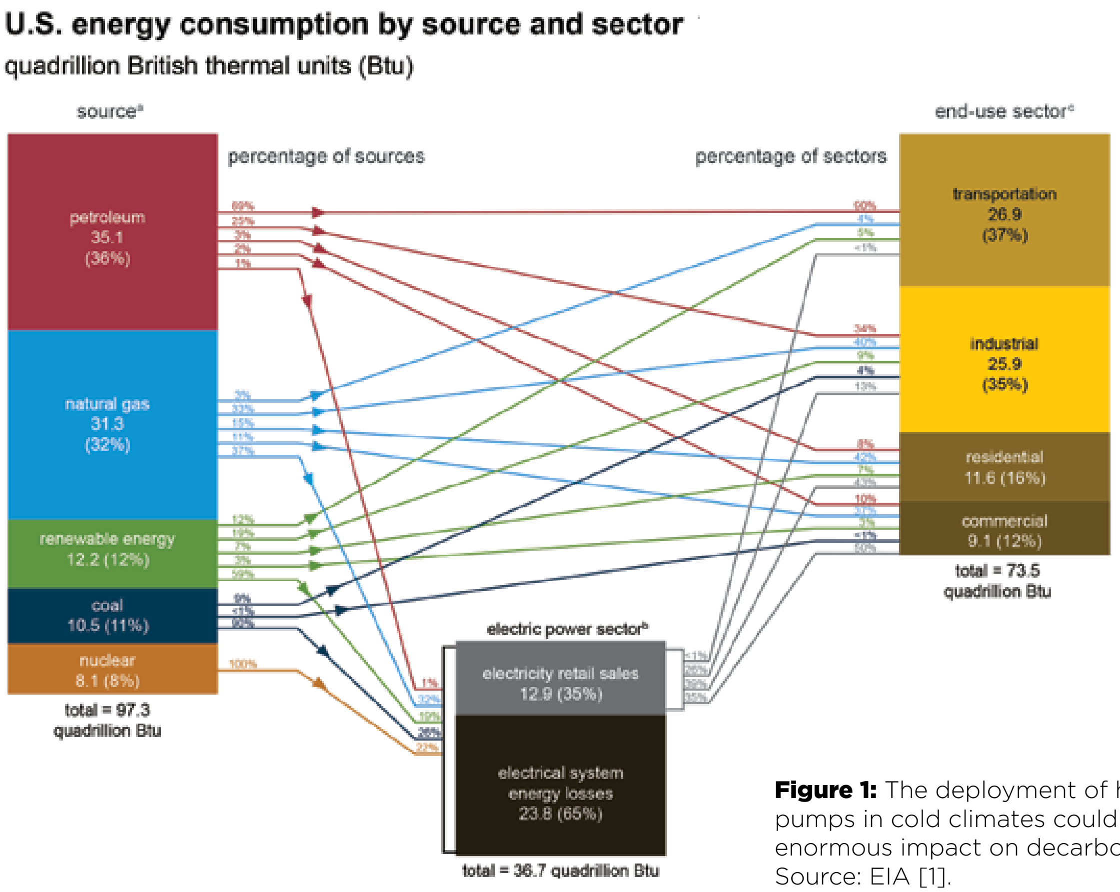


Figure 1: The deployment of heat pumps in cold climates could have an enormous impact on decarbonization. Source: EIA [1].

HVACR Engineers Focus on Cold-Climate Heat Pumps

Smaller-Diameter Copper Tubes Improve the Performance of Outdoor Evaporators

BY FRANK GAO, HARRY SCHMITZ, YORAM SHABTAY, KERRY SONG

The development and deployment of cold climate heat pumps (CCHPs) is important to the energy future of our planet. The data on energy consumption (Fig. 1) clearly shows why [1]. In 2021, the United States consumed 97.3 quadrillion Btus of energy. That's equivalent to 3250 GW of power running for one year, that is, 3250 GW-yr of energy [2].

