Personal Cooling and the Roving Comforter

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Summary

Today we heat and cool buildings to a single target temperature. Some problems with this conventional regime can be readily observed: first, people have differing opinions of the appropriate target temperature; and second, conditioning a whole building requires much more energy than conditioning the air immediately surrounding the occupants. In contrast to most conventional approaches to decreasing energy consumption, personal cooling offers a plug and play solution by providing localized space conditioning directly to individuals. This shift in perspective, from the room air temperature to the individual, opens new possibilities to enable more sustainable cooling architectures for energy efficient space and building design at lower cost.

Introduction

Space cooling represents a significant energy technology market in the United States, since most households (87 % in 2015 [1]) and commercial buildings (80 % in 2012 [2]) are equipped with cooling equipment. In addition to human comfort, space cooling helps to maintain safe storage temperatures for various goods, products, or equipment (data centers), while also providing comfortable working conditions to increase worker safety and productivity. Cooling large spaces to maintain desired ambient conditions necessitates significant energy and financial expenditures. Recent data suggests that space cooling accounts for 6 % of energy use in U.S. residences [3], which is reflected in homeowners spending \$35 billion of their total energy-related costs on space cooling in 2010 [4]. Furthermore, 9 % of energy use in U.S. commercial buildings is attributed to this energy sector [5], or \$25 billion in 2010 [6].

Improvements in space cooling technologies include tuning existing systems, reducing heat loads to minimize the burden on cooling systems, replacing older equipment with higher efficiency equipment, and adjusting to the changing demand determined by building occupancy. Although these solutions can decrease the net energy required for the same cooling demand, the general approach to space cooling is energy inefficient: maintaining a single target temperature within an entire building to satisfy small portions of occupied space.

What is the penalty paid for cooling a whole building instead of an individual person? For a sense of perspective, consider a building with 232 m^2 (2500 ft^2) and 2.4 m (8 ft) high ceilings. This represents a conditioned volume of 566 m^3 (20,000 ft^3). With a typical human body volume of 0.075 m^3 (2.6 ft^3), the building is 7500 times larger! If a hypothetical monthly \$75 cooling bill could be proportionally reduced, it would be \$0.01. Of course, one could argue that volume correlates to stored energy, whereas area correlates to heat gain. Along these lines, assuming the building is above ground with two stories and an aspect ratio of 2:1, the external surface area would be 455 m^2 (4900 ft^2), compared with 1.75 m^2 (18.9 ft^2) of a person. This gives a ratio of 260, and our hypothetical monthly bill would be reduced to \$0.29.

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The purpose of going through these simplistic comparisons is to demonstrate the huge potential of localized cooling to dramatically change the energy requirements of keeping people comfortable. Rethinking the traditional approach to space cooling and reducing energy consumption is critical to our energy infrastructure as cooling demand is only expected to increase both nationally and internationally as incomes rise and urbanization advances.

Personal Cooling

Personal cooling is the use of localized thermal management to maintain a comfortable ambient temperature to an individual without entirely relying on a centralized conditioning system. This approach to air conditioning offers numerous benefits over traditional systems. First, adapting the thermal environment around the individual rather than cooling unoccupied space within a building results in significant energy savings. In environments conditioned with centralized systems, such an approach allows building temperature set points to be increased to save energy, with additional cooling demand provided locally through personal cooling technologies. For example, a recent study suggested that by increasing the cooling set point of a building from 22.2°C (72°F) to 25°C (77°F), an average of 29 % of cooling energy savings can be achieved [7]. Furthermore, personal cooling offers the ability to adapt to the local surroundings and personal preference, recognizing that thermal comfort is a result of both human perception and heat transfer. The elements of heat transfer include convection to surrounding air, evaporation from the skin, and radiation with surrounding surfaces, all of which are impacted by the local environment within a building.

