0, 8.0, and 10.0 m/s, respectively. As a continuous snow drift was not formed

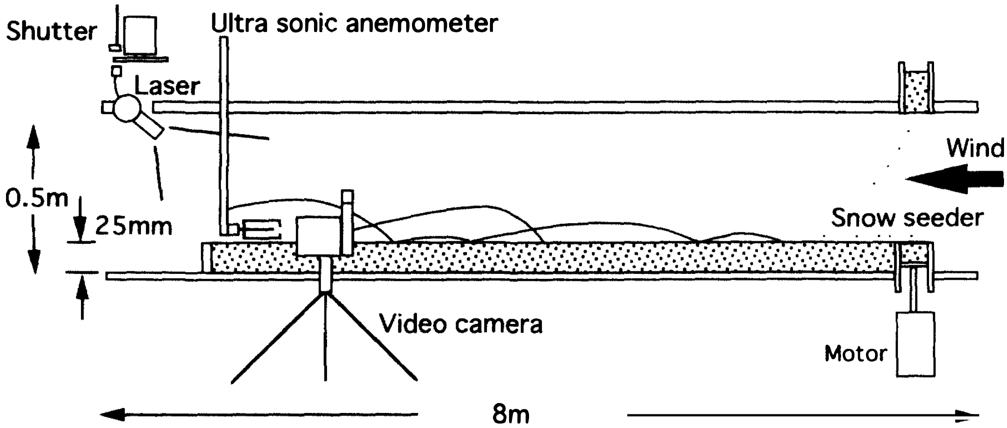

Fig. 1. Schematic diagram of the wind tunnel.

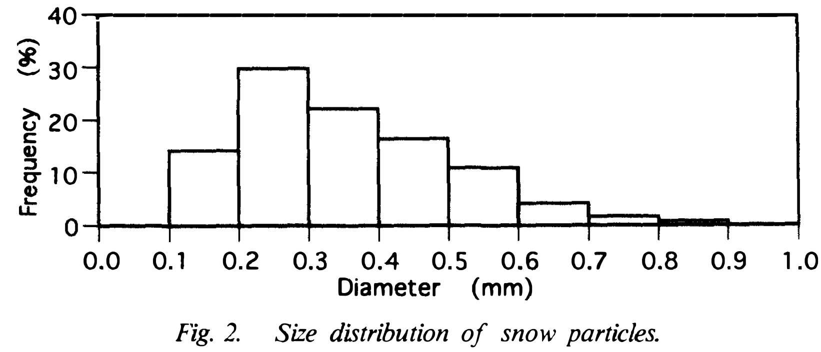

Fig. 2. Size distribution of snow particles.

spontaneously, that is without seeding snow particles, below the friction velocity of 0.15 m/s, the fluid threshold friction velocity of the snow particles used in the experiments was considered larger than 0.15 m/s but smaller than 0.23 m/s, and hence the impact threshold friction velocity must be below 0.15 m/s.

Drifting snow particles were illuminated from above with a laser sheet cut with a rotary shutter; their trajectories were recorded with a video camera system. Some examples are shown in Fig. 3. Impact velocities (ν_I), impact angles (α_I), ejection velocities (ν_E), and ejection angles (α_E) were estimated from the particle paths. The analysis was done only in a 1 cm (at most) layer from the snow surface to avoid the effect of wind and gravity. Definitions of the velocities and angles are shown in Fig. 4.