In units of GW-yr, primary sources included petroleum (1172), natural gas (1045), renewables (407), coal (351), and nuclear (270). Similarly, end-uses included transportation (898), industrial (865), residential (387) and commercial (304). Between these two sides of the ledger is the electric power sector, which is neither a primary source nor an end user as indicated in Figure 1. This sector consumed 1225 GW-yr, selling only 431 GW-yr to end users. Electrical systems energy losses account for the discrepancy of 795 GW-yr.

Figure 1 further reveals that industrial, residential, and commercial end uses accounted for 33, 15, and 11 percent of all the end uses of natural gas. That's a whopping 59 percent of the natural gas sources. Giant steps toward decarbonization will come from replacing natural gas with electricity from renewable sources.

Figure 1 suggests that the deployment of heat pumps in cold climates could have an enormous impact on decarbonization. Heat pumps uniquely act as energy multipliers, not only enabling electrification but also using much less energy compared to electrical resistance heating or gas heating, even in cold climates.

This paper reviews the latest trends in the development of cold climate heat pumps as well as their deployment.

Breakthroughs Wanted

In view of the above analysis as well as recent geopolitical and climate events, it's not surprising that research, development, demonstration, and deployment (RDD&D) on heat pumps are accelerating.

Fortunately, recent parallel breakthroughs in heat exchangers have consequences for CCHPs. This was especially evident at expos and conferences in the past year, including the 2022 Chillventa, 2022 Interclima, 2023 AHR Expo, 2023 ISH Expo as well as the May 2023 IEA Heat Pump Conference in Chicago. These have been reviewed in recent issues of the *MicroGroove Update* newsletter [3].

Technology breakthroughs made in recent years allow for a new generation of air source heat pumps (ASHPs) to extract heat even at temperatures well below the freezing point of water. At recent expos, OEMs displayed products that boasted efficiencies well above the breakeven point with electrical resistance heating even at frigid temperatures. OEMs typically are guaranteeing stable operation even with outdoor temperatures as low as –15 °F (– 26 °C), effectively satisfying the heating demand in extremely cold areas.

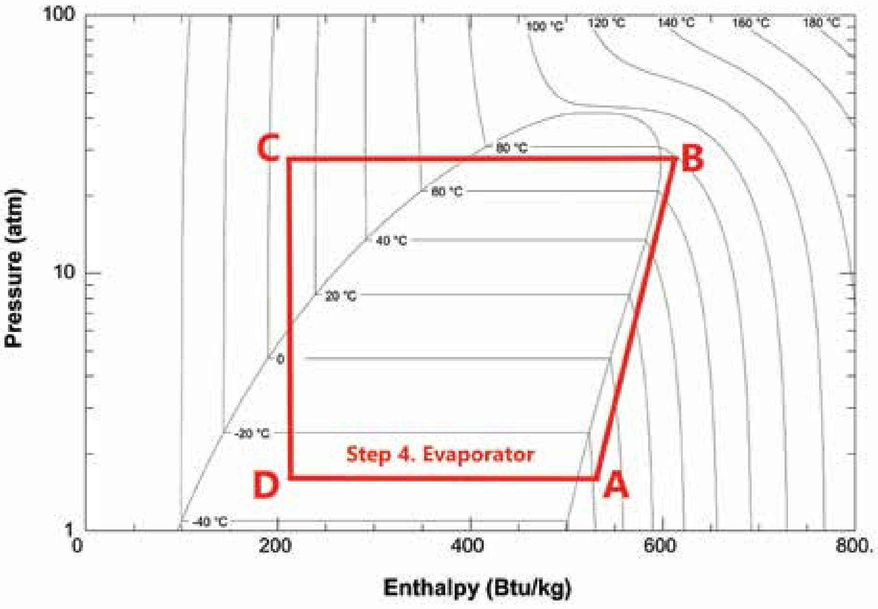


Figure 2: Moliere Diagram for R290 (propane). A vapor compression cycle (VCC) typically involves cycling the pressure, enthalpy and temperature through four stages: (Step 1) a compressor (A-to-B), (Step 2) a condenser (B-to-C), (Step 3) an expansion valve (C-to-D) and (Step 4) an evaporator (D-to-A). Step 3 happens when liquid propane expands and cools to subzero temperatures. Step 4 happens when energy is absorbed from the outdoor ambient as the liquid propane evaporates at constant pressure. This diagram was generated by REFPROP software. NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP): Version 10. https://www.nist.gov/srd/refprop

How can they do that?

