PREDICTIVE MODELING OF ICY POROUS ANALOGS UNDER PHASE CHANGE DYNAMICS. M. Potter\(^1\), J. Baglino\(^2\), A. Moure\(^2\), N. Jones\(^2\), J. Andrade\(^2\), M. Choukroun\(^1\), S. Yearicks\(^1\), and J. Bescup\(^1\), X. Fu\(^2\), E. Marteau\(^1\);
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**Introduction:** Potentially habitable icy Ocean Worlds, such as Enceladus, Europa, and Ceres, are scientifically compelling bodies and key targets in the robotic exploration of the solar system. Enceladus, and tentatively Europa, have a unique present-day activity that manifests as water-rich plumes ejecting materials from their internal habitable ocean onto their surfaces [1]. Plume deposits are expected to consist of fine-grained ice particles that evolve via sintering, possibly transforming initially unconsolidated deposits into consolidated porous ice [2,3]. Sintering affects a wide range of ice physical properties, such as density, cohesion, strength, friction coefficient, roughness, hardness, thermal conductivity, and surface albedo. These properties have critical implications for both the interpretation of remote sensing data and the successful in-situ robotic exploration of these Worlds. To date, most of these properties remain poorly constrained, thus hindering the development of robust sampling, mobility, and landing systems.

To improve our understanding of Ocean Worlds icy surface conditions and to describe changes in the surface properties when interacting with robotic systems, this work aims to develop calibrated geomechanical models of icy porous materials that predict (1) the properties of icy porous surfaces on Ocean Worlds under natural deposition process, before lander touchdown and (2) changes in the surface material properties when interacting with robotic systems, as induced by external thermal and/or pressure gradients. To this end, in this work, models combining the phase-field method (PFM) and the level-set discrete element method (LS-DEM) are used to study the changes in the microstructure of the icy material associated with phase transitions and their influence on the macroscopic mechanical properties. Modelling predictions are correlated to microstructural and mechanical property measurements obtained from physical experimentation using icy simulant materials.

**Computational Methods:** We use a phase-field model to simulate dry snow metamorphism process. The model captures phase changes between ice and water vapor controlled by the Gibbs-Thomson condition on the ice-vapor interface [5-7]. The model unknowns are the ice \(\phi_i(x,t)\) and air \(\phi_a(x,t)\) phases, the temperature \(T(x,t)\), and the vapor density \(\rho_v(x,t)\), all of which are defined in the entire problem domain. The phase-field unknowns take values of 0 outside the corresponding phase, 1 inside. The governing equations are expressed as:

**Equation (1)**

\[
\frac{\partial \phi_a}{\partial t} = 3M_0 \left( \frac{1}{\epsilon} \phi_a (1-\phi_a)(1-2\phi_a) - \epsilon \nabla^2 \phi_a \right) - \alpha_{\text{sub}} \phi_a (1-\phi_a)^2 \rho_v - \rho_v^{\text{sat}}(T)
\]

**Equation (2)**

\[
\rho(\phi_a) c_p(\phi_a) \frac{\partial T}{\partial t} = \nabla \cdot [K(\phi_a) \nabla T] - \rho(\phi_a) L_{\text{sub}} \frac{\partial \phi_a}{\partial t}
\]

**Equation (3)**

\[
\frac{\partial (\phi_a \rho_v)}{\partial t} = \nabla \cdot [\phi_a D_v(\phi_a) \nabla \rho_v] + \rho_i \frac{\partial \phi_a}{\partial t}
\]

The ice phase can be computed as \(\phi_i = 1 - \phi_a\). In equation (1), \(\rho_i\) is the ice density, \(\rho_v^{\text{sat}}\) is the saturated vapor density of ice, \(\epsilon\) represents the interface width, and \(M_0\) and \(\alpha_{\text{sub}}\) are parameters controlling the phase-change kinetics. The temperature equation (2) accounts for thermal diffusion and latent heat release/absorption during phase transitions, where \(L_{\text{sub}}\) is the sublimation latent heat, and \(\rho_i\), \(c_p\), and \(K\) are the phase-dependent density, specific heat capacity, and thermal conductivity, respectively. The vapor equation (3) accounts for vapor diffusion in air and mass conservation of water as it transitions between the ice and water vapor, where \(D_v\) is the temperature-dependent vapor diffusion coefficient [4].

**Figure 1** illustrates a simulation using our model of two ice grains sintering for 18 days in a closed domain of 2 mm in length. In **Figure 2**, we apply our model to simulate the sintering of an ice bead pack (2 mm in length) over 36 hours under a small temperature gradient.

![Figure 1: Two-grain sintering simulation. The background shows the deviation in vapor density from the minimum vapor density \(\rho_{v,\text{min}} = 2.5\times10^{-3} \text{ kg/m}^3\).](image)
Figure 2: Bead pack with imposed temperatures T = -1°C and T = 0°C on the top and bottom, respectively, which displays a coarsening effect over time as it develops into a more connected structure. The background shows the deviation in vapor density from the minimum vapor density $\rho_{v, \text{min}} = 2.5 \times 10^{-3} \text{ kg/m}^3$.

Model Validation with Physical Experimentation:
To validate developed models, icy simulant materials are prepared and analyzed for their microstructure and morphology as described below.

Icy Simulant Material Preparation. To generate icy simulant materials, spherical ice particles on the order of hundreds of microns in diameter (Figure 3) are prepared according to previously established methods [8]. Briefly, atomized water droplets produced by a commercial-off-the-shelf (COTS) chemical sprayer (Chapin, 11.4 L) are flash-frozen upon contact with a large LN2-Dewar reservoir. Smaller diameter (tens of microns) ice particles are generated by submerging an atomizer in distilled water with simultaneous capture of atomized water droplets in a small LN2-filled Dewar. After flashing freezing in LN2, ice particles are transferred to pre-chilled sealed containers or pre-chilled sealed glass slides and stored in a freezer for later use/observation after a specified duration of time.

Microstructure Characterization. Cryogenic optical microscopy is executed using a Keyence VHX 7000 digital microscope equipped with a Linkam LTS420 cryostage. As mentioned previously, icy simulant particles stored for a specified time/temperature in a sealed glass slide are transferred under cold (-80°C) conditions to a cryostage with a setpoint of -80°C. Keyence VHX 7000 software is used to analyze particle shape/morphology and sintering neck size as a function of thermal history. After cryogenic imaging, the sealed glass slide containing icy particulate material is carefully transferred back into a freezer for later use/observation. Microstructural measurements obtained from physical experimentation as described are used for the validation of developed models. X-ray microcomputed tomography of the samples will also be conducted at cryogenic temperatures at the JPL’s Analysis and Test Lab to investigate the distribution of porosity and the 3D packing arrangement of the ice particles within the sample. [9]

Conclusions: To improve our understanding of Ocean Worlds and enable robotic exploration in new terrains, in this work, we have developed and numerically implemented a phase-field model that describes the microstructural evolution of porous ice driven by ice-vapor phase change processes. The preliminary results of our simulation captures the sintering of spherical ice grains in both a simple two-grain geometry, and in a realistic bead pack composed with various ice bead sizes. These results will be validated through physical experiments. Methods for physical experimentation were developed and improved to aid in model validation via observation of ice particle microstructure and morphology. Results will ultimately aid in establishing geomaterial and technological bases that can be applied to advance robotics applications, and help to redefine new frontiers for planetary exploration of Ocean Worlds, Mars Polar Regions and the Permanently Shadowed Regions of the Moon.

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