

# Optimization of copper-tube coils for energy-efficiency and charge reduction in heat pumps, air conditioners and refrigerators

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## ABSTRACT

Smaller-diameter copper tubes offer favorable thermal performance and material savings but may restrict air and refrigerant flow without proper design. Heat exchangers can be optimized using simulation tools and a multi-objective genetic algorithm (MOGA). The examples in this paper show how to realize performance objectives while meeting design constraints of actual applications. Replacing microchannel aluminum tubes with 5 mm copper tubes in a heat pump application reduced the material mass as much as 28 percent while maintaining equivalent capacity and airside pressure drop. Switching from 6.25 mm to 5 mm tubes in an R600a residential refrigerator reduced the internal tube volume by 41 percent while maintaining acceptable airside pressure drop. In a PTAC application, the target COP was reached while reducing the material cost by 50 percent. These and other applications demonstrate that charge reduction and efficiency gains can be achieved through the use smaller-diameter copper tubes.

Keywords: Copper, Heat Transfer Coefficient, Pressure Drop, Airside Pressure Drop, Heat Exchanger, Microfins, MicroGroove, CoilDesigner, Genetic Algorithm, MOGA.

## 1. INTRODUCTION

Smaller-diameter copper tubes offer many advantages for heat pumps, refrigeration equipment and air-conditioners, regardless of the type of refrigerant; hence, a steady progression from larger diameter tubes such as 9.52 mm to smaller diameter tubes such as 7 mm, 6.25 mm or 5 mm has taken place over the past twenty years as manufacturers have sought to realize design objectives. Heat exchanger design is often facilitated by computer modelling, where thermal-hydraulic performance of airside and refrigerant-side surfaces is predicted by empirical correlations from experimental data. In recent years, new empirical tube-side correlations and computational fluid dynamics (CFD)-based airside correlations have been developed for smaller-diameter tube-fin heat exchangers. Implementation of these newer correlations in coil modelling software, such as CoilDesigner®, has allowed designers to weigh the benefits of smaller-diameter tubes.

Tube-side behaviour of refrigerants in smaller diameter copper tubes has been measured in laboratories around the world. For examples, Longo et al. (2018a) and Jige et al. (2018) researched flow boiling of low-GWP refrigerants and Longo et al. (2018b) investigated condensation in smaller diameter copper tubes. Also, the effects of various microfin geometries on smaller diameter copper tube performance were investigated by Inoue et al. (2018). Research underpinning the airside correlations is discussed by Nasuta et al. (2018) and Bacellar et al. (2015). Using laboratory measured correlations for smaller diameter copper tubes, including tubes with inner-grooves or microfins, ensures that computer modelling can predict system performance within a few percent. The availability of comprehensive correlations for airside heat transfer and airside pressure drop of small-diameter tube-fin heat exchangers allows optimization with a multi-scale methodology

(Bacellar et al., 2016). Design of experiments is used to sample a wide design space of tube-fin geometries relevant to small-diameter tube-fin heat exchangers. CFD tools then are used to simulate and characterize thermal-hydraulic performance on a small scale and new airside correlations are developed from these simulations. These correlations are then implemented into heat exchanger simulation software (such as CoilDesigner) so the entire heat exchanger can be optimized in accordance with relevant operating conditions and constraints.

Typically there are multiple constraints and objectives in the design of heat exchangers and the design space to be explored through simulations is very large. A Multi-Objective Genetic Algorithm (MOGA) was used in sampling the design space for several of the case studies presented here. Genetic algorithms were originally developed by Holland (1975) and have been reviewed in textbooks by Goldberg (1989) and Engelbrecht (2007). Evolutionary algorithms and specifically genetic algorithms (GA) are widely used in many fields. These algorithms are based on ideas about natural selection and natural genetics as originally developed in the 1960s and 1970s by John H. Holland at the University of Michigan. Interest in this multidisciplinary subject has only increased in recent years as computer simulations have improved in accuracy.

MOGA is an especially powerful approach toward optimization of designs in which there are multiple constraints and objectives. A description of the use of MOGA in the optimization of heat exchangers was presented by Li et al. (2018). MOGA allows for a large space of design solutions to be searched in a computationally efficient manner. The system performance can be simulated for each candidate solution and if the performance improves then it can be the basis for further mutations, i.e., alterations of variables.

