LASER INDUCED FLUORESCENCE - PARTICLE TRACKING VELOCIMETRY (LIF-PTV) MEASUREMENTS OF WATER FLOW THROUGH SNOW

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ABSTRACT: LIF-PTV-measurements of the micro-scale water flow through the pore space of a wet snow sample driven by either gravitational or capillary forces are presented. For the measurements, fluorescent micron-sized particles in the water are illuminated with a laser light sheet and tracked with a high-speed camera. The results show the existence of a potential preferential flow path and a loop flow in a pore space in case of a gravity driven flow. Generally, the water flow is found to be highly 3-dimensional. The average flow velocities in the pore spaces are 11.3 mm/s for the gravity driven flow and 9.6 mm/s for the upward flow driven by capillary forces. Flow acceleration and deceleration was stronger for the gravity driven flow with particle decelerations stronger than accelerations in both cases.

1 INTRODUCTION

Many wet and gliding snow avalanches caused several accidents during the winter 2011/2012 in the European Alps, demonstrating the need for a better understanding of the formation of these events. Predicting regional wet snow avalanche danger depends on factors like the structure of the snowpack, the energy transferred from the atmosphere and the ground into the snowpack and the rate of water percolation through the snow. A lack of knowledge exists on the micro-scale water flow through snow. Most studies mainly quantify the total flow through the snow matrix for different snowpack layers neglecting the micro-scale flow dynamics and preferential flow path generation. A detailed description as a basis for quantitative understanding, however, requires investigations of the micro-scale velocity fields in the pore space.

In this contribution, we present spatiotemporally highly resolved LIF-PTV measurements of water flow velocities in the pore space of a wet snow sample for both, a gravity driven flow as well as a flow driven by capillary forces. LIF-PTV uses micron-sized, fluorescent and density matched particles as tracers in the water that are illuminated with a laser light sheet. The fluorescent light of the particles is recorded with a high-speed camera.

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LIF-PTV measurements were extensively used for investigations of the flow fields in porous media and fills (e.g. Northrup et al, 1991; Arthur et al, 2009), however, to our best knowledge, this is the first study applying LIF-PTV to snow. The presented experiments using a very basic setup aim to show that LIF-PTV measurements in snow are principally feasible and that LIF-PTV may open a wide range of investigations of water percolation through a snowpack under various conditions. Analysing capillary effects, the transition from water filled pores to melt water percolation, water flow through the boundary between two different adjacent snow layers or the transport of particles like algae or particulate matter within the snowpack are just a few examples of potential future investigations with LIF-PTV.

2 EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experimental setup consists of two rectangular acrylic glass reservoirs each 50 × 50 × 100 mm stacked on top of each other (Fig. 1). The bottom of the upper reservoir filled with water is perforated to carefully sprinkle ice cooled water seeded with fluorescent particles onto the top of the wet snow sample in the lower reservoir. This setup is supposed to simulate a very strong rain event (about 0.1 - 0.5 mm/s) onto a snowpack. When sprinkling the seeded water on top of the wet snow sample (density approximately 300 - 400 kg/m^3), the water percolates downward through the saturated pore space due to gravity. The water below the snow sample is collected in a water basin (Fig. 1).

From there, the water is pumped back to the upper reservoir. The snow sample containing the water with the fluorescent particles is illuminated with a green laser light sheet from the side (Fig. 1). The laser is a 5 W DPSS 532 nm cw-laser and the excited fluorescent particles (Rhodamin B doped PMMA, size distribution: 20-50 µm, density: 1.19 g cm^{-1}) emit light at a wavelength of 584 nm. The trajectories of the particles are filmed with a CMOS-high-speed camera (sampling frequency: 200 Hz) equipped with a 70-180 mm micro objective and a high-pass filter with a cut-on frequency of 540 nm. The seeding density of the fluorescent particles in the water was 0.5 mg/l for these preliminary experiments. The maximum achievable measurement resolution with this setup is 15 µm × 15 µm per pixel, however, this can be improved by using special optics for the high-speed camera.

