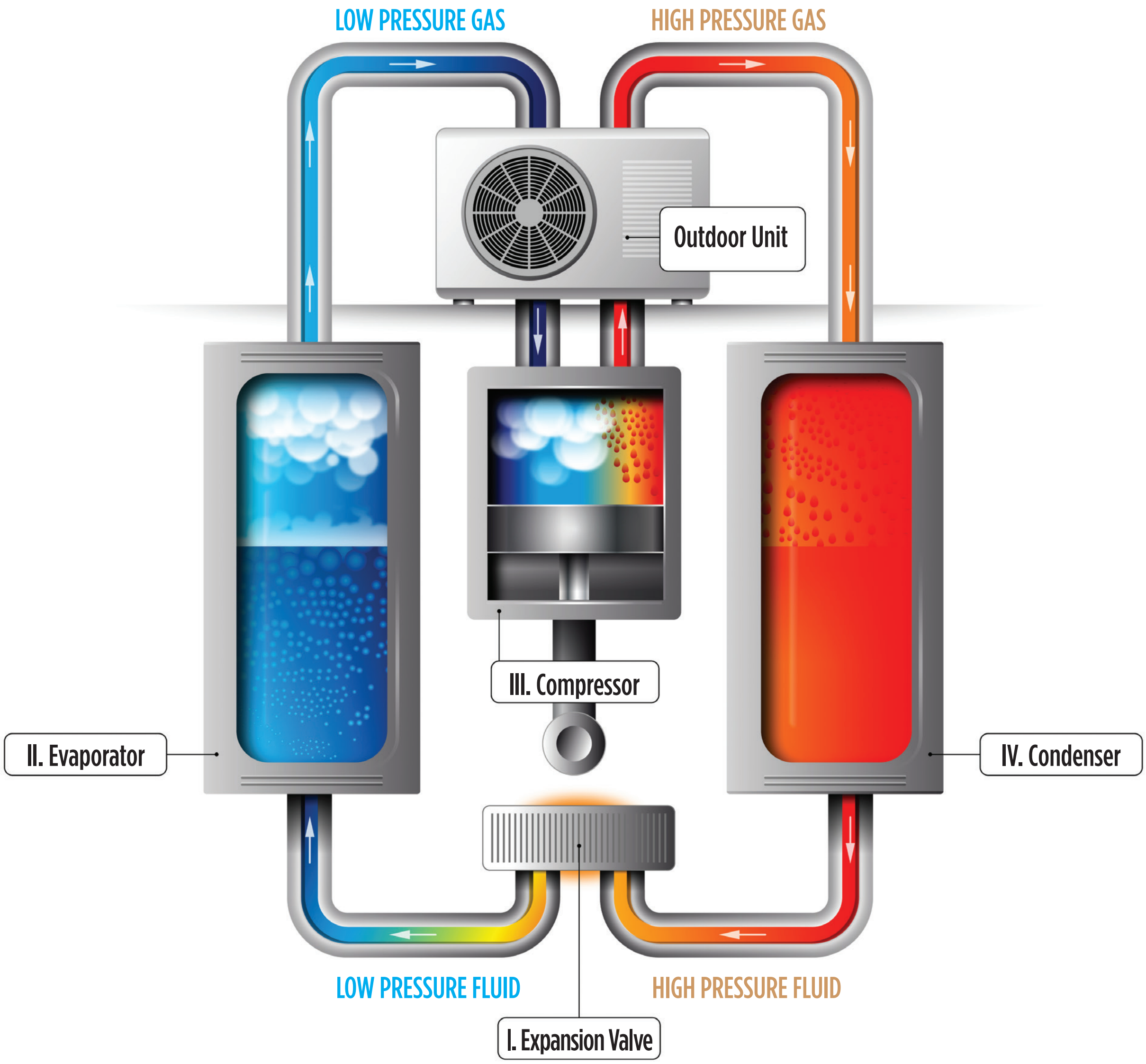



# Heat Pumps Deliver High Efficiency Heating

## Five Trends in Heat Pump Design for Residential Heating

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

Throughout history and up to modern times, mankind has accomplished heating mainly by burning fuels such as coal, oil and natural gas and later also by electrical resistance heating. Nonetheless, there is another method of heating: heat pumps.

According to the Second Law of Thermodynamics, isolated systems will always arrive at a state of thermodynamic equilibrium. In other words, temperature differences will even out. Through the vapor compression cycle (VCC), however, refrigerant can be heated or cooled further than the ambient (Fig. 1).

