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A simplified approach for the simulation of unconstrained melting in macrocapsules

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The study of heat transport and flow inside macro-encapsulated phase change materials (PCM) is crucial for understanding and improvement of latent heat thermal energy storages (LHTES). Therefore, the investigation of melting and solidification processes with computational fluid dynamics has gained increasing attention in recent years. Melting of PCM in macrocapsules can be divided into constrained and unconstrained melting. In constrained melting, the solid PCM is hindered from moving in the liquid PCM, e.g. by slabs mounted inside the capsule. In unconstrained melting, the solid can freely move in the liquid PCM. The direction and magnitude of the motion depends on gravity, the thermophysical properties of the PCM and the thermal boundary conditions on the capsule wall. The solid density of most PCM exceeds their liquid density, thus the solid body sinks to the bottom of the capsule if the capsule wall is uniformly heated. Between the capsule wall and the remaining solid PCM a thin fluid film remains, which results in higher heat transfer rates from the capsule wall to the solid PCM compared to constrained melting. For spherical or horizontal cylinder capsules immersed in water baths and Stefan numbers of up to 0.2, differences in melting times of more than 50% have been observed in experiments [1-4].

A widely used method for the simulation of solid-liquid phase change is the enthalpy-porosity method (EPM), which is implemented in OpenFOAM via the fvOptions solidificationMeltingSource. However, the EPM originally does not take unconstrained melting into account, as the velocity in solid cells is forced to zero by a Carman-Kozeny momentum equation source term that mimics a porous medium to allow treating solid and liquid phases in one common set of governing equations. Quite often, in an attempt to simulate unconstrained melting via EPM, the Carman-Kozeny constant, or mushy zone constant, is lowered to values that do not fully suppress the velocity in the solid. This does not give a physical description of the solid body motion; a forecast of unconstrained melting processes cannot be achieved. Instead, the solid velocity can be obtained from a force balance on the solid-liquid interface which has to be captured from the volumetric liquid fraction field. Various approaches of interface reconstruction and solid body velocity computation have been presented [5-7] and successfully validated against experimental data. However, the fluid-structure interaction has shown to be best solved by implicit coupling schemes, which can be computationally expensive.

In this work, a simplified approach for the computation of solid PCM motion is presented. Approximate correlations for primitive shapes of macrocapsules are obtained from scale analysis from analytical solutions [8-11] and are implemented in the solidificationMeltingSource. By avoiding interface reconstruction and computation of the resulting force thereon, computational cost is reduced, while reasonable accuracy is provided in a simple, yet physical description of solid body motion.
The presented method does not claim to replace force balance approaches for arbitrary boundary conditions and geometry, but it is believed that it provides an improvement in the simulation of unconstrained melting in macrocapsules for many users working on LHTES design and analysis.

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