

Heat-Exchanger Simulations Fast-Track Adoption of MicroGroove Copper Tubes

Powerful algorithms help to explore design space of ecofriendly products and to discover products with superior performance.

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Computer simulations and design case studies illustrate how to design high-efficiency heat exchangers using smaller diameter copper tubes. The International Copper Association has supported research initiatives both in the USA and China for more than a decade. The main purpose of this research is to explore the design space for coils made from smaller-diameter copper tubes to work with new refrigerants, charge limitations and energy regulations.

This white paper outlines the design principles that serve as a foundation for

the development of modern software tools for simulating the performance of smaller diameter copper tubes in ACR applications. It also describes the latest versions of two widely available simulation tools, including HXSim from the International Copper Association and CoilDesigner® customizable software tool from The Center for Environmental Energy Engineering (CEEE) at the University of Maryland. Finally, several case studies demonstrate the use of multi-objective genetic algorithm (MOGA) in the optimization of heat exchangers in various product categories.

Pioneering Work in China

Early in the development of smaller diameter copper tubes for heat exchangers, designers were guided by general principles, or “rules of thumb,” and fin designs were not optimized for smaller diameter tubes. Progress was made in China by a research consortium that used a knowledge-based evolution method (KBEM) to eliminate unfeasible or impractical designs and simulations were performed, allowing for more efficient sampling of the design space [1-4].

From this research, various design principles emerged of great value

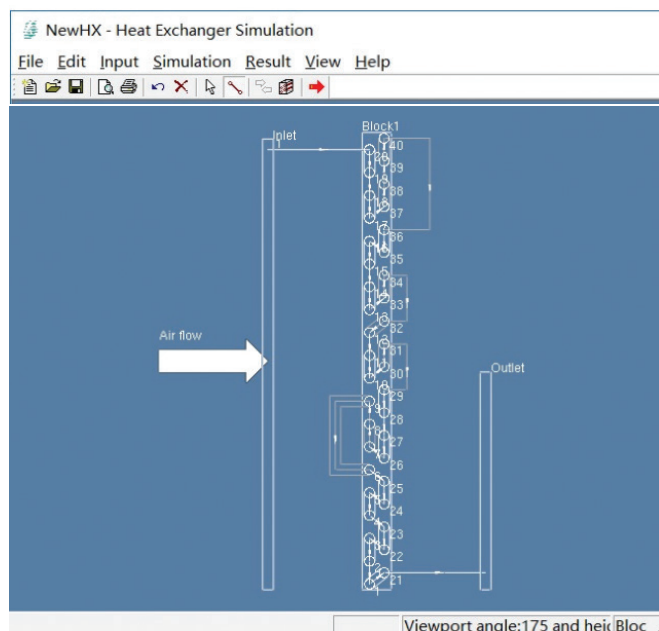


Figure 1: I-type heat-exchanger in 2D view.

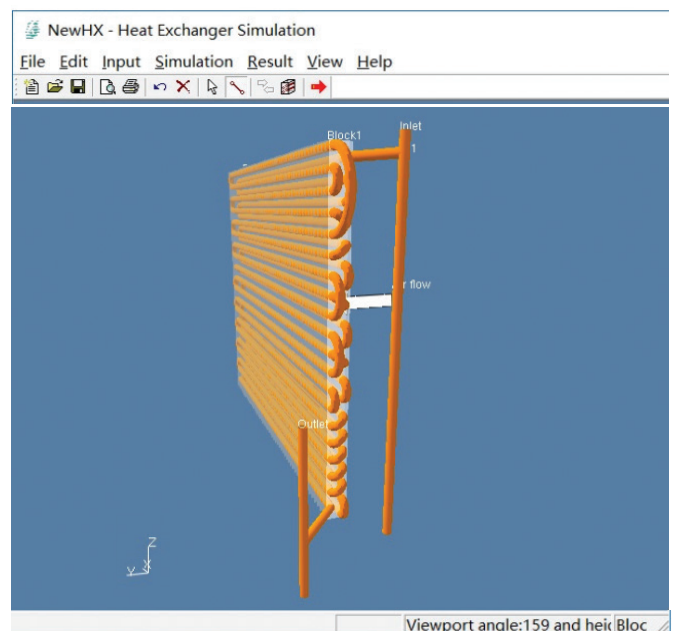


Figure 2: I-type heat-exchanger in 3D view.

