Heat Pumps for Cold Climates

By **Kurt Roth, Ph.D.,** Associate Member ASHRAE; **John Dieckmann**, Member ASHRAE; and **James Brodrick, Ph.D.,** Member ASHRAE

The majority of air-source heat pumps (ASHPs) are installed in moderate to warm areas of the United States, mostly south of the Mason-Dixon Line.

Two major issues make conventional ASHPs unattractive as a heat source in cold climates. First, buildings in colder climates often have appreciably smaller design cooling loads than design heating loads. Second, ASHP heating capacity and coefficient of performance (COP) decrease as the outdoor temperature, *To*, decreases because the temperature lift across the compressor increases. For these reasons, conventional ASHPs sized to meet cooling loads cannot meet the full heating loads at lower *To,* necessitating extensive use of costly, and energy-inefficient, electric resistance heating.

Conceptually, a heat pump designed for a cold climate would have sufficient capacity to meet heating loads around *To*~0°F at a reasonable COP, and would require limited (ideally, no) electric-resistance heat on an annual basis. Such a design would enable effective use of heat pumps in much colder climates than current designs. For example, it could extend the region where heat pumps could reduce heating primary energy consumption or cost over much of the northern U.S.

Several design modifications and technologies have been proposed or introduced (alone and in combination) for cold-climate heat pumps.

- *Sizing the ASHP for heating instead of cooling* • can increase capacity. It does not, however, address the problem of reduced heating cycle efficiency and capacity as *To* decreases. It also can lead to excessive cycling—and the resulting efficiency decrease—at moderate heating loads and during cooling season (since the system is oversized for those conditions).[1] Excessive cycling can, in turn, significantly decrease dehumidification effectiveness.[2]
- *Multiple or modulating compressors* • address mismatched loads by sizing compressor capacity to meet heating design loads at full capacity, while part-load operation efficiently satisfies cooling loads and dehumidification.[2,3] The problem of reduced heating cycle efficiency as *To* decreases still remains.[4]
- *Geothermal heat pumps,* • also known as ground- or water-coupled or ground- or water-source heat pumps (GSHP), overcome the problem of reduced cycle efficiency in cold ambient air by extracting heat from the soil or groundwater at approximately constant underground temperatures. In theory, they can achieve near-constant heating and cooling efficiencies year-round. In practice, in colder regions the quantity of heat extracted from the ground (during the heating season) is larger than that rejected to the ground, which depresses the ground temperature around the loop and GSHP efficiency. Still, effectively designed GSHPs in the northern U.S. can achieve average heating COPs on the order of 3 (including pumping power).[5]
- *Increased outdoor coil capacity* • enables the ASHP extract more heat at a given *To*.
- *Carbon dioxide* • *(CO_2) refrigerant cycles* that exploit the thermodynamic characteristics of CO_2 to provide about 35% greater capacity at *To* = 17°F. This decreases the use of electric resistance heating and also significantly reduces system oversizing relative to the design cooling load. CO_2 also rejects heat over a wider temperature range, enabling higher air delivery temperatures without thermodynamic penalty.[6]
- *Mechanical liquid subcooling* • increases capacity (~10%) and efficiency (~5%).
- *Optimization of the indoor and outdoor coil* • circuiting for heating mode also could enhance capacity and efficiency.

Within the past five years, at least two U.S. companies have introduced ASHPs designed for cold climates. Units developed by both companies have two compressors that operate in series. At moderate *To,* a single compressor (with multiple capacities) operates to meet the heating loads. When *To* falls below the point where the single compressor can effectively meet the heating load, a second “boost” compressor with a large volumetric capacity also runs. In one unit, the refrigerant exiting the first compressor enters the second compressor.[7] The other unit has a heat exchanger that transfers heat between two vapor-compression cycles, i.e., the condenser of the first cycle serves as the evaporator of the second cycle, but each cycle uses separate refrigerant.[8] Both configurations decrease the lift of both compressors, increasing their efficiencies and capacities.

In addition, two-stage units can incorporate a refrigerant economizer that expands a portion of the liquid refrigerant leaving the condenser to a pressure between that of the evaporator and condenser (i.e., the inlet pressure of the second compression stage). This expanded refrigerant accepts heat from the liquid refrigerant, subcooling the liquid prior to expansion, and further increasing cycle capacity and efficiency. As a result, their heating capacities drop off more slowly than conventional ASHPs while maintaining a COP of greater than 2 at T_o = 0°F.[1,9]
The rest of this article focuses on these recently introduced ASHPs optimized for cold climates.

