Nordic Hydrology, 21, 1990, 287-298

Condensation of Humidity onto a Snow Covered Roof

Paper presented at the 8th Northern Res. Basins Symposium/Workshop
(Abisko, Sweden – March 1990)

Bo Nordell

Dept. Water Resources Engineering (WREL)
Luleå University of Technology, Sweden

In an approach to explain why snow loads on roofs increase when an early melting period occurs, the increased snow load is seen as condensation of humidity of the air onto snow covered roofs. 2-D simulations were performed with the Fluent model. The humidity of the air is considered as small droplets. The condensation rate is 3-5 kg/m^2 h. The simulations show that the wind side of the roof is more subjected to condensation than the lee side. This study indicates that short-term condensation onto snow covered surfaces should be paid more attention.

Background

There is an old saying in the north of Sweden "You must shovel away the snow from your roof before the warm sunny days of the late winter". The meaning of this saying is that the snow load on a roof is rapidly increasing when an early melting period occurs after a period of cold winter days.

My approach to explain this saying is that the increased snow load is caused by condensation of the humidity of the air onto the snow cover of the roof. Usually the air is dry during cold periods. When an early melting period starts, warm humid winds are blowing from the Atlantic Ocean.

Estimations of condensation by different methods for horizontal surfaces are not applicable to solve this problem since the wind functions used in most models are not relevant for condensation on sloped plane surfaces some metres above ground.

The aim of this pre-study is to estimate the short-term rate of condensation onto snow covered roofs to see if it is worth-while to perform more detailed research.

Performed simulations are made using Fluent (Fluent/PC 1986), a FDM-model for fluid flow problems. Air humidity is considered by assuming that there are small water droplets with a diameter of about 5×10^{-5} m in the air. This corresponds to 1.5×10^{10} droplets/kg of water (see Table 2). The 2-D two-phase flow simulations are made for roof slopes of 0°, 30°, 45° and 60°. Computations are performed assuming the air to be saturated at a temperature of 5°C. Simulated wind velocities are 3 m/s and 5 m/s.

Literature Review

Some measured condensation rate data reported in the literature are summarized in Table 1. These are net daily condensation or condensation rates over longer periods. In some of the referred studies, performed measurements show that condensation occurs during the night and evaporation during daytime hours.

Tabel 1 – Measured maximum condensation rates

Author	maximum condensation rate	
Lemmelä (1972)	0.7 mm/day	
Bengtsson (1980)	0.8 mm/day	
Lang (1981)	0.8 mm/day	(3,000 m.a.s.l)
Harstveit (1981)	13.4 mm/50 days	
Harr (1982)	882 mm/y	(fog drip)
Fuji (1982)	6 mm/month	(Antarctica)
Kaser (1982)	0.25 mm/h	(3,500 m.a.s.l)
Santeford (1971)	51 mm/2 h	

Harr (1982) measured condensation in form of fog drip on trees in Oregon, USA. During a 40-week period net precipitation in a forest totalled 1,739 mm. During the same period, 1,388 mm was measured in a standard rain gauge in a clearing nearby. The difference (between 1,739 mm and 1,388 mm) is explained by fog drip. In another study over a one-year-period, the fog drip was 882 mm of the total precipitation of 2,494 mm under the tree canopy, which means 35 % of the total precipitation.

Lauscher (1977) carried out measurements of condensation onto snow surfaces in Austria. The only conclusion he could draw from his data was that out of 212 days with snow cover, rime or condensation occurred during 103 days.

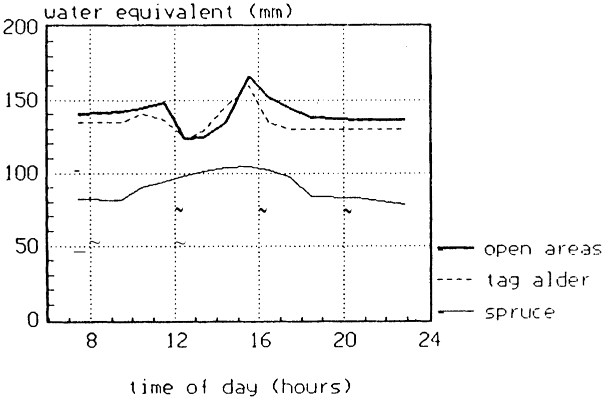

Fig. 1. Change of water equivalent with time when there were clear skies, a maximum temperature of 7° C, a corresponding relative humidity of 55 % and no precipitation. After Santeford (1972).