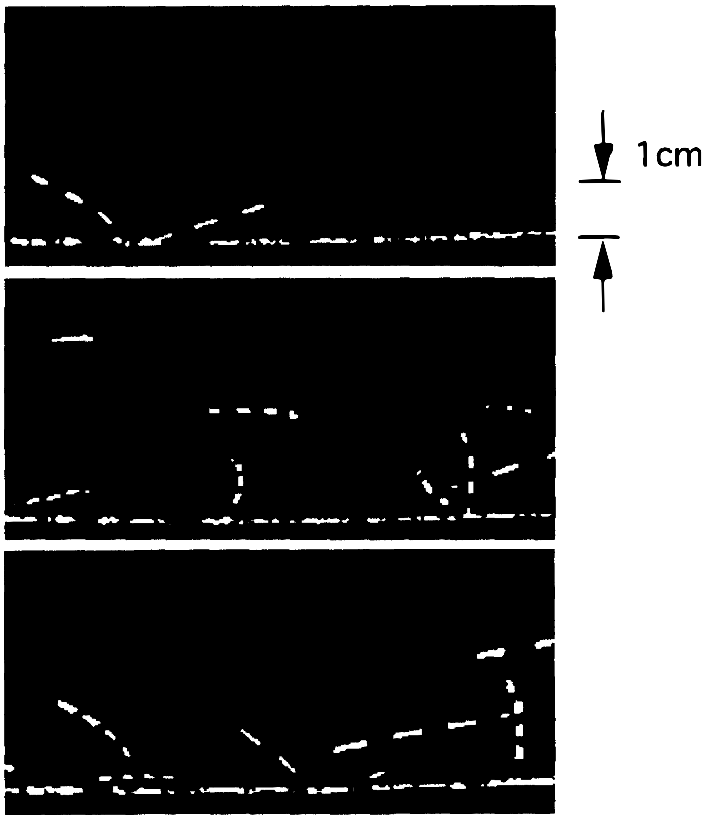

Fig. 3. Photographs to show trajectories of particles. Friction velocity is 0.15 m/s. Wind direction is from right to left. Time intervals of marks on each trajectory are 1.9 ms.

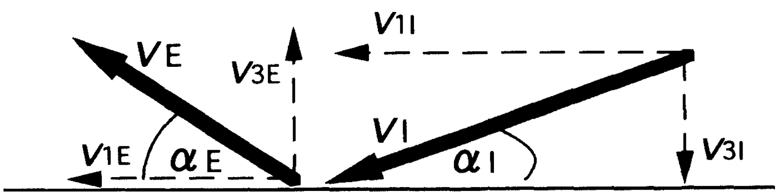

Fig. 4. Definitions of velocities and angles.

3. Results

Trajectories of more than 450 particles were analyzed for each friction velocity. Frequency histograms of ν_I and ν_E are shown in Fig. 5. Except for the case of a friction velocity of 0.15 m/s, average impact ($\overline{\nu_I}$) and ejection velocities ($\overline{\nu_E}$) increased with the friction velocity from 1.3 to 2.0 m/s and from 0.9 to 1.7 m/s, respectively. The ratio of $\overline{\nu_E}$ to $\overline{\nu_I}$ increased from 0.69 to 0.85 with the friction velocity. At the friction velocity of 0.15 m/s, the drift could be maintained only by seeding snow particles both from above and

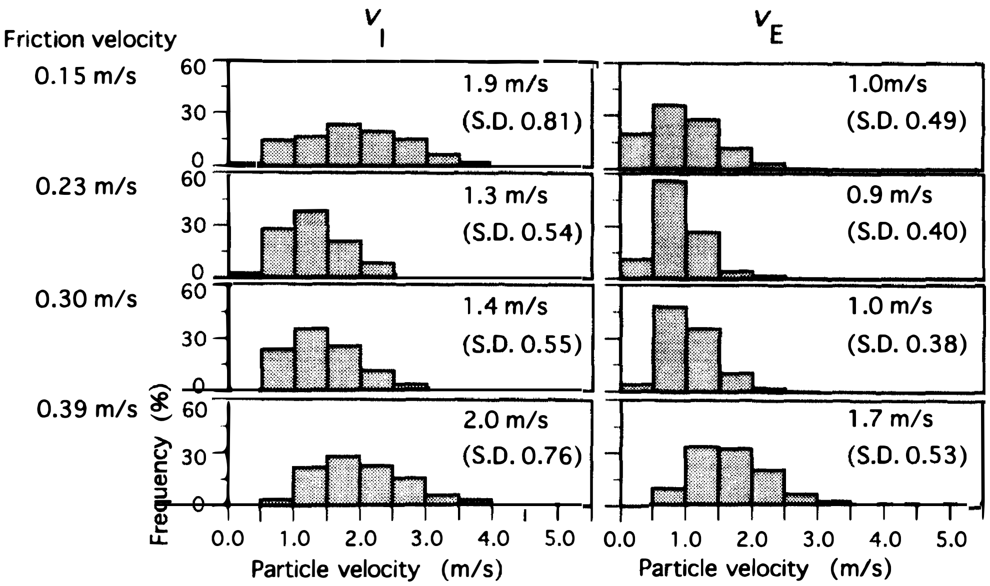

Fig. 5. Frequency histograms of impact velocities (ν_I) and ejection velocities (ν_E).