The first requirement is a large outdoor evaporator. As the liquid refrigerant passes through an expansion valve, its pressure drops, and its temperature plummets. The temperature of the refrigerant, when it enters the outdoor evaporator, is below the outdoor ambient of a cold winter night.

The key to the function of the CCHP is an evaporator coil large enough to capture heat from the outdoors despite the relatively small temperature differences between the refrigerant and outdoor ambient temperature. Much heat also is captured from the latent heat of evaporation as seen in a typical Pressure-Enthalpy (P-h) or Moliere Diagram (Fig. 2). Using propane as a refrigerant, the liquid refrigerant can be cooled to 3 °C and then as it expands the temperature drops to – 30 °C. This segment of the vapor compression cycle for R290 refrigerant is indicated by the line between points C and D.

Smaller diameter copper tubes offer high heat transfer coefficients (HTCs) and extra circuits allow for enough cold refrigerant to flow through the evaporator and pick up heat from the cold air. A cold climate heat pump adds heat from the ambient to the work of the compressor.

Even if no heat is picked up from the ambient, the compressor performs 15 kW of work on the refrigerant, and this work is converted to heat. A CCHP is not going to be less efficient than electrical resistance heating albeit the CCHP is more complex. Depending on the outdoor ambient temperature, the 15 kW of work can be amplified or multiplied by removing heat from the outdoor ambient air. A properly sized evaporator pulls enough heat from the cold climate ambient to provide COP > 2 on most or all "heating days" even in the coldest climate zones. COP > 4 would be commonplace for many heating days.

Evaporator Simulations

A key to efficient CCHPs is the evaporator design. To assist in the design of such heat exchangers, the International Copper Association developed a user-friendly simulation software program named HXSim. It is available to qualified designers at no charge. The use of HXSim software

TABLE 1
EFFECTS OF REDUCING TUBE DIAMETER ON HEAT EXCHANGER DESIGN

	5 mm	7 mm	7.94 mm	9.52 mm
Fins per Inch (FPI)	14	13	16	17
Number of Tubes	228	228	164	164
Coil Depth (mm)	50.8	66	65	88
Airside Pressure Drop (Pa)	50	62	68	73
Air Velocity (m/s)	2.45	2.45	2.42	2.42
Fin Weight (kg)	13.44	16.23	19.36	19.49
Internal Volume (liter)	3.99	8.58	8.50	12.40
Refrigerant Side Pressure Drop (kPa)	4.1	4.7	4.4	3.6
Refrigerant Flow (kg/min)	3.31	3.31	3.31	3.36
Refrigerant Velocity (kg/min)	5.92	5.51	5.74	4.96
Refrigerant Charge (kg)	0.52	1.13	1.10	1.64
Output (kW)	14.4	14.35	14.35	14.4

Table 1 shows the differences in heat exchanger properties that occur as tube diameter is varied from 9.52 mm to 5 mm, while maintaining the same output. Inputs were adjusted to produce an output of about 14.4 kW for a constant flow rate of about 3.3 kg/min. In this initial study, the number of smaller diameter tubes (5 mm and 7 mm) was increased from 164 to 228 and coil depth was decreased to accommodate the refrigerant flow rate, which was held approximately constant for all four coils.

has been described in past issues of the *Appliance Design & HVACR Report.* [4-5]

A presentation at the most recent International Congress of Refrigeration (ICR2023.org) describes various capabilities of the HXSim software in considerable detail [6]. The authors of that paper describe simulations run on a simple L-shape coil with two rows of 5 mm tubes. They varied the internal tube surface enhancements (microfins), fin types and fin densities. Simulations were also run for an L-type, 15 kW evaporator with six rows of copper tubes, varying the diameter, tube spacing, fin density and tube circuitry. Results are compared with respect to weight, refrigerant charge and pressure drop (Table 1). The paper is available for downloading from MicroGroove.net on the HXSim landing page.