MOGA has ushered in a new era of design in many fields and especially in heat exchanger design as evidenced by the case studies presented in this paper. Optimized heat exchanger designs that would otherwise be missed can be identified through the combination of accurate simulations and MOGA. Five manufacturer-driven case studies in design optimization are presented here to illustrate the value of optimization as applied to a new generation of tube-fin heat exchangers made from MicroGroove™ smaller diameter copper tubes.

## 2. CASE STUDIES

Five different optimization studies were performed by Optimized Thermal Systems in collaboration with the International Copper Association and five different manufacturers. In each case, copper tubes with diameters of five millimetres or less were specified and MOGA was used to optimize the configurations of heat-exchanger-geometry parameters. The case studies included (1) heat-pump condensers to replace microchannel tubes with smaller diameter copper tubes; (2) a window air-conditioner condenser to improve system efficiency while reducing cost and refrigerant charge; (3) a refrigerator-freezer condenser to reduce hydrocarbon refrigerant charge; (4) the condenser of a packaged terminal AC system to minimize raw material costs and airside pressure drop while maintaining performance; and (5) an evaporator coil for a heat pump water heater to maximize capacity and minimize fan pumping power.

### 2.1. Heat-Pump Condenser

This optimization was for drop-in replacements of the existing microchannel heat exchanger (MCHX) condensers in a commercial heat-pump system. The manufacturer's objective was to develop a tube-fin heat exchanger with equivalent performance of its existing MCHX design. Geometric constraints included the coil height, width and depth; fin density, refrigerant pressure drop and refrigerant charge.

An initial study used currently available wavy and louvered fin patterns for 5 mm tubes. The replacement condensers showed a 15 to 38% increase in airside pressure drop for wavy fin patterns; and 29 to 42% increase for louvered fin patterns, while maintaining less than a four percent decrease in heating capacity compared to the baseline MCHX commercial condenser. The material mass was reduced by as much as 35%.

MOGA was then used to explore fin patterns not yet available in the market. The design space consisted of variable ranges consistent with current manufacturing capabilities. This optimization found 5 mm tube-fin designs competitive with the baseline microchannel condenser. The additional degrees of freedom allowed the optimizer to identify designs with airside pressure drops and capacities similar to the baseline. The best design demonstrated a reduction of 28 percent in material mass while maintaining the same airside pressure drop and capacity as the baseline.

Other designs were found with capacity increases of up to three percent and airside pressure drop decreases as great as 19 percent while maintaining other performance metrics within the constraints specified by the manufacturer. A smaller residential-sized condenser was also optimized as a drop-in replacement following a similar approach. Airside pressure drop decreases as great as 20 percent were realized while maintaining the drop-in replacement constraints.

## 2.2. Window AC Condenser

For another manufacturer, an exploratory study of small-diameter (5 mm) copper tubes was conducted on an existing 5.3 kW (1.5 ton) window air conditioning system. The objective was to improve system efficiency while reducing cost and refrigerant charge.

Tube-fin heat exchangers with 5 mm copper tubes and aluminium slit fins were initially modelled using available off-the-shelf configurations. The manufacturer provided baseline performance data for an existing unit, including fan curves. The initial study showed that 5 mm condenser designs using commercially-available slit fins could improve system coefficient of performance (COP) while maintaining capacity.

**Table 1. Optimization Results for Drop in Replacement of Window Air Conditioner**

| Design                      | Tube Material<br>(kg) | Fin Material<br>(kg) | Percent Material Reduction<br>Simulated | Percent Charge Reduction<br>Simulated | COP<br>Simulated<br>(Measured) | Percent COP Improvement<br>Simulated<br>(Measured) |
|-----------------------------|-----------------------|----------------------|-----------------------------------------|---------------------------------------|--------------------------------|----------------------------------------------------|
| Baseline                    | 1.8                   | 2.5                  | —                                       | —                                     | 2.60<br>(2.86)                 | —                                                  |
| Slit fin, 17 fpi            | 1.4                   | 2.0                  | 21                                      | 24                                    | 2.76<br>(2.97)                 | 6.1<br>(3.8)                                       |
| Louver Fin<br>15 fpi, 3 row | 1.0                   | 1.3                  | 47                                      | 46                                    | 2.64                           | 1.5                                                |
| Louver Fin<br>13 fpi, 4 row | 1.3                   | 1.4                  | 37                                      | 10                                    | 2.77                           | 6.5                                                |