Santeford (1972) reports high condensation rates on snow from a clear sky in the Lake Superior Region. The water equivalent, density and quality of the snow pack at any of the 17 locations could change sufficiently during the day for hourly changes to be noted; on warm sunny days with air temperatures near 4°C and humidities above 50 %, the water equivalent of the snow was noted to increase from about 9 am to a peak occurring at 3-4 pm and then to decrease rapidly toward the evening, when the water equivalent would be nearly the same as that in the early morning hours. The peak values of condensation during the day, determined from water equivalent measurements, were 51 mm on open areas and tag alder and 25 mm on spruce as shown in Fig. 1. The increase in water equivalent occurred without precipitation.

Calculations gave the result that 1) no snow melt could occur; 2) no condensation could occur; and 3) evaporation from the pack had to occur. However, snow surveys and flow hydrograph indicated that condensation and subsequent drainage did occur. Furthermore, since the ice content of the snow pack did not change, condensation onto the snow pack must have occurred with no net melting of ice.

Santeford concludes that the condensation occurs just above the snow surface, so that the latent heat is released largely to the air rather than to the snow pack and thus the heat is carried into the general air mass by eddy turbulence.

Performed measurements over longer periods of time often concern net condensation over that period, but condensation and evaporation are often balanced over the day. Hourly measurements are seldom performed. The empirical calculation models commonly used in hydrological studies are verified against measurements over longer periods of time. Consequently, the models do not give accurate condensation rates for shorter periods of time (hours).

Evaporation/Condensation Theory

A common approach in estimating the rate of evaporation and condensation on a plane horizontal surface is to use an aerodynamic method in which the turbulent mixing process is considered. This method is based on a simple bulk aerodynamic equation originally proposed by Dalton in 1802, Eq. (1)

$$E = f(u)\,(e_s^* - e_2) \qquad (1)$$

where

E - evaporation/condensation (kg/day)

$f(u)$ - $a\,(1+b\,u)$ = wind function (m/s)

$e_s{}^*$ - saturated vapor pressure (mb) at the temperature of the vapor saturated film (water temperature for deep lakes)

e_2 - vapor pressure (mb) of the air at a height of 2 m where also u is recorded.

A wind function often used is $f(u) = a\,(1+b\,u)$ with $a = 0.13$ and $b = 0.72$ (Lindh and Falkenmark 1972). The method is applicable for areas with large homogeneous fetches. The coefficient a depends on the roughness of the surface and the wind function, as well as the stability of the air.

Extreme Values of Condensation

The upper limit of condensation rate is obtained if all the humidity of the saturated air, which is transported horizontally towards the surface, is condensated on the surface

$$E^{\max} \equiv u\,\sin(\alpha)\,A\,(r_{a,To} - r_{a,Ts}) \qquad (2)$$

where

$E^{\max}$ - maximum rate of condensation (kg/m^2 s)

A - area = 1 (m^2)

u - wind speed at the height of the roof (m/s)

α - slope of the roof (°)

r_a - water content of air (kg/m^3) using index To at temperature To and temperature Ts at surface temperature Ts.

Eq. (2) does not consider that turbulent mixing processes transport humidity to the surface which results in zero condensation for a horizontal roof. By using Eq. (1), which gives the rate of condensation onto a snow cover on horizontal ground, the minimum rate of condensation is determined.

The minimum rate of condensation, as given by Eq. (1) is 1.6 kg/m^2 d for saturated air at a temperature of 5°C and a wind velocity of 5 m/s. The upper limits of condensation as given by Eq. (2) for different roof slopes, and snow surface temperature of 0°C, are 34.6, 29.9, 24.4 and 17.3 kg/m^2 h for roof slopes of 90°, 60°, 45° and 30° respectively.

The Simulation Program – Fluent/PC

The condensation simulations were performed with Fluent/PC which is a fluid flow simulation program (Fluent/PC 1986). Fluent/PC incorporates the state-of-the-art modelling techniques in computational fluid dynamics (CFD) for simulating a wide range of fluid flow problems. Two-phase flows are simulated by considering humidity as small water droplets in the air. The simulation model is not further described in this paper. The Fluent/PC Technical Reference (1986) gives detailed information about the model and a number of solved fluid flow problems are well described.