The upshot is that small diameter round copper tubes in heat exchanger coils can reduce refrigerant charge, increase efficiency, and decrease the size of CCHPs.

Rapid Innovation

A designer of cold-climate heat pumps needs to first set design criteria. What will be the end uses? How will the energy be transferred from the outside evaporator to the various spaces in the residential or commercial space? What will be the required capacity?

Marek Miara from the Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany, developed a system of classification of heat pump solutions for multifamily buildings [7]. Heat pump products and building solutions are classified according to a simplified schematic for the visualization of multifamily buildings. This project was developed within the context of Annex 50 of the IEA Heat Pumping Technologies Technical Collaboration Programme (IEA HPT TCP) and will continue as part of Annex 62 on "Heat pumps for multifamily buildings in cities" [8].

Global OEMs are developing CCHPs for the USA, Europe, China, Japan and South Korea. They are re-positioning their heating products to take advantage of game changing CCHP technology.

Dozens of companies, large and small, around the world, are intent on capitalizing on the rapid energy transition. These companies will fail or succeed according to the basic rules of market competition: Whoever produces superior products at low cost will dominate the marketplace.

These companies will succeed by developing the sustainable technologies and services internally, through acquiring technology-rich companies, or by partnering with successful companies. A case in point is global A.C. and comfort-control giant Carrier Global Corp., who recently acquired a successful technology-rich unit of the Viessmann Group, a German industrial firm. The Viessmann unit acquired by Carrier makes heating boilers and heat pumps [9].

It's no secret that European heat-pump technology in general is "way ahead" of the heat pump technology currently available in the USA. That partly has to do with its accelerated HFC phasedown as well as the high cost of energy in the European Union.

Rapid Implementation

To have a meaningful effect on energy consumption, heat pumping technologies must be implemented on a broad scale in real world applications globally. A case study from China serves as a preview of things to come. The project is described as the largest air source heat pump (ASHP) central heating project in China and one of the largest in the world [10].

Participants in the project included Guangdong New Energy Technology Development Co., the China Heat Pump Alliance (CHPA), Emerson Climate Technologies (Suzhou) Co.,

Figure 3: More than 1200 units of ASHPs were deployed as heating sources for approximately four million square meters of living spaces in large residential buildings. The challenge was how to best distribute these units and move the heat from the ASHPs to the living spaces.

Figure 4: The "cold island" effect occurs if the air circulation around the ASHP units is not optimized. In this case, all the stations were designed as frame structures at least eight meters above the ground.

and the Harbin Institute of Technology. Emerson Climate Technologies (now Copeland) provided a "vapor injection technology," which allows the system to be used down to ambient temperatures as low as – 30 °C, delivering hot water at temperatures high enough to heat living spaced through radiators.

Zhao County is in the southwest of Hebei province, about 280 km (170 mi) south of Beijing. In 2019, the local government decided to replace coal-burning power plants with ASHPs, to reduce running costs and air pollution. This part of north China has cold winters and requires considerable space heating in winter. The space heating necessary during the heating season was estimated as 138 MW. A simple calculation suggested that 1200 ASHPs (each producing 120 kW of heating) could produce 144 MW of heating.

The challenge was how to best distribute these units and move the heat from the ASHPs to the living spaces. More than 1200 units of ASHPs were deployed as heating sources for approximately four million square meters of living spaces in large residential buildings (Fig. 3). (Note that 4,000,000 sqm is about 43,000,000 sq ft.) That's enough heating for a community of about 30,000 apartments in a cold region of China.