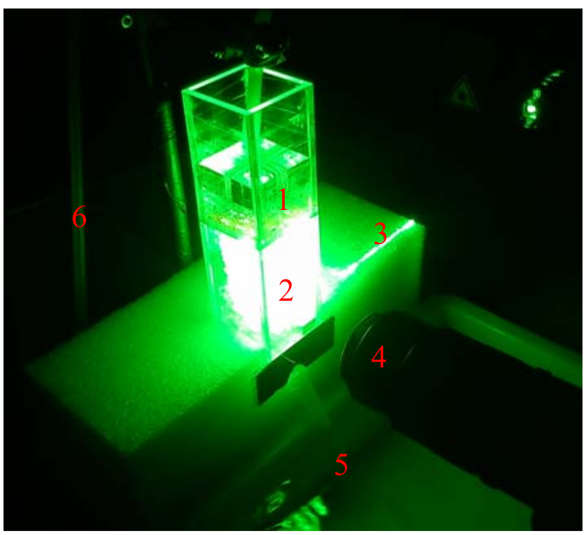

Figure 1: Experimental Setup: 1) Upper reservoir with seeded water; 2) Lower reservoir with wet snow sample; 3) Laser light sheet; 4) Lens of high-speed camera with cut-on filter 5) Water basin 6) Tube for pumping water into upper reservoir.

The non-intrusive measurement of velocities in multiphase porous media using optical detection techniques typically requires refractive index matching (e.g. Northrup, 1991). This means that the refractive index of the fluid phase and of the solid phase of the porous medium need to be identical so that the system gets transparent. This results in a direct optical access to the pores. The refractive index of water at an atmospheric pressure of 1 bar, a temperature of 0 °C and a wavelength of λ = 589 nm is n = 1.33346 (Thormählen et al, 1985) while ice has a refractive index of about n = 1.31 under similar conditions. Thus the advantage of our setup to comparable studies typically using acrylic materials with $n \approx 1.49$ (e.g. Arthur et al, 2008) is that the refractive indices of water and ice are quite similar. Nevertheless, the difference of about $\Delta n = n_{water} - n_{ice} \approx 0.02$ already results in blurry fluorescent particles filmed with the camera once the light passes more than one or two ice crystals. This limits the possible measurement depth of this tentative experimental setup to a focal plane of 5 mm and less within the snow sample behind the acrylic class. At this depth, the influences of the surface forces of the acrylic glass on the water flow are assumed to be negligibly small. All measurements presented here were recorded with a focal plane of about 5 mm behind the reservoir glass. To obtain larger depth, however, refractive index matching will be required, which can be achieved by adding liquids to the water like organosilicone fluids for example.

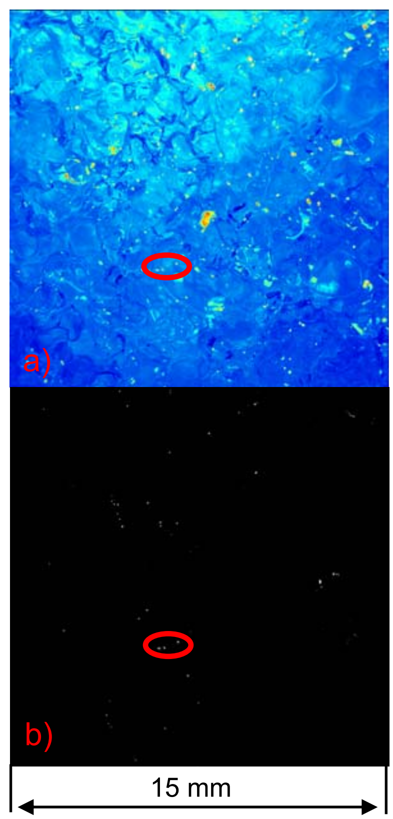

Figure 2: a) Raw image (false colours) of the high-speed recording where the small bright spots are the fluorescent particles. The wet snow matrix is slightly indicated. b) Processed image used for the particle tracking algorithm.