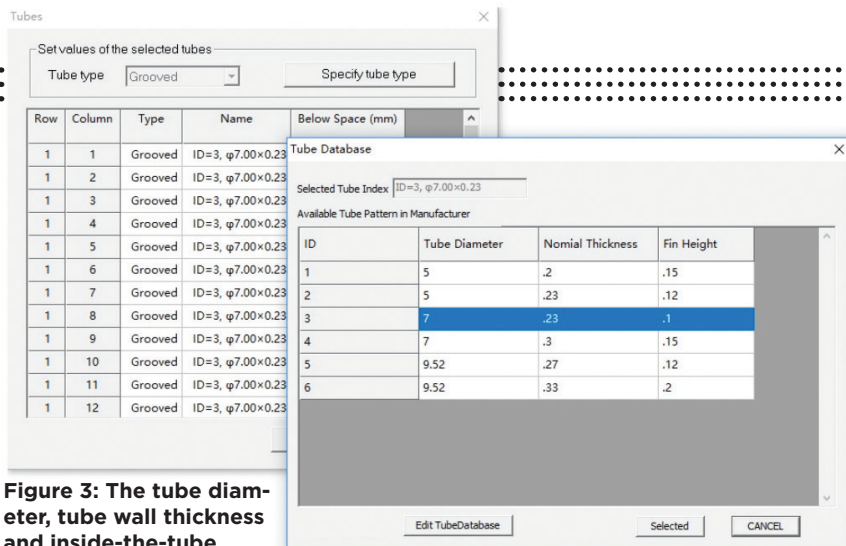


Figure 3: The tube diameter, tube wall thickness and inside-the-tube enhancements can be varied.

to anyone seeking to optimize material usage in air conditioning and refrigeration applications, whether for an evaporator or a condenser. The design and optimization of heat exchangers require the use of computational fluid dynamics (CFD) methods to analyze the airflow around the tubes and fins and also involves computer simulations of refrigerant flow and temperatures inside the tubes. The research consortium refined useful design principles as applied to smaller diameter copper tubes. These principles were developed into a step-by-step procedure that simulates and optimizes every aspect of the heat exchanger design, from tube spacing to fin type and tube circuitry.

This methodical approach to the design of heat exchangers using smaller diameter copper tubes is summarized by the following steps.

Step 1: Determine the best ratio of transverse tube pitch to longitudinal tube pitch by fin efficiency analysis.

Step 2: Optimize transverse tube pitch and longitudinal tube pitch by analysis of performance and material cost.

Step 3: Optimize fin pattern by comparing performances of fins with different patterns through CFD-based simulations.

Step 4: Test the performance of heat exchanger with smaller diameter tubes.

Step 5: Optimize the Tube Circuitry

These steps in the design of heat exchangers for air conditioning and refrigeration applications using smaller diameter copper tubes as described here are intended as a general guideline. Specific choices and recommendations are not given here, since such choices may depend upon other components in the system design.

Simply put, an air conditioning or refrigeration system consists of a compressor for work input; and condenser and evaporator coils for heat output and input, respectively. Maximizing the heat exchanger efficiency while minimizing the physical envelope and materials usage is the goal of most heat exchanger engineers.

Much attention has been focused in recent decades on refrigerants and valves for controlling and regulating refrigerant flow. Yet in the past twenty years, significant advances have also been made in the design of evaporator and condenser coils. These advances

have been motivated by the conflicting needs to increase energy efficiency while also reducing materials usage.

It has long been understood that smaller diameter tubes increase the local heat transfer coefficient (HTC or "alpha") that governs the heat transfer between the refrigerant and the inside of the tube wall. The challenge has been to fabricate smaller diameter tubes and assemble them into heat exchanger coils. The proving ground has been the highly competitive, high-volume manufacture of residential air conditioning (RAC) systems, including window-type air conditioners as well as split units. The same design principles apply as well to larger commercial units, heat pumps, and distributed heating units.