The VCC works as follows:

I. Cooled refrigerant passes through an expansion valve.

II. The refrigerant picks up heat as it expands through outdoor evaporator.

III. The compressor adds work energy as it increases the pressure and temperature of the refrigerant.

IV. Heat gained from Steps II and III is released through the condenser.

Then the cycle repeats.

Depending on the outdoor and indoor ambient temperatures as well as the efficiencies of the coils, the heat output can be many times the work input. This advantage over electrical resistance heating is of great interest for energy efficiency. The ratio of heat output to work input is also called the coefficient of performance (COP).

Such a device is called a "heat pump." Air conditioners, refrigeration equipment and indeed any appliance that uses the VCC could be labeled a "heat pump." In this article, the term "heat pump" is restricted to refer to equipment and appliances that use the VCC for heating.

## Wanted: Imaginative New Heat Pump Designs

The need for better heat pump designs is urgent for two overarching reasons: First and foremost, heat pumps can replace equipment and appliances that currently burn hydrocarbons. This "electrification" or "decarbonization" allows for heating to be accomplished with clean renewable energies such as hydroelectric, geothermal, solar, and wind.

Second, thanks to the laws of thermodynamics, heating by the VCC is ***much more efficient*** than heating by combustion or electrical resistance. Heat pumps significantly increase the system efficiency by moving outdoor energy indoors. The kinetic energy from the compressor is added to the thermal energy absorbed from the outdoor ambient. The heating capacity (in Btu/h, or kilowatts) is typically many times the compressor power (in horsepower, or kilowatts).

Suffice it to say, the nations of the world are addicted to fossil fuel. Weaning one and all from fossil fuel will depend in part upon imaginative new designs of heat pumps. New principles relating to the application of the VCC are emerging with the potential to revolutionize heating as much as cooling.

Several of these trends are as follows:

1. Ground source heat pumps (GSHPs)
2. Air source heat pumps (ASHPs)
3. Air-To-Water heat pumps (ATW HPs)
4. Low GWP refrigerants
5. Cold climate air source heat pumps (CC-ASHPs)

The intelligent application of new heat pump technology itself can substantially reduce the release of carbon dioxide into the atmosphere.

Let's take a closer look at these trends.

***1. Ground Source Heat Pumps***

In past decades, ground source heat pumps (GSHPs) or water source heat pumps generated much enthusiasm. The main selling point was that such heat pumps could work well even in cold climates. Typical temperatures at a depth of a six to ten feet (that is, below the frost line) are steady at about 55 °F (13 °C).

GSHPs remain popular in many locales. Closed loop systems circulate heat-carrier fluid through pipes installed in the ground. Open loop systems pump groundwater stored in aquifers and mines. Heat pumps are used to extract the low-grade heat from warm carrier fluid or groundwater and upgrade it to more useful temperatures (> 40 °C) required for the heating of buildings. The cooled carrier fluid or groundwater is then returned to the subsurface and the cycle repeats.

GSHPs can be used for heating, cooling or both, i.e. heating during winter and cooling during summer. Figure 2 compares working temperatures and depths for various types of GSHPs as well as geothermal heating and engineered geothermal systems (EGS).

These methods of heating are especially interesting for district heating where large heat pumps can serve thousands of homes. An interesting twist on GSHPs is the use of coal-mine water as an open-loop heat source.

In Great Britain, for example, the Coal Authority owns most unworked coal as well as former coal mines. The