Energy Savings Potential

At moderate temperatures, ASHPs have superior primary energy efficiency, e.g., at T_o = 45°F–50°F, an ASHP consumes about half the primary energy of a gas furnace with an 80% annual fuel utilization efficiency (AFUE). As T_o decreases, however, its primary energy efficiency* decreases rapidly and, below the balance point (i.e., where the heating load equals heat pump capacity), requires inefficient electric resistance heat.[10]

We carried out a simple analysis comparing the performance of a two-stage cold-climate ASHP to three conventional heating options, 80% and 90% AFUE furnaces and a 85% AFUE oil heat boiler, to meet the hourly space heating loads of ~3,000 ft^2 (280 m^2) homes constructed since 2000 in Chicago, Minneapolis, and New York.† The heating COP and capacity data are based on curve fits for laboratory test data for an ASHP designed for cold climates.‡ When the heat pump lacked sufficient capacity to meet space heating loads, the model assumed that the system activated electric resistance heating to meet the remaining heating load.

The analysis found that, relative to an 80% AFUE furnace, the heat pump designed for cold climates will achieve negligible primary energy savings in Minneapolis and appreciable savings in Chicago and New York (~12% and 19%, respectively). When compared to an AFUE = 85% oil boiler, the heat pump reduces primary energy consumption by about 12% in New York, and has a marginal primary energy impact in both Chicago and Minneapolis. Relative to a high-efficiency furnace (AFUE = 90%), it would realize moderate primary energy savings in New York (~6%), negligible savings in Chicago, and consume more (~9%) primary energy in Minneapolis. In all three cases, the heat pump modeled had an average annual COP of between 2.6 and 3.0, similar to GSHPs in those climates.[5]

In addition, the heat pump offers some energy savings during the cooling season relative to units meeting the minimum SEER required for residential central air-conditioning units. Due to the relatively small space cooling loads in the target climates, the annual and national cooling energy savings would be small.

Market Factors

In heating-dominated climates, heat pumps compete for market share against furnaces and boilers. Using the prior energy consumption analyses described for the homes in Chicago, Minneapolis, and New York and applying average residential energy costs,§ the heat pump designed for cold climates would reduce space heating energy costs by approximately 28 to 38% relative to an AFUE = 80% gas furnace and 19% to 30% relative to an AFUE = 90% gas furnace. Relative to an AFUE = 85% heating oil-fueled boiler, the estimated energy cost savings range from 51% to 58%.

As expected, the percent savings are greatest in the warmer location (New York) and least in the coldest location (Minneapolis), with the maximum energy cost savings occurring in the Chicago climate.

Preliminary information suggests an approximate installed cost premium of between $3,000 and $4,000 relative to conventional ASHPs.[1] This estimate is based on products from a single manufacturer, so the entry of an additional manufacturer into the market will likely decrease the first cost premium, e.g., one manufacturer estimates that their reentry into this market will decrease the incremental first cost by approximately $1,000.[8] Taking this at face value and comparing conventional ASHP costs with those of gas furnaces and oil boilers,[11] heat pumps designed for cold climates should have a first-cost premium of about $4,500 to $5,500 relative to an AFUE = 80% gas furnace, $3,900 to $4,900 relative to an AFUE = 90% gas furnace, and $2,600 to $3,700 relative to an AFUE = 85% oil-fired boiler). These translate into simple payback periods (SPPs) on the order of nine to 11 years, 11 to 13 years, and two to three years, respectively. All of these SPPs would decrease when compared to the additional cost of installing a central air-conditioning system. Interestingly, a GSHP has an installed cost premium of approximately $1,200 to $2,200[1,11] while achieving a similar heating COP in colder climates (including parasitics).

In addition, laboratory test data indicate that at least one ASHP designed for cold climates can deliver air at higher temperatures than conventional ASHPs, i.e., at 99°F (37°C) or higher under most conditions.1

ASHPs designed for cold climates are new products and, as such, they have not yet had the opportunity to establish their reliability. Limited field testing of an earlier model of a cold climate ASHP found that it had significant reliability issues.8,12 In addition, the earlier model did not approach its laboratory performance in the field, i.e., the units had significantly lower COPs and also delivered air at appreciably lower temperatures than anticipated.12 It is not clear if newer models have addressed these reliability issues and performance discrepancies. To realize their energy and energy cost savings potential—and, ultimately, their market potential (since cost savings impact SPP)—newer units will need to match their laboratory performance in the field.
In addition, both developers are smaller companies that will need to establish the full infrastructure to successfully market and support these products.

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Kurt Roth, Ph.D., and John Dieckmann are principals with TIAX LLC, Cambridge, Mass. James Brodrick, Ph.D., is a project manager with the Building Technologies Program, U.S. Department of Energy, Washington, D.C.