The heating medium was water heated to 55 °C (131 °F) and returned at 45 °C (113 °F) at the end of the radiator. For floor heating, the water was supplied at 45 °C (113 °F) and returned at 35 °C (95 °F) at the end of floor heating.

For this large and complex project, detailed knowledge of the climate was essential to determine the initial investment and operating costs. From the beginning, the historical climate and environmental characteristics of Zhao County were investigated.

A factor in the systems design was to avoid the "cold island" effect, which occurs if the air circulation around the ASHP units is not optimized. In this case, all the stations were designed as frame structures at least eight meters above the ground (Fig. 4). That allows cold air from the units to flow downward into nearby open spaces. The ASHP units at each station were arranged in-line with no more than three units in the row direction.

Some other features of the ASHP were the use of vapor injection technology for the compressors of the ASHP unit. The winter climate record data indicated that ambient temperature could go as low as – 15 °C. Vapor injection technology brings the benefits for ASHP heating in cold ambient conditions. According to Copeland laboratory test results, this technology can improve heating capacity by 21 to 40 percent and efficiency by 7 to 22 percent, depending on the ambient temperature. Vapor injection technology allows the system to be used down to ambient temperatures as low as – 30 °C, delivering hot water at temperatures high enough even for heating through radiators.

The 1200 units of ASHP were managed with higher system performance in mind, using Internet of Things (IoT) technology. Depending on the temperatures of outlet water and return water, the operation of the individual ASHPs could be adjusted for better system efficiency.

This project serves as a real-world example from which much can be learned about large scale implementation of heat pumps in cold regions.

It is fully described in a paper by Zhao ***et al.*** titled "Largest Air Source Heat Pumps Central Heating Project in China" and presented at the 2023 IEA HPC in Chicago [10].

Tubes to Coils to Systems

Components for CCHPs include heat exchangers with smaller diameter copper tubes. Efficient copper tubes lead to efficient coils and ultimately to efficient heat pumping technologies and systems.

The first step in designing a CCHP would be to select the tubes for the evaporator. The next step would be to select a suitable refrigerant, consistent with the regional regulations regarding GWP and flammability. Smaller diameter tubes are advantageous in both cases because they allow for less refrigerant charge for any desired capacity.

Heat pumps can range in size from a few kilowatts to hundreds of kilowatts. They can run on conventional refrigerants such as R410A (GWP of 2088), natural refrigerants such as R290 or R744, or R32 (GWP of 675).

R290 (propane) offers excellent performance, providing 70 °C hot water even at low outdoor temperatures. However, because of its flammability, its indoor use has been limited to only the smallest capacity indoor split units. Its adoption rate in various regions of the world will be heavily dependent on regulations on charge usage driven by concerns about flammability. Propane has been used successfully in refrigerated cabinets where charge limitations can be managed using smaller diameter copper tubes in the evaporators and condensers of refrigerated cabinets, for example. However, heat pumps typically require larger refrigerant charges.

One popular model of CCHP that uses propane as a refrigerant is an air-to-water "monoblock" heat pump, which is self-contained and located outside. Space heating is accomplished by circulating hot water or other liquid to the indoor radiators and floor heating systems. In this manner, no flammable refrigerant is used indoors.