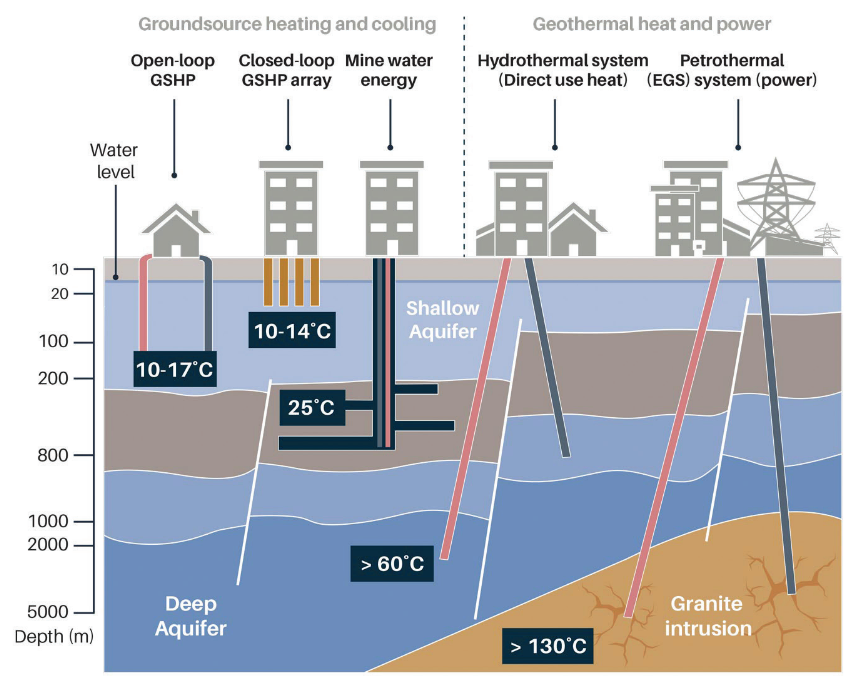



**Figure 2**: Comparison of groundsource heating and cooling with geothermal heat and power. Acknowledgement: CP22/041 Geothermal Energy Technologies, BGS © UKRI. All Rights Reserved. Sourced: https://www.bgs.ac.uk/geology-projects/geothermal-energy/

Coal Authority is a non-departmental public body of the United Kingdom government sponsored by the Department for Business, Energy & Industrial Strategy. According to the Coal Authority, one quarter of the population of the UK lives in settlements on coal fields. Often these abandoned coal mines are filled with water, offering a plentiful source of geothermal energy for domestic heating [1, 2].

***2. Air Source 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, air source heat pumps 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 HPs 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. Microchannel heat exchangers are rarely used in outdoor evaporators because of issues with drainage, freezing and defrosting.

The IDU could be configured to allow heated air from the condenser to be directed through a system of ducts; alternatively, the condenser could be remote from the compressor. Refrigerant from the compressor could be routed through insulated copper pipes to wall units 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 recently was introduced into the marketplace. These units use smaller-diameter copper tubes in a reversable 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.

An important figure of merit for heat pump selection is the number of heating degree days. These are essentially weather statistics for different regions. An outdoor temperature 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. For example, one such calculator is available at degreedays.net.

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

Condensers and evaporators in such heat pumps can be readily modeled for performance under various operating conditions using HXSim simulation software. HXSim is available at no charge from the International Copper

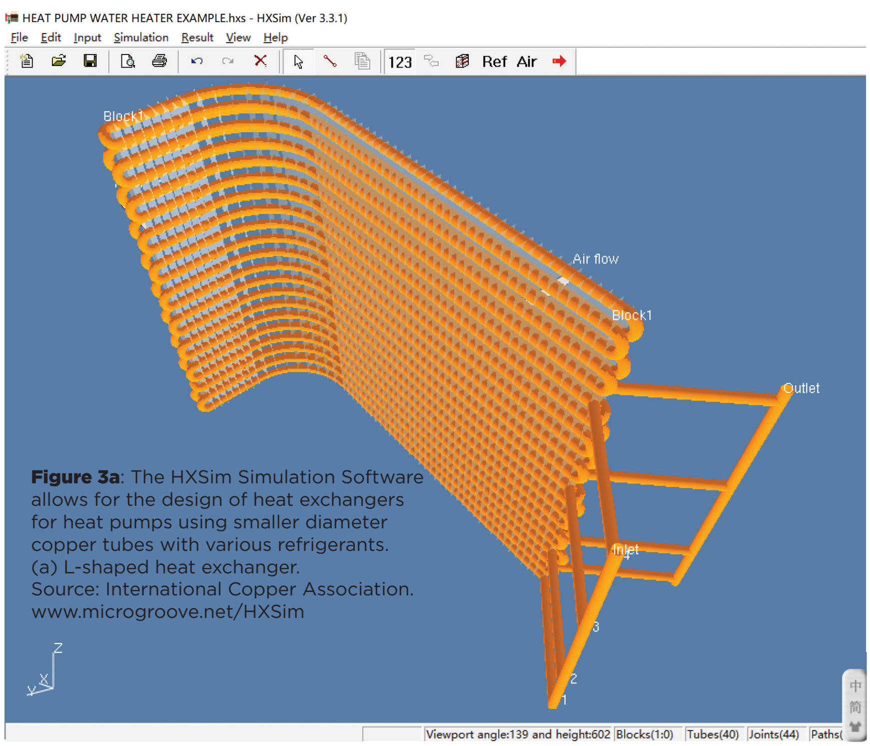
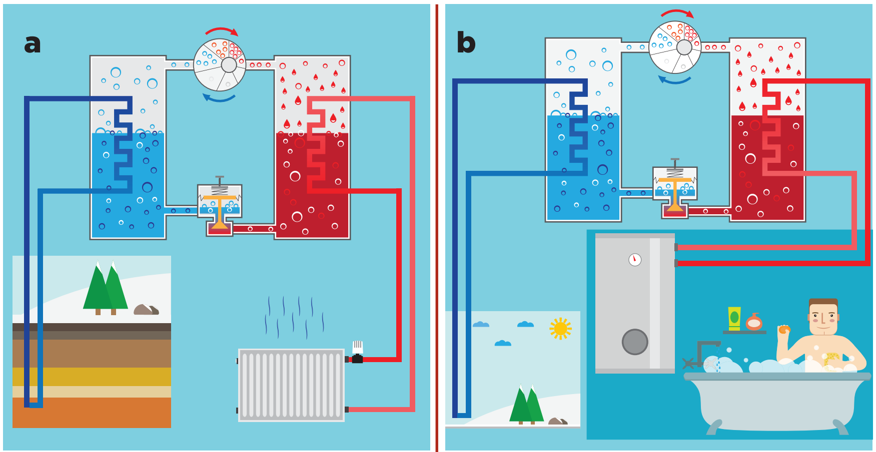