Initially, prototypes were made simply by replacing larger-diameter copper tubes with smaller diameter copper tubes. The footprint of the heat exchanger in the product was unchanged and the fins in the coil designs were not optimized to the smaller diameter tubes. This could be referred to as the "cut-and-try method." Nonetheless, the results were immediate and dramatic and this intensified interest in further development.

Consider that if tube diameter is halved then the cross sectional area is cut by 75 percent. Besides reducing the amount of tube material, refrigerant volume could also be reduced. Furthermore, it is well known from

Table 1: Meanings of Parameters in Dimension Input Window

Parameter	Unit	Remark
Block type	—	I, L or C
Rows	Number	The number of rows of tubes in the heat exchanger
Depth	mm	Depth of fin-and-tube heat exchanger
Height	mm	Height of heat exchanger
Length	mm	Length of heat exchanger
Ambient Temperature	°C	Ambient Temperature
Fin type	—	Input by clicking button "Fins"
Fin pitch	mm	For variable fin pitch, click button "Specify"
Fin name	—	The name of the fin of the block
Continuous fins	—	Continuous planes or separated as bands
Control volume number	—	The maximum number is 10

tube stress analysis that the burst pressure increases as the tube diameter decreases, hence wall thickness could be decreased, resulting in a further savings of material.

Once OEMs fully understood how smaller-diameter copper tubes provide major competitive advantages, they embarked upon systematic approaches to optimize coils for specific products using various refrigerants.

Step 1: Tube Pitch Ratio

An evaporator coil or condenser coil is, of course, a component in a system and the tubes and fins are subcomponents. The first step toward an optimal heat-exchanger design is to select the tube pitch ratio, which may be quite different for smaller-diameter tubes compared to conventional tubes because the airflow around the tubes is not obstructed as much for smaller tubes.

If there are two rows of tubes then the ratio (P_t/P_l) between transverse and longitudinal tube spacing must be approximated before any further steps can be taken. Initially, values commonly used in heat exchanger designs are selected for fins with high efficiency with operating conditions such as airflow and tube-wall temperature as defined by the applications. The tube pitch ratio is then optimized for the particular application using CFD calculations.

Step 2: Tube Spacing

How far apart should the tubes be spaced in a multi-row design? The outside air pressure drop must be equal to or less than the design criterion; if the tubes are spaced too closely, this air pressure drop may be too high. The objective is to maximize performance while minimizing the cost. An overly large fin size would cost more to manufacture because it uses more fin material. It would also result in a heat exchanger that is larger-than-necessary. For evaporator coils, the condensate film that forms on the fin influences the choice of fin size. Tube

spacing dictates the “fin size” that will be used in fin-design simulations. In most cases, the tube pitch ratio and tube spacing are interrelated.

Step 3: Fin Design

The next step is to optimize the fin pattern. The two most common types of fin patterns are the louver fin and the slit fin (or slotted fin). The CFD method is used to simulate both fin patterns. For the louver pattern, the independent variables are the louver angle and the louver number; the louver height and pitch are determined by these independent variables. For the slit pattern, the slit height is determined as one-half the fin pitch, so the only independent variable is the slit number.

It should again be stressed that the fin patterns that worked best for larger diameter tubes are not optimized to smaller diameter tubes and related fin sizes. Thus it is necessary to re-examine the design space for all types of fin patterns using CFD simulations. Only in this manner can the fin pattern be optimized for smaller diameter tubes. Ease of manufacture and assembly can also be a factor in the selection of the fin pattern.

The final fin pattern design that is selected may be specific to the final application. The objective in all pattern designs is to maximize the heat transfer capacity while meeting the requirement for a low air pressure drop. Of course, efficient heat transfer through the coils results in higher energy efficiency for the system because the refrigerant releases more of its heat in the condenser and absorbs more heat in the evaporator. Other criteria like tube-side pressure drop are examined and changes to circuitry are made if needed.

