Fundamentals of the Mechanics of Snow Storms

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Abstract

Snow storms or blizzards are regarded as a two-phase turbulent streams with hard particles, arising on the interface of wind streams and snow cover. The magnitude of the solid flux is not constant when it reaches maximum. It suffers rather regular vibrations subsequently which are explained by the changeable drawing pressure within the thin boundary layer. The author is of the opinion that this principal fact explains the origin of the characteristic forms of free snow cover relief.

In contrast to sand storms and soil erosion, in a snow stream marked phase transitions occur owing to flake evaporation. Numerous tests showed that snow evaporation took place at a more intensity during snow storms as compared that in the absence of the snow transfer, which may partly be explained by the exposure of all surfaces of flakes in a snow stream.

A theory of analytical calculation of wind and snow protection barrier action which is substantiated by numerous laboratorial and field data was developed.

I. Introduction

Snow-storms or deflation of snow cover is of great theoretical and practical importance in as much as snow-storms play an essential role in a general hydrological balance, in forming snow-covers and glaciers.

Practical applications of this problem in the field such as drift-fighting on roads, airports, in cities, towns and settlements, also in the field of land-reclamation are evident. Recently tests were carried out on a large scale on the use of wind transfer of snow for avalanche fighting and in the matter of water-supply of large cities and hydroelectric power stations in mountainous regions (Akkuratov, 1956; Hopf, 1958; Peev, 1959).

An ordered theory of snow-storms did not exist up to the present, which often led to misunderstandings of its mechanism, and resulted in false solutions and considerable loss of money.

This deficiency is mainly explained by an extraordinary complication of the problem and by the fact that different specialists worked on it without mutual coordination.

Research work on snow-storm laws was carried out for many years by the author and his colleagues. Based on our work we seem to have the possibility of formulating principles of theory of snow-storms.

II. The Fundamental Equations of Snow Storms

Snow-storms or blizzards are regarded as a two-phase turbulent streams with hard particles, arising on the interface of wind streams and snow cover.

The equation of the transfer of the motion quantity for such a stream may be written as follows

$$\rho(1-s)\left[\frac{\partial \boldsymbol{v}}{\partial t}+(\boldsymbol{v}\cdot\nabla)\boldsymbol{v}\right]+\rho_s s\left[\frac{\partial \boldsymbol{v}_s}{\partial t}+(\boldsymbol{v}_s\cdot\nabla)\boldsymbol{v}_s\right]+\boldsymbol{K}=\rho(1-s)(\boldsymbol{g}+\boldsymbol{E})+\rho_s s\boldsymbol{g}-\nabla\cdot(\Pi+T),$$

where

- ρ, ρ_s are mass densities of air and hard particles,
- s volumetrical concentration of particles in the stream,
- t time,
- $\boldsymbol{v}$, $\boldsymbol{v}_s$ vectors of the mean velocities of the air and of hard particles,
- ∇ Hamilton's operator,
- $\boldsymbol{K}$ vector of sublimation,
- $\boldsymbol{g}$ acceleration vector of gravity,
- $\boldsymbol{E}$ acceleration vector of the forces of the electrical origin,
- Π, T tensors of the molecular and turbulent stresses.

A study of this equation with the application of our experimental data and of that of other investigators allowed us to give a comparative estimation of its members and to obtain the main criterion of snow-storms.

Within the limit of this information it is possible to refer to some important results of these investigations.

Vector $\boldsymbol{E}$ is too small in comparison with the vector $\boldsymbol{g}$. If we assume, that the extreme relative charge of the snow particles is 0.3 e.s.u./mg (Gschwend, 1920; Stäger, 1925) and that the gradient maximum of the potential of the electrical field is 10 kV/m (Gschwend, 1920; Pearce, 1949), we may know that modulus $\boldsymbol{E}$ will form only 10% of modulus $\boldsymbol{g}$. Hence it may be deduced that electrical charges of snow-flakes have no essential influence on the mechanics of snow-storms, although it may be responsible for such phenomena as luminous effects, radio interferences etc., which take place during intense blizzards.

If normal stress magnitude can be neglacted, it would be possible to express tensor $\Pi+T$ approximately by the following formula (Дюнин, 1959; Dyunin, 1961)

$$(\Pi+T)_{ik}=\rho(\nu+2\alpha^2 l\Delta v)\left(\frac{\partial v_i}{\partial x_k}+\frac{\partial v_k}{\partial x_i}\right),$$

where

- ν is coefficient of the molecular kinematic viscosity,
- α turbulation coefficient,
- Δv characteristic relative velocity of the stream,
- l characteristic linear dimension of the stream.