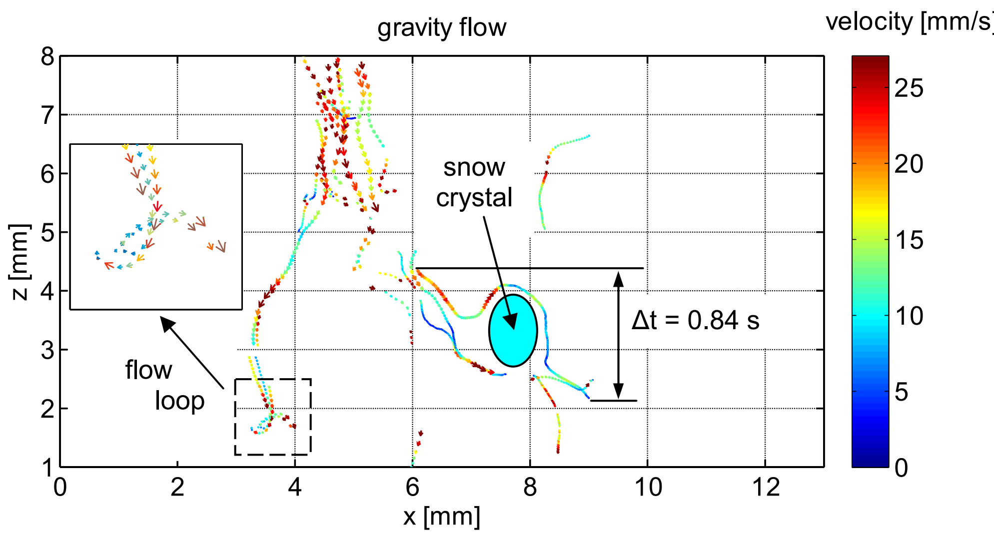

Figure 3: Particle trajectories for the gravity driven flow. Colour of arrows indicate particle velocities.

3 RESULTS AND DISCUSSION

In this section, the particle trajectories and the corresponding particle velocities as well as basic velocity statistics for a gravity driven flow and a flow driven by capillary forces through a wet snow sample are presented.

3.1 *Gravity driven flow*

Fig. 2a shows a raw image of the water saturated wet snow sample in the lower reservoir with small bright spots (e.g. as indicated in the red circle) which are the fluorescent tracer particles. The background image reveals the structure of the snow sample where wet snow crystals with an average diameter of about 1 mm can be identified. However, the image does not allow for a detailed characterization of the snow sample and the pore space due to the limited resolution. This would require other measurement techniques like computer tomography (e.g. Coléou et al, 2001). The raw images are processed to remove the background so that solely the moving, fluorescent particles remain before applying the tracking algorithm (Fig. 2b). The algorithm then detects the individual particles in the consecutive images and calculates the corresponding velocity vectors.

The resulting particle trajectories are summarized in Fig. 3. Each vector is labelled with a colour indicating the particle velocity at a specific location. The travel time of a relatively long particle track is included (Δt = 0.84 s). The total measurement time was 1.35 s. The path of this particle shows a strong deflection around a snow crystal of a size of about 1 mm. A wider flow path with a relatively high particle density and high particle velocities occurred around {x, z} = {5 mm, 7 mm} in Fig. 3, suggesting the existence or the development of a preferential flow path. This preferential flow path most likely developed because the experiment was already running several seconds before the LIF-PTV measurement were started. Another interesting feature is found at {x, z} = {4 mm, 2 mm} in Fig. 3. Particles enter a small pore space with a relatively high velocity of about 20-25 mm/s, get deflected by the snow matrix performing almost a 360° loop at a lower velocity around 10-15 mm/s and leave the pore space again at a high velocity. This flow loop and all other trajectories show that the flow within the snow sample is highly 3-dimensional.

That the fluorescent particles can just be tracked over limited distances has two reasons. The first reason is that the optical access is limited since no refractive index matching has been performed (see Section 2). Once the fluorescence light of a particle has to pass several ice-water boundaries, the particle gets too blurry to be tracked. The second reason is that the flow is highly 3-dimensional and the thickness of the focal plane is just about 1 mm. Most particles are thus only a short period of time within the focal plane.

The average particle velocity is $|V_{avg}|$ = 11.3. The maximum velocity is $|V_{max}|$ = 27.1 mm/s. The maximum vertical and horizontal particle velocities are 22.5 mm/s and 26.1 mm/s, respectively. The velocity vectors from the particle trajectories in Fig. 3 also allow for determining flow accelerations and decelerations. The maximum flow acceleration was 2.1 m/s^2 and the maximum flow deceleration was -3.1 m/s^2.

3.2 *Flow driven by capillary forces*

In a second experiment, the snow sample in the lower reservoir (Fig. 1) was carefully placed in a Petri dish filled with seeded, ice cooled water. Due to capillary action, the water level within the snow sample got raised up to a height where the gravitational force of the water column equals the capillary forces. The LIF-PTV velocity measurements were performed while the water flew upwards within the snow sample.

Fig. 4 shows two particle trajectories of fluorescent particles lifted by capillary action. Because the seeding in the water filled Petri dish was very low, just two particles were tracked during the total measurement time of again 1.35 s. The travel time of both particles is included in Fig. 4. Both trajectories end at a height of approximately 6 mm where the particles got stuck within the snow matrix. In this case, the trajectories end because the gravitational forces balance the capillary forces and the fluorescent particles do not get transported higher up in the snow matrix. This is nicely supported by the strongly decreasing velocities at the upper end of the particle trajectories. Due to the simple experimental setup, it was not possible to relate the height of the tracked particles to the height of the water level in the Petri dish.