Right-Sizing Heat Pumps

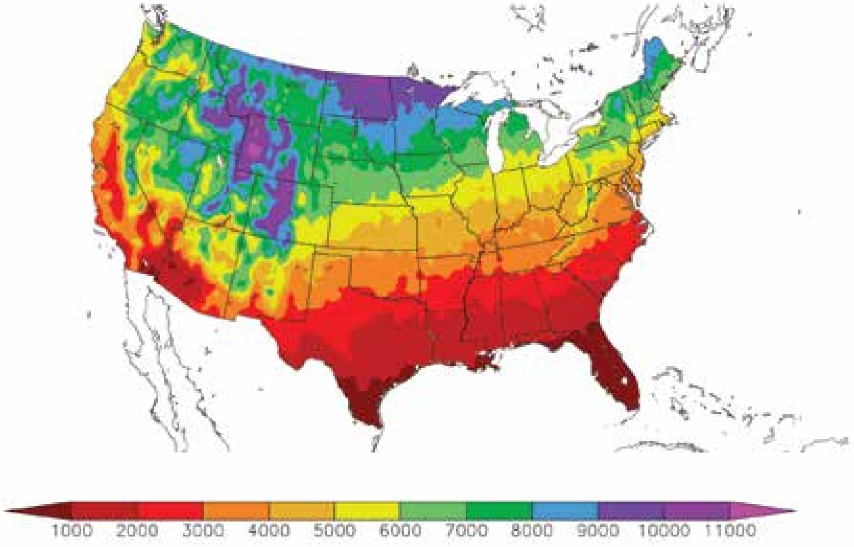
Air source heat pumps (ASHPs) can be further classified as Air-To-Air (ATA) heat pumps and Air-To-Water (ATW) heat pumps. The common denominator is that the evaporator captures heat from the ambient air.

ASHPs offer several advantages compared to GSHPs. The main advantage is lower cost. In the USA, where ducted furnaces and central AC are everywhere, ASHPs look a lot like central air conditioners, but the roles of the outdoor unit (ODU) and indoor unit (IDU) are reversed. Indeed, many brands of ASHPs are reversible. They can be used for cooling in the summer and heating in the winter, especially in lower latitudes where winters are mild. ATA ASHPs in the heating mode use the ODU as an evaporator and the IDU as a condenser. Ducted systems are especially common in legacy homes that previously used a gas furnace for heating.

When the ODU serves as an evaporator, the copper tubing in round tube plate fin (RTPF) heat exchangers tends to be larger in diameter than the copper tubing in outdoor condensers. Copper tube diameters as large as 3/8 inches (9.52 mm) or 1/4 inches (6.35 mm) are not uncommon for this application. In RTPF style heat exchanger, condensate drains easily away from the flat vertical fins. Microchannel heat exchangers are rarely used in outdoor evaporator because of issues with drainage that leads to the condensate freezing over the heat exchanger.

The IDU could be configured to allow heated air from the condenser to be directed through a system of ducts; alternatively, the IDU could be remote from the ODU. Refrigerant from the compressor could be routed

Figure 5
HEAT DEGREE DAYS (BASE 65) 8/1/2022 – 7/31/2023



through insulated copper pipes to wall units (condenser) hung in various living spaces. Either of these configurations would be considered an ATA ASHP.

A new generation of low-cost, mass-produced window units was recently introduced into the marketplace. These units use smaller-diameter copper tubes in a reversible configuration. In other words, the compressor can pump refrigerant to the indoor facing heat exchanger in the heating season, or to the outdoor facing heat exchanger in the cooling season. Since these window units typically do not operate efficiently at temperatures below 45 °F they are not considered heating systems *per se* but are useful as efficient supplemental space heaters for most heating days, especially in milder climates.

The number of heating degree days is a figure of merit for heat pump selection. These are essentially weather statistics for local areas. An outdoor temperature of 1°F below 65 °F for a 24 h period represents one heating degree day; an outdoor temperature of 45 °F for a 24 h period represents 20 heating degree days; and so on. Thanks to the abundance of weather stations across the USA and most other countries, extensive historical databases of local temperatures are available. Heating degree days can be readily calculated for no charge using various online apps [11].

High Plains Climate Center has tools for creating climate maps for the USA [12]. Figure 5 shows how Heating Degree Days vary across the USA, ranging from 1000 in Texas and Florida to more than 10,000 on the border with Canada.

The trend now is toward ASHPs. Except for extremely cold climate zones, ASHPs can provide adequate heating for most heating days throughout the year although COPs will drop on very cold winter nights. Using the latest technology, the ASHPs are saving energy for homeowners even in New England.