III. Vertical Distribution of Mean Wind Velocities in a Snow-Wind Flow

It can be shown, that in this case the profile of the boundary layer velocities of the stream will differ from the generally accepted logarithmic or power laws. If the mean stream characteristics change only vertically, the given profile will be as follows:

$$v_1 - v_0 = \frac{1}{\alpha} \cdot \sqrt{\frac{\tau_0}{\rho} \cdot \log_e\left(\frac{x_3}{\delta}\right)},$$

where

v_0 is a certain velocity, corresponding to the boundary conditions,

τ_0 contact stress of friction on the snow cover surface.

The magnitude δ in a pure stream on not too small levels is numerically equal to the height of roughness knobs. In a two-phase stream δ sharply increases and the magnitude τ_0 decreases. This important conclusion, by many tests (Дюнин, 1959, 1963, 1965), do not coincide with the conclusions given by Liljequist (1957).

This can be demonstrated in Fig. 1, in which the experimental data of measurements at each height of the velocities of a pure stream and that of snow-storms where the air is in maximum saturation by hard particles are registered. The theory is satisfactorily confirmed both here and in the processing of Bagnold (1941) and Chepil's (1945) data obtained by research of sand and soil deflation.

It is interesting, that the obtained theoretical profile of wind velocities is actually only for heights not more than 20~50 cm. For greater heights this law is true only for plane and flat surfaces with homogeneous roughness.

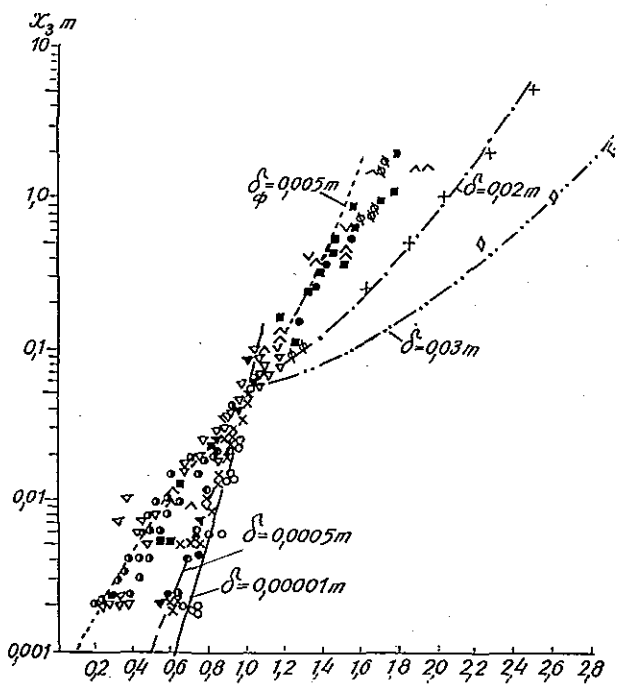

Fig. 1. Vertical distribution of mean wind velocities in the clean flow and in the snow-wind flow with the different heights of roughness knobs and with the height $\delta_\phi = 0.005$ m of "fictitious knob"

IV. The Transporting Ability of Wind

Subsequent development of theory has led to the formulation of the following very simple formula for the transport capacity of snow-storm:

$$Q = A \frac{\rho D^2 (v_h - v')^3}{\delta^2 \log_e (h/\delta)},$$

where

- A is dimensionless coefficient as a universal constant,
- D mean diameter of the nucleus of boundary layer eddies proportional to the roughness knob dimensions,
- v_h translational wind velocity of the stream on the height h,
- v' wind velocity of the initial particle transfer on the same height h,
- Q rate of snow stream in g/m·sec or the weight transfer of snow per second over 1 m of the stream front.

As already said, the magnitude δ increases as the snow-storm becomes saturated with snow. Hence, the magnitude Q is decreasing and the growth of the transport capacity of the wind terminates as is. Thus, excess snow falls out from the stream and the snow deficiency is defrayed owing to deflation (wind erosion).

It is interesting to note that in these cases the greatest rate of snow stream Q_{max} is independent of the specific gravity of the hard particles rising in the air stream, which is confirmed by Bagnold and Chepil's tests.

Numerous field and laboratorial measurements were carried out in order to check out the theory (Дюнин, 1960, 1963). Special field aerodynamic canals of different sizes were used. The canal, which was made most recently, was 21 m long, 0.5 m height and 0.42 m wide. The rate of snow stream in the field was measured by means of the special "snow collecting boxes" and photodensitometers. In the aerodynamic canals this value was determined by direct weighing. Kinematical fields of the pure and two-phase streams, structure and texture of snow, snow temperature, temperature and moisture of the air, evaporation of snow and other factors were throughly measured.