**Figure 3a**: The HXSim Simulation Software allows for the design of heat exchangers for heat pumps using smaller diameter copper tubes with various refrigerants. (a) L-shaped heat exchanger. Source: International Copper Association. www.microgroove.net/HXSim

**Figure 4a / 4b**: Heat pumps can produce hot water: (a) Ground source heat pump (GSHP) for space heating. (b) Air source heat pumps (ASHP) for domestic hot water.a




Association via its microgroove.net website [3]. HXSim 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. The use of HXSim software has been described in a past issue of the ***Appliance and HVAC Report*** [4]. A recent issue of the ***MicroGroove Update*** newsletter compares HXSim with other heat exchanger simulation packages [5].

Outdoor evaporators for heat pumps come in many shapes and sizes. In the United States, they are typically C-Type heat exchangers similar to the outdoor condenser for a residential central air conditioning system. Simple I-Type (flat slab) heat exchangers also can serve as evaporators in split systems. Figures 3a and 3b show 3D representations of C-shaped and L-shaped heat exchanger blocks with smaller diameter copper tubes for use in a heat pump as simulated with HXSim simulation software.

### *3. Heat Pump Water Heaters*

A heat pump water heater (HPWH) could derive its heat from a ground source or an air source. Either of these heat pumps is more efficient than a fossil-fuel-burning boiler. Output can be used for space heating or domestic hot water (Fig. 4a and 4b).

Heat from the compressed refrigerant is transferred to the water through a finless condenser coil or brazed plate heat exchanger. The hot water can then be pumped to radiators or baseboard heaters; or radiant heating can be accomplished by pumping hot water or a secondary fluid through a network of pipes built into floors or walls.

Chinese medicine advocates "keep the feet warm and the head cool." Radiant heating through floors emits heat near the feet and the heat gradually decreases from the floor to the ceiling. This approach is in accord with the health preservation principle of traditional Chinese medicine and has become popular in China. The Shanghai office of the International Copper Association China (ICA China) recently released a study on a residential systems using ground and air sources with ATW and ATA heat pumps [6]. The company Leomon Technology (Cihu Technical Area, Maanshan. China) offers various heat pump products that are used in such systems. Its website hosts several informative blogs in English on heat pumps, radiant floor heating and related topics [7]. Leomon Technologies has more than twenty years of experience in the refrigeration and heating industry in China.

Heat pumps have received much attention from the U.S. Department of Energy (DOE), the California Energy

