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Future Energy

Distributed and localized cooling with thermoelectrics

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Thermoelectric semiconductors provide a quiet, refrigerant-free alternative to traditional vapor compression cooling (VCC). It has long been assumed that the figure of merit, *ZT*, of thermoelectrics is too low to compete with VCC. While this may be true for typical VCC designs where a large temperature drop is required, distributed cooling systems may require only *ZT* = 0.5 which is available today. In this perspective we outline the concept of Distributive Cooling using thermoelectrics to heat or cool only where it is needed and when it is needed. Only the uncomfortable occupant needs heating or cooling, not the entire room, vehicle or building. Such a system level efficiency improvement could revolutionize the way we think about HVAC and provide disruptive technologies that make a real difference to global energy use and climate change.

The energy use and dramatic environmental impact of refrigerants collectively imposes the need to transform cooling technology to address climate change in a significant manner. Heating, ventilation, and air conditioning (HVAC) accounts for over 25% of electricity use in the USA, and by 2060 energy use from cooling could overtake heating. Refrigerant management, i.e., replacing the high global-warming-potential refrigerants themselves, is the largest (10%) component of the climate change solution proposed by Project Drawdown (see Note S1). Enhancing energy efficiency through smart, efficient HVAC systems could transform energy usage and facilitate rapid integration of renewable energy.

In the current centralized architecture for heating and cooling, a large fraction of the energy consumed is simply wasted. HVAC systems are typically designed to heat or cool an entire building or vehicle in the worst-case scenario,[1] and this results in continuous operational inefficiency.[2] Such "overcooling" and then reheating is ubiquitous because platform designs emphasize reliability, simplicity, and initial cost even if energy consumption, user comfort, and health are more valuable to the operators and occupants. Such energy intensive, centralized heating and cooling has been the design theme for many decades even though component technologies have advanced significantly.

Heating or cooling only where and when it is needed (referred to as distributed HVAC) (Figure 1) builds upon the theme of localized as opposed to centralized heating or cooling. Distributed HVAC has the potential to dramatically improve the energy efficiency and reduce the overall energy consumption of a variety of platforms including residential and office buildings, vehicles, storage containers, and warehouses. Instead of heating/cooling an entire building, everywhere, all the time, it can be much more efficient to heat or cool only the occupants or objects that need it, and only when and where discomfort is sensed.[4]

Electric vehicles will likely be an early adopter of distributed HVAC (Figure 1) because every watt spent on climate control results in reduction of the vehicle range or adds to battery cost and weight. Distributed heating and cooling systems are anticipated to sense occupants' discomfort and then automatically control heating or cooling of seats, steering wheel, windows, etc., as well as direct airflow where it is needed. Where today's car can require up to 5 kW for the HVAC system, tomorrow's might only use 100–200 W to cool the car seat and other accessories.[5]

The whole building environment does not need to be at the same temperature; rather, the occupants' local environment and the building's global environment can have separate temperatures. Advances in controls and sensing, supported by the internet-of-things, have reached a level that can address the requirements for implementing distributed HVAC in the built as well as the transportation environment.[6] Examples for these advanced controls would be net-zero commercial buildings such as "The Edge" in Amsterdam, and One Angel Square in Manchester, UK. Smart building control systems can also achieve grid integration, wherein a building can participate in demand response to lower energy costs and/or shift loads to times when electric power is available from renewable resources.

Separate HVAC zones for individual rooms is known to provide better comfort and improved energy efficiency. Distributed HVAC for large buildings typically involves hot and cold water to store heat and move it from room to room. Smaller buildings and individual homes can simply distribute the humidity and temperature-controlled air