In addition to reducing cooling in unoccupied spaces, other benefits of personal cooling include space conditioning where centralized conditioning is infeasible, addressing barriers to entry in the market, and improving local air quality. In areas where centralized conditioning is impractical, such as in large warehouse spaces, personal cooling can condition immediate space around workers to improve safety and productivity, or in specific areas that require lower ambient conditions. Secondly, decentralized systems offer a much faster rate of market adoption as the infrastructure required for large-scale cooling systems is not required, and initial capital costs are more flexible. Furthermore, costly retrofits to entire or parts of centralized cooling systems can be delayed or reduced with the use of personal cooling devices. An additional potential benefit is improved local air quality achieved through embedding a filtering system in the conditioning device.

Recognizing the potential of personal cooling as well as the significant challenges that exist to deploy personal cooling on a large scale, ARPA-E (Advanced Research Projects Agency-Energy) developed the Delivering Efficient Local Thermal Amenities (DELTA) program. This program aims to develop technologies that adjust the physical space around the human body rather than the entire building and that address key challenges including cost, waste heat management, operating time, and personal comfort evaluation. One such technology is the Roving Comforter, a highly efficient and mobile personal cooling device.

Roving Comforter – RoCo

The Roving Comforter, or RoCo, is a portable device that provides personal thermal management for individuals in inadequately air-conditioned or even unconditioned environments. This technology is being developed through research conducted by the University of Maryland, Oak Ridge National Laboratory, and the newly formed start-up, Mobile Comfort. It incorporates the latest components for compact vapor compression, high-conductivity phase change thermal storage, low-cost sensing and controls, battery technology, and emerging understanding and techniques regarding personal thermal comfort. As shown in Figure 1, the portable device requires no external wires or ventilation while in use.

Though many versions and features are currently being investigated to adapt to the needs of various target markets, the three main components are a movable yet stable platform, highly efficient thermal management module, and intelligent nozzles. The portable platform increases the flexibility of the cooling device to service multiple areas. The first prototype incorporated a robotic platform to enable it to follow one or several designated occupants and provide cooling as required, using technologies such as omnidirectional Wi-Fi from wearable devices.

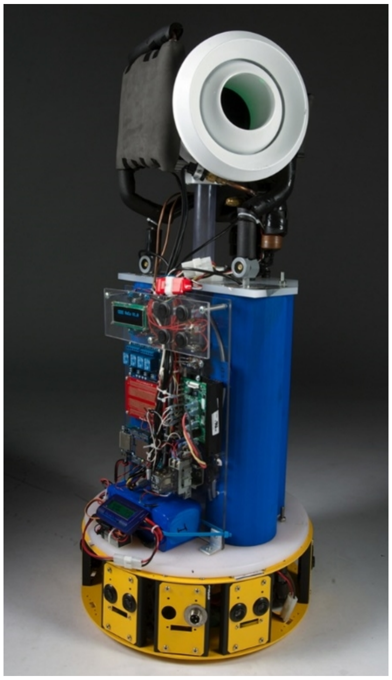

Figure 1. First RoCo prototype. Credit: John T. Consoli/University of Maryland.

The heart of this personal cooling device is the next generation miniature heat pump system with built-in waste heat storage. Equipped with a mini-compressor and compact air-to-refrigerant heat exchangers, the system delivers cooling with minimal power consumption. An onboard battery provides power to the compressor. Additionally, the condenser incorporates a phase change material (PCM) that stores heat removed from the refrigerant as latent heat during operation to further increase the energy efficiency of the device. Use of a PCM enables higher energy storage density with lower refrigerant condensing temperatures due to the near isothermal PCM transition from solid to liquid as shown in Figure 2. Incorporation of high conductivity graphite foam within the PCM has been shown to increase the rate of waste heat storage and decrease the temperature gradient within the storage material.

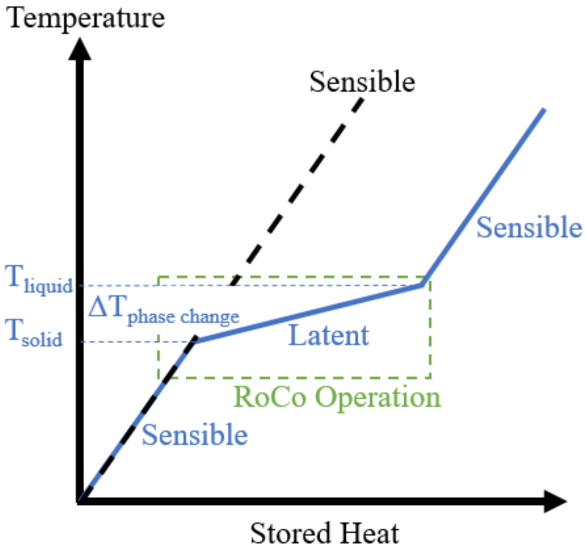

Figure 2. Comparison of stored heat to temperature for sensible and latent heat storage materials.