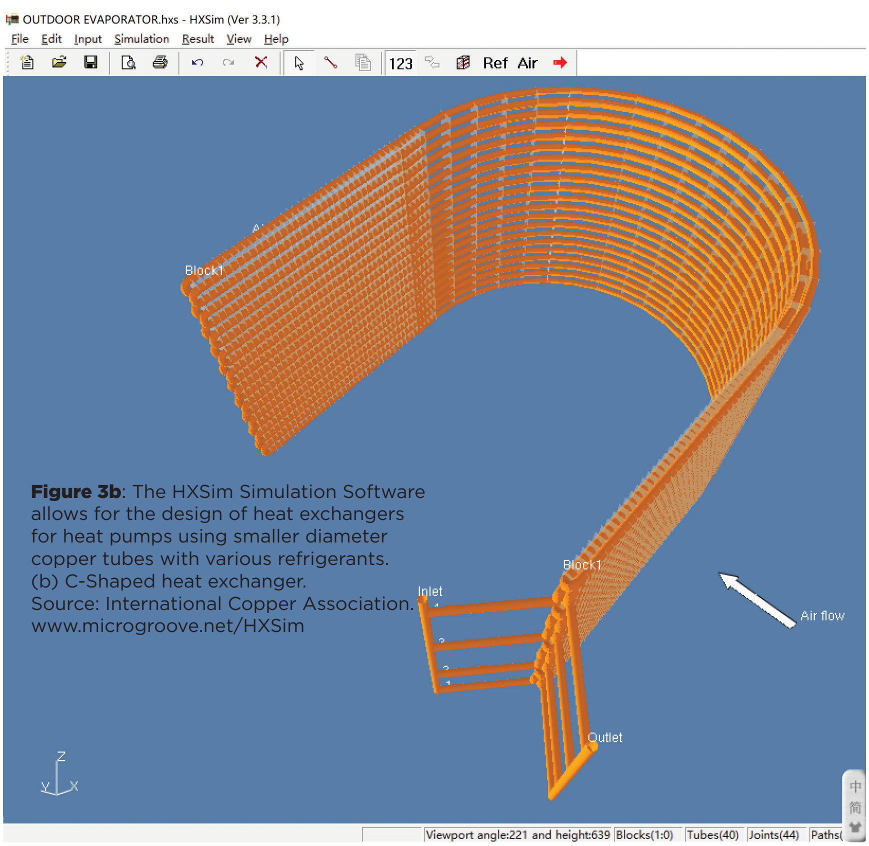



**Figure 3b**: The HXSim Simulation Software allows for the design of heat exchangers for heat pumps using smaller diameter copper tubes with various refrigerants. (b) C-Shaped heat exchanger. Source: International Copper Association. www.microgroove.net/HXSim

Commission (CEC), the European Heat Pump Association, the EIA International Heat Pump Forum, the American Council for an Energy-Efficient Economy (ACEEE) and many other government agencies and non-governmental organizations (NGOs). The DOE is authorized to establish and amend energy conservation standards and test procedures for consumer water heaters [8].

The 2022 Hot Water Forum (HWF) included several sessions dedicated to heat pump water heaters [9]. At the virtual conference, Amruta Khanolkar of the New Buildings Institute described 120v plug-in HPWHs, including an overview of market opportunities and technology readiness [10]. Case studies were presented on HPWHs for various regions of the country as well as for manufactured homes. Many case studies were also presented on commercial HPWHs (CHPWHs) for multifamily homes as well as restaurants. An HXSim case study at the 2022 HWF demonstrated that refrigerant charge reduction can be achieved without affecting heating capacity by reducing copper tube diameters from 9.52 mm to 5 mm in the evaporator coil [11].

The universal adoption of HPWHs presents a tremendous opportunity to reduce GHG emissions. Unfortunately, adoption of this energy efficient technology has been slowed by the low cost of natural gas as an energy source as well as the low installed cost of gas-fired water heaters and electrical resistance water heaters. Consequently, HPWHs for residential heating has been slow to catch on in the USA compared to Europe, for example. Equity is an important issue in the adoption of HPWHs. Field tests have been undertaken across the USA in different climate regions, including the South as well as colder climates in the Midwest and Northeast. The economics of HPWHs have been scrutinized by many research teams presenting at the 2022 HWF.

