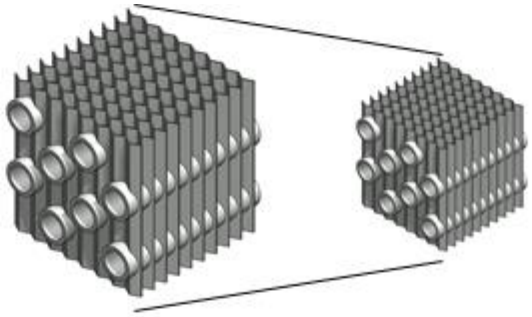
Sub-Zero Condenser Optimization

Conducted by Optimized Thermal Systems, Inc.

Sponsored by the International Copper Association

Optimized Thermal Systems, Inc. (OTS) recently conducted a design and optimization study for Sub-Zero Group, Inc. to identify small-diameter copper tube-fin heat exchangers suitable to replace the condenser of a residential refrigerator system. OTS used CoilDesigner®, a heat exchanger design and simulation software tool, to evaluate the performance of various designs and perform an optimization study using a multi-objective genetic algorithm. The primary objective of the project was to design a condenser coil that can provide equal performance with a lower refrigerant charge. Secondary objectives were to reduce the total footprint of the coil and reduce total tube and fin material mass.

The baseline condenser coil uses copper tubing, flat plate fins and a low fin density. The condenser has two refrigerant circuits, with each circuit serving an independent vapor compression cycle for the refrigerator and freezer compartments. A CoilDesigner® model of the condenser was developed and validated against experimental data. Prior to evaluating potential small diameter replacements, a study was conducted to evaluate the effect of refrigerant circuitry on the existing coil performance. Three operation modes were evaluated: both circuits running, refrigerator circuit running, and freezer circuit running. It was found that by extending both refrigerant circuits to cover the entire face area of the coil instead of half of the face area, the thermal performance of the circuit improved during single circuit operation; heat load and refrigerant sub cooling increased for both refrigerator and freezer circuits. From this review, the best circuitry design was selected and used as the baseline reference for the optimization study.

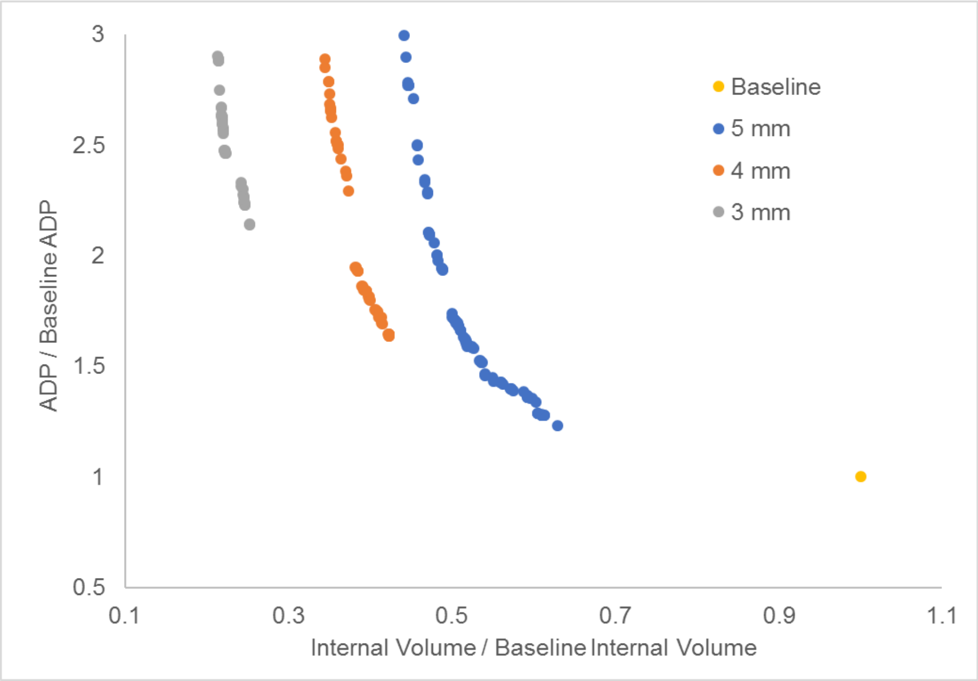


A multi-objective optimization study was conducted to find small-diameter tube condensers that provide a reduction in internal volume to enable lower refrigerant charge. Five-millimeter, four-millimeter, and three-millimeter designs were evaluated in the study. All designs used wavy-herringbone fins with a reduced fin thickness as compared to the baseline. The fin thickness was reduced to fit within the test range of the air-side heat transfer and pressure drop correlation used to evaluate coil performance. The objectives of each optimization study were to minimize internal volume and minimize airside pressure drop. The design variables used in each study included horizontal spacing, vertical spacing, number of tubes per bank, fin density, wavy fin pattern depth, and tube length. The acceptable ranges of the variables used were based on the ranges supported by the airside heat transfer and pressure drop correlations used. The resulting designs were required to have equal or greater heat rejection and refrigerant subcooling as the baseline coil. Also, all designs were required to keep saturation temperature drop within one degree of the baseline.

The optimization solver used in this study relies on genetic algorithms to find the best designs. Genetic algorithms are a method for solving optimization problems based on natural selection. From a population of candidate solutions, individuals are selected at random to produce “children” for the next generation. Over successive generations, the population "evolves" toward an optimal solution.

Tube Diameter	Internal Volume Reduction	Footprint Reduction	Tube Material Reduction	Fin Material Reduction
5 mm	41%	57%	61%	68%
4 mm	62%	68%	74%	58%
3 mm	78%	81%	79%	65%

The figure below shows the optimized results of this study for each tube diameter evaluated (five, four and three millimeters). Significant reductions in internal tube volume were found over the baseline. The best five-millimeter design provided a reduction in internal tube volume of 41% over the baseline, along with a 57% reduction in coil footprint. The best four-millimeter design provided an internal tube volume reduction of 62% and a coil footprint reduction of 68%. The best three-millimeter design provided an internal tube volume reduction of 78% and a coil footprint reduction of 81%.



All optimized designs resulted in higher air-side pressure drop. This increase is due to multiple factors, including the fin type, fin density and face area of the coils. The baseline system used flat fins, but all optimized designs used wavy fins which inherently create more pressure drop. The face area of all coils was reduced to maintain the tube spacing ratio, which when using a fixed airflow volume results in increased air velocity. However, reduced internal volume was considered more important for this application than the pressure drop. The fan motors used in this system can overcome the increased resistance and handle additional air-side pressure drop.

In addition to the optimization study, a preliminary design review was done on replacing the tube-fin condenser with a bare tube (no fins) heat exchanger. An 0.8-millimeter bare tube design was developed that reduced internal volume by 45% while maintaining cooling capacity and air-side pressure drop of the baseline.

In summary, OTS identified several new condenser designs with significant potential to reduce internal volume while maintaining performance, thereby reducing total system charge. The increased airside pressure drop of the designs can be accommodated by the existing fan motors. The reduced footprint of the coils allows for a smaller enclosure, and the reduced fin and tube material mass results in per-unit cost savings.