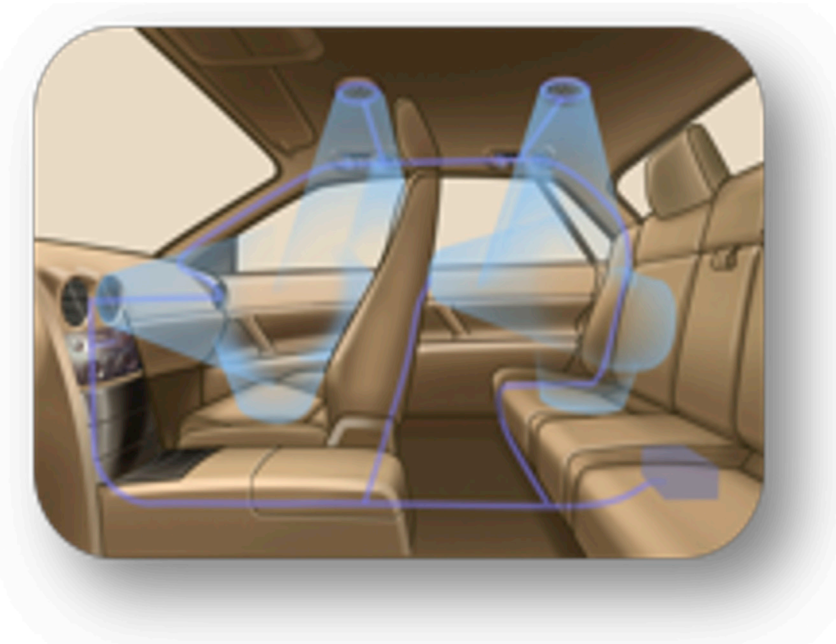

Figure 1. Distributed cooling anticipated for vehicles
Where traditional HVAC systems require up to 5,000 W of power, cooling the car seat of only the uncomfortable passenger might require only 100–200 W of electrical power, thus extending the range of an electric vehicle.
From Maranville.[3]

to select zones when it is needed. Such systems have relatively low cost but only take limited advantage of the distributed HVAC concept.

Micro-distributed HVAC on-demand concepts might include individual bed, seat, desk, floor, and surface heating and cooling.[4] Enabling this distributed architecture will be a new generation of associated sensors and controls. Individual micro-climates would then unobtrusively follow each individual throughout the day. The micro-distributed heat pumps for both heating and cooling could reject heat to the room HVAC controlled by the macro-distributed system. Although a micro-distributed cooling device will add heat to a room, the target room temperature can be raised leading to an overall decrease in room HVAC needed.

Solid-state heat pumps, such as thermoelectric (TE) Peltier coolers will enable micro-distributed HVAC. These economical small semiconductor devices can instantaneously provide heating or cooling with no moving parts, no noise nor harmful liquids or gases. Thus, solid-state TE heating/cooling has potential to provide transformative effects on the environment, platform design, user experience, and energy demand.

The coefficient of performance (COP), j, defined as the heat removed, Q_c, divided by the electrical power consumed, W, is limited by thermodynamics to be less than that of a Carnot engine, $\Delta T/T_c$, where T_c is the temperature (in Kelvin) being cooled and ΔT is the difference between T_c and the heat rejection temperature T_h.

$$\phi = \frac{Q_c}{W} = \frac{T_c}{\Delta T}\phi_r$$

For a typical thermoelectric cooler (TEC) (shown in Figure 2), the fraction of Carnot COP, j_r, is 10%–20% and increases with device ZT.

Thermoelectric (Peltier) coolers are commonly used in systems requiring only 100 W of cooling or less because of cost and low COP at large ΔT. However, thermoelectrics can be competitive at low ΔT (Figure 3). Although vapor compression cycles (VCCs) can exceed 50% of Carnot under ideal conditions, their COP does not improve substantially when operating at smaller ΔT like a TE system. The USA requirements for EnergyStar certification, COP > 3.7 for ΔT of 8K (EER = 12.5 under EER test conditions) (see Note S2), is only 9.8% of Carnot. This is close to a thermoelectric figure of merit of 0.5, which is easily obtainable with commercial TE coolers even considering heat exchanger losses.[7] Larger ΔT might be needed for humidity control (or required for refrigeration) where VCC systems can maintain good COP, whereas TE systems tend to have a constant j_r.

Complex heat exchanger designs can be devised that reduce the ΔT requirement, making the COP of TE systems competitive to VCC. In a micro-distributed HVAC system, a change of only a few degrees could be sufficient to provide comfort. Advanced heat exchanger technologies[5] that reduce ΔT will be an enabling technology for the use of small, distributed cooling systems. The cost of small heat pumping systems is typically dominated by the heat exchanger. Thus, the cost in US dollars per W of a micro-distributed HVAC system (such as the seat in Figure 2), is typically controlled by heat flow system cost and ZT (which determines the relative COP).[10]

For systems meeting these minimum efficiency requirements, cost becomes the main driver. Large VCC systems have cost, COP, and ΔT advantage. The cost of the VCC reduces slowly as its size is reduced, making them easy to oversize.[1] The cost of TE, in comparison, typically scales linearly with size,[10] making them ideal for small systems.