Step 4: Build and Test

At this stage, a reality check is necessary. An actual heat exchanger needs to be built and thoroughly tested in a laboratory wind tunnel. The heat transfer capacity can be

experimentally measured as the refrigerant and air flow rates are varied. The former controls the internal rate of heat transfer and the latter determines the external rate of heat transfer. Heat transfer through the tube wall is a small factor due to its high conductivity and small thickness. The various components of the heat transfer can be represented as a circuit diagram.

Today's CFD simulations are very good. Case studies specifically on designs using small diameter copper tubes have been presented at numerous international conferences [5-6] including most recently at the 2019 IIR International Congresses of Refrigeration in Montreal [7].

The results of a well-designed simulation can be expected to agree well with experiment. Nonetheless, there is no substitute for the real thing. The experimental measurements can be used to develop prediction correlation equations, which can be used in further refining the heat exchanger design simulation program.

Step 5: Tube Circuitry

Tube circuitry simulations answer the questions about how many separate tube paths (branches) should be included in the circuit and what should be the length of each branch. If the paths are too short then the refrigerant might not reach the target temperature; if too long then the inside pressure drop may be too great, which is an important consideration as tube diameter decreases.

Temperatures vary throughout the heat exchanger as the refrigerant passes through the various circuit branches. Branches can be placed in the first or second row. Tubes at similar temperatures can be placed farther apart or closer together. The problem of optimization can become a complicated puzzle indeed. Fortunately, there are sophisticated software programs to do hard calculations. The software is based on the differential equations governing

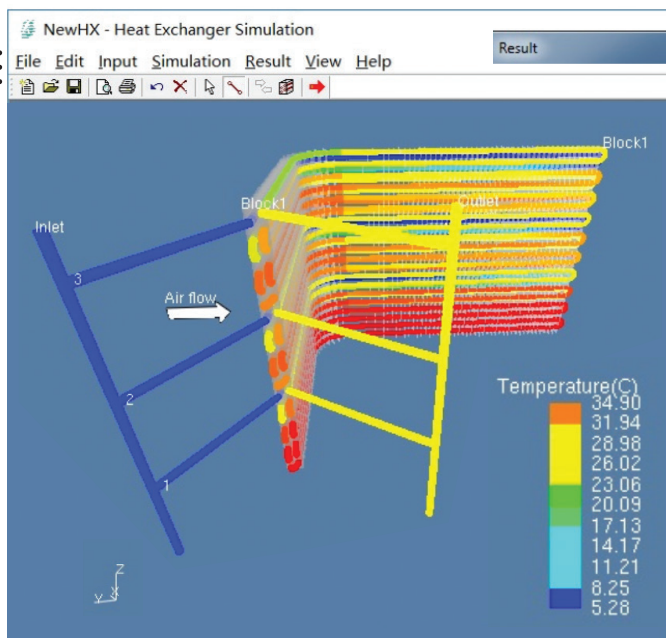


Figure 4: Simulation results in color gradation for an L-Type heat exchanger.

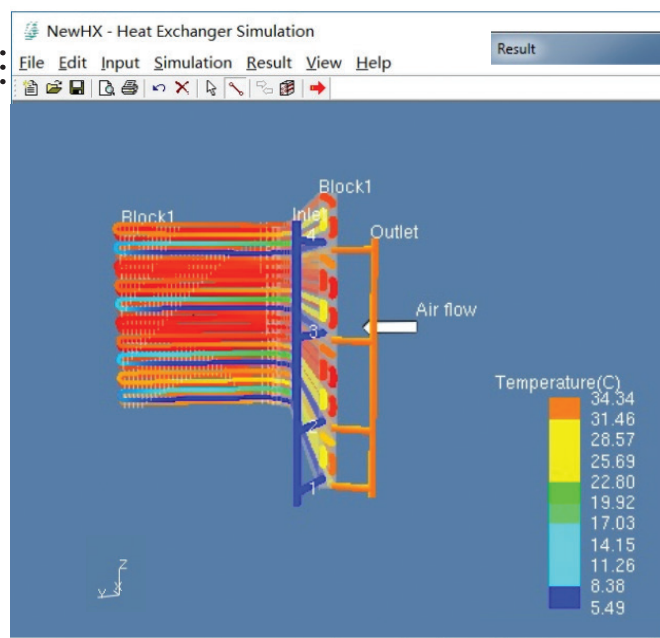


Figure 5: Simulation results in color gradation for an L-Type heat exchanger.

heat transfer and mass flow through the tube branches. The design space of possible tube configurations can be quite large so a knowledge-based search method is commonly used to reduce the search space.

