



Annex 53

Advanced Cooling/Refrigeration Technologies Development

Task 1 Report

Operating Agent: USA

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Energy and Transportation Science Division

**IEA/HPT Annex 53 Advanced Cooling/Refrigeration Technologies Development – Task
1 Report**

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ANNEX 53 TASK 1 REPORT—IDENTIFY FOCUS AREAS FOR ANNEX TECHNICAL CONTRIBUTIONS

1 BACKGROUND AND INTRODUCTION

Air conditioning (AC) and refrigeration systems account for a large share of today's global energy consumption, and this demand is expected to increase sharply over the next 50 years unless actions are taken to ameliorate the increase. The adoption of AC in developed countries increased rapidly in the twentieth century, and the twenty-first century is expected to see increased adoption in developing countries—especially those with hotter climates and large, growing populations, such as India, China, Brazil, and Middle Eastern and African nations. The International Energy Agency (IEA) projects that by 2050, AC energy consumption levels will increase by 4.3 times over the 2010 levels for non-Organization of Economic Coordination and Development (OECD) countries vs. only 1.5 times for OECD countries (Figure 1).¹

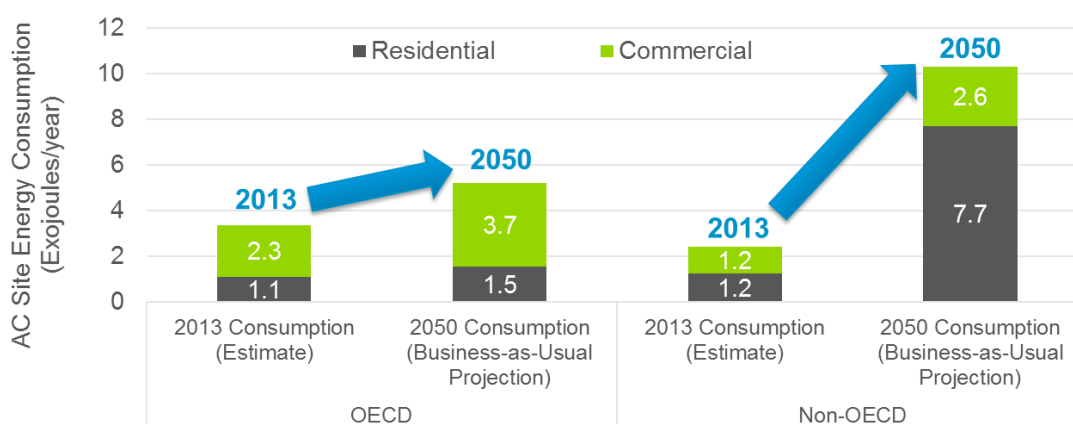


Figure 1: Anticipated global AC demand increases (courtesy Navigant Consulting, Inc.; source: IEA Energy Technology Perspectives 2016)

The demand for refrigeration is expected to increase at a similar rate to the demand for space cooling. Most of the demand for refrigeration is related to food preservation and storage, and the food demand is expected to increase 70% by 2050 relative to 2010.² India, for example, has the largest refrigerated warehouse capacity of any country in the world: >140 million m³ of space in 2016, which is an 8% increase since 2014.³ Moreover, a huge increase in refrigerated transport capacity also is needed to properly serve the warehouse capacity and reduce food wastage. India is estimated to have 9,000 refrigerated trucks currently, but the country needs >600,000.² The need for much cleaner and more efficient refrigeration systems is critical. The UN Food and Agriculture Organization (FAO) estimates that about one-third of all global food produced is wasted, resulting in huge environmental consequences. FAO estimates that this wastage occupies a land area the size of Mexico, its production consumes 250 km³/y of water, and it accounts for 3.3 billion tons/y of CO₂ emissions.

Stationary AC systems alone account for nearly 700 million metric tons of direct and indirect CO₂-equivalent emissions (MMTCO₂e) annually. Indirect emissions from electricity generation account for about 74% of this total, direct emissions from hydrofluorocarbon refrigerants account for 7%, and hydrochlorofluorocarbon refrigerants account for 19%. With regard to

¹W. Goetzler et al. 2016. "The Future of Air Conditioning for Buildings," US Department of Energy Report DOE/EE-1394, July 2016. <https://www.energy.gov/eere/buildings/downloads/future-air-conditioning-buildings-report>

²University of Birmingham. 2015. "Doing Cold Smarter," Birmingham Energy Institute. <http://www.birmingham.ac.uk/Documents/college-eps/energy/policy/Doing-Cold-Smarter-Report.pdf>

³V. Salin. 2016. "2016 Global Cold Storage Capacity Report," Report for the Global Cold Chain Alliance.

refrigeration for food preservation, if all the additional food transport trucks needed in India alone were produced to use current diesel-powered cooling technology, then the impacts from NO_x and other emissions would be enormous. Transitioning to low-global warming potential (GWP) alternative refrigerants could eliminate most direct greenhouse gas (GHG) emissions from AC and refrigeration, theoretically leading to up to a 26% global reduction in annual GHG emissions related to AC and refrigeration—even without improving system efficiency.¹

Global action, both short term (e.g., increasing the deployment of current “best” technologies) and long term (research, development, and demonstration [RD&D] for advanced, higher-efficiency technology solutions), is urgently needed to address this challenge. Annex 53 was initiated in October 2018 to help address the long-term RD&D need. Its main objective is to share information to encourage the development of high-efficiency and low-GWP AC and refrigeration heat pump (HP) technologies. The Annex is led by the United States, and other participating countries include the People’s Republic of China, Germany, Italy, and South Korea. Sweden has announced its intention to join as well, and the Annex is open to new members through the end of 2020.

This report introduces the advanced AC and HP (AC/HP) systems and refrigeration technologies that Annex participants are investigating. This report provides a summary of the technologies from each research and development (R&D) institution involved in the Annex. These brief reports describe the basic AC/HP/refrigeration cycle concepts underlying each project, a brief description of each project (e.g., current development status, plans for further development, and some indication of performance vs. current systems), and initial target markets and applications.

2 SUMMARY OF THE TECHNOLOGIES UNDER INVESTIGATION

The technical scope of Annex 53 is very broad by design. It is unlikely that there will be only one or even a few “right” solutions to the challenge. Technologies of interest follow two distinct paths: those based on the well-known and widely used vapor compression (VC) system and those based on nontraditional cooling approaches that are being increasingly investigated (Figure 2). VC technology has had decades of RD&D, which is still ongoing. VC could continue to be the system of choice, especially for the near future and possibly for the long term. However, if VC cycle (VCC) systems continue to use fluorocarbon-based refrigerants with nonzero GWP—even in small amounts—they will remain vulnerable to further refrigerant restrictions. Nontraditional technologies (e.g., magnetocaloric [MC], elastocaloric [EC], electrochemical compression [ECC]) generally are not subject to this challenge, since they do not rely on refrigerants in the traditional sense. However, all the nontraditional technologies discussed herein will require additional development before they can significantly impact the market.



Figure 2: Two possible future paths for refrigeration and AC systems (courtesy Navigant Consulting, Inc.; source: US Department of Energy Building Technologies Office, Emerging Technologies Program)

This section is divided into two parts that deal with the two general future paths described previously. VC or other compression-based projects are covered in Section 2.1, and nontraditional technology-based projects are covered in Section 2.2.

2.1 Advanced VC-Based Project Descriptions

Table 1 provides a summary of each VC-related project investigated by the Annex 53 participants. Brief summaries and the development status and plans for each project are included.

Table 1: Advanced VC focus

R&D institute	Technology description	Initial target market/application
Korea Institute of Machinery and Materials (KIMM), South Korea	Membrane-based HP; vacuum pump compression; water as refrigerant	Building AC and dehumidification (DH)
Tsinghua University, China	Novel two-stage VCC system with double internal heat exchangers (HXs) and zeotropic refrigerants	Residential AC and HP; development focus thus far has been heating
City University of Hong Kong, China	Hybrid-energy HP (combined absorption-compression cycles)	Using renewable energy or waste heat recovery as a thermal energy source (e.g., solar cooling)
Institute for Advanced Energy Technologies (ITAE), Italy	Adsorption transformation for cooling (thermal compression)	Integration with renewable energy sources; waste heat recovery in industrial processes; integration in combined cooling, heat, and power; mobile AC/refrigeration
University of Maryland, USA	a) ECC: selective fluid pumping via chemical process (no moving parts) b) Electrohydrodynamic (EHD)-enhanced electrochemical DH	Building AC for latent and sensible cooling; evaluating the integration of NH ₃ ECC with NH ₃ synthesis to produce and store liquid NH ₃ for use as internal combustion engine fuel
Oak Ridge National Laboratory (ORNL), USA	Expansion loss pressure exchanger (PEX) technology applied to advanced VC systems	VC refrigeration, particularly systems using CO ₂ as the refrigerant

2.1.1 Membrane heat pump (South Korea)

Lead PI: Dr. Seok Ho Yoon (KIMM)

Description: With the developmental advances in nanotechnology, various functions of membranes are being investigated, including applying membrane technology to HPs or ACs for DH and cooling (Woods 2014). A membrane HP is composed of a membrane DH unit and cooling unit, and it uses water as a refrigerant. The membrane DH unit uses a membrane with a channel that allows water to pass through but blocks air passage. Since the driving force for DH uses the partial pressure difference of water vapor, a vacuum pump is required. The cooling unit can apply various techniques. Korean researchers combined membrane technology with nanocomposite technology to develop a new membrane material with selective permeability of air and water. This membrane has hydrophilic nanochannels. The researchers developed various organic-inorganic and organic-organic composite membranes. Indirect evaporative cooling equipment was used for the cooling unit. An overall system schematic is shown in Figure 3.