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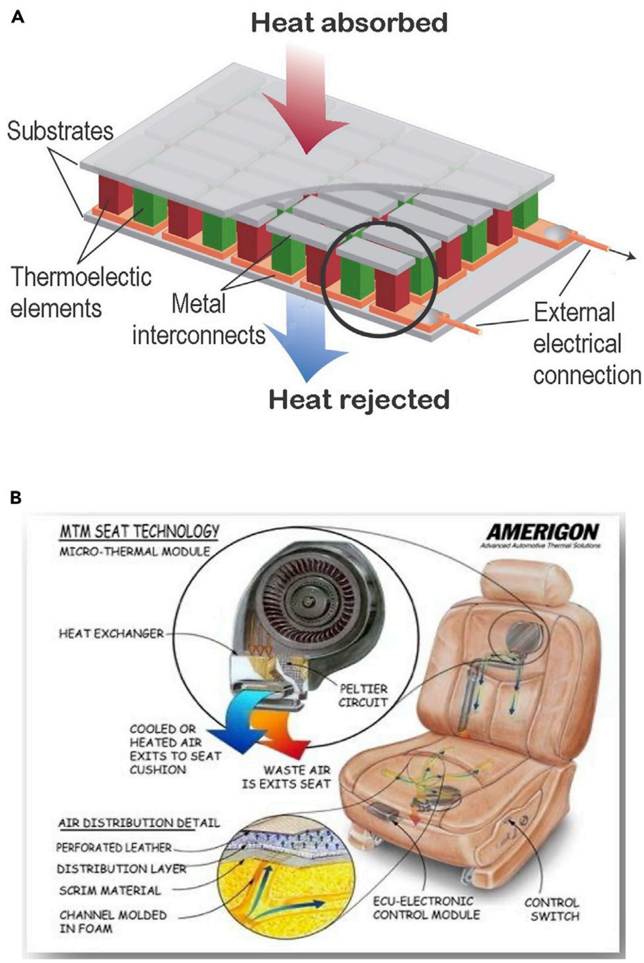

Figure 2. Thermoelectrically cooled seat

(A and B) Shown is a (A) thermoelectric cooling or heating module (from Snyder[8]) and a (B) car seat design (from Lofy and Bell[9]) The all-solid-state thermoelectric device and small fan provides instant cooling or heating at a precise location.

Thus for cooling power of 1 kW or more VCC is always used, but for applications requiring 100 W or less, thermoelectric Peltier coolers are preferable.[11] Improvements in TE materials, heat exchangers, and controls as well as cost reductions will gradually push the market for Peltier cooling to larger systems starting with small refrigerators and micro-distributed HVAC units.

Heat pumps work like a refrigerator in reverse, providing thermal heating power greater than the input electrical power (Q_h/W > 100%) by pumping heat from the cool ambient. Heat pumps can be highly efficient heating —even more efficient than using waste heat that is available at seemingly no cost (e.g., from power plants).[12]

Even more localized are wearable thermoelectric devices[13] to provide immediate heating and cooling at an exact location on the body. Beyond improving comfort by managing body heat within healthy levels,[14] such systems can affect the perception of thermal comfort simply by adding user control.[15] By making a slightly warmer room more comfortable, overall energy demand can be reduced. The flexible technology rapidly being developed for wearables can also be incorporated in furniture, beds, and other accessories in direct contact with the occupant. For portable cooling systems, their power supply will be an additional issue. Again, for effective use an integrated system design including the heat exchanger is imperative.[13]

Much of the research in TE is focused on new thermoelectric materials. For distributed HVAC ZT > 0.5 might be sufficient providing opportunity for non-toxic and recyclable materials. Devices will need to be durable as well as inexpensive.

However, for such ideas to be economically transformational and impactful to society requires a convergence of technology, design, and consumer behavior. Systems are likely to first appear in the automotive industry because this convergence is ingrained, and energy efficiency needs of EVs are so pressing. For the built environment, aspects of a distributed HVAC concept have been proposed and even demonstrated on a small scale, but the concept has not proliferated because of a lack of convergence. Beyond a techno-economic analysis to estimate market impact, a coherent collaboration is needed to gauge consumer and regulatory acceptance as well as life cycle analysis to predict the impact on sustainability. Ultimately, the convergence of all stakeholders—engineers, designers, builders, owners, regulators, and users—is needed for the adoption of energy-efficient distributed HVAC technology in residences to have an impact on personal comfort, society, and climate change.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2021.02.011.

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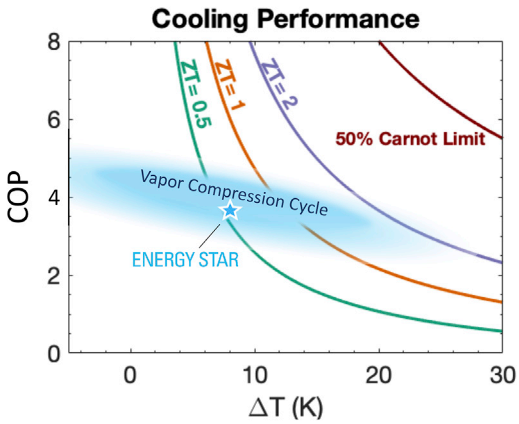

Figure 3. Thermoelectric cooling performance

The coefficient of performance (COP) of a thermoelectric system is highly dependent on the temperature difference, ΔT. Thermoelectric systems can be competitive at small ΔT compared with commercial vapor compression cycle systems.

See also Figure S1.

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