Once the fin pattern and tube circuitry have been optimized then the heat exchanger is ready for use in the product design. The time to market for new products can be shortened by using the design principles outlined above.

Technologies for manufacturing smaller diameter copper tubes are now available as well as the equipment for making coils using such tubes. These technologies have been developed and proven in the highly competitive manufacture of residential air conditioners. The same manufacturing technologies can be applied to a wide range of air conditioning and refrigeration products. The only limitation is the imagination of the designer.

The HXSim Platform

The above fundamental design elements are now built into a user friendly package of simulation tools. Imagine a simulation program that allows one to build a coil from the most basic elements and then predict

the performance in intricate detail. Furthermore, imagine a practically limitless choice of design criteria. Then imagine that this software tool could be run on a desktop computer via a user-friendly graphical user interface (GUI) and that it comes with an easy-to-follow user's manual. And, finally, just imagine that it is available at a nominal charge. That in a nutshell is the HXSim "Small Diameter Copper Tube Air Conditioning Heat Exchanger Simulation Tool."

According to the manual, the main function of HXSim is to give accurate calculation results for predicting the capability of small-diameter copper-tube air conditioning heat exchangers in steady state conditions.

Once the user inputs the coil design parameters, the software calculates such quantities as heat exchange capacity, refrigerant-side pressure drop, and airside pressure drop; and it displays the results in easy-to-understand graphic or tabular formats.

The GUI makes it easy to enter data and observe simulation results. Both 3D and 2D options are available (Figs. 1 and 2).

HXSim can simulate fin-and-tube heat exchangers for a variety of refrigerants and types of heat exchangers. The user can vary the

tube size, fin design, and tube circuitry as well as many other parameters. The tool gives the heat exchanger engineer deep insights into the interrelationships between various coil design parameters.

This powerful software tool was developed at Shanghai Jiao Tong University (SJTU) for many years under the auspices of the International Copper Association. The project was overseen and coordinated by the renowned Professor Guoliang Ding of the Institute of Refrigeration & Cryogenics in Department of Power & Energy Engineering at SJTU.

HXSim represents the next big step in simplifying the design of advanced MicroGroove heat exchangers. Professor Ding has continued to spearhead the development of heat exchangers using smaller diameter copper tubes in a variety of air conditioning and refrigeration products as well as heat pumps.

Inputting the Design Parameters

The latest version of HXSim (version 3.0) is well documented with a user manual submitted by Professor Guoliang Ding. The manual is available for download from the technical literature webpage of the microgroove.net. [8]

When using the program to design a MicroGroove heat exchanger, the most basic input has to do with the type of refrigerant, the type of heat exchanger and the heat exchanger dimensions. The three main “Types” of heat exchanger blocks are the I-Type, L-Type and C-Type. (The most basic block shapes roughly correspond to the shapes of the letters I, L or C.)

The detailed meanings of the dimension input window are shown in Table 1. In these inputs, the “Row number” is of first importance. Only after inputting the row number can the column number of each row and the tubes in each column be defined.

Next the designer can input the row spacing and the column numbers for the tube locations. Then the fin-type can be selected and data can be entered on the joints. The “Connect Tubes” function is a vital step, which can also be accomplished through the easy-to-use 2D or 3D graphical user interface.

The program allows the user to select the inlet airflow, which does not need to be uniform across the heat exchanger. A number of variables are available with respect to the inlet airflow.

A database of tube types as well as fin types is available for use. The outer diameter of the MicroGroove tubes may be as small as 4 mm. The tube wall thickness and inner tube

enhancements can also be varied. See Figure 3.