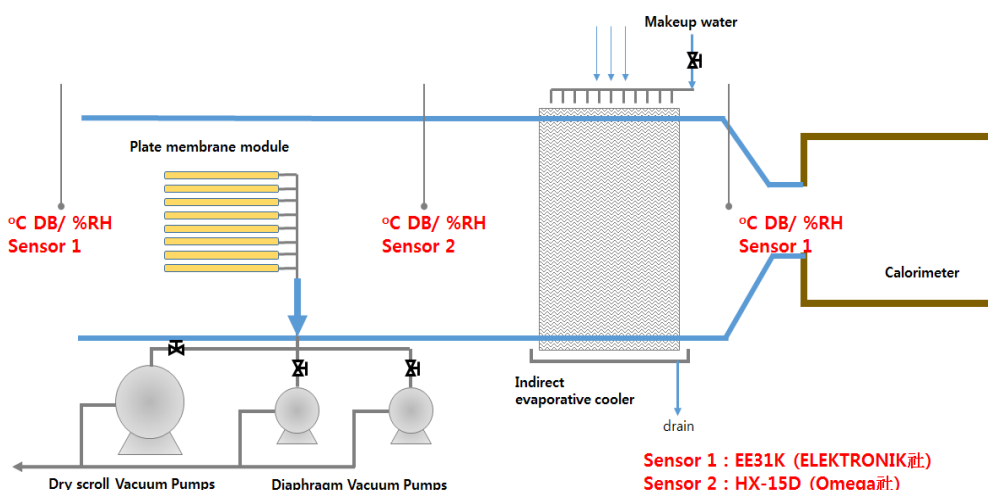


Figure 3: Schematic of the membrane HP

Development status and plans: The representative DH membrane being used in the KIMM pilot system is a hydrophobic polyurethane (PU)-based dense membrane that has a nonionic water vapor channel composed of silica particle clusters. Silica particles that are 150 nm in size are surface modified with a silane coupling agent to control dispersion in the PU membrane. The membrane contains 4.8 wt % of silica particles, and its thickness is about 10 μm . According to the ASTM E96 method (desiccant method, 38°C, 90%), the measured water vapor transport rate is about 150 $\text{g}/\text{m}^2\text{h}$ (Kim et al. 2019).

A large amount of membrane was needed to match the capacity of the pilot lab's test membrane HP system. Membranes were produced in a roll-to-roll production facility, as shown in Figure 4. The solution was coated on a release film and followed by thermal drying. The production conditions were modified several times to optimize the quality by making the film thickness uniform.



Figure 4: Manufacturing process of large-area membranes

A pilot system with integrated DH and cooling units was built, as shown in Figure 5. The DH unit comprises more than 100 membrane modules, each 300 × 200 mm with DH membranes attached to both sides. Each module is individually connected to a vacuum manifold made of silicone tubes. An indirect evaporative cooling unit and the DH and cooling units connect to ducts for air supply to and return from the conditioned space. The pilot system will be used for performance tests on various operating conditions. Preliminary pilot system tests were conducted under the conditions specified by the Korean standard for AC KS C 9306 (entering dry bulb temperature: 27°C, entering wet bulb temperature: 19°C). The preliminary results (Figure 6) confirm the feasibility of the pilot system by showing that the system reduced the process (room) air relative humidity by 3–5% and reduced the dry bulb temperature by ~5°C,.

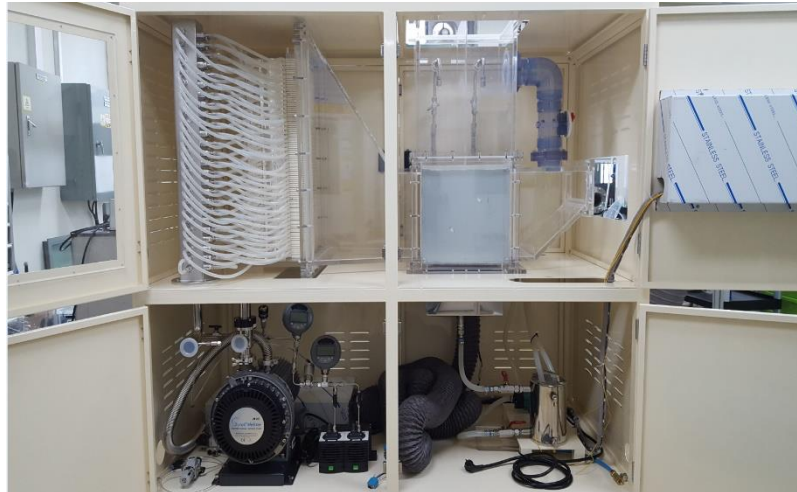


Figure 5: Pilot system of the membrane HP: (top left) the DH unit; (top right) an indirect evaporative cooling unit; (bottom left) the vacuum pump (compression) system; and (bottom right) the water supply module

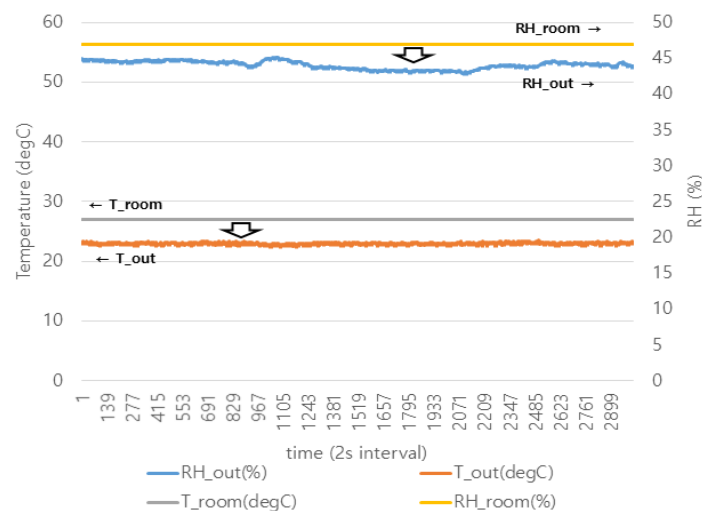


Figure 6: Preliminary test result of pilot membrane HP

Project References:

Kim J., Kim D. H., Kim Y., Kim H. S., Seo Y. -S., Park H. G., and Yoon S. H. 2019. "Analytic Approach to Analysing the Performance of Membrane Dehumidification by Pervaporation," *Journal of Mechanical Science and Technology*, Vol. 33, No. 6, pp. 1–6.

Woods J. 2014. "Membrane Processes for Heating, Ventilation, and Air Conditioning," *Renew. Sustain. Energy Rev.*, Vol. 33, pp. 290–304.

2.1.2 Novel two-stage VC system with zeotropic refrigerants

Lead PI: Dr. Baolong Wang (Tsinghua University)

Description: The underlying technical concept in this project is to use zeotropic refrigerant mixtures in a VC system to achieve higher system efficiencies by matching the HX temperature changes of the mixtures or to glide to the temperature change of the source and sink fluid streams. Theoretically, using zeotropic refrigerants with the Lorentz cycle could achieve this. However, in most cases, the temperature variations of the evaporator and of the condenser fluids are very different. For example, for a room air conditioner in cooling mode, the indoor air temperature changes from 26 to 13°C due to the DH requirement, but the air in the outdoor unit is heated only from 35 to 40°C (for a high-energy efficiency room air conditioner). For a heat recovery HP, the water on the wastewater side can be heated by ~3–5°C. Comparatively, the hot water is heated from 60 to 90°C. Therefore, the simple Lorentz cycle cannot fit this demand.

This project's goal is to develop a novel two-stage VC cycle, that can maintain different refrigerant concentrations in the evaporator and condenser to match the temperature profiles in both HXs.

Development status and plans: According to previous research on a (quasi) two-stage compression cycle, using a flash tank (FT) economizer can realize different concentrations of a zeotropic mixture in the evaporator and condenser. Evaluations using a zeotropic mixture of R-1234ze and R-32 concluded that FT concentration shifting lowers energy efficiency even though the temperature matching is improved. Accordingly, a novel double internal auto-cascade (DAC) two-stage compression system with a double intermediate HX (IHX) was proposed and is under development. Figure 7 provides a system schematic and p-h cycle diagram of this system. The DAC can effectively modulate the refrigerant concentration going to the evaporator and the injection port and provide a refrigerant richer in the high-pressure component to the evaporator, enhancing the system performance. Considering the mixture R-32/R-1234ze(E) in Figure 7, for a -15°C dew point in the evaporator (branch 4) and a 50°C bubble point in the condenser (branch 1), the R-32 fractions are 55.4% (w_a), 52.6% (w_b), 50.0% (w_c), and 42.2% (w_d).