MOGA was then used to assess the performance of fin designs not yet available. Designs with as much as a 15% improvement in COP and more than a 60% reduction in material consumption were identified. The manufacturer constructed a prototype 5.86 kW (20,000 BTU·h<sup>-1</sup>) system for testing, using one of the commercially available 5 mm slit fin heat exchangers.

Simulations predicted the new system would achieve a 6.1% higher COP and use 24% less refrigerant charge inside the condenser, while reducing total material mass by 21 percent. The manufacturer's experiments found that COP was increased by 3.8% while reducing the entire system's charge level by 10%. The manufacturer expressed that the new coil was about 40 percent less expensive than the original design.

## 2.3. Refrigerator-Freezer Condenser

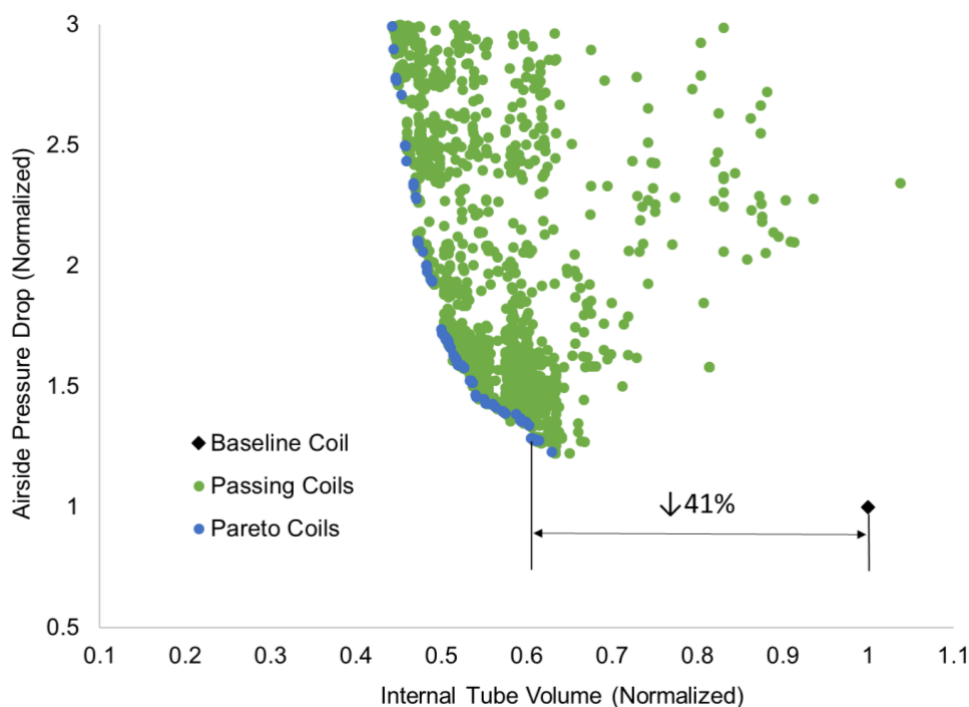
For a third manufacturer, the condenser for a refrigerator and freezer was optimized for reduced refrigerant charge using smaller-diameter copper tubes. This condenser had three operation modes, including refrigerator circuit running, freezer circuit running and both circuits running,

The objective was to find small-diameter tube condensers that provide a reduction in internal volume to enable lower refrigerant charge while minimizing airside pressure drop. All designs used wavy-

herringbone fins with a reduced fin thickness compared to the baseline 6.25 mm copper tube design. Variables included tubes per bank, tube length, horizontal spacing, vertical spacing, fin density, and wavy fin pattern depth.

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. From this review, the best circuitry design was selected and used as the baseline reference for the optimization study. Significant reductions in internal tube volume were found over the baseline. The best 5 mm design provided a reduction in internal tube volume of 41 percent over the baseline, along with a 57 percent reduction in coil-volume (footprint) as shown in Fig. 1.



