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Air cavity migration in ice as a case study for temperature gradient metamorphism of snow: time-lapse X-ray microtomography observation and phase-field simulations.

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Temperature gradient metamorphism of snow is a mechanism of snowpack transformation resulting from the coupling of elementary physical processes: heat conduction, vapour transport in the pore space and phase change at the ice/air interface. An important feature of this mechanism is that it produces a faceted microstructure with sufficiently strong gradient, as a consequence of the anisotropy of the kinetic coefficient of ice.

To model this mechanism at the pore scale, the phase field method appears to be a relevant choice. Indeed, this method is well suited to describe interface evolution problems coupling phase change to other physics. In the case of snow, Kaempfer and Plapp (2009) developed such a model so that temperature gradient metamorphism could be addressed, with however an isotropic kinetic coefficient. Now, a desirable extension of this model is to add the ability to reproduce faceting. This asks for further model developments.

For this, one needs suited experimental data to guide modelling and perform validations. Experiments using real snow are ideal to establish correlations between macroscopic conditions and properties. However, these present variability and complex geometry, which makes interpretation of comparison with microstructural model difficult. Instead, for microstructural modelling, it is practical at first to dispose of experimental data that imply all targeted processes but on a simpler case and, if possible, on which computationally light simulations can be performed.

To that purpose, we submitted a monocrystalline ice block containing a spherical air cavity of 190 µm in diameter to an external temperature gradient of 45 K/m, parallel to the c-axis of the ice, with a mean temperature of -4℃ using CellDyM cryogenic cell (Calonne et al 2015). We followed the evolution of the cavity using time-lapse X-ray microtomography for 4 days, scanning every 3 hours, with a resolution of about 7.4 µm. The cavity migrates in parallel to the gradient, towards the warm side. The speed of the bubble is constant to 0.00046 µm/s. Hexagonal faceting is observed on the sublimating part of the interface while the condensing part remains rounded.

Then, simulation of this problem has been carried out using a COMSOL multiphysics implementation of Kaempfer and Plapp's model (2009). First, the overall migration of the cavity could be retrieved, underlying the facts that the core physics is captured. Next, as expected, differences in terms of shapes appear clearly so that faceting can be studied. Finally, valuable information on temperature gradient metamorphism get out of these works, and constitutes the first steps for addressing the faceting problem in further modelling investigations.

Kaempfer, T. U., & Plapp, M. (2009). Phase-field modeling of dry snow metamorphism. Physical Review E, 79(3), 031502.

Calonne, N., Flin, F., Lesaffre, B., Dufour, A., Roulle, J., Puglièse, P., Philip, A., Lahoucine,F., Geindreau, C., Panel, J.M., Rolland du Roscoat, S. & Charrier, P. CellDyM: A room temperature operating cryogenic cell for the dynamic monitoring of snow metamorphism by time-lapse X-ray microtomography. GRL 2015. DOI : 10.1002/2015GL063541

Significance statement

Air cavity migration in ice under a temperature gradient has been followed by time-lapse X-ray microtomography and simulations have been performed using a phase-field model. This study implies the same physical processes as temperature gradient metamorphism of snow, these are works towards improvement of snow metamorphism modelling.

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