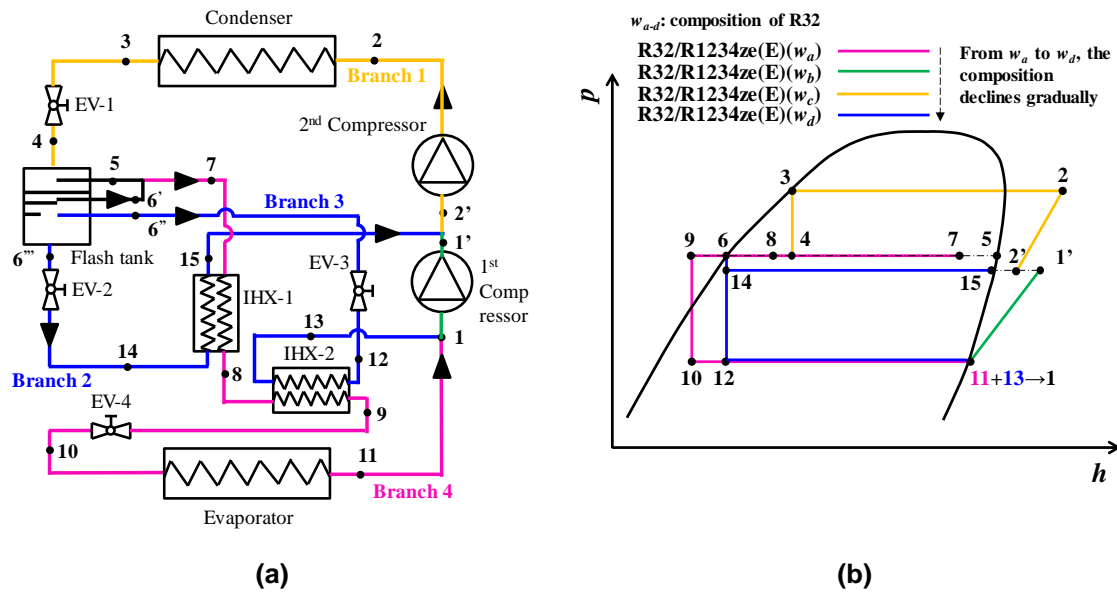


Figure 7: Schematic and p-h diagram of the DAC two-stage compression system:
(a) schematic diagram and (b) p-h diagram

Initial comparisons of the two-stage systems using FT and IHX approaches have shown promise for the DAC system. Compared with an FT system, the heating capacity increased by up to 9.6%, and the coefficient of performance (COP) increased by up to 6.1%. Compared with an IHX system, the heating capacity increased by up to 2.1% and the COP increased by up to 2.5%. Although the theoretical analysis illustrated a potential for improving efficiency, the initial gains are modest. The DAC will be developed further.

2.1.3 Hybrid-energy heat pump (combined absorption-compression cycles)

Lead PI: Dr. Wei Wu (City University of Hong Kong)

Description: Two types of hybrid-energy HP cycles were studied. The first cycle was the compression-assisted absorption cycle, as shown in Figure 8. A compressor is located between the evaporator and absorber (low-pressure compression-assisted), as shown in Figure 8(a), or between the generator and condenser (high-pressure compression-assisted), as shown in Figure 8(b). With auxiliary compression, the absorption cycle can operate efficiently under low driving water temperatures, high cooling water temperatures, and low chilled water temperatures.

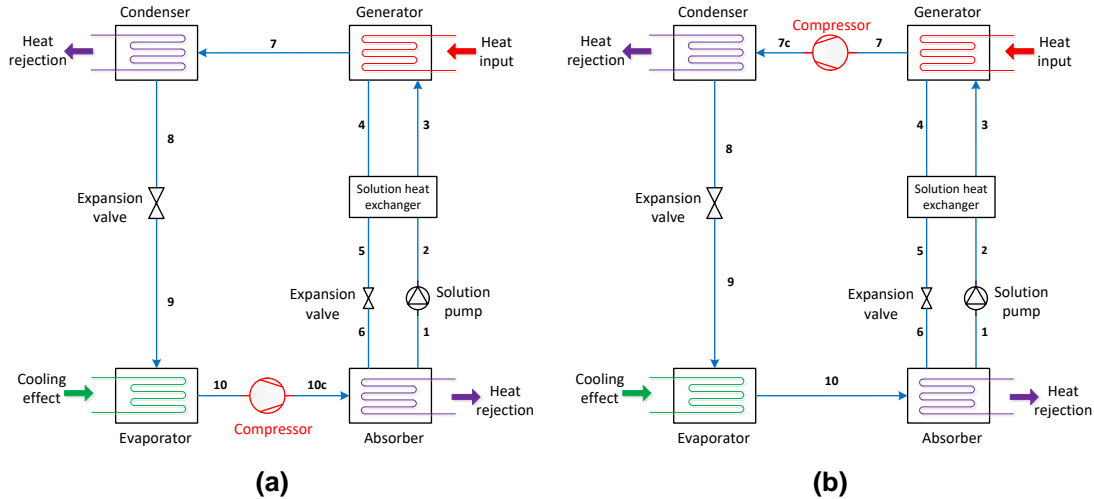


Figure 8: Schematic diagrams of the compression-assisted absorption cycle: (a) low-pressure compression assisted and (b) high-pressure compression assisted

The second cycle studied was the parallel absorption and compression cycle, as shown in Figure 9. The mechanical compressor and thermal compressor are installed in parallel, sharing the condenser and evaporator. This hybrid absorption-compression cycle can gradually transform from an absorption cycle to a VCC with various absorption-compression cycles in between, making it very flexible for accommodating different conditions.

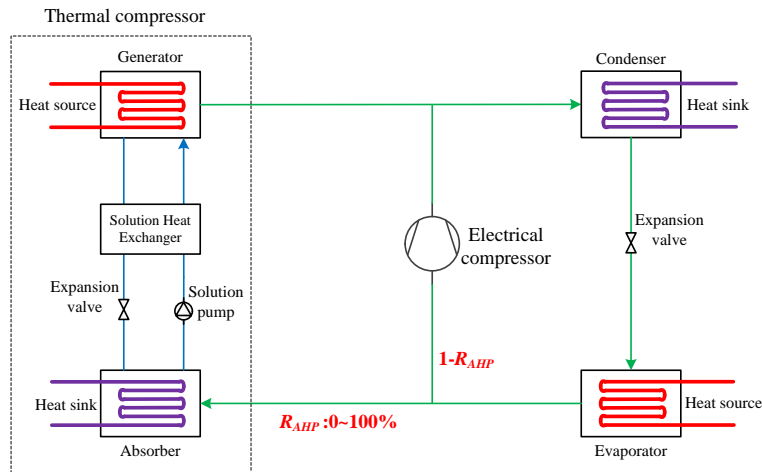


Figure 9: Schematic diagrams of the parallel absorption and compression cycles

A wide range of thermal energy sources can be used, including natural gas, recovered waste-heat, and solar-thermal or solar photovoltaic thermal (PV/T).

Development status and plans: The compression-assisted absorption cycles were studied for space heating. Low-pressure compression-assisted and high-pressure compression-assisted absorption HPs were analysed. The low-pressure compression-assisted absorption HP was experimentally investigated. The heating performance improved significantly under low generation temperatures and low evaporation temperatures. The parallel absorption-compression cycle was proposed to improve the heating efficiency and adjust the heating-to-cooling capacity ratio. The investigated absorption cycles included the single-effect hybrid cycle and GAX (generator/absorber heat exchange) hybrid cycle, and the working fluids included the $\text{NH}_3\text{-H}_2\text{O}$, $\text{NH}_3\text{-salt}$, and $\text{NH}_3\text{-ionic liquid}$. The use of oil-free compressors was envisioned for the systems to avoid oil handling issues.

The future research plans are outlined as follows.

- (1) Investigate the hybrid-energy HP concept that is used for thermal energy storage. With auxiliary compression, the charging temperature of absorption thermal energy storage can be decreased, the energy storage efficiency can be increased, and the energy storage density can be increased. Compared with the current absorption thermal energy storage, the charging temperature is expected to decrease by 10°C, and the energy storage density is expected to increase by 20%.
- (2) Investigate the hybrid-energy HP concept used for solar cooling. The parallel absorption-compression cycle can very flexibly accommodate changing outdoor conditions and various climate zones. Compared with current VC cooling systems, it is expected to use 20% less electricity.

2.1.4 Adsorption transformation for cooling (thermal compression)

Lead PI: Dr. Alessio Sapienza (ITAE)

Description: The operation of an adsorption cooling machine is based on the reversible adsorption-/desorption of a refrigerant fluid (e.g., water, ammonia, ethanol) on or from a porous material (e.g., zeolites, silica gel, active carbons) realized in the so-called “thermal compressor or adsorber” consisting of an adsorbent material integrated in a HX. The cooling cycle is realized by a system layout that is basically composed of one adsorber, one evaporator, and one condenser. The typical thermodynamic transformations of an adsorption cooling/refrigeration/heating cycle comprising two isosteres and two isobars are shown in Figure 10, as presented on the Clapeyron diagram $\ln(P)$ vs. $(-1/T)$.