**Figure 1: The best 5 mm design reduced internal tube volume by 41 percent**

All optimized designs had a higher airside drop in pressure (ADP), i.e., the ratio of the ADP to the baseline ADP was greater than one. This increase is due to multiple factors, including the aggressive fin type, fin density and face area of the coils. The baseline system used flat fins while the optimized designs used wavy fins, which inherently create more pressure drop. The face areas of all coils were reduced to maintain the tube spacing ratio, which when using a fixed airflow volume results in increased air velocity. However, the increases in airside pressure drop for the designs identified are not a problem for this application. The fan motors used in this system can overcome the increased resistance without significant increase in power consumption.

In summary, several new condenser designs were identified 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 cassette and allows for regulations that would limit the charge of flammable refrigerant in the system.

## 2.4. PTAC Condenser

A fourth manufacturer sought to optimize a drop-in replacement for the condenser of an existing packaged terminal air conditioner (PTAC) product. The objectives were to minimize raw material costs and airside pressure drop while providing the same heat rejection. Geometric constraints included the coil height, width, and depth.

Fig. 2 highlights the optimization results. Using a commercially available slit-fin pattern (light blue triangles), one design reduced raw material costs by 47% and lowered the airside pressure drop by more than 15%, while reducing internal volume by 58% and maintaining acceptable refrigerant pressure drop. Further optimization studies, using fin geometries not yet available but consistent with current manufacturing capabilities, yielded as much as 50% savings in raw material costs while keeping pressure drops close to the baseline (green squares). The greatest reduction in internal volume of 62% used two tube banks in the airflow direction (dark blue dots). However, one existing slit-fin design showed a similar reduction in cost and air pressure drop as indicated by the single light blue triangle near the cluster of dark blue dots.

In summary, new condenser designs with significant potential to reduce costs while maintaining performance were identified. Reductions in airside pressure drop are favourable for noise reduction and material savings and make it possible to develop energy-efficient systems at a low cost. Furthermore, the study indicated that a currently-manufactured fin sheet provides excellent performance comparable to other optimized designs. This finding means that the manufacturer can achieve a high level of savings using an available fin die.

