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Ice thawing via Joule heating: developing a conjugate-heat-transfer solver for phase transition

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Tanks containing frozen liquids are a common occurrence in automotive applications: water-based mixtures are particularly susceptible to freezing, and even oils and fuels can gel when exposed to an extremely cold environment.
In order to use these frozen liquids, it is necessary to thaw them: a widely-used technology involves electric heating, whereby one or more heating elements are installed inside the tank. Upon application of an electric current, Joule (resistive) heating occurs. Typically, the electrical resistance of these elements is not constant: it is desirable to have a resistance which increases with temperature, in order to limit the maximum temperature inside the tank.
The design of an effective heater is quite challenging, as the thawing process depends crucially on geometry and power distribution in space; this is not only due to performance considerations, as safety during operation is paramount. In particular, there are application-specific temperature thresholds which cannot be exceeded at any time. For this reason, several design-testing loops are currently required, which are both costly and time consuming.
A detailed numerical analysis of the problem can be quite effective in reducing design time; further, it can provide a level of detail which is difficult to appreciate during testing. However, it is currently challenging to develop a complete, reliable model of the thawing process with existing commercial general-purpose tools. For this reason, we have developed a dedicated solver, based on the CHT (Conjugate-Heat-Transfer) family of the OpenFOAM v1806 library.
In this talk, we briefly discuss the structure of this solver, and further we compare results with analytical and experimental data. In particular, the solver includes three main features: a non-linear model of Joule heating, an enthalpy-based description of phase change and an iterative coupling of the interface conditions for temperature and electric potential across multiple domains.
With respect to Joule heating, it is important to consider applications where the electrical resistance depends strongly (even exponentially) on temperature: this is often the case in automotive applications, where PTC (Positive-Temperature-Coefficient) heaters are employed in order to passively limit heating. Numerically, this introduces a stiff source term in the energy equation which requires specific treatment.
With respect to phase change, for our applications it is important to track accurately the position of the interface between solid and liquid regions of the flow domain. We implemented an enthalpy-based phase-change model.
With respect to the interface conditions across multiple domains, we introduced a continuity condition for the electric potential, and further we implemented an additional internal iteration in order to control time-discretization errors due to the explicit formulation of interface conditions in CHT-based solvers.

To conclude, we present numerical results and we compare them with analytical benchmarks and experimental tests, showing a close match between the numerical predictions and the reference data.