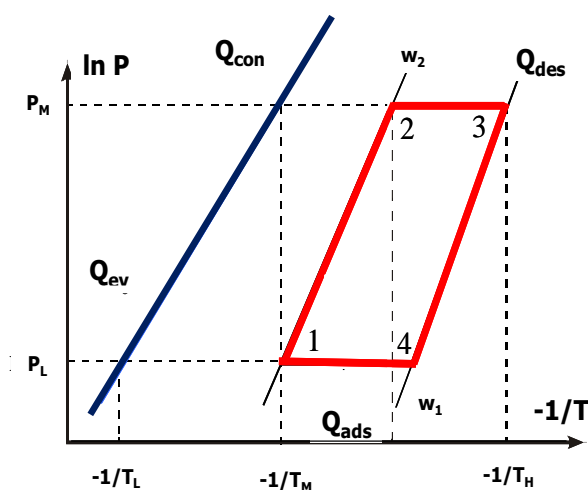


Figure 10: Typical thermally driven cooling/refrigeration/heating adsorption cycle on the P - T diagram

Development status and plans: Although the thermodynamic properties of the adsorption heat transformer (AHT) cycle were comprehensively studied, the dynamic optimization of AHT adsorbers is still an issue. AHT dynamics are a complex process involving all the main machine components (i.e., the adsorber, evaporator/condenser). The performance of each component is affected by the HX design (e.g., geometry, material), adsorbent configuration (e.g., loose grains or coating), grain size, layer thickness, and other main variables (e.g., heat carrier flow rates and condenser/evaporator efficiency).

This project goal is to expand the knowledge of adsorption machine dynamics by developing innovative components (i.e., adsorbers, evaporators). New sorbent material will be

investigated, and innovative system design layouts—in terms of HX design and sorbent configurations—will be developed. The developed components will be experimentally tested by specific test benches that are available at ITAE. An experimental evaluation will allow for the full characterization of real performance in terms of COP and specific cooling power under real operating conditions.

2.1.5 Electrochemical compression

Lead PIs: Dr. Chunsheng Wang, Dr. Yunho Hwang, Dr. Reinhard Radermacher (University of Maryland)

Description: The ECC is a mass transport device capable of selectively pumping fluids via an electrochemical process without moving mechanical parts. The ECC uses the same ion exchange membranes found in hydrogen fuel cells; however, although fuel cells consume gas to generate electrical potential, the ECC consumes electricity to increase the pressure by moving the working fluid across the membrane without creating any net chemical changes in the working fluid.

Development status and plans: The University of Maryland has two ongoing projects related to ECC: electrochemical ammonia compression and EHD-enabled electrochemical DH (Figure 11). The ammonia ECC project is being investigated for its potential use in VCCs (Tao et al. 2019). With a corporate partner, the University of Maryland team will develop and evaluate a scaled-up ECC that can compress large volumes of gas. Thus far, continuous ammonia compression from 1.5 to 9.5 bar with isentropic efficiency reaching up to 70% has been achieved. Moreover, ammonia separation was demonstrated from dilute streams with ammonia concentrations as low as 8% molar fraction.

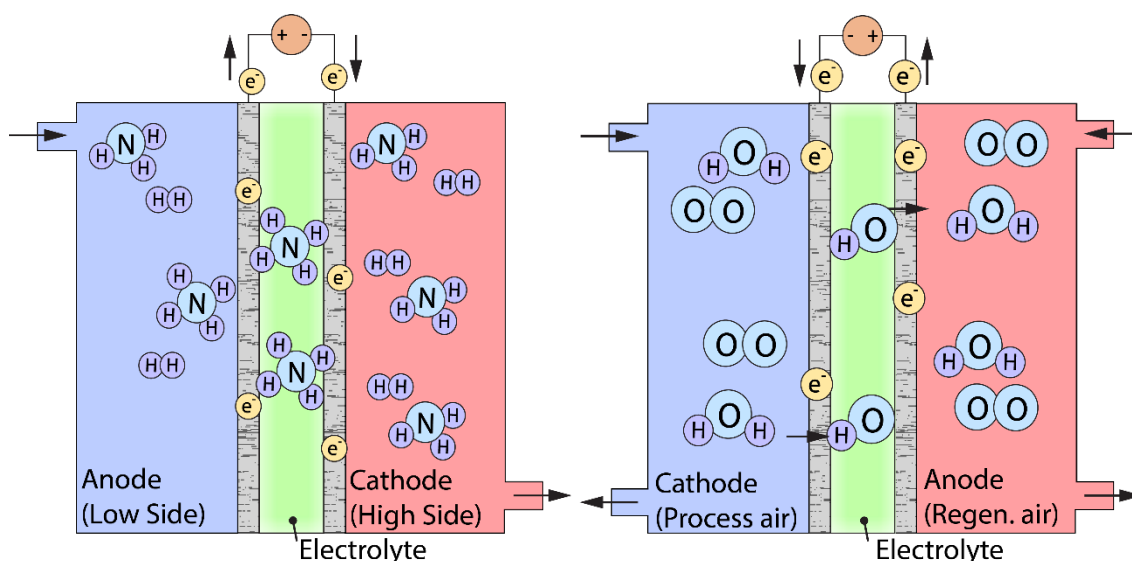


Figure 11: Schematic diagram of ammonia ECC (left) and EHD-enabled DH processes (right)
(courtesy the University of Maryland)

The EHD DH project deals with the electrochemical transport of water vapor for DH applications. Although researchers already demonstrated the potential for using electrochemical cells for water transport, they noted that the DH performance could be limited by poor mass transfer to the membrane surface (Qi et al. 2017). Therefore, using the EHD effect could increase the rates of water vapor transfer to the membrane. This project is still in its early stages, and the initial efforts will focus on developing the electrochemical membrane and the EHD test facility.

Both ECC technologies are intended for use in AC applications. The ammonia ECC could be used to drive an HP or refrigeration cycle using ammonia as the refrigerant, and the water ECC could be used as a dehumidifier to reduce the latent cooling load in AC applications. Additionally, the ammonia ECC is being investigated for use in energy storage technology. Ammonia can be used as a form of carbon-free fuel for internal combustion engines. Therefore, the possibility of integrating the ammonia ECC with the Haber-Bosch ammonia synthesis process is under investigation.

Project References:

Qi R., Li D., and Zhang L. -Z. 2017. "Performance Investigation on Polymeric Electrolyte Membrane-Based Electrochemical Air Dehumidification System," *Applied Energy*, Vol. 208, pp. 1,174–1,183.

Tao Y., Hwang Y., Radermacher R., and Wang C. 2019. "Experimental Study on Electrochemical Compression of Ammonia and Carbon Dioxide for Vapor Compression Refrigeration System," *International Journal of Refrigeration*, Vol. 104, pp. 180–188.

2.1.6 Expansion loss reduction using PEx technology with advanced VC systems

Lead PI: Dr. Brian Fricke (ORNL)

Description: A PEx consists of a cylindrical rotor with an array of channels arranged around the rotor's axis. The rotor spins between two stationary end plates, each of which contains ports for controlling the fluid flow into and out of the rotor channels. Through rotation, the channel ends are periodically exposed to different port pressures, initiating compression and expansion within the rotor channels. Thus, the pressure of a high-pressure stream can be transferred to a low-pressure stream to raise the pressure of the low-pressure stream and reduce the pressure of the high-pressure stream. A cutaway view of a PEx and a rotor are shown in Figure 12.