Limitations and Assumptions

The simulated wind velocities are 3 and 5 m/s. The relative turbulent intensity, known to be in the order of 10% near a channel wall (Reynolds 1989) is assumed constantly 10%. The condensation simulations are simplified to a two-phase, two-dimensional, turbulent flow problem. The size of the droplets is of great importance since they must be small enough to follow the air stream, to behave like air. The constant physical properties of air and water like density, viscosity *etc.* are chosen at a temperature of 5°C.

In calculations and laboratory tests, of ice accretion on wires and atmospheric rime icing problems caused by humid air, a spectrum of droplet sizes are used. Particle sizes of about 10^{-5} to 5×10^{-5} m are often used, see Gates (1988) and Makkonen (1984). For that reason the simulations were performed for three different particle sizes ranging of 10^{-4} m to 10^{-5} m. In this work only one droplet size is used for each case.

Table 2 – Particle size, mass and number of particles

case	part. diam. (m)	part. mass (kg)	No of particles per kg of water
1	10^{-4}	5.2×10^{-10}	1.9×10^{9}
2	5×10^{-5}	6.5×10^{-11}	1.5×10^{10}
3	10^{-5}	5.2×10^{-13}	1.9×10^{12}

Mesh

The height and the length of the 2-D flow domain are 20 m and 64 m respectively. The FDM-mesh used was 20 × 44 cells. The size of the cells, close to the building, was chosen 0.5 × 0.5 m and the size of the cells was made to increase with distance from the building. The size of the cells was varied from 6.1 m to 0.5 m. The flow domain and the location of the building are shown in Fig. 2. The short-side of the building is 9 m and the length is 16 m (only used to calculate the total mass of

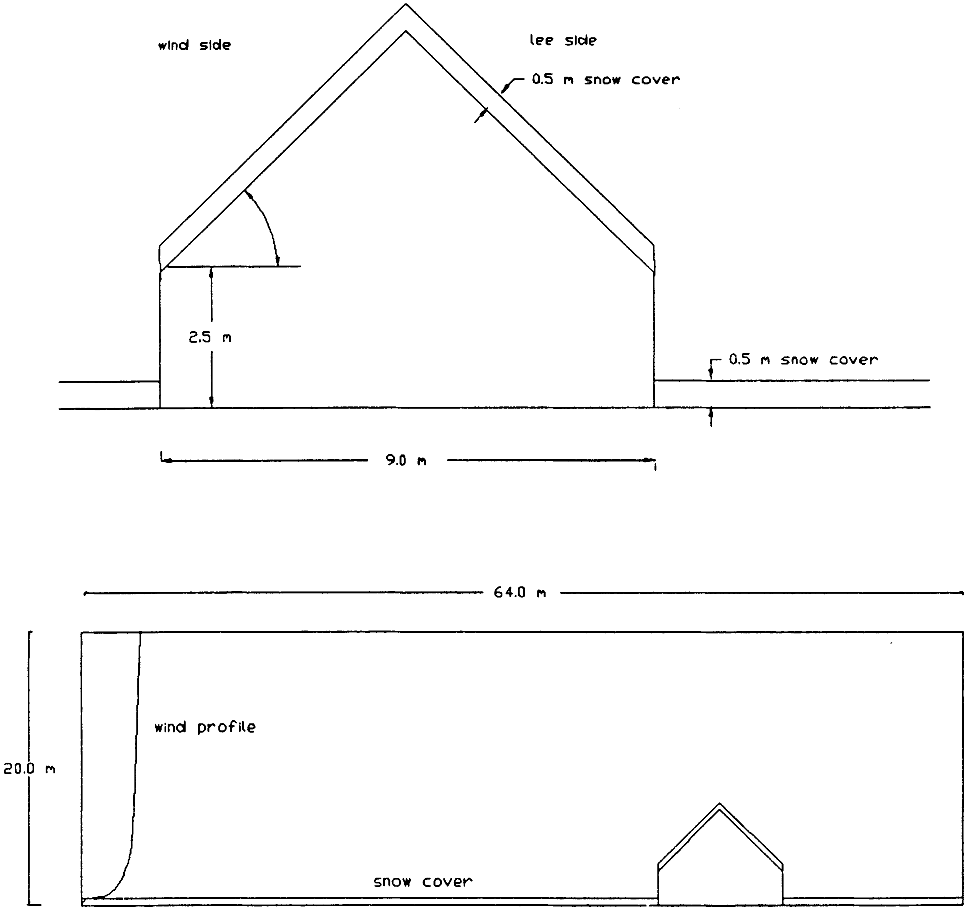

Fig. 2. Size and geometry of the flow domain used in the fluent simulations. The air stream flows from left to right.