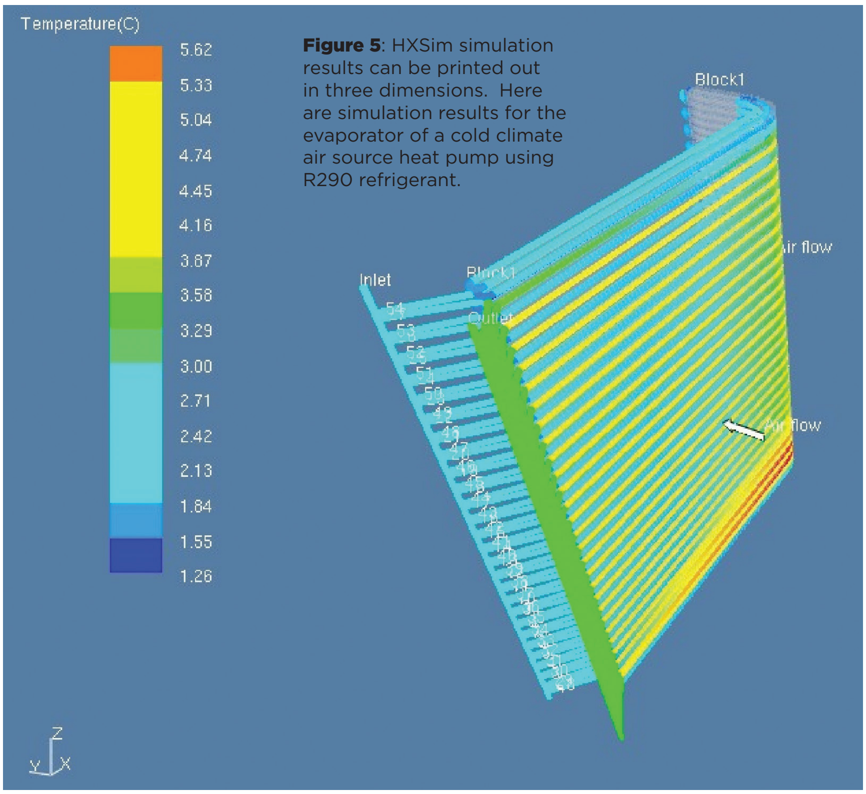



**Figure 5**: HXSim simulation results can be printed out in three dimensions. Here are simulation results for the evaporator of a cold climate air source heat pump using R290 refrigerant.

Commercial HPWHs for restaurants and affordable multifamily housing are of keen interest.

Despite lackluster sales, many OEMs exhibited HPWHs at recent trade shows. Notable were residential appliances from A.O. Smith, Gree, Rheem, Rinnai, Stiebel Eltron and others. Bradford White Water Heaters provides the AeroTherm® Series Heat Pump Water Heater as described in a video on its website [12].

***4. Low GWP Refrigerants for Heat Pumps***

Heat pumps offer much higher energy efficiencies than natural gas or electrical resistance heating. The high coefficients of performance (COPs) of heat pumps are the driving force behind their adoption. The COP of a heat pump is the ratio of useful heating or cooling divided by the work input. That said, there is a one catch. Most of today's heat pumps contain HFCs or HFC-HFO blends. The advantages of high COP are offset by the high Global Warming Potential (GWP) of the HFCs. Refrigerant GWP has been discussed extensively at recent conferences, including IIR's TPTPR Conference [13] and the Purdue's Herrick Conferences [14-15].

The current generation of HFO-HFC blends are far from ideal. HFO-HFC blends suffer from thermal glide [16]. Furthermore, some HFOs break down into trifluoroacetic acid (TFA), which is harmful to life even in small concentrations [17]. TFA is a "forever chemical," which remains in the environment for a long time. While ultralow GWP HFOs may be friendly to the atmosphere, they may be harmful to the environment in other ways.

For these reasons and others, several industry leaders are advocating for the use of low-GWP ***natural refrigerants*** such as hydrocarbons (R290 and R600a) as well as carbon dioxide (R744) and ammonia (R717). While these have

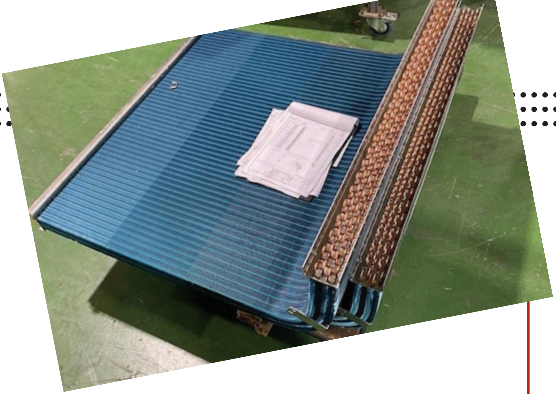


**Figure 6**: The evaporator modeled in Figure 5 was built and tested confirming the accuracy of the simulation. This L-shaped evaporator is made from 216 hairpin copper tubes with 5 mm outer diameter. There are four hairpin tubes in each of the 54 circuits.

mainly been used in refrigeration equipment, there is a growing push to use them in other applications.

In particular, dramatically higher charge limits have been approved by the the International Electrotechnical Commission (IEC) safety standard for propane (R290) and other flammable refrigerants in household air conditioners, heat pumps and dehumidifiers [18]. These increases are being put on the fast track, especially in the light of the urgency to install more heat pumps in Europe to alleviate dependence on fossil fuels.

Yoram Shabtay of HTT and Peter Mostovoy of Lordan described an ODU for an R290 Heat Pump Water Heater at the 2022 ATMOsphere America Summit [19]. While R290 is flammable, there is an option of placing components charged with R290 outdoors where charge limit conditions could be relaxed. This approach opens up new possibilities for developing heat pumps with low-GWP natural refrigerants. In this case, the 14 kW evaporator is made with 5 mm diameter copper tubes. Heat exchanger designs were simulated using HXSim software (Fig. 5) and performance was verified on the actual units (Fig. 6).