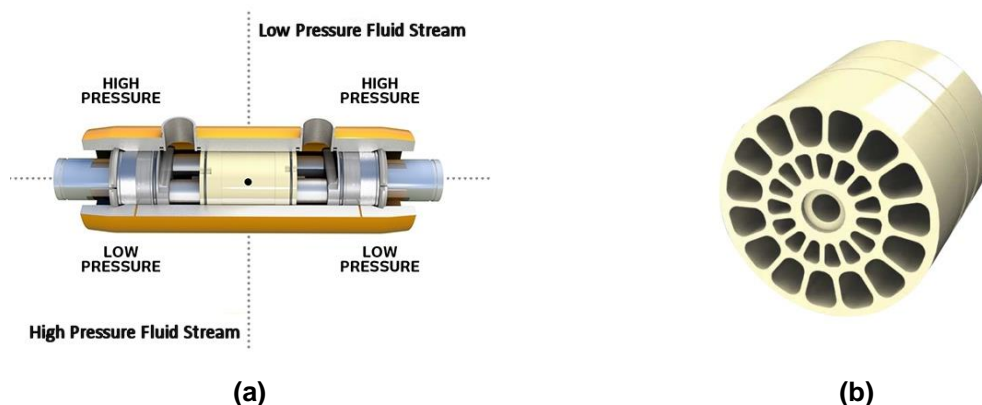


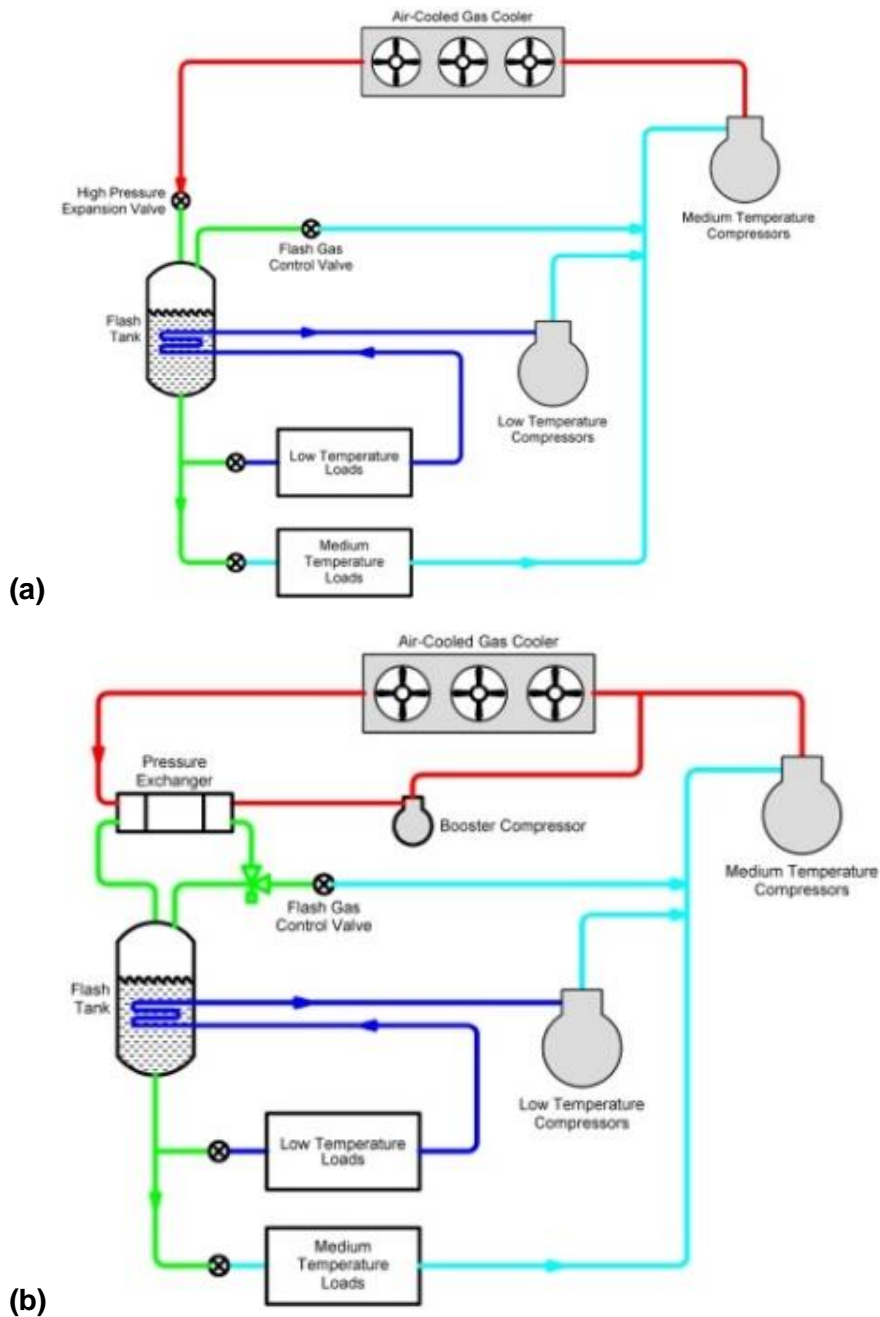
Figure 12: PEx: (a) cutaway view of the PEx, showing the rotor (center) and the inlets and outlets for low-pressure and high-pressure flows, and (b) detail of rotor (Energy Recovery, 2017)

PExs were successfully used in reverse osmosis water desalination applications to provide energy recovery and reduce pumping requirements. This project will apply the technology to VC refrigeration applications and evaluate its potential to enhance efficiency.

Development status and plans: The proposed PEx technology has fundamental resemblance to an HX. HXs transfer "heat" energy between two fluid streams, whereas the PEx transfers "work" energy. To characterize the PEx performance, a pressure "effectiveness" parameter analogous to HX effectiveness will be developed. PEx performance was modeled and

simulated using computational fluid dynamics (CFD). A comparison of the initial CFD modeling results of the existing experimental data from the desalination applications shows very good agreement.

Further work will continue developing a PEx analytical model and refining the CFD modelling. A manufacturer (Energy Recovery Inc.) was engaged and will design and fabricate a prototype PEx suitable for CO₂ refrigeration applications. The device performance will be evaluated using a laboratory test rig. After the device performance is evaluated and characterized, a suitable PEx will be installed to replace the high-pressure expansion valve in a CO₂ booster refrigeration system for experimental evaluation, as shown in Figure 13.



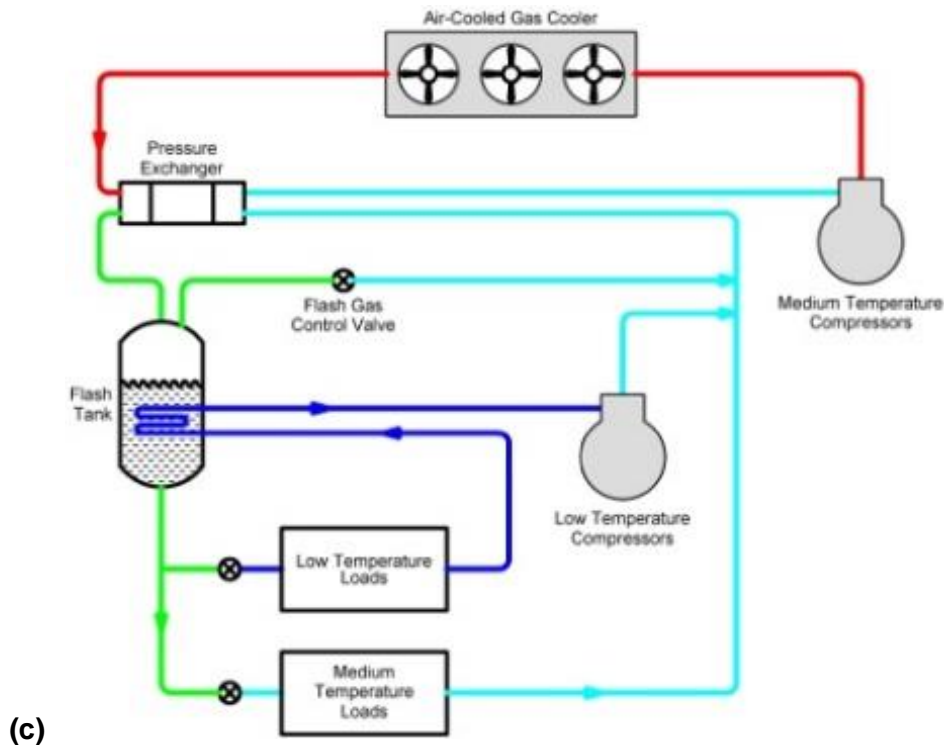


Figure 13: Transcritical CO₂ booster refrigeration system configurations: (a) basic cycle without PEx, (b) cycle with the PEx on flash gas bypass, and (c) cycle with the PEx on medium-temperature compressor suction

Project References:

Energy Recovery. 2017. <http://www.energyrecovery.com> Energy Recovery, Inc., San Leandro, CA.

Enle Xu, Yue Wang, Liming Wu, Shichang Xu, Yuxin Wang, and Shichang Wang, Computational Fluid Dynamics Simulation of Brine–Seawater Mixing in a Rotary Energy Recovery Device, *Ind. Eng. Chem. Res.* 2014, 53, 18304–18310

Groll, E., Kim, J.-H., 2007. Review Article: Review of recent advances toward transcritical CO₂ cycle technology. *HVAC&R Research* 13(3), 499-520.

2.2 Nontraditional Technology-Based Project Descriptions

Table 2 summarizes the nontraditional cooling cycle-related projects covered by the Annex 53 participants. A brief summary and the development status and plans for each project are included.

Table 2: Nontraditional technologies

R&D institute	Technology description	Initial target market/application
University of Maryland, USA	EC cooling	Low-capacity applications, such as small refrigerators
Xi'an Jiao Tong University, China	EC cooling	Initial: portable beverage coolers With further development: residential Refrigerator or personal cooling device Thermal-driven EC: solar-thermal AC or refrigerator; waste heat recovery mobile AC
Shanghai Jiao Tong University, China	Evaluation of environmental impact of electrocaloric (EIC) materials	Personal cooling devices, electric vehicle battery thermal management or seat coolers, data center on-chip cooling
Fraunhofer Institute for Physical Measurement Techniques (IPM)	Active caloric heat pipe concept applied to MC systems	MC heat pipe: deep freezer for medical applications
Ames Laboratory, USA	High-power density MC systems	Residential AC
ORNL, USA	Alternative cooling technology using MC materials	Residential refrigerators or AC

2.2.1 Elasto-caloric cooling

Lead PIs: Dr. Ichiro Takeuchi, Dr. Yunho Hwang, Dr. Reinhard Radermacher (University of Maryland)

Description: The main characteristic of EC materials is that a phase transition can be induced in them with the cyclic application and removal of physical stress. The special characteristics of this phase transition depend on the material and it always involves a significant change in entropy. The entropy change manifests itself as a material temperature change when the external field is applied or removed adiabatically, and it manifests as heat exchange between the material and the surroundings when the external field is applied or removed isothermally. Nitinol is a commercially available EC alloy. To use it as a solid-state refrigerant, it is conceptually necessary to perform the following four steps (see Figure 14).