RoCo operation ends once the PCM has fully undergone phase change as further heat storage through sensible heating would increase the temperature of the condensing refrigerant, decreasing the overall efficiency. Though the operating time determined by the application governs the required mass of PCM, the objective is to design the PCM condenser to provide cooling on demand and discharge the waste heat when conditioning is not required.

To discharge the stored heat, the RoCo functions in a thermosiphon mode of operation. Refrigerant enters the lower section of the thermosiphon loop as a liquid and absorbs heat from the PCM. The heat addition causes the refrigerant to evaporate and rise to the top where it is condensed by a heat removal mechanism. The condensed liquid flows back to the lower portion of the loop and is heated again. The cycle repeats and leads to a continuous operation until the PCM has re-solidified. During this discharge operation, the compressor and the expansion valve are bypassed to reduce pressure drops. Thermosiphons operate with relatively small temperature differences between the heat source and heat sink, and without any moving parts, making them ideal for operations where low cost, energy efficiency, and reliability are important.

Optimally delivering the conditioned air is achieved through intelligent nozzle design. Thermal comfort studies reveal that various parts of the human body have different sensitivity levels for thermal sensation. The use of intelligent nozzles allows the RoCo to not only adjust supply air locations, but also adjust supply air conditions. Examples of advanced functionality include storing preference data such as air temperature and velocity for different human metabolic rates or tracking and adjusting nozzle location as the user moves throughout a room.

Combining these three areas of innovation results in a personal cooling device that offers significant energy savings. An example of the reduction in energy consumption for two climate scenarios is shown in Figure 3. The greatest benefit is demonstrated for mild climates resulting from an increased building temperature set point supplemented with localized cooling to maintain the same thermal comfort level.

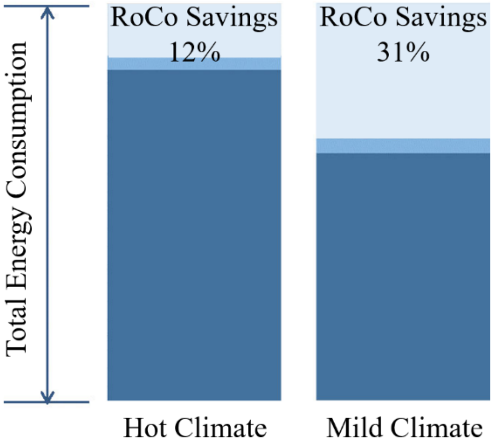

Figure 3. RoCo energy savings from expanded temperature set points for the same thermal comfort in different climates.

The first RoCo prototype was showcased at the 2016 Advanced Research Projects Agency-Energy (ARPA-E) Energy Innovation Summit. A later prototype was displayed at Maryland Day on the University of Maryland campus and was demonstrated at the 2016 Maker Faire. The most recent prototype was demonstrated at the 2017 ARPA-E Energy Innovation Summit. Ongoing research includes methods to reduce the cost through component and PCM selection, understanding operating requirements of various markets, and conducting personal comfort evaluations.

Conclusion

Innovation in space cooling is necessary for the next generation of energy efficient buildings. Air conditioning is traditionally provided by centralized systems that cool a building space to a target temperature. Personal cooling enables localized space conditioning, reducing the amount of wasted energy used to cool unoccupied building areas. One invention addressing this need is the Roving Comforter. This portable conditioning device is being developed to allow higher building temperature set points, while keeping the occupants comfortable at a lower energy consumption. Use of a movable platform, highly efficient thermal management module, and intelligent nozzles enables the Roving Comforter to provide flexible space cooling anywhere at any time.

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Acknowledgements

This material is based upon work supported by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000530.

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