In summary, users can input parameters such as dimensions of heat exchanger, tube and fin geometry, refrigerant circuitry and operating conditions through the interactive GUI. The details of the heat-exchanger shape, tubes, fins, refrigerant and air-flow are entered via data input dialog windows. Clicking the “Ok button” checks the values and closes the window. A warning dialog shows if the input data entered into some edit box is not apropos.

Outputting the Performance Results

Once all the inputs have been provided, the user is ready to run a simulation. Figure 4 and 5 shows how simulation results can be presented as a three-dimensional colored graph. Actually, a much finer analysis is available with steady-state values of temperature and pressure available at practically any point in the path of the refrigerant.

The simulation package will output calculated quantities such as heat exchange and outlet conditions of both refrigerant and air. The calculated results can be displayed in tables and charts as well as 3D colored visualization of the properties at every location in the coil. It is also possible to print 2D and 3D heat exchanger

graphs. Results can be saved and files can be serialized allowing for the application of various optimization algorithms.

The following menu items are available only after the simulation of heat exchanger is accomplished.

“Chart” provides an access to see both inlet and outlet state parameters of air/refrigerant in every control volume of every tube through a selected refrigerant path in charts.

“Table” provides an access to see both inlet and outlet state parameters of air/refrigerant in every control volume of every tube through a selected refrigerant path in a whole table.

“Graph” provides an access to open the results window which shows the simulation results.

Additionally, the menu item “Cost” provides an access to open the cost window which shows the heat exchanger cost. This menu item is available independently of the simulation results.

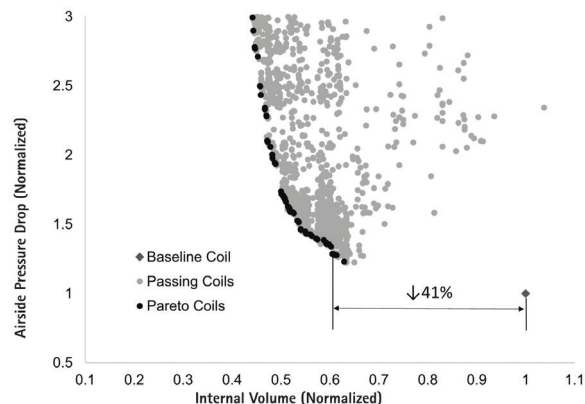
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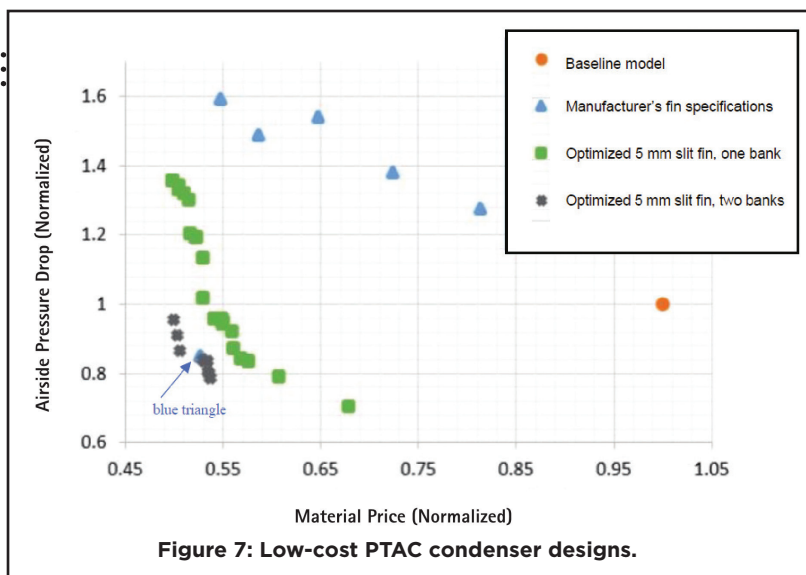
The International Copper Association wants you to become an expert in the design of heat exchangers made from smaller-diameter copper tubes. The HXSim software package makes it easier than ever to grasp the relationship between

Table 2: Optimization Results for Drop-in Replacement of Window Air Conditioner

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

Figure 6: The best 5 mm design reduced internal tube volume by 41 percent.





various design parameters. It helps to strike a perfect balance between cost limitations and performance objectives.