condensation). The roof begins at a height of 2.5 m. The slope of the roof is varied; angles of 0°, 30°, 45° and 60° are simulated. Thus two wind velocities, three droplet sizes and four different slopes were simulated which means that 24 different cases were run. Each case needs 8 hours on a PC/AT computer which means a total computer time of 192 hours.

Snow Permeability

The ground and the roof are assumed to be covered with 0.5 m of uniform snow. The snow is considered to be rather soft and fluffy; the intrinsic permeability of such snow is chosen 10^{-7} m^2 as calculated from an equation found in Yen (1988) after Ergum (1952).

Simulations

The water droplets are injected along an 8 m vertical line from the snow cover at the entrance of the flow domain. The injected droplets saturate the air with a presumed temperature of +5°C. Injected particles are tracked from the injection point. Each particle that hit the snow covered roof is trapped, and attached to the snow cover. For each case 200 particles were followed. It should be noted that since only 200 particles are tracked for each case the results include random effects of the turbulent flow and repeated runs of the same case do not give the same result. Consequently the calculated values are uncertain up to the same unspecified degree.

Results

The simulated condensation rates are summarized in Figs. 3-7. The mass of condensation as a function of droplet size, for different roof slopes, is shown in Fig. 3. The particle size is obviously of greatest importance. The calculations give a maximum condensation rate of 9.4 kg/m^2 h for a droplet size of 10^{-4} m and a minimum rate of about 2.0 kg/m^2 h, for a droplet size of 10^{-5} m, see also Fig. 4.

Assuming that 5×10^{-5} m is an appropriate diameter of the water droplets, the calculation shows that the condensation rate is about 3 to 5 kg/m^2 h at the wind side of the roof for a wind velocity of 5 m/s. A wind velocity of 3 m/s results in a proportionally lower mass of condensation, see Fig. 4. As the calculated mass of condensation is split up in wind side and lee side of the roof, it is obvious that the wind side of the roof is much more subjected to condensation.

There is a tendency of increased condensation at the 30° sloped roof which can be seen in Fig. 4. At the wind side of the roof, this is the result for the 5 m/s cases. The plane roof has not a wind and lee side and thus the same condensation rate is given for both cases. In Fig. 5 the mass of condensation is given for one droplet size, 0.05 mm, to stress the difference between the wind side and the lee side of the roof.

The total condensated mass of water and the increase of snow load, does not follow the values per m^2 since the area of the roof increases with the slope. To estimate the total snow load increase per hour the plane area of the building is assumed to be $9 \times 16 = 144$ m^2. The maximum value, about 1,000 kg/h, is obtained for a droplet size of 0.1 mm and a wind of 5 m/s. For a droplet size of 0.05 mm and a wind of 5 m/s the total snow load increases 400 to 600 kg/h of which about 400 kg are deposited at the wind side. For a wind velocity of 3 m/s the total mass is lower, see Fig. 6. Finally the total snow load is given as a function of roof slope. Instead of a maximum, a minimum is found for a 30° slope of the roof.