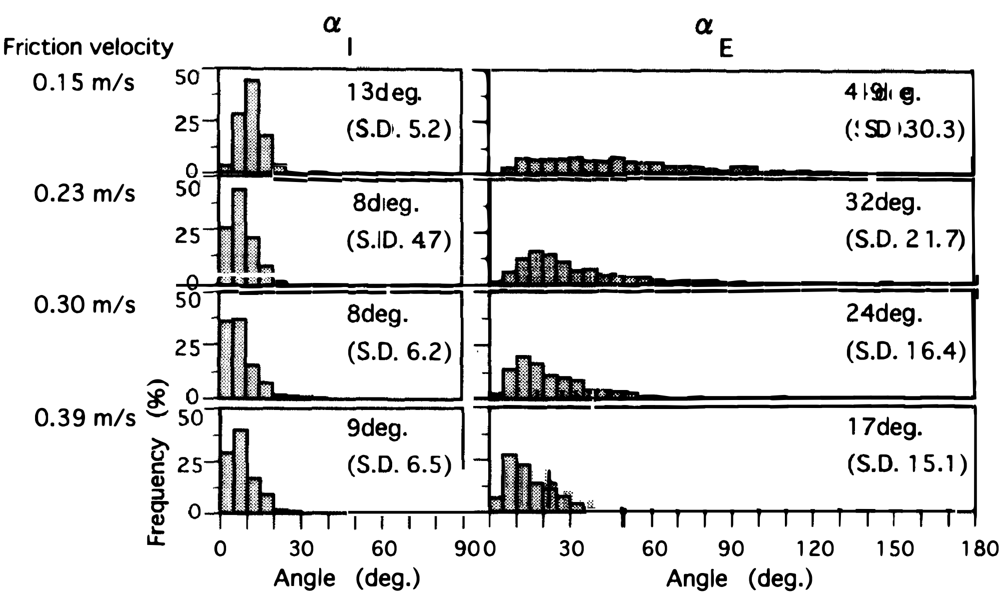

Fig. 6. Frequency histograms of impact angles (α_I) and ejection angles (α_E).

below, so that it was sometimes irregular and intermittent. We should take account of this effect in the analysis of the data at 0.15 m/s.

Similar frequency histograms of α_I and α_E are shown in Fig. 6. Though average impact angles ($\overline{\alpha_I}$) were rather constant around 8 degrees, average ejection angles ($\overline{\alpha_E}$) showed a decrease from 32 to 17 degrees with the friction velocity. Standard deviations of α_E were larger than those of α_I. The histograms at the friction velocity of 0.15 m/s were again different from those at other velocities.

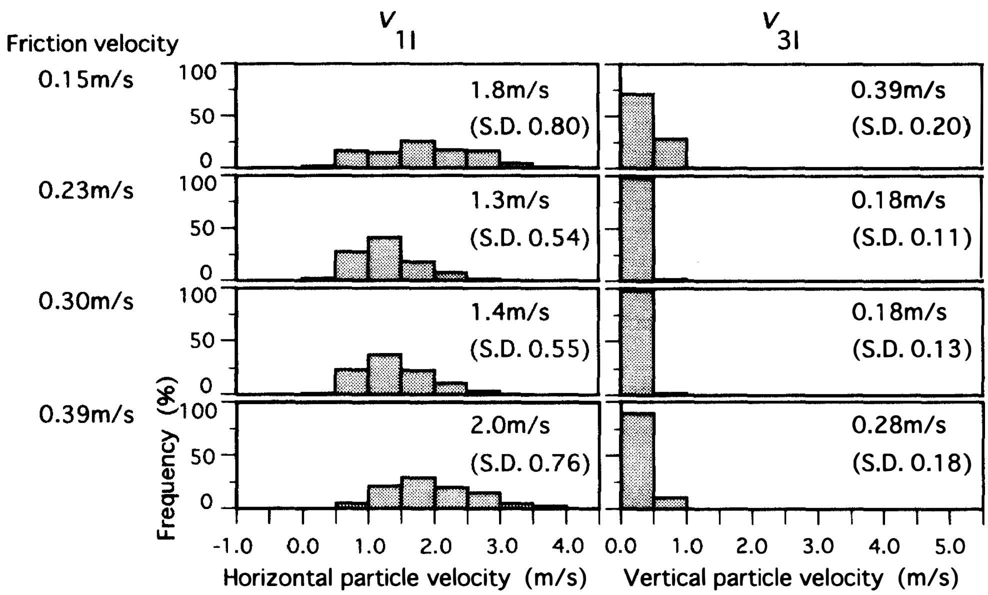

Fig. 7. Frequency histograms of horizontal (v_{1I}) and vertical components (v_{3I}) of the impact velocities.