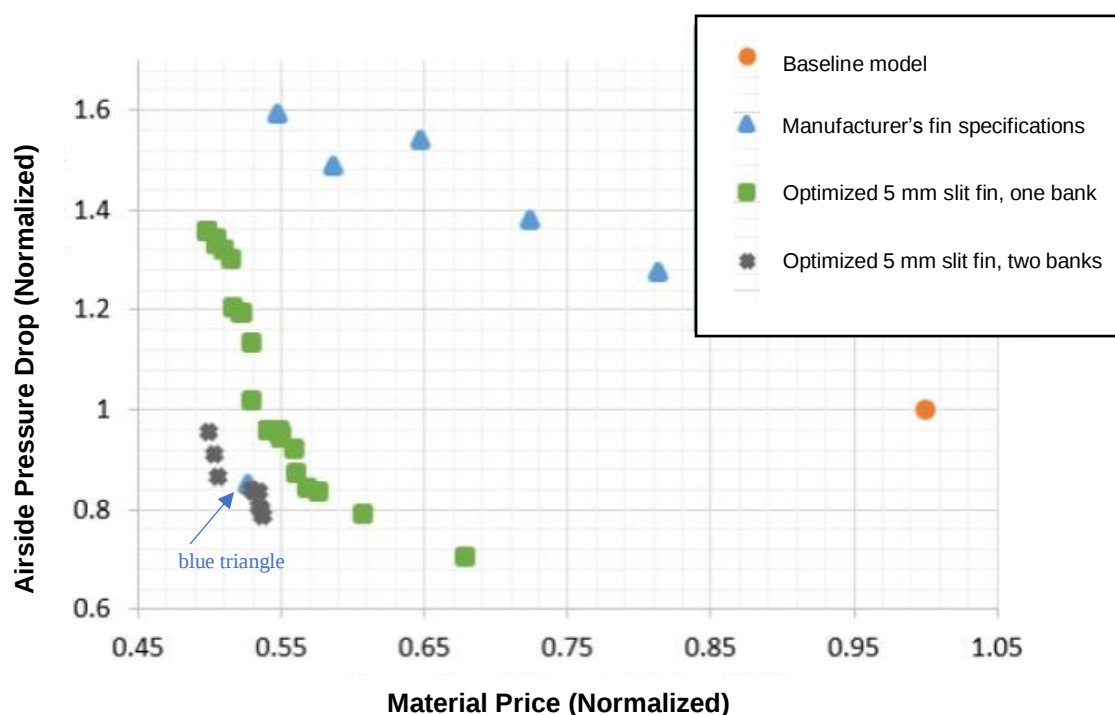


Figure 2: Low-cost PTAC condenser designs

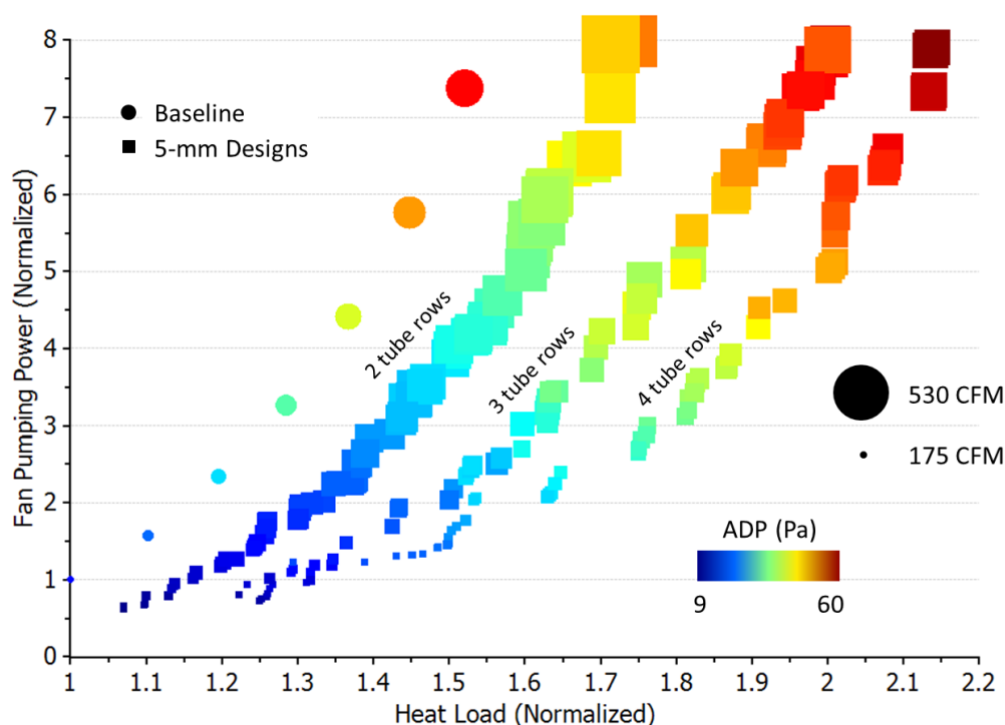
## 2.5. Residential HPWH Evaporator

A fifth manufacturer sought to optimize the evaporator of a residential heat pump water heater (HPWH). Objectives were to maximize capacity and minimize fan pumping power, and the constraints were the existing size and operating conditions. In other words, capacity must exceed the baseline, outlet refrigerant pressure must match or exceed the baseline and superheat must equal or exceed the baseline. These objectives were achieved using CoilDesigner and MOGA.

An initial analysis was conducted with the goal of replacing the baseline evaporator with a higher-capacity coil using smaller diameter copper tubes within the size constraints. The baseline evaporator coil uses 7.94 mm (5/16 inch) copper tubing laced through louvered aluminium fins and R134a refrigerant flowing through two refrigerant circuits.