- 1) **Loading:** a stress is applied adiabatically to the material, and the temperature increases.
- 2) **Heat rejection:** maintaining the stress, the material is allowed to cool.
- 3) **Unloading:** the stress is removed, the phase transformation is reversed, and the temperature decreases below the original temperature.
- 4) **Cooling:** the material can now provide cooling, and while cooling, the temperature increases, and the cycle can begin again.

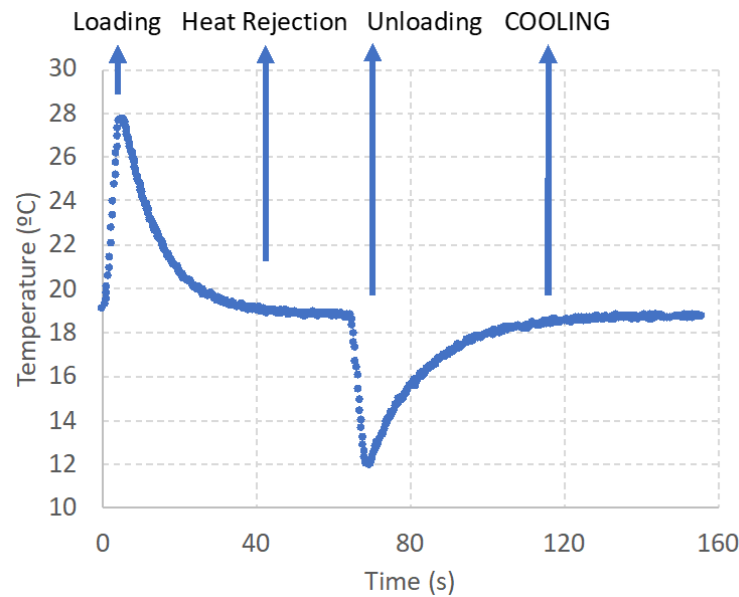


Figure 14: Temperature variation during Nitinol loading and unloading

Development status and plans: The conceptual EC regenerator design (Figure 15) consists of layered stacks of short tubes of Nitinol, and the transformation is induced by compression. The flow pattern in the regenerator is like the one observed in a shell and tube HX. The length of the tubes is calculated to prevent buckling, even without external tube support. The distance between the tubes is one of the most important variables expected to influence the structural stability of the system, HX coefficient, and pressure drop. Individual layers of 23 tubes were homogeneously compressed successfully (Emaikwu et al. 2019). The integrated system performance will be initially evaluated on the maximum temperature lift values, which correspond to a zero-cooling capacity. The COP and comparison with VCC will be reported as the cooling capacity is increased at the expense of the temperature lift.

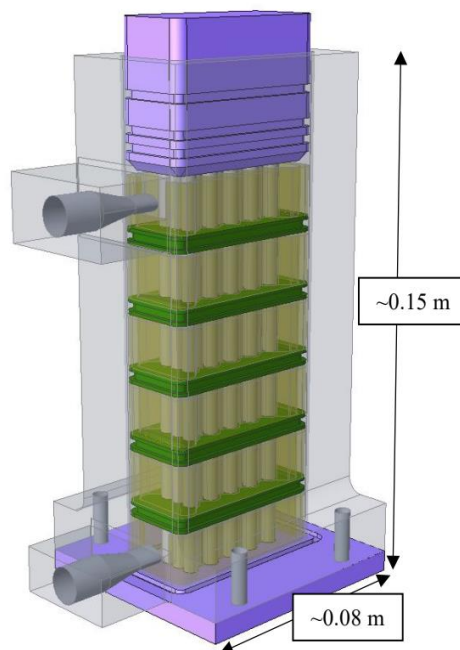


Figure 15: EC regenerator schematic

Project Reference:

Emaikwu N., Catalini D., Muehlbauer J., Takeuchi I., Radermacher R., and Hwang Y. 2019. "Development of a Cascade Active Elastocaloric Regenerator," *American Society of Mechanical Engineers 2019 ES 13th International Conference on Energy Sustainability Co-Located with the Summer Heat Transfer Conference*.

2.2.2 Elastocaloric cooling

Lead PI: Dr. Suxin Qian (Xi'an Jiao Tong University)

Description: Two ongoing EC-related research projects are currently under way. The first project aims to investigate the loss characteristics for single-stage and active-regeneration-based EC cooling systems. A universal simulation model accurate enough to characterize single-stage cycles and active-regeneration cycles will be developed. The model will be used to illustrate the potential and major EC cooling system losses and to explore potential solutions for improving cooling performance.

The second project, which is co-funded by an HP manufacturer, aims to develop a new class of EC cooling systems driven by low-grade thermal energy. The concept uses a heat-activated actuator made of high-temperature shape memory alloy (SMA) to drive the low-temperature super elastic SMA refrigerant, as shown in Figure 16. Since the force-displacement characteristics of the actuator and refrigerant are intrinsically matched, the actuator can reduce the driver's footprint more than 10 times compared with a mechanical driver. The simulation and experiments will be performed to (1) demonstrate the applicability of the heat-driven cooler concept and (2) identify the suitable low-grade heat source to drive such a cooling system.

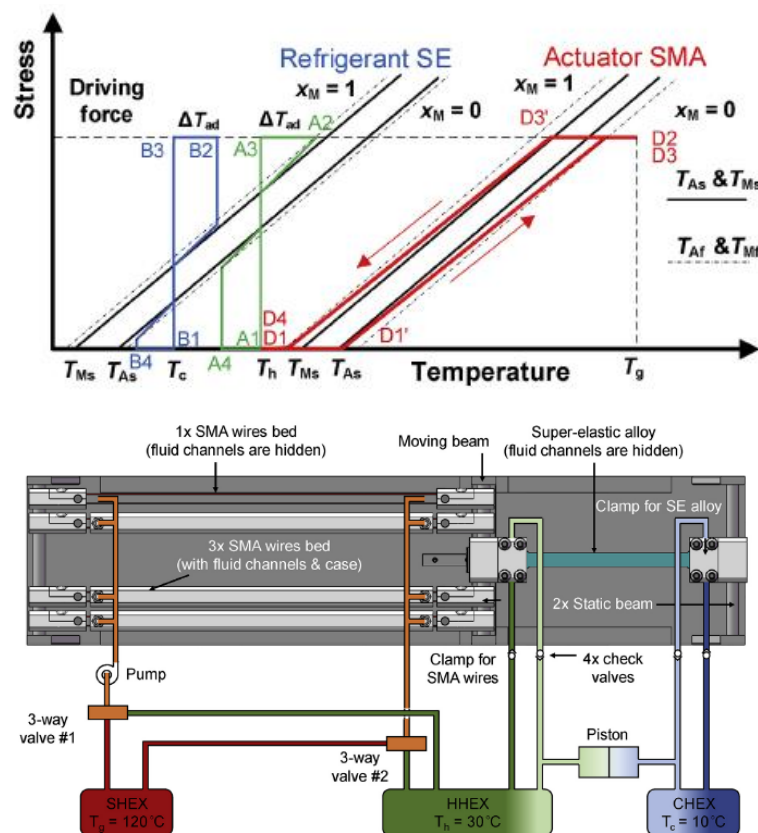


Figure 16: Principle of a heat-driven EC cooling system: (top) cycle diagram and (bottom) system schematic

Development status and plans: For the first project, extensive numerical studies have indicated that—unlike the $1 \text{ W/cm}^2\text{K}$ heat transfer coefficient (HTC) achieved in packed-bed regenerators—the tube-shaped or plate-shaped bed has only an HTC of $\sim 0.1\text{--}0.2 \text{ W/cm}^2\text{K}$. This is a significant factor limiting the performance of current EC cooling systems. One approach to overcome this limitation is to use a heat transfer design without heat transfer fluid, like the designs delivered by Saarland and Karlsruhe (Bruederlin et al. 2017, Schmidt et al. 2015). A proof-of-concept beverage cooler prototype with an expected cooling capacity of 50 W based on NiFeGa is being developed to test this concept (Figure 17).

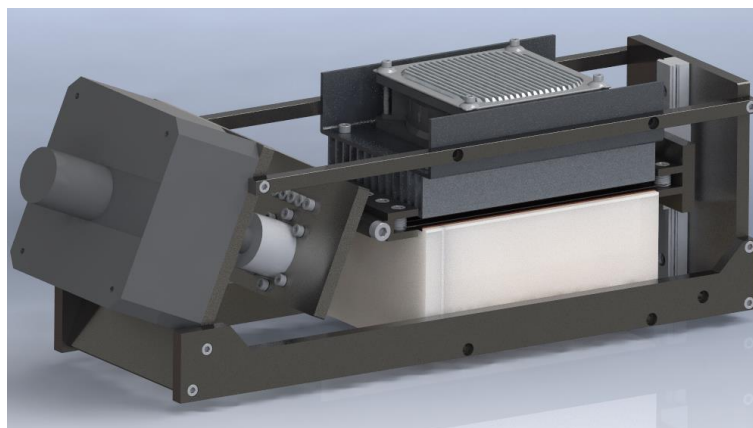


Figure 17: Design concept of an EC-based beverage cooler without liquid heat transfer fluid

For the second project, a theoretical investigation of the heat-driven EC system's potential was completed (Qian et al. 2019). Details of the best method for selecting and matching the geometric parameters for the actuator SMA and refrigerant SMA were investigated, including the impacts of the length, cross sectional area, and shape factor. The thermodynamic constraints on the actuator SMA phase-change temperatures were illustrated and will serve as a guideline for the best method for choosing the actuator SMA properties. Then, a proof-of-concept prototype system design will be developed and optimized with an estimated temperature lift of 25 K and a cooling capacity of 10 W. The prototype is expected to be delivered by Q2 in 2020. Extensive tests will be conducted to investigate the role of the driving-source temperature, operating flow rates, operating frequency, and other parameters to physically prove that heat-driven cooling is feasible.