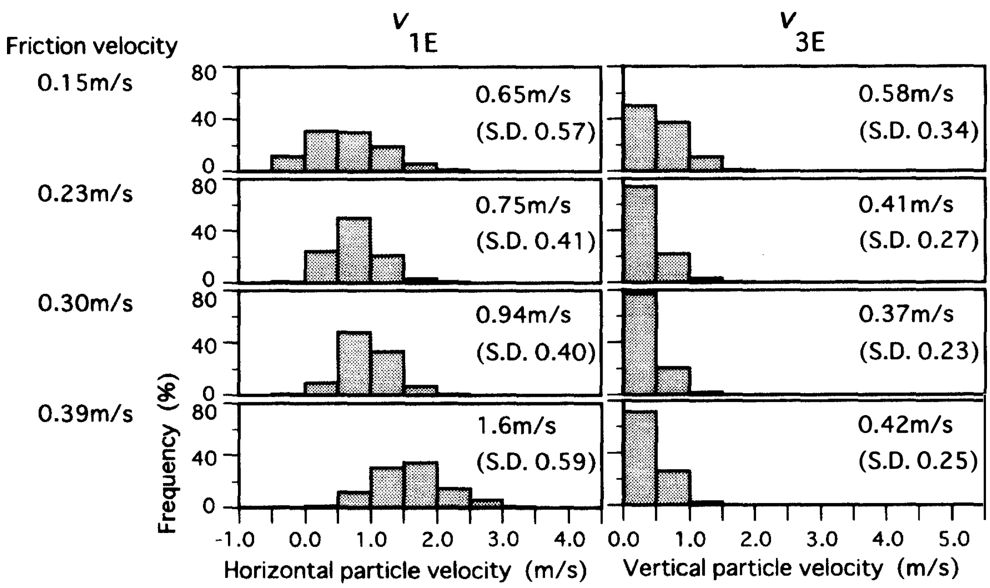

Fig. 8. Frequency histograms of horizontal (v_{1E}) and vertical components (v_{3E}) of the ejection velocities.

Figures 7 and 8 show horizontal (ν_{1I}) and vertical components (ν_{3I}) of ν_I and horizontal (ν_{1E}) and vertical components (ν_{3E}) of ν_E, respectively. ν_{1I} and ν_{1E} gradually increased with the friction velocity, while ν_{3I} and ν_{3E} did not change much. With the increase of friction velocity the ratio $\overline{\nu_{1E}}/\overline{\nu_{1I}}$ increased from 0.58 to 0.80, but the ratio $\overline{\nu_{3E}}/\overline{\nu_{3I}}$ decreased from 2.3 to 1.5.

The relations between ν_I and α_I and between ν_E and α_E are plotted in Fig. 9. It is