The average particle flow velocity is $|V_{avg}|$ = 9.6 mm/s for the capillary driven flow which is just slightly lower than for the gravity driven flow ($|V_{avg}|$ = 11.3 mm/s). The maximum velocity is $|V_{max}|$ = 21.9 mm/s which is again lower than for the gravity driven flow ($|V_{max}|$ = 27.1 mm/s). This can be explained by the fact that no preferential flow paths with high flow velocities develop for the flow driven by capillary forces. The maximum vertical and horizontal flow velocities are 21.9 mm/s and 11.6 mm/s. The maximum flow acceleration was 1.2 m/s^2 and the maximum flow deceleration was -1.8 m/s^2 (2.1 m/s^2 and -3.1 m/s^2, respectively, for the gravity driven flow).

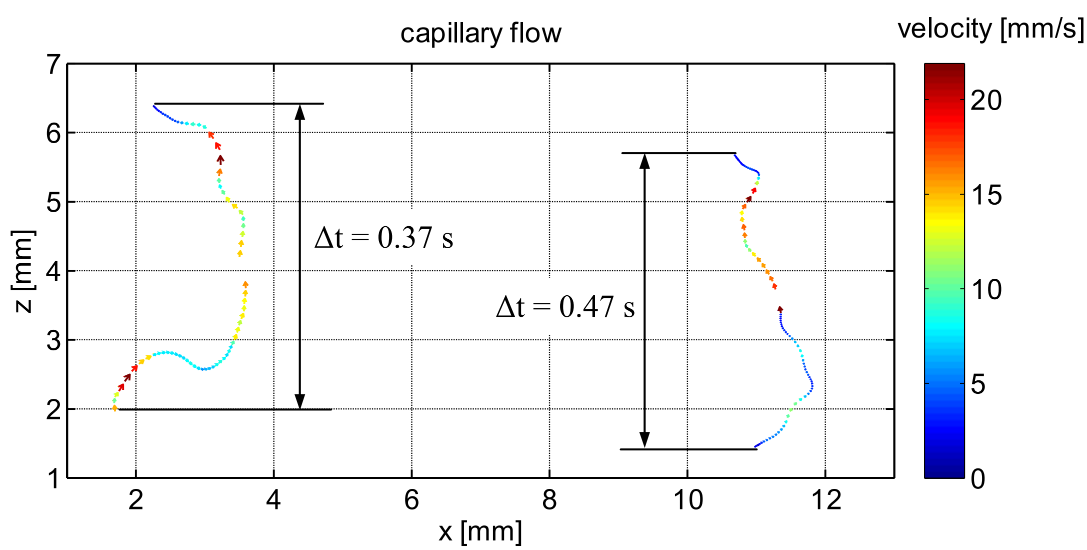

Figure 4: Particle trajectories for the upward flow driven by capillary forces. Colour of arrows indicate particle velocities.

4 SUMMARY AND CONCLUSIONS

The presented results show that LIF-PTV measurements of water percolation through snow are in principal feasible enabling a wide range of future investigations that may incorporate analysing the generation of preferential flow paths or the transport of particles within the snowpack. It was shown that the LIF-PTV measurements can be used to determine valuable velocity statistics that may improve the modelling of the water flow through snow.

Despite the fact that no refractive index matching (see Section 2) has been performed, the water flow within the snowpack was measurable up to a depth of about 5 mm behind the acrylic glass of the lower reservoir. Nevertheless, refractive index matching is intended for future experiments to be able to measure deeper within the snowpack avoiding influences of the reservoir glass on the water flow. Another, not yet mentioned limitation is that under natural conditions, the pore space in the snowpack is typically not saturated with water as in the present measurements. As a result, an additional phase, an air-phase within the pore space occurs, making refractive index matching impossible and limiting the LIF-PTV measurements to depth close to the acrylic glass of the reservoir. Nevertheless, it is expected that for experiments with an air phase in the snow, measurements similar as shown here can be performed. Such measurements still have large potential for getting fundamental information on water percolation through snow for unsaturated cases. An alternative solution would be the use of fibre optics or an endoscope to get direct access to the pore space (Northrup et al, 1991).

The measurement resolution can be improved down to less than 1 μm × 1 μm with better optics for the high-speed camera. This may allow for resolving the velocity fields in single pore spaces for example. Therefore, fluorescent polystyrene particles (1.05 g/cm^3) of a size of 1 μm and less can be used. Those particles have a better flow following behaviour than the particles used in the present experiments (20-50 μm, 1.19 g/cm^3).

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