Project References:

Bruederlin F., Ossmer H., Wendler F., Miyazaki S., and Kohl M. 2017. "SMA Foil-Based Elastocaloric Cooling—From Material Behavior to Device Engineering," *J Phys D Appl Phys*, Vol. 50, p. 424003.

Schmidt M., Schütze A., and Seelecke S. 2015. "Scientific Test Setup for Investigation of Shape Memory Alloy Based Elastocaloric Cooling Processes," *Int J Refrig*, Vol. 54, pp. 88–97. doi:10.1016/j.ijrefrig.2015.03.001.

Qian S., Wang Y., Yuan L., and Yu J. 2019. "A Heat Driven Elastocaloric Cooling System," *Energy*, Vol. 182, pp. 881–899.

2.2.3 Evaluation of the environmental impact of EIC materials

Lead PI: Dr. Xiaoshi Qian (Shanghai Jiao Tong University)

Description: Since the giant EIC effect (ECE) in dielectrics was discovered more than 12 years ago, EIC cooling technology (Figure 18) has quickly gained attention in both academia and

industry. Electric field-polarization coupling effects, which underpin the ECE and EIC cooling cycles, are one of the most efficient forms of energy conversion, approaching 90% efficiency. EIC solid-state cooling represents a zero-GWP technology, making it a highly efficient refrigeration alternative. EIC materials are mostly wide bandgap, insulating dielectrics, which operate as electricity-driven capacitors and have advantages in cyclic energy efficiency and device integration. Currently, many promising material candidates with well-developed manufacturing processes and several device prototypes for applications beyond traditional VC refrigeration have been realized. However, the method of evaluating the energy efficiency and environmental impact of EIC cooling technology is still unclear. This project reports an evaluation method based on the total equivalent warming impact (TEWI) and the material COP (COP_{mat}).

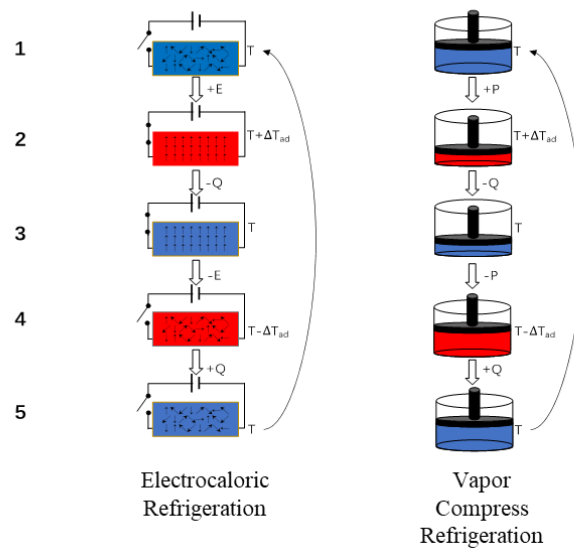


Figure 18: Schematics of EIC and VC refrigeration processes

Development status and plans: TEWI analyses of several different cooling systems including VC, EIC, and thermoelectric (TE) were conducted. Each system was evaluated for operation over a fixed temperature span of 10 K at a room temperature of 300 K. All the materials and cycles in the evaluation exhibited a temperature change of $\Delta T > 10$ K, as reported in the literature. Active regeneration was not considered in the model to eliminate the involvement of the case-sensitive factors resulting from various device designs. The COP_{mat} was evaluated by considering the $\Delta T = 10$ K and the respective energy input to generate the temperature change. Additionally, for all caloric cooling technologies, the ideal input energy recovery (e.g., 100% charge recovery for the VCC and ECE) was considered (Qian et al. 2016). Simulations indicated that EIC devices can operate much more efficiently than air conditioners based on the VCC. This is because electric field-polarization coupling that underpins the ECE is one of the most efficient forms of energy conversion, approaching 90% efficiency. Furthermore, EIC materials can perform heat exchange directly without IHXs (Gu et al. 2014, Qian et al. 2013). These factors can result in more than a 30% increase in COP_{mat} compared with VC-based devices under similar conditions.

Figure 19 presents the COP_{mat} and the $TEWI_{mat}$ for the VCC, EIC cycle, and TE system under the thermodynamic cycle conditions described in the preceding paragraph. The basis of the $TEWI_{mat}$ calculation is from the COP_{mat} calculated by following the approach in Qian et al. (2016). Detailed calculations are found in Shi et al. (2019).

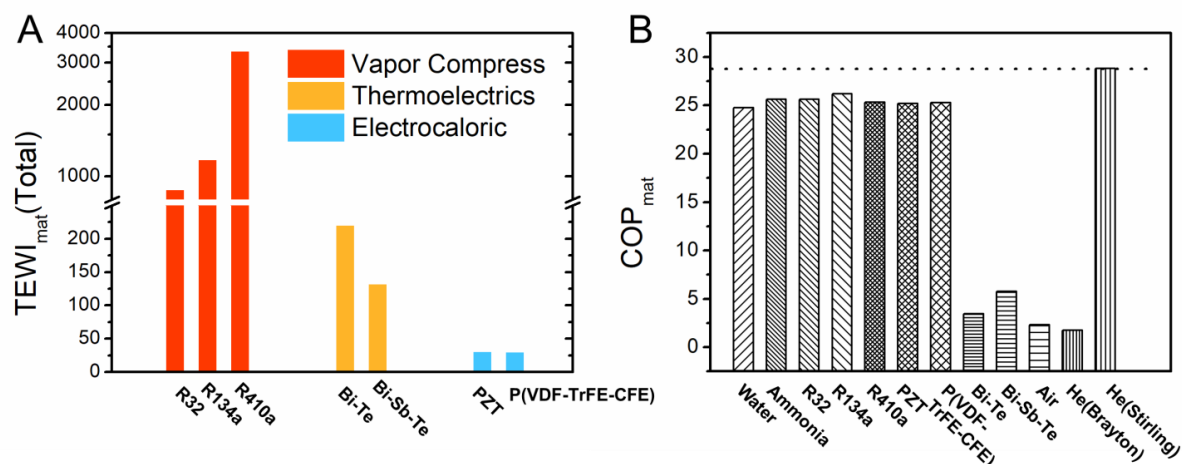


Figure 19: Material TEWI (a) and COP (b) evaluation of the VC, EIC, and TE cycles working fluid/material options; the dotted line indicates the Carnot COP (reprint with permission from Cell Press)

Taking out the device loss, the material COP in the VCC was quite high, reaching 90% of the Carnot COP (Chen et al. 2009). However, the TEWI_{mat} was enormous due to the uncontrollable leakage. The EIC featured zero direct emission, whereas the TE refrigeration—the only one being commercialized—exhibits low material COP that contributes greatly to the TEWI_{mat}.

The comparison in Figure 19 assumes that the three caloric cooling techniques and the VC-based technology have the same energy recovery capability. For the EIC cooling concept, this assumption is close to reality. Due to their low-loss, charge capacitor nature, EIC materials exhibit very high charge-discharge energy reversibility with a 3–5% electrical energy loss. Additionally, the total discharged energy of the EIC materials can be easily recycled (i.e., recovered) and used to charge a second EIC cooling bed via a charge recovery converter. In capacitor devices, charge recovery is commonly used to enhance the efficiency of a device, such as a piezoelectric actuator, in which a charge recovery of over 90% has been achieved. Most recently, Defay et al. (2013) demonstrated a two-bed EIC device with a charge recovery circuit. An 86% energy recovery was achieved that led to a COP_{mat} enhancement approaching 300%.

Project References:

- Defay E. et al. 2013. "The Electrocaloric Efficiency of Ceramic and Polymer Films," *Advanced Materials*, Vol. 25, pp. 3,337–3,342. doi:10.1002/adma.201300606.
- Gu H., Qian X. -S., Ye H. -J., and Zhang Q. M. 2014. "An Electrocaloric Refrigerator without External Regenerator," *Applied Physics Letters*, Vol. 105, p. 162905. doi:10.1063/1.4898812.
- Shi J. et al. 2019. "Electrocaloric Cooling Materials and Devices for Zero-Global-Warming-Potential, High Efficiency Refrigeration," *Joule*, Vol. 3, No. 5, pp. 1,200–1,225. doi:10.1016/j.joule.2019.03.021.
- Qian S. et al. 2016. "Not-in-Kind Cooling Technologies: A Quantitative Comparison of Refrigerants and System Performance," *International Journal of Refrigeration*, Vol. 62, pp. 177–192. doi:10.1016/j.ijrefrig.2015.10.019.
- Qian X. -S. et al. 2013. "Large Electrocaloric Effect in a Dielectric Liquid Possessing a Large Dielectric Anisotropy Near the Isotropic–Nematic Transition," *Advanced Functional Materials* Vol. 23, pp. 2,894–2,898. doi:10.1002/adfm.201202686.