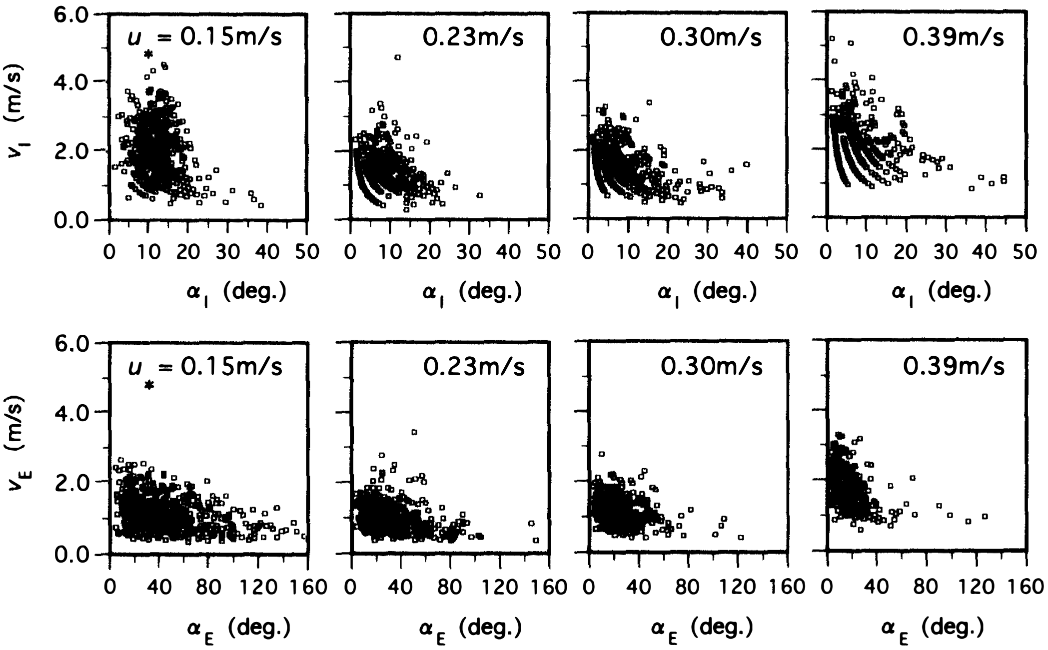

Fig. 9. Relations between the impact velocity (ν_I) and angle (α_I) and between the ejection velocity (ν_E) and angle (α_E).

Table 1. Experimental data

	Willetts and Rice (1985)			Nalpanis *et al.* (1993)			Araoka and Maeno (1981)	Present study			
Material	Quartz sand			Builders' sand			Snow	Snow			
$\overline{d}$ (μm)	150-250	250-355	355-600	90-150	150-300	150-300	200	360			
u_* (m/s)	(0.39)	(0.39)	(0.39)	0.18	0.20	0.205	0.19	(0.15)	0.23	0.30	0.39
$\overline{\nu_E}$ (m/s)	2.40	2.16	2.25	0.81	0.88	0.76	1.04	(1.0)	0.9	1.0	1.7
$\overline{\alpha_E}$ (deg.)	33.4	24.9	21.3	35.0	34.0	41.0	49	(49)	32	24	17
$\overline{\nu_I}$ (m/s)	3.94	3.56	3.60	1.30	1.40	1.50	1.9	(1.9)	1.3	1.4	2.0
$\overline{\alpha_I}$ (deg).	9.6	11.7	12.7	11.0	13.0	14.0	11	(13)	8	8	9
$\overline{\nu_E}/\overline{\nu_I}$	0.61	0.61	0.63	0.62	0.63	0.51	0.55	(0.53)	0.69	0.71	0.85
$\overline{\nu_{1E}}/\overline{\nu_{1I}}$	-	-	-	-	-	-	-	(0.36)	0.58	0.67	0.80
$\overline{\nu_{3E}}/\overline{\nu_{3I}}$	-	-	-	-	-	-	-	(1.5)	2.3	2.1	1.5
$\overline{\alpha_E}/\overline{\alpha_I}$	3.5	2.1	1.7	3.2	2.6	2.9	4.5	(3.8)	4.0	3.0	1.9

clear that faster impact particles have smaller impact angles and slower ones have larger impact angles. A similar tendency can be recognized for the ejection particles as well.

The obtained numerical results are summarized in Table 1 together with those of other researchers.

4. Discussion

ARAOKA and MAENO (1981) measured v_I, v_E, α_I and α_E of saltating snow particles with a photographic technique in a cold wind tunnel. The average wind velocity at the center of the wind tunnel was 5.0 m/s, which corresponds to the friction velocity of 0.19 m/s. Our results for similar friction velocities can be said to roughly agree with theirs taking account of the experimental errors involved.

NALPANIS *et al.* (1993) measured v_I, v_E, α_I and α_E of sand particles with a similar technique. Since the fluid threshold friction velocity of their dry sand particles was about 0.18 m/s (particle diameter 188 μm) and 0.16 m/s (118 μm), the friction velocities used in their experiments are a little above the fluid threshold, and thus it is reasonable to compare their result with our 0.23 m/s data. We see that $\overline{v_E}/\overline{v_I}$ and $\overline{\alpha_E}/\overline{\alpha_I}$ at those friction velocities are similar.

WILLETTS and RICE (1985) carried out collision experiments using three different particle diameters on a sand surface, and distinguished rebounding and splashed particles. The friction velocity (0.39 m/s) of their experiments was below the fluid threshold and the actual velocity might be even weaker due to the partition set in their wind tunnel. Their result of $\overline{v_E}/\overline{v_I}$ corresponds to that at the friction velocities of 0.15 and 0.23 m/s in our experiments.

It is important to note that snow and sand particles have different restitution and friction coefficients, but they behave similarly at impact.