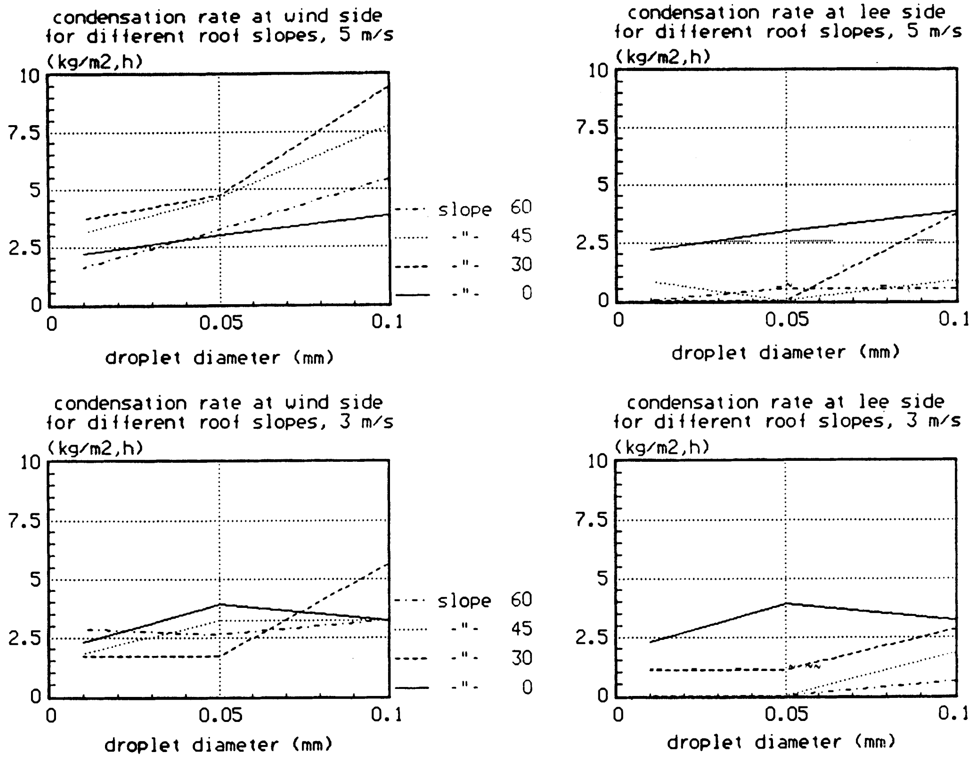

Fig. 3. Calculated mass of condensation per m^2 of the roof for wind velocities of 5 and 3 m/s as a function of droplet size of the humidity for different roof slopes. Left ≡ wind side; right ≡ lee side.

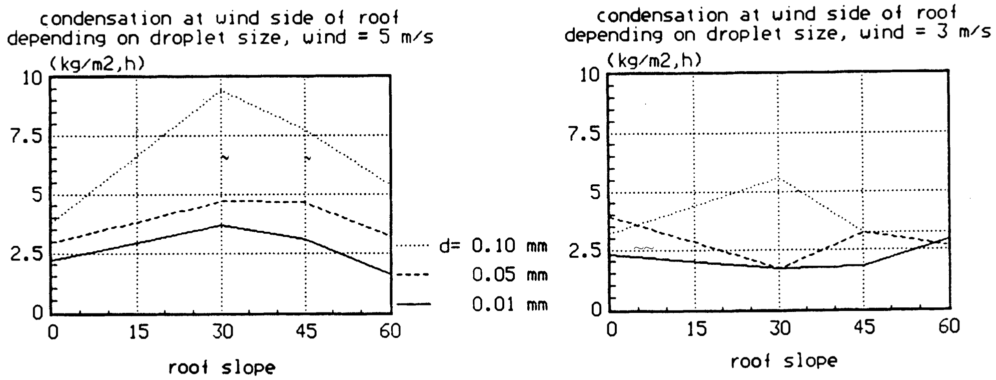

Fig. 4. Calculated mass of condensation per m^2 of the roof for wind velocities of 5 and 3 m/s as a function of roof slope, for different droplet diameters. Left ≡ wind side; right ≡ lee side.

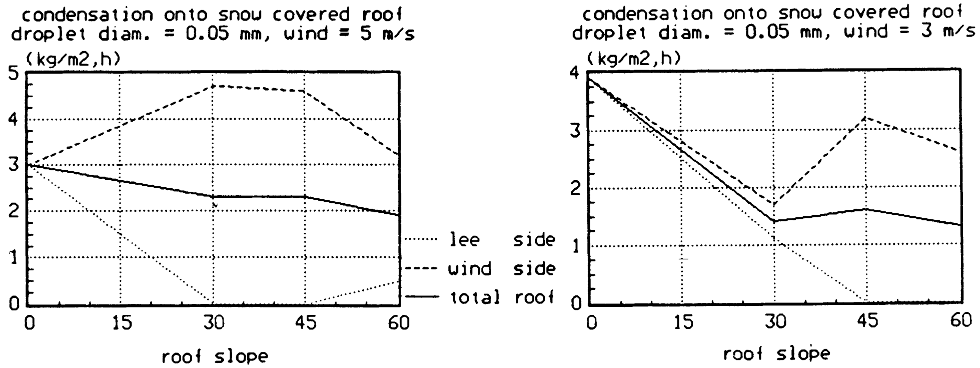

Fig. 5. Calculated mass of condensation per m^2 of the roof for wind velocities of 5 and 3 m/s as a function of roof slope. Droplet diameter ≡ 0.05 mm. Left ≡ wind side; right ≡ lee side.