2.2.4 Active caloric heat pipe concept applied to MC systems

Lead PI: Dr. Kilian Bartholomé (Fraunhofer IPM)

Description: MC cooling technology is a promising candidate for efficient and environmentally friendly cooling. MC materials heat when they are exposed to a magnetic field and cool once this field is removed. The future market viability of this technology depends on how efficiently it can transfer heat (i.e., cooling energy) between the MC material and an HX. One key issue is the increase in the system's frequency. The faster a system can be operated, the more cooling power can be realized with a certain amount of MC material and magnets. A smaller issue is the prospective costs of such a system. To this end, Fraunhofer IPM has developed a new concept based on active heat pipes.

Development status and plans: The working principle of this active MC heat pipe concept was demonstrated for one- and two-segment systems. The first experimental results indicate that a system frequency larger than 10 Hz can be realized. This concept is illustrated in Figure 20. Development work is focused on increasing the cooling power of the system and the system's frequency to reach more than 10 Hz. A demonstrator system that reaches a temperature span of 10 K and works at a system frequency of 10 Hz is planned for the end of 2019.

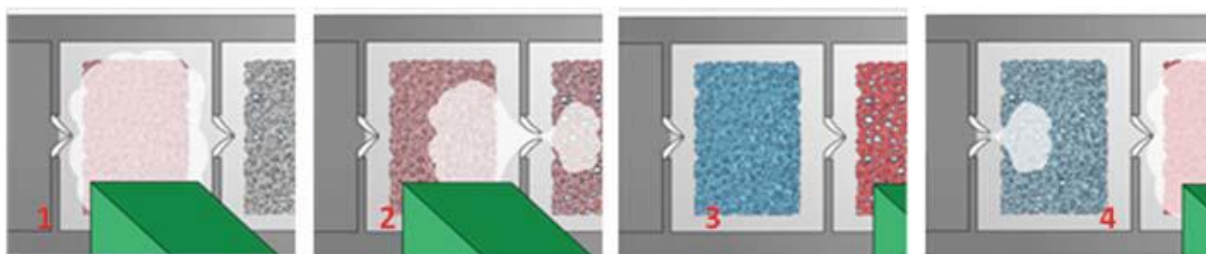


Figure 20: Operational mode of MC segments. (1) The heat generated by the magnetic field causes the fluid in the MC material to evaporate, increasing the pressure in the segment. (2) The check valve opens, allowing the vapor to flow into the adjoining element. Due to the unidirectional flow direction of the valves, the vapor cannot flow back into the previous element. (3) Once the magnet is switched off by moving the magnet away from the segment, the MC material cools below the starting temperature, and the vapor pressure drops. (4) The vapor pressure is now lower than in the previous segment. Gaseous fluid flows in, and heat from the previous segment is absorbed.

2.2.5 High-power density MC systems

Lead PI: Dr. Julie Slaughter (Ames Laboratory)

Description: MC cooling technology could be more energy efficient and have a lower environmental impact than VC systems. Several MC devices have been demonstrated at scales commensurate with residential refrigeration and AC; and most, if not all, of these systems use an active magnetic regenerative (AMR) cycle (Fortkamp et al. 2018). The AMR cycle allows heat to be pumped across a temperature span much larger than the adiabatic temperature change of the MC material. Optimizing AMR cooling has demonstrated performance near that of standard VC systems (Fortkamp et al. 2018, Eriksen et al. 2015). However, MC devices are not yet commercially viable due to the high system costs, which are mainly driven by the permanent magnet arrays required to generate fields on the order of 1–1.5 T. Focusing on system-level designs to increase power density and decrease magnetic fields, Ames' project goal is to demonstrate an efficient MC cooling prototype that combines high operating frequencies, reduced parasitic losses, and compact magnet designs.

Development status and plans: This project's goal is to demonstrate system-level performance of high-power density MC systems using gadolinium (Gd) -based MC materials to support a 35 K temperature span or lift with a hot environment (heat sink) temperature of 308 K.

Performance targets include operation frequencies ≥ 10 Hz, magnetic fields ≤ 1 T, and equivalent or better efficiencies than those of current state-of-the-art MC systems. Increasing the operation frequency for MC AMR systems increases the power density, resulting in a more compact device with a smaller magnetic field. Table 3 compares the existing Gd-based MC systems and their performance with target values for the current project. Although some of the targets were achieved (e.g., COP and power levels) and others are close (power density per kilogram of active material and temperature span), the goal is to achieve all of the targets simultaneously and lower the system manufacturing costs to demonstrate the technical and commercial viability. Although the target power level for proof-of-concept hardware (100 W) is significantly lower than that required for residential AC, the temperature span, efficiency, and performance are anticipated to be scalable to full-size systems.

Table 3: Comparison of reported Gd-based MC systems with target performance levels for this project

System	Max B (T)	Frequency (Hz)	T-span (K) (at load)	Power (W) (at span)	COP	W/kg of AMR (at zero span)
Eriksen et al. 2015	1.13	0.75	20 (at 0 W)	140 (at 5 K)	4.6 (at 140 W, 5 K)	82
Trevizoli et al. 2016	1.69	1	18 (at 5 W)	22 (at 3 K)	1.7 (at 19 W, 3 K)	447
Tura et al. 2011	1.4	4	25 (at 0 W)	50 (at 10 K)	1.0 (at 50 W, 2.5 K)	454
Tušek et al. 2013	1.15	0.3	15 (at 0 W)	5.5 (at 5 K)	5 (at 5.5 W, 5 K)	40.7
Fortkamp et al. 2018	1.34	1	19 (at 50 W)	110 (at 8 K)	6.1 (at 80 W, 10.5 K)	64.7
Griffith et al., in press	1.45	2	20 (at 0 W)	20 (at 0 K)	-	1,000
Proposed work targets	≤ 1.0	≥ 10	35 (at 0 W)	100 (at 0 K)	≥ 4.0	$\geq 1,000$

Project References:

Fortkamp F. P., Eriksen D., Engelbrecht K., Bahl C. R. H., Lozano J. A., and Barbosa J. R. 2018. "Experimental Investigation of Different Fluid Flow Profiles in a Rotary Multi-Bed Active Magnetic Regenerator Device," *Int. J. Refrig.*

Eriksen D. et al. 2015. "Design and Experimental Tests of a Rotary Active Magnetic Regenerator Prototype," *Int. J. Refrig*, Vol. 58, pp. 14–21.

Griffith L. D., Czernuszewicz A., Slaughter J. C., and Pecharsky V. K. "CaloriSMART: Small-Scale Test-Stand for Rapid Evaluation of Active Magnetic Regenerator Performance," *Energy Convers. Manag.* (in press)

Trevizoli P. V., Nakashima A. T., Peixer G. F., and Barbosa J. R. Jr. 2016. "Performance Evaluation of an Active Magnetic Regenerator for Cooling Applications—Part I: Experimental Analysis and Thermodynamic Performance," *Int. J. Refrig.*, Vol. 72, pp. 192–205.

Tura A. and Rowe A. 2011. "Permanent Magnet Magnetic Refrigerator Design and Experimental Characterization," *Int. J. Refrig.*, Vol. 34, No. 3, pp. 628–639.

Tušek J., Kitanovski A., Zupan S., Prebil I., and Poredoš A. 2013. "A Comprehensive Experimental Analysis of Gadolinium Active Magnetic Regenerators," *Appl. Therm. Eng.*, Vol. 53, No. 1, pp. 57–66.

2.2.6 Alternative cooling technology using MC materials

Lead PI: Dr. Ayyoub Momen (ORNL)

Description: This project's goal is to use the MC effect to develop a regenerator with higher efficiency than conventional VC refrigeration technologies. Alternative approaches to MC regenerators (MCRs) include a multiple-stage MCR and a solid-state MCR. In the multiple-stage approach (e.g., the 16 stages in Figure 21), multiple MC materials with different Curie temperatures were combined to optimize the MC effect according to the temperature distribution along the axis, as shown in Figure 21(a) (Zhang et al. 2017). The solid-state MCR approach uses a high-conductivity material (e.g., copper) to transfer the cooling power between the MC material and the target (Zhang et al. 2016).

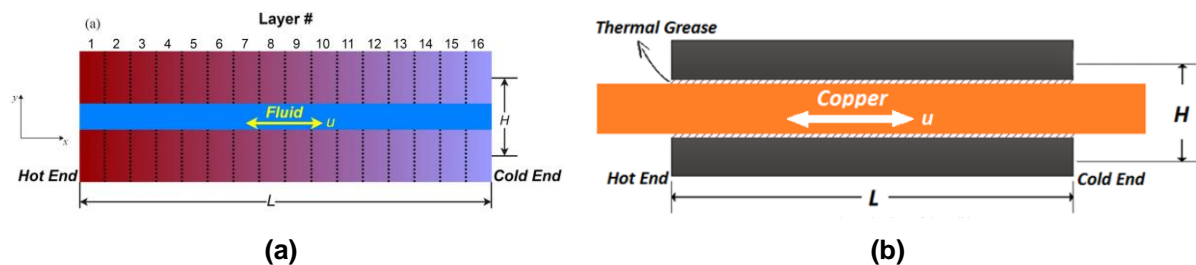


Figure 21: (a) MC regenerator with 16 stages of MC materials and (b) solid-state MC regenerator

Development status and