The main criterion of the snow-storm is the magnitude, which is drawn from the next formula

$$\phi = \frac{Q \cdot \log_{10}(h/\delta)}{(v_h - v')^3} \left(\frac{1}{\rho} - \frac{1}{\rho_s} \right).$$

The maximum values of ϕ varied in a rather narrow limit from 0.015 to 0.034 according to experimental data.

V. The Limit Length of Snow Storms

It was found, that the maximum value order of ϕ is the same in other two-phase streams (river deposit movements, sand and dust storms etc.). The magnitude ϕ depends mainly on the size of deflation basin (open field) and on snow surface physics nature. Coherency rate of the surface particles varies under the action of many factors, namely the time of wind action, air temperature and others.

In the snow-stream the flakes are transferred by suspension, by jumps (saltation) and slip. The saltation is always predominant. The snow slip entirely ceases when the wind velocities reaches more than 10 m/sec, measured at a height of 5 cm. The saltation from the windward edge of a snow-gathered zone progressively increases owing to snow-cover destruction by the bombardment of jumping particles up till the time when snow-storm maximum saturation by snow is reached. The length of the part for a distance of which the magnitude ϕ reaches its maximum is called the *limit length of snow-storm*. According to measured data of a snow storms this length varied under field conditions from 200 to 500 m and more, depending on the state of snow-cover surface. The newer and more mobile the snow is, the smaller the limit length of snow-storm results. In the aerodynamic canals it was possible to shorten the limit length to some meters, but such a state did not last for long.

In one to two minutes of wind exposure the artificial snow cover was strengthened by wind, the snow transfer was reduced and limit length sharply increased, overstepping the canal length. On Fig. 2, it shows the change of ϕ along the aerodynamic canal for very friable snow when the wind velocity at a height of 5 cm above the snow surface is 5 m/sec. It is interesting that the magnitude ϕ is not constant when it reaches its maximum. It suffers rather regular vibrations subsequently which are explained by the changeable drawing pressure within the thin boundary layer. We are of the opinion that this principl fact explains the origin of the characteristic forms of the free snow cover relief.

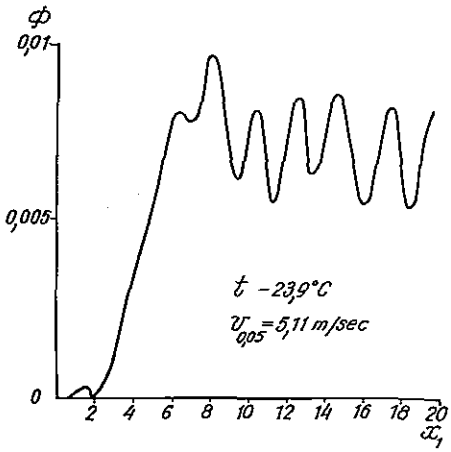

Fig. 2. Change of criterion ϕ along the aerodynamic canal. The wind speed at the height 0.05 m is 5.11 m/sec and the air temperature is −23.9°C. (In a torrent of snow storm)

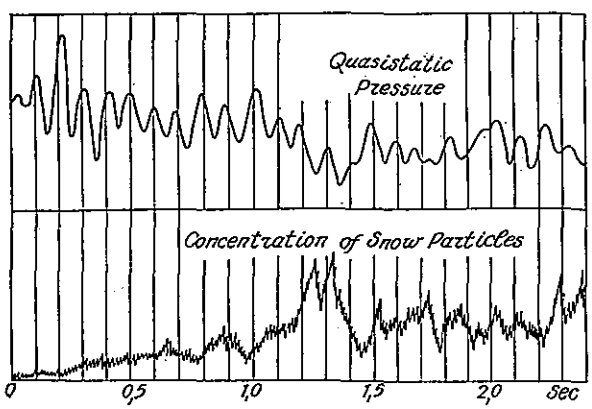

Fig. 3. Oscillogram of the quasi-static pressure and the concentration of snow particles. Hard expense of snow is 200 g/m²·sec. Wind velocity at the height of 0.2 m is 12.0 m/sec. Temperature is −8.4°C

The existence of a difference of the quasi-static pressures in the boundary layer and its close connection with dynamics of transport of snow were confirmed by numerous experiments, carried out by various methods. Figure 3 shows oscillogram of synchronous measurements of the superficial difference of quasi-static pressures and the volume concentration of these snow-particles carried out with the help of a thin plate, established at the level of the surface of the aerodynamic canal, and with a photodensitometer.