Condensers and evaporators in such heat pumps can be readily modeled for performance under various operating conditions using HXSim simulation software. (As mentioned, HXSim is available at no charge from the International Copper Association via its microgroove.net website.) The software can model I-type, L-type and C-type heat exchanger blocks with copper tubes as small as 4 mm in diameter for many different refrigerants.

Outdoor evaporators for heat pumps come in many shapes and sizes. In the United States, they are typically C-Type heat exchangers like the outdoor condenser for a residential central air conditioning system. Simple I-Type (flat slab) and L-Type heat exchangers also can serve as evaporators. Figure 6 shows 3D representations of an L-shaped heat exchanger block with smaller diameter copper tubes as simulated with HXSim simulation software.

Toward the Future

The magic of thermodynamics revolutionized our modern world. It ushered in the age of air conditioning, leading to major demographic changes and creating whole industries dedicated to comfort. Simultaneously, refrigeration led to the creation of a global cold chain, crossing national boundaries "from farm to fork" in ways never possible before.

Yet the whole story has not yet fully unfolded. The use of heat pumps for heating has barely begun, mainly because there has been no need. If necessity is the mother of invention, then innovations in heat pump designs can be assured in the next few years.

The stakes couldn't be higher. ●

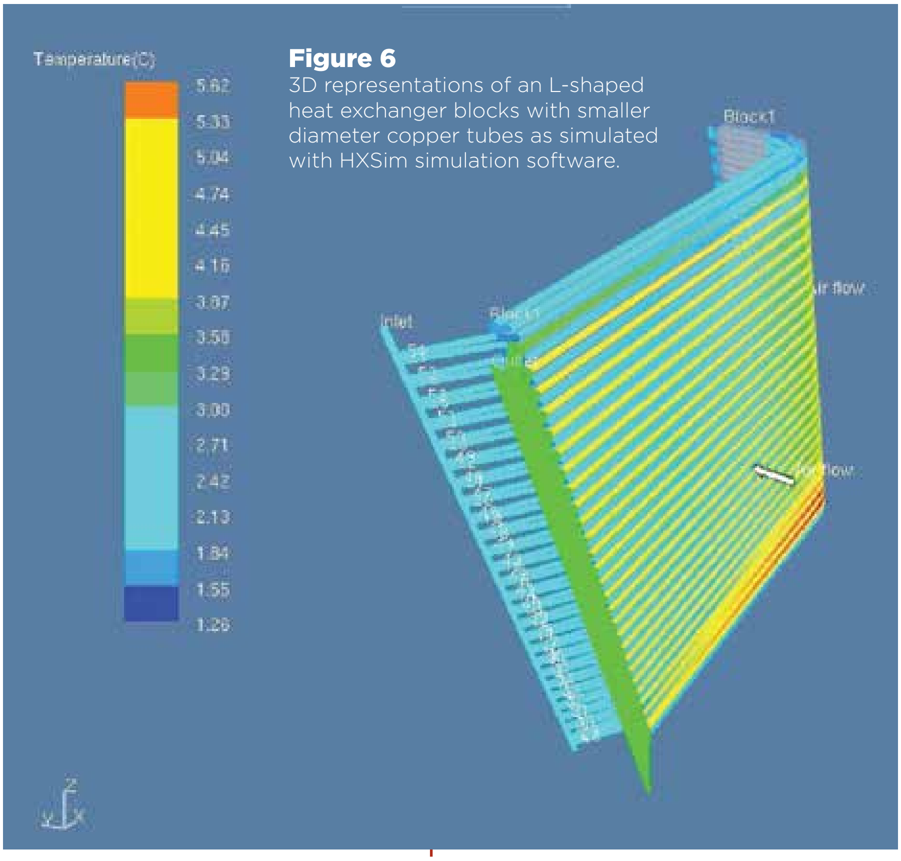


Figure 6
3D representations of an L-shaped heat exchanger blocks with smaller diameter copper tubes as simulated with HXSim simulation software.

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