Running HXSim simulations on proposed designs allows one to accurately predict the performance of the coils before building and testing prototypes and investing in the tooling to manufacture coils in volume.

HXSim is not the only simulation tool available on the R&D marketplace today. Many coil manufacturers and heat transfer engineers have developed their own specialized software programs for simulating the performance of heat exchangers. ICA has supported the development of tube correlations through contracts with many universities and research laboratories.

Nonetheless, for an easy-to-use

and inexpensive, yet powerful and accurate, tool for the design and simulation MicroGroove coils, the HXSim platform can't be beat.

For more information on HXSim, contact the MicroGroove Team Leader or one of the MicroGroove team members.

CoilDesigner Simulation Tool

Another option for OEM product designers is the CoilDesigner® software, a proprietary heat exchanger simulation and design optimization tool developed by the Center for Environmental Energy Engineering (CEEE) at the University of Maryland. CoilDesigner is a highly customizable software tool that allows designers to simulate and optimize the performance of heat exchangers. Using CoilDesigner

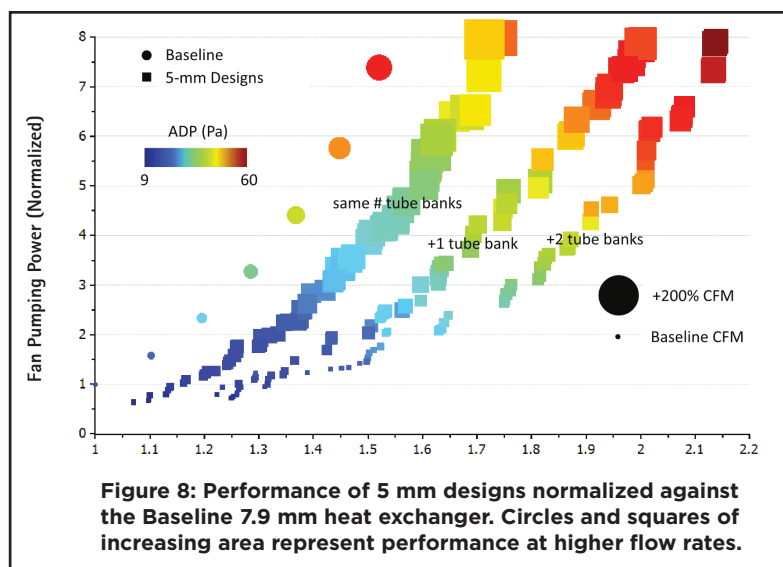
simulations, OEM users can shorten product development costs and quickly bring products to market.

Optimized Thermal Systems, Inc. (OTS) has an exclusive license agreement with the University of Maryland to provide customized versions and assist in the development of CoilDesigner software [9]. OTS works with various HVAC&R designers around the globe to optimize heat exchanger geometry, including investigation of the use of small diameter copper tubes. CoilDesigner includes the latest heat transfer and pressure drop models published in the open literature and users can also plug-in proprietary models.

Collaboration

OTS and the International Copper Association, Ltd. (ICA) developed educational materials to broaden the exposure of students, academics and professionals to the concept of tube-fin heat exchangers using small diameter Microgroove™ tubes. The OTS-ICA educational program engaged people from various institutions and backgrounds in a collaborative effort to advance the art of tube-fin heat exchangers. Comprehensive training materials were developed to present the benefits of tube size reduction in the context of tube-fin heat exchangers. Participants were also given a demonstration and trial version of CoilDesigner® software, allowing them to explore the performance of tube-fin heat exchangers with small diameter tubes using novel correlations.

As a result of the OTS-ICA collaboration, webinars were developed that focus on air-to-refrigerant heat exchanger design, parameterization and optimization. Three webinars remain available for viewing free of charge and are an excellent education resource for anyone seeking a high level of proficiency in the design of heat exchanger coils:



1. Effective Design of Small Diameter Copper Tube-Fin Heat Exchangers

2. Construction of Small Diameter Copper Tube-Fin Heat Exchangers

3. Advantages of Small Diameter Copper Tube-Fin Heat Exchangers

Information about the OTS-ICA educational outreach program and webinar series is available on the microgroove.net website [10].