The difference of pressures, contributing to the lifting of superficial particles, essentially decreases in the process of development of saturating the torrent with snow-storm particles, and is very effective to the change of the concentration of hard particles.

Thin plates lying freely on the polished even metallic bottom of the aerodynamic canal are lifted easily by the wind-torrent. But if the same torrent is saturated with snow-particles, the plates stay in their places and are torn off only when the concentration of flying snow-flakes sharply decreases.

The independent measurements with the help of thin statical tubes showed the samed results.

The thickness of the boundary layer, in which the above mentioned difference of pressures is realized, is very small and does not exceed 2~3 mm over the snow-cover. This difference is the chief factor of the snow-deflation on an absolutely plain bedding surface on which an inevitable subsequent formation of microreliefs forms, changing in turn the structure of the field of pressure. It is interesting that the slope of the bedding surface for 30~35 degree in relation to the horizon does not essentially influence the maximum snow-removing by the invariable wind.

VI. The Up-Snow-Storms

It is necessary to distinguish the movement of the falling snow-flakes (deflational snow-storms) from the movement of snow-particles that had not yet touched earth during a windy superficial snow-storms (the up-snow-storms). The vertical component of the solid flux vector of up-snow-storms corresponds stricly to the intensity of atmosphere sediments (floating material). Hence the unequality of the snow-covering on the plane surface depends only on the wind-deflations.

If there are high obstacles, in irregular areas, especially in mountainous localities, the situation changes, because the distribution of falling particles depend on the field of the wind speeds. For example, the increasing of the snow cover height Hm in time t day on the leeward side behind the high building with a flat roof may be expressed by the following formula:

$$\frac{\partial H}{\partial t} \cong 10^{-3} \frac{i}{\gamma_s}\left(1+\frac{B}{B_g}\theta-\xi\frac{H_w}{w}\frac{\partial v_w}{\partial x_1}\right),$$

where

i is quantity of falling atmosphere sediments in a unit of time in mm water/day,
γ_s specific gravity of snow cover,
B width of the roof,
B_g width of the accumulation area of the snow falling from the roof,
θ, ξ dimensionless coefficients,

H_w the height of the wind layer, in which the aerodynamic influence of the building is perceived,

v_w the mean wind speed in this layer,

w the speed of the snow flakes falling down.

VII. Evaporation of the Snow-Storm Paricles

In contrast to sand storms, in a snow stream marked phase transitions owing to flake evaporation occurs. A study on this problem revealed unexpected results. Up to the present it was considered that snow evaporation is very small under natural conditions. Our numerous tests showed that snow evaporation took place intensively during snow-storms at a much higher rate than in the absence of snow transfer, which is explained by the exposure of all surfaces of flakes, due to the snow-storm. However, the intensity of blizzard evaporation of snow is still insufficient in order to regard vector of sublimation $\boldsymbol{K}$ as an essential factor in a snow-storm differential equation. But the blizzard snow losses arising from evaporation are very large. If we attribute all the snow evaporation to a snow-cover area unit, it may be described by Sherwood's criterion:

$$Sh = 2\left[f_1 + \frac{Qb\psi\psi_s}{\gamma l_s v_s} f_2\right],$$

where

ψ_s, ψ are coefficients of the mutual influence of particles and of its forms,

γ, l_s mean density and size of particles,

b thickness of the steam diffusion layer,

f_1, f_2 coefficients of snow-cover and snow-storm particle evaporation, taking into account the influence of the wind and the various thermal transfer types,

v_s mean translation as velocity of the entire mass of snow particles.

The second value is equal to zero in the absence of snow transfer, but during a snow-storm it becomes very large as much and increases in proportion to the square of the wind velocity. If evaporation from the surface of the snow-cover without wind does not exceed several millimeters (of water) in winter in a month, during intense snow-storm evaporation, depending on the air temperature and moisture, it forms from some several millimeters *in twenty-four hours* and more (Дюнин, 1961). It is possible to explain with the help of the above mentioned, the frequently observed snow disappearance in the open steppes in winter, although the snow quantity directly blown off by wind into the forests standing on the leeward side of the field forms only a small part of the general snow losses. Another interesting conclusion is that the wide snow-protection zones (shelter belts, snow and wind protections of several rows) always gather more snow than narrow snow-protection zones (protections of one row, snow screen lines etc.) with the identical snow drifts on the field side. Snow particles cannot be transferred unlimitedly to any great distances. The limited transfer distance conditioned by its evaporation does not exceed 2~5 km under Siberian- and North conditions. All these conclusions are confirmed by the tests.