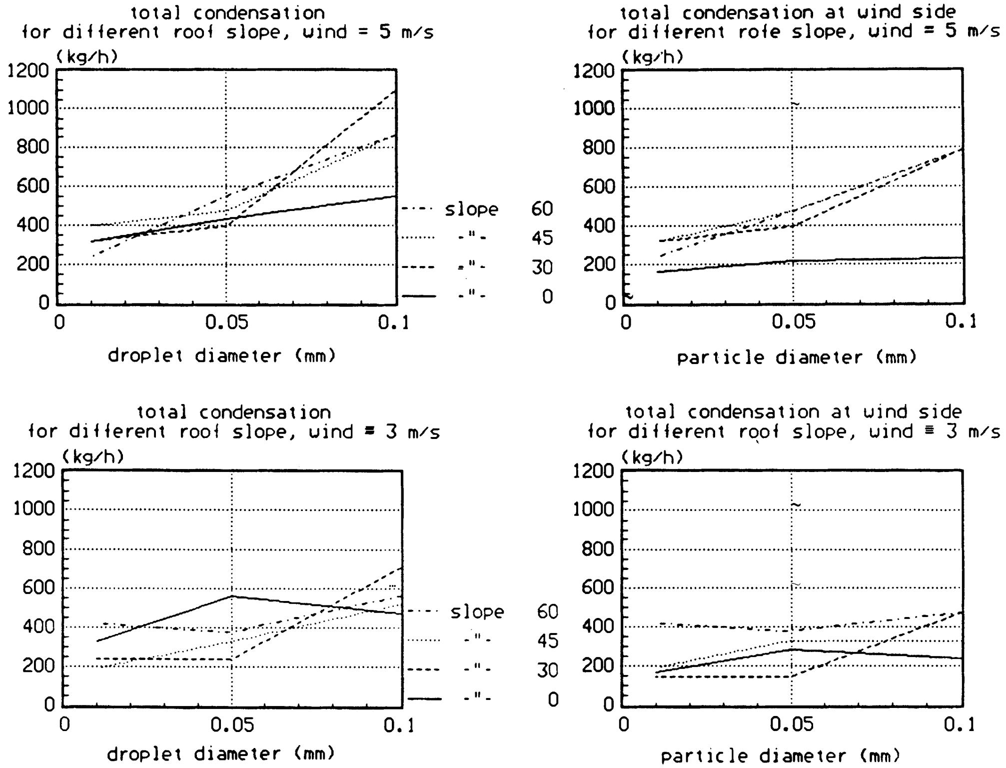

Fig. 6. Calculated total mass of condensation on the roof for wind velocities of 5 and 3 m/s as a function of droplet size. Left ≡ total roof data; right ≡ wind side data.

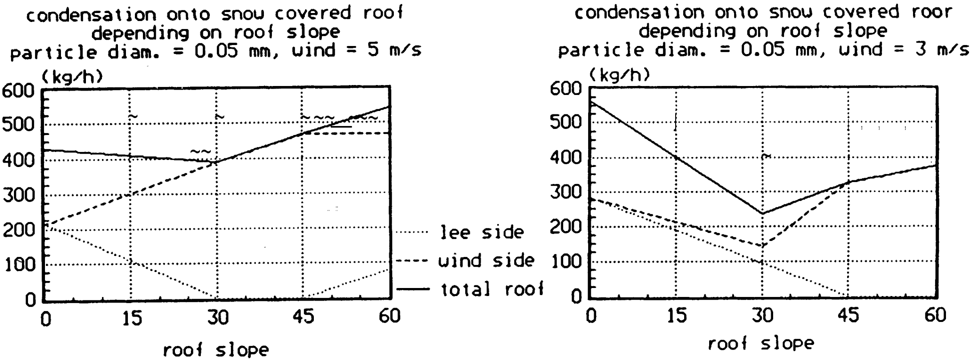

Fig. 7. Calculated total mass of condensation on the roof for wind velocities of 5 and 3 m/s as a function of roof slope.