***5. Cold Climate Air Source Heat Pumps (CC-ASHPs)***

The R290 heat pump application described in the last section also happens to be suitable for operation in cold climates. Most major AC manufacturers now boast cold-climate air source heat pumps (CC-ASHPs). These heat pumps have features that make them attractive and practical even at higher latitudes. High COPs in cold climates could spur the adoption of heat pumps for space heating as energy costs increase (Fig. 7).

The Northeast Energy Efficiency Partnership (NEEP) is one of six Regional Energy Efficiency Organizations (REEOs) funded in part by the US Department of Energy to support state efficiency policies and programs. NEEP maintains a product listing of CC-ASHPs [20].

Consider that the ODU of a CC-ASHP is an evaporator. As the refrigerant expands, it reaches temperatures even colder than the outdoor temperatures, since heat must be transferred from the environment to the refrigerant. According to Leomon Technologies, CC-ASHPs may have COPs of 3.8 around 8.3 °C (47 °F) but COPs drop to 2.3 around minus 8.3 °C (17 °F) [21].

If the outside temperature drops too low, backup resistance heating may be required. Some CC-ASHPs are reported can operate below zero, i.e., at outdoor temperatures < 0 °F (< minus 18 °C), according to ***Consumer Reports*** [22]. A CC-ASHP with a COP greater than one presumably would be ***more efficient*** than a boiler or electric resistance heaters even on the coldest nights of the heating season.

It is desirable for CC-ASHPs to incorporate a defrost cycle. Consequently, optimal operating cycles are under investigation. The idea is to briefly reverse the flow of the refrigerant to melt any ice buildup on the fins and tubes of the heat exchanger. The Copper Development Association sponsored research on this topic by Optimized Thermal Systems [23].

Remarkably, CC-ASHPs using low-GWP refrigerants are already under development as mentioned in the previous section [19].

**Figure 7**: Even at temperatures below freezing, today's cold climate air source heat pumps (CC-ASHPs) deliver heating more efficiently than either burning fossil fuels or electrical resistance heating.

### Toward the Future

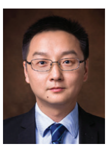
The magic of the VCC revolutionized our modern world. It ushered in the age of air conditioning, leading to major demographic changes and creating whole industries dedicated to comfort. Simultaneously, refrigeration led to the creation of a global cold chain, crossing national boundaries "from farm to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

Yet the story of the VCC has not yet been fully written. 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.

Many agree that rebates and tax incentives will be required to stimulate broad adoption of heat pumps on the scale necessary to meet energy conservation goals. The recently passed "Inflation Reduction Act of 2022" includes numerous incentives for heat pumps and other energy saving products. Details can be found in the final bill as well as numerous online reports [24].

The stakes couldn't be higher. ●


***Frank Gao*** *is the Market Director for HVACR for the International Copper Association (ICA). He is the team leader for MicroGroove campaigns.*



***Kerry Song*** *is a Project Manager with the ICA. He is also the Secretary-General of Refrigeration and Air-conditioning Heat Exchanger Technology Alliance in China.*

***Yoram Shabtay*** *is President of Heat Transfer Technologies. He has extensive background in heat exchangers development and production and has been working with the ICA for over two decades.*

***Harry Schmitz*** *is a Senior Account Supervisor with the Kellen Company. He has worked with ICA for over two decades as a technology communicator.*



**References:**

**1.** _______, "Geothermal energy from abandoned coal mines," The Coal Authority, Nottinghamshire, United Kingdom.
https://www2.groundstability.com/geothermal-energy-from-abandoned-coal-mines/

**2.** Rebecca Morelle, "Could super-sized heat pumps make gas boilers extinct?" ***BBC News***, 18 March 2022.
https://www.bbc.com/news/science-environment-60772187

**3.** ICA Partners with SJYU to Offer Powerful Heat Exchanger Simulation and Design Software.
See www.microgroove.net/HXSim for instructions on downloading the simulation software and user guide.