VIII. Practical Applications

By means of the differential equation of a snow-storm it is possible to analize the processes of the snow transfer not only on flat country but also on rough country with the presence of various obstacles and artificial snow protection structures.

A theory of analytical calculation of snow and wind protection barrier action was worked out which was well confirmed by many laboratorial and field data (Дюнин, 1963).

According to these results we have also made attempts to apply some of our suggestions in practice (Дюнин, 1963; Комаров, 1959).

Thus for example, new structures of the road snow-protection afforestations with wide intervals and with narrow field parts, which provides economical results in planting materials and improves working conditions of the green plantations were worked out.

It was also suggested that in the structure of the green wind break shelter belts (Дюнин, 1963), the following would be advisable: The belts are divided on several small parts through their front line with corresponding empty intervals, the width of each part of belt should be sufficient for forming forest conditions and intervals between these parts are such that their effects on the wind are similar to that of one-row alleys well blown through by wind, which, as it is known, guarantee a most uniform moisture remaining on the fields. The intervals between belt parts and the part sizes must, of course, be set according to calculation.

We apply now special snow fences with a rarefied lower part in polar regions. These fences take less material and are lighter than the old standard fences and give better results in stopping snow without replacement and are not burried under snow.

On some roads of the USSR, inclined shields for blowing off snow from the road beds are used. In other countries inclined snow fences are sometimes used for the purpose of the snow retention. We have proved that the sizes of the zone for snow protection or snow blowing actions of any obstacles depend on their resistance to the wind. Therefore the inclined snow fences which has a minimal resistance to wind streams are unpractical. We therefore suggest that they should be replaced by screens placed vertically and normaly to wind direction. Numerous other suggestion were made.

At present we are continuing our studies on the obtained results and are studying the three dimensioned snow-wind-stream in mountainous avalanche danger areas.

A detailed account of the theory is given in the papers (Дюнин, 1963; Дюнин, 1965).

References

1) Аккуратов, В. Н. 1956 Прогноз наступления лавинной опасности по величинам метелевого переноса и температурного сжатия снега, "Вопросы использования снега и борьба со снежными заносами и лавинами", сб. статей, Изд. АН СССР, Москва, 167–183.

2) Дюнин, А. К. 1950 О полуэмпирической теории турбулентного пограничного слоя. Известия Сибирского отделения АН СССР. No. 5, 129–131.

3) Дюнин, А. К. 1960 Опытные исследования закономерностей метелей. Известия Сибирского отделения АН СССР. No. 1, 17–32.

4) Дюнин, А. К. 1961 Испарение снега, Изд. Сибирского отделения АН СССР, Ново-

сибирск, 119 pp.

5) Дюнин, А. К. 1963 Механика метелей, Изд. Сибирского отделения Академии Наук СССР, Новосибирск, 378 pp.

6) Дюнин, А. К. Борщевский, Ю. Т. и Яковлев, Н. А. 1965 Основы механики много компонентных потоков. Изд. Сибирского отделения АН СССР, Новосибирск, 76 pp.

7) Комаров, А. А. 1959 Повышение эффективности снегозащитных средств на железных дорогах Сибири, Новосибирск, 106 pp.

8) BAGNOLD, R. A. 1941 The Physics of Blown Sand and Desert Dunes, New York, 374 pp.

9) CHEPIL, W. S. 1945 The transport capacity of the wind. *Soil Sci.*, **60**, 6.

10) DYUNIN, A. K. 1961 Fundamentals of the theory of snow-drifting. *Nat. Res. Coun., Canada, Techn. Trans.*, **952**, 26 pp.

11) GSCHWEND, P. 1920 Beobachtungen über die Elektrischen Ladungen einzelner Regentropfen und Scheeflocken. Jahrbuch der Radioaktivität und Elektronik B. 17. H. 1, No. 65, 62–79.

12) HOPF, I. 1958 Über die Bedeutung, Art und Verteilung wind-abhängiger Bauten in der Lawinenverbauung und vorbeugung. *Allgemeine Forstzeitung*, 69. F. 5/6.

13) LILJEQUIST, G. H. 1957 Wind Structure in the Low Layer, Norsk Polarinstitut, Oslo, 53 pp.

14) PEARCE, D. C. and CURRIE, B. W. 1949 Some qualitative results on the electrification of snow. *Canad. J. Phys.*, **27**, No. 1.

15) PEEV, C. D. 1959 Der Einfluss von Hangneigung und Exposition auf die Lawinen Bildung. *Geogr. Berichte*, H. 12, 138–150.