Discussion and Conclusions

It should be emphasized that the use of this type of fluid flow modeling may give erroneous results without corresponding field and laboratory tests. There are numerous possibilities that the assumptions made to simplify the problem result in errors.

However, the simulated results are quite remarkable. A condensation rate of 5 kg/m^2 h means that the snow load on the roof increases considerably during a day. The condensated humidity could refreeze during the night and the snow load could increase over a period of several days. It must be pointed out that the quality of the snow changes during such a period that is the snow is less permeable to air as the snow gets more compact. This is not considered in the calculations.

The result of this prestudy indicates that short-term condensation onto snow covered surfaces may have to be considered when designing snow load. Another example is condensation on snow covered hill slopes, which results in a raised centre of gravity of the snow, and consequently an increased risk of avalanches. Finally, it seems worth-while to perform more detailed studies on short-term condensation onto snow surfaces and indeed, experience saved in old sayings should be paid more attention.

Acknowledgement

This study is a final work for the course "Hydrological Processes and Engineering Applications" given by prof. Don Gray, Univ. of Saskatoon, Canada, at Luleå University of Technology during the winter 1988/89. I would like to acknowledge professor Gray for an excellent course.

References

Bengtsson, L. (1980) Evaporation from a Snow Cover, Review and Discussion of Measurements, *Nordic Hydrology, Vol. 11,* pp. 221-234.

Fluent/PC Technical Reference (1986) Creare Incorporated, Etna Road, P. O. Box 71, Hanover, New Hampshire, 03755 USA.

Fujii, Yoshiyuki, and Kusunoki, Kou (1982) The Role of Sublimation and Condensation in the Formation of Ice Sheet Surface at Mizuho Station, Antarctica, *J. Geophysical Research, Vol. 87,* No C6, pp. 4293-4300.

Gates, E. M., and Liu, A. (1988) A Stochastic Model of Atmospheric Rime Icing, *Journal of Glaciology, Vol. 34,* No. 116, pp. 26-30.

Harr, R. Dennis (1982) Fog Drip in the Bull Run Municipal Watershed, Oregon. Water Resources Bulletin, AWRA, Vol. 18, No. 5.

Harstveit, K. (1981) Measuring and Modelling Snow melt in Dyrdalen, Western Norway, 1979 and 1980, *Nordic Hydrology, Vol. 12,* pp. 235-246.

Kaser, G. (1982) Measurements of Evaporation from Snow. Arch. Met. Geoph. Biokl., Ser. B, 30 pp. 333-340, Innsbruck, Austria.

Lang, H. (1981) Is Evaporation an Important Component in High Alpine Hydrology? *Nordic Hydrology, Vol. 12,* pp. 217-224.

Lauscher, F. von (1977) Reif und Kondensation auf Schnee und die wahre Zahl der Tage mit Reif, *Wetter und Leben, Vol. 29,* No 3, pp. 175-180, Vienna, Austria.

Lemmelä, R. (1972) Measurements of Evaporation-Condensation and Melting from a Snow Cover. Proc. of the Banff Symposia, 1972, The Role of Snow and Ice in Hydrology, Vol. 1, pp. 670-677.

Lemmelä, R., and Kuusisto, E. (1974) Evaporation-Condensation and Snowmelt Measurements in Finland, *Nordic Hydrology, Vol. 5,* pp. 64-74.

Lindh, G., and Falkenmark, M. (1972) Hydrology – an introduction to water resources (*Hydrologi – en inledning till vattenresursläran*), Studentlitteratur, Lund 1976 (in Swedish).

Reynolds, A. J. (1989) *Turbulent flows in engineering,* John Wiley & Sons, London.

Makkonen, L. (1984) Modeling of Ice Accretion on Wires, *Journal of Climate and Applied Meteorology, Vol. 23,* pp. 929-939.

Santeford, H. S., Alger, G. R., and Meier, J. G. (1972) Snowmelt Energy Exchange in the Lake Superior Region, *Water Res. Res., Vol. 8,* No. 2.

Yen, Yin-Chao (1988) On the pressure drop through a uniform snow layer, CRREL, Report 88-14, US Corps of Engineers, September 1988.

Ergum, S. (1952) Fluid flow through packed columns, Chemical Engineering Progress, 48(2), pp. 89-94.

First received: 27 February, 1990
Accepted: 22 May, 1990

Address:
Department Water Resources Engineering (WREL),
Luleå University of Technology, S-951 87 Luleå,
Sweden.