**4.** Yoram Shabtay and Kerry Song, "Heat-Exchanger Simulations Fast-Track Adoption of MicroGroove Copper Tubes," ***Appliance & HVAC Report***, September 2020, Page 14.
https://www.appliancehvacreport.com/magazines/2020_v2i4/#page/14

**5.** _________, "Real Insights in the Age of Simulations: Accuracy of Modeling of Heat Exchangers is Uncanny," ***MicroGroove Update***, Volume 11, Issue 2.
https://microgroove.net/microgroove-update-newsletter

**6.** _________, Residential systems in China using ATW and ATA heat pumps, the International Copper Association, China Office. Translated from Chinese. Download from MicroGroove Technical Literature Webpage.
https://microgroove.net/technical-literature

**7.** _________, "Air Source Heat Pump and Underfloor Heating," China Heat Pump blog, (Leomon Technology: Cihu Technical Area, Maanshan. China). Website showcases Chinese heat pump products "
https://www.chinaheatpumps.com/About-us.html

**8.** "Appliance and Equipment Standards Rulemakings and Notices: Consumer Water Heaters"
https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=32

**9.** The 2022 ACEEE Hot Water Forum (virtual conference). Program and slide decks available online. https://www.aceee.org/2022-hot-water-forum-virtual

**10.** Amruta Khanolkar, "Retrofit Ready Game Changing Technology: 120V HPWHs," 2022 ACEEE Hot Water Forum. 2022 ACEEE Hot Water Forum.
https://drive.google.com/file/d/1xIyqsbHITvoGYVO5WPrQiccON4NmcS2q/view

**11.** Yoram Shabtay, "Simulations Demonstrate the Advantages of Smaller Diameter Copper Tubes in ,https://drive.google.com/file/d/149nkK_p5fhCNbJvMLbxkztdV7cLu9vZb/view

**12.** _____, "The AeroTherm® Series Heat Pump Water Heater," Bradford White Water Heaters. (See Video)
https://www.bradfordwhite.com/aerotherm/

**13.** 6th IIR Conference on Thermophysical Properties and Transfer Processes of Refrigerants, Online Conference, September 2021.
https://iifiir.org/en/events/6th-iir-conference-on-thermophysical-properties-and-transfer-processes-of-refrigerants

**14.** Proceedings of the 202One Purdue Herrick Conferences online.
https://docs.lib.purdue.edu/iracc/

**15.** 2022 Purdue Herrick Conferences, Program Online.
https://engineering.purdue.edu/Herrick/about/news/Conferences/2022

**16.** Michael Petersen, Steve Kujak, "Review of Lower GWP Refrigerants For Retrofitting R-410A Applications," 2022 Purdue Herrick Conferences.
https://www.conftool.com/Herrick2022/index.php?page=browseSessions&form_session=25

**[17].** Michael Garry, "ATMO America: Scientist Urges U.S. EPA to Broaden Definition of PFAS to Include F-Gases, TFA," June 20, 2022.
https://r744.com/atmo-america-scientist-urges-u-s-epa-to-broaden-definition-of-pfas-to-include-f-gases-tfa/

**18.** Michael Garry, "Higher Hydrocarbon Charges Unanimously Approved in IEC Standard for Home ACs and Heat Pumps," Hydrocarbons.com, News Item, May 2, 2022.
https://hydrocarbons21.com/higher-hydrocarbon-charges-unanimously-approved-in-iec-standard-for-home-acs-and-heat-pumps/

**19.** Yoram Shabtay and Peter Mostovoy, "A Cold Climate R290 Heat Pump Water Heater Case Study," 2022 ATMOSphere America.
Slideshow: https://atmo.org/announcement/atmo-america-2022-hvac-heat-pumps/
Video: https://www.youtube.com/watch?v=Oa-v9TdtuiU&t=22s

**20.** _________, "NEEP's Cold Climate Air Source Heat Pump List," Northeast Energy Efficiencies Partnerships, Boston, Mass. https://ashp.neep.org/#!/product_list/.

**21.** _________, "Do Air Source Heat Pumps Work in Cold Weather?" China Heat Pump blog, (Leomon Technology: Cihu Technical Area, Maanshan, China).
https://www.chinaheatpumps.com/Do-Air-Source-Heat-Pumps-Work-in-Cold-Weather.html

**22.** Liam McCabe , ***Consumer Reports***, "Can Heat Pumps Actually Work in Cold Climates?," August 2, 2022.
https://www.consumerreports.org/heat-pumps/can-heat-pumps-actually-work-in-cold-climates-a4929629430/

**[23].** Dennis Nasuta, Song Li and Regina Hong, "3 mm to 5 mm Microgroove Heat Exchangers in Frost-Developing Conditions," Copper Development Association Webinar with Optimized Thermal Systems, December 7, 2021.
ICA-OTS Landing Page: https://microgroove.net/ots-ica-educational-outreach
YouTube: https://www.youtube.com/watch?v=WPL4YqLOjOk

**[24]** "Inflation Reduction Act of 2022," Wikipedia, Wikimedia Foundation, 15 August 2022,
https://en.wikipedia.org/wiki/Inflation_Reduction_Act_of_2022