The baseline model predictions matched the experimental testing data. Cooling capacity was predicted within one percent without requiring correction factors. Correction factors were applied to match outlet superheat within one degree Celsius and refrigerant pressure drop within one percent. Air pressure drop was validated against a manufacturer prediction software to be within two percent. MOGA was used to select and simulate heat exchanger candidates until optimal configurations were identified. Optimization studies included designs throughout a wide range of geometry configurations

and then focused on commercially available heat exchanger geometries. The algorithm allowed the air flow rate, refrigerant flow rate, and fin and tube density to be varied, generating and simulating thousands of new heat exchanger designs. For each configuration, the non-dominated set of Pareto-optimal points are shown in Fig. 3. Using greater air and refrigerant flow rates, new 5 mm designs can more than double capacity compared to the baseline. As such, this study seeks to maximize capacity while minimizing fan pumping power.



**Figure 3: Performance of 5 mm designs normalized against the baseline 7.9 mm heat exchanger. Circles and squares of increasing area represent performance at higher flow rates.**

Three designs were selected for further review. Design 1 maintains equivalent fan pumping power to the baseline model but increases capacity by 32%. Design 2 increases capacity by 50% when compared to the original baseline but requires a 104% increase in fan pumping power. Design 3 is capable of increasing capacity by 100 percent but requires a 401% increase in fan pumping power. Design 1 and 2 mainly differ in air flow rate. The manufacturer plans to build and test a prototype 5 mm coil similar to the Design 1 coil and further evaluate the trade-offs between flow rates and inlet conditions.

The baseline design does not compete with the new 5 mm designs on performance even at higher flow rates. When provided with an 86% higher air flow rate, the capacity of the baseline design increases by more than 35%; this requires 4.5 times more fan pumping power. A 5 mm design operating at the same fan power can reject nearly 90% more capacity than the original baseline. Throughout the design space, the best 5 mm designs deliver 30 to 40 percent more capacity at the same fan power as the 7.9 mm baseline.

In summary, new evaporator designs support a HPWH system with significantly greater capacity than the baseline system. The new systems can deliver greater quantities of hot water and/or recover the tank temperature more quickly after water draws, improving user comfort and satisfaction. In general, because they provide more heat transfer surface area within the allowable space, 5 mm heat exchangers deliver 30 to 40% more capacity than the baseline for the same fan power input. New evaporator designs can increase capacity by as much as 100% by increasing the fan power. In all scenarios presented here, for a given fan power, the 5 mm designs can always deliver more capacity than the 7.9 mm baseline heat exchanger.

### 3. CONCLUSIONS

Diverse case studies from five manufacturers clearly demonstrate the advantages of smaller copper tubes and the value of MOGA for design optimization. MicroGroove heat exchangers clearly outperform heat exchangers made from larger diameter copper tubes with performance comparable to microchannel heat exchangers. Results for specific applications are summarized as follows:

- (1) Heat-pump condenser. The MOGA-optimized designs were similar to the baseline microchannel coil with regard to airside pressure drop and capacity.
- (2) Window AC condenser. MOGA designs increased the efficiency of the heat exchanger while reducing materials usage and refrigerant charge. MOGA designs improved the COP by as much as 15% and reduced material usage by more than 60%.
- (3) Refrigerator-freezer condenser. Hydrocarbon refrigerant charge was dramatically reduced in the 5 mm designs. MOGA designs reduced the internal tube volume up to 41 percent along with a 57% reduction in overall coil volume compared to the baseline 6.25 mm copper tube designs.
- (4) PTAC condenser. Raw material costs and airside pressure drop were reduced while maintaining performance. MOGA designs provided as much as 50% savings in raw material costs while keeping the pressure drop close to the baseline. The best design reduced the overall internal volume by 62%.
- (5) HPWH evaporator. MOGA was used to show that capacity could be doubled by increasing fan power; and that 5 mm designs delivered more capacity than the 7.9 mm baseline heat exchanger for a given fan power.

MOGA facilitates the optimization of heat exchanger performance using algorithms that mimic evolution in nature by carrying forward the traits of successful designs into future populations. MOGA has proven effective in the optimization of MicroGroove heat exchangers for commercial and residential air-conditioners as well as refrigerators, heat pumps and hot-water heat pumps.

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### NOMENCLATURE

|     |                            |      |                                   |
|-----|----------------------------|------|-----------------------------------|
| ADP | airside drop in pressure   | fpi  | fins per inch                     |
| CFM | cubic feet per minute      | HPWH | heat pump water heater            |
| COP | coefficient of performance | MOGA | multi-objective genetic algorithm |

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