In Figs. 3 and 6 it is evident that some snow particles were ejected windward, that is α_E is larger than 90 degrees. Since entrained particles can be expected to move leeward, the windward motion must be due to the splash process at collision. According to RUMPEL'S (1985) geometrical analysis of collisions of particles, which were assumed to be perfectly elastic (Fig. 10), when a particle collides with a target particle at the impact angle α_I (β is the angle between the horizontal line and the center line of the impact and target particles), the ejection angle (α_E) is given as $180-(2\beta-\alpha_I)$. This means that the impact particle can be ejected windward when the quantity $2\beta-\alpha_I$ is smaller than 90 degrees, namely α_E is larger than 90 degrees. This condition will be given when β is smaller or α_I is larger, that is, when smaller impact particles collide at larger impact angle since β increases with the increasing impact particle diameter.

The decrease of α_E with the friction velocity (Fig. 6) can be explained as follows. First, the average diameter of drifting snow particles becomes larger with increasing friction velocity. According to the geometrical analysis stated above, the average ejection angle of larger particles becomes smaller. Second, as the target particles are not fixed, so that they can move at collision, and the center line component of momentum of the impact particle is transferred to the target particles to cause their rearrangement. Accordingly the ejection angle of the impact particle becomes significantly smaller than α_E as shown by $\alpha_{E(\text{not fix})}$ in Fig. 10. The third effect is the air drag. The horizontal air drag acting on the ejection

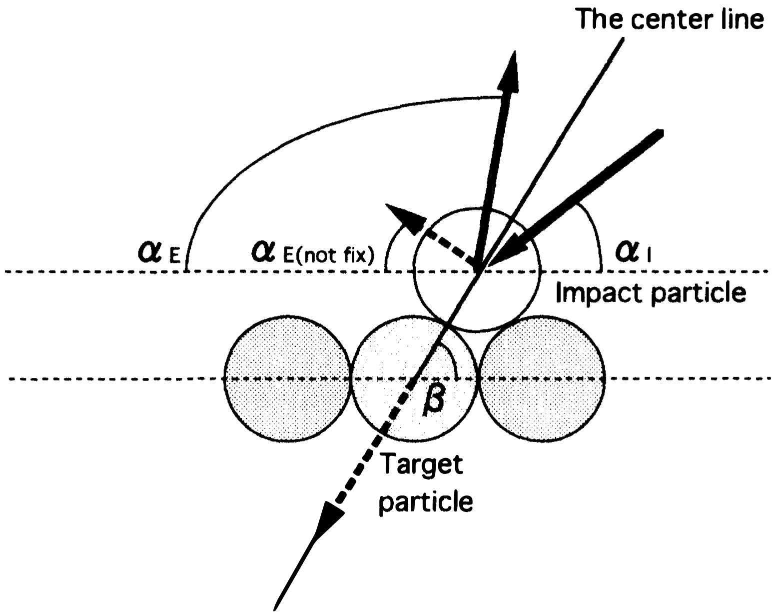

Fig. 10. Schematic diagram of collision between an impact and target particles at the surface.

particles increases with friction velocity, and decreases α_E.

Finally a short discussion of the physical implication of the ratios, $\overline{\nu_E}/\overline{\nu_I}$, $\overline{\nu_{1E}}/\overline{\nu_{1I}}$ and $\overline{\nu_{3E}}/\overline{\nu_{3I}}$, is important to understand the general impact process in the snow drift. The ratios can be explained as the restitution coefficients because they are the ratios of velocities before and after the impact. The ratio $\overline{\nu_E}/\overline{\nu_I}$ corresponds to the restitution coefficient describing an intrinsic physical property of the snow particles. The observed values ranging from 0.53 to 0.85 are reasonable compared to the restitution coefficient of ice (HIGA *et al*., 1996). The two ratios, $\overline{\nu_{1E}}/\overline{\nu_{1I}}$ and $\overline{\nu_{3E}}/\overline{\nu_{3I}}$, are respectively the horizontal and vertical restitution coefficients defined by KOSUGI *et al.* (1995). It is important to note that the value of $\overline{\nu_{3E}}/\overline{\nu_{3I}}$ ranges from 1.5 to 2.3 and is larger than unity (Table 1). This means that the vertical velocity of impact particles increases by 50 to 130 percent at each impact. The result is important for the development of snow drift because the larger vertical velocity results in particle saltation to a higher level where stronger wind blows. Only the averages were analyzed in the present study. However, the restitution coefficients for individual particles and their frequency distributions are required to obtain a clearer picture of the impact process, and such analyses are now in progress.

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