Correlations

ICA worked with Optimized Thermal Systems Inc. (OTS) to implement the newly developed correlation equations into its software design tool.

Airside heat transfer around smaller diameter tubes can be modeled with unprecedented accuracy, opening the door to new, more energy efficient heat exchanger designs [11-12]. Airflow around smaller diameter tubes faces less resistance than airflow around traditional tubes. Research supported by ICA and conducted by OTS compares the performance of slit fins and louver fins for smaller diameter (3 mm to 5 mm) copper tubes [13]. As a result, CoilDesigner can simulate the performance of coils designs made with MicroGroove tubes. Research on airside and refrigerant-side correlations, particularly for 5-mm MicroGroove tubes, has been made readily available to HVAC&R system designers and heat exchanger engineers.

MOGA: The Next Big Thing

MOGA is a specific type of algorithm within a branch of the scientific field of “complexity.” More specifically, MOGA is a Multiple-Objective Genetic Algorithm. The application of MOGA methodology has a long history in many branches of science and technology. Only recently has MOGA moved to the forefront in the design community as a consequence of the abundance of computing power at low cost. When applied to heat exchanger design,

MOGA frees the designers to do creative research encompassing a design space envelope rather than focusing on the task of searching for a single optimal design.

MOGA systematically varies the parameters of a coil design and simulates the performance for each selected set of parameters. Genetic Algorithm (GA) is a type of evolutionary algorithm. A population of possible solutions is evaluated in each iteration. In a Multi-Objective (MO) algorithm, the decision or selection is made from the resulting Pareto space after the search is complete. Heat exchanger designs that more closely meet the design objectives are selected from the resulting options. 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 MicroGroove case studies developed by OTS in collaboration with ICA and various OEMs. A 2019 paper titled “Optimization of copper-tube coils for energy efficiency and charge reduction in heat pumps, air conditioners and refrigerators” reviewed five simulation studies using the Multi-Objective Genetic Algorithm [7].

Genetic algorithms were originally developed by Holland (1975) [14] and have been reviewed in textbooks by Goldberg (1989) [15] and Engelbrecht (2007) [16]. 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.

“Complexity: Very Short Introduction” by John H. Holland describes the broad branch of science of which MOGA is just one part [17].

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) [18]. 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 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.

MOGA Case Studies

Case studies presented at ICR 2019 [7] 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.

These diverse case studies demonstrate the advantages of smaller diameter copper tubes and the value of MOGA for design optimization. In most applications, MicroGroove heat exchangers can clearly outperform heat exchangers made from larger diameter copper tubes and performance can be 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 about 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 percent and reduced material usage by more than 60 percent (Table 2).

(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 percent reduction in overall coil volume compared to the baseline 6.25 mm copper tube designs (Figure 6).

(4) PTAC condenser. Raw material costs and airside pressure drop were reduced while maintaining performance. MOGA designs provided as much as 50 percent savings in raw material costs while keeping the pressure drop close to the baseline. The best design reduced the overall internal volume by 62 percent (Figure 7).

(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 7.94 mm baseline heat exchanger for given fan power (Figure 8).

The use of MOGA facilitated 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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9. CoilDesigner is a highly customizable software tool that allows designers to simulate and optimize the performance of heat exchangers. Optimized Thermal Systems, Inc. (OTS) has an exclusive license agreement with the University of Maryland to provide customized versions and assist in the development of CoilDesigner software. OTS actively works with various

HVAC&R designers around the globe to optimize heat exchanger geometry, including investigation of the use of small diameter tubes. Visit www.optimizedthermalsystems.com for additional information.

10. Three educational webinars presented by Optimized Thermal Systems, Inc. (OTS) and the International Copper Association, Ltd. (ICA) are available on the MicroGrooveTech YouTube Channel. Slideshows can be downloaded from the microgroove website. <https://microgroove.net/ots-ica-educational-outreach>.

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