HPC FOR OPTIMIZING HIGH-TEMP HEAT EXCHANGERS

Cranking up the AC is pretty much nonnegotiable on a hot day when your car's a rolling oven. But air conditioning chugs fuel, consuming up to 30% in internal-combustion engines and 40% of battery range in electrics.

This guzzling derives from the difference between the ambient and condensing temperatures of the refrigerant and the historical constraints of AC designs. Conventional AC extracts heat and moisture from the inlet air and chills the cabin through the vents. With the help of an additional heat exchanger, pre-cooling the inlet flow can reduce the temperature difference at the cost of increased pumping power. The solution would require improved designs that minimize total energy consumption by balancing the processes in play.

Engineers at Materials Sciences, LLC, (MSC) saw a way forward if high-performance computing (HPC) and additive manufacturing (AM) were brought to bear.

Through the DOE HPC4Mfg program, MSC engaged Lawrence Livermore National Laboratory for collaboration on a new design methodology that would allow full geometric freedom, account for holistic system behavior, and boost efficiency. The team applied topology optimization (TO) to devise super-efficient, compact heat exchangers with complex geometries. The optimization is so demanding that the computational power of big parallel machines combined with machine learning (ML) is required to crunch the problem. This combination of resources and knowledge is available only at LLNL.

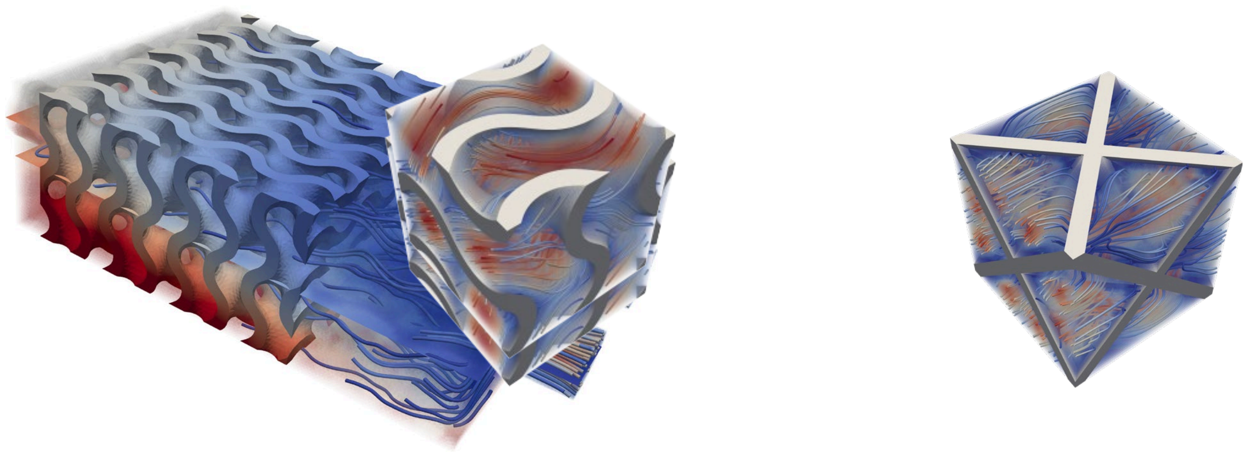
The strategy was to use ML homogenization to reduce computational complexity and derive macroscopic properties by analyzing the unit cells of periodic microstructures.

To compute both unit cells and optimized topologies, LLNL leveraged MFEM, a free, lightweight, scalable C++ library for finite-element methods. Engineers developed a set of scalable solvers for simulating fluid flow and heat transfer through intricate geometries and combined the solvers with ML techniques to generate homogenized macroscale models.

The result: ML models with customized loss functions for calculating physical responses for a large class of complex microstructures and validating them against experimental data. This groundbreaking approach reproduces the directional behavior of the flow in the cells, allowing precise, physically correct, and computationally cheap simulations of the entire heat exchanger. The optimization process delivers performance designs responsive to actual, not mimicked, behavior; and the high fidelity of the simulations obviates follow-up tuning and manual intervention, shortening the design cycle.

In reducing the differential between ambient and condensing temperatures, these advances save up to 30% of energy consumption in the compressor. By employing TO heat exchangers, an estimated two-times-lower temperature difference can be achieved, increasing the battery range of electric cars by 13% and reducing gas consumption by 10%.

If adopted by car manufacturers and subcontractors nationally, this modification could yield a 9.2% savings in gasoline consumption annually by light-duty vehicles. The technology can be fitted for any industrial or energy-generating process that requires heat exchange, with eVTOL aircraft, battery cooling, and electronics cooling in space applications among the many promising candidates.



(left) 3D heat-sink design with a limited number of periodic cells. Detailed analysis of such a relatively simple topology requires hours of computational time on the biggest computers available at LLNL. The solution for larger, more realistic cell distributions is to analyze an extensive number of small unit cells (right) under different flow regimes and wall thickness parameters and derive a homogenized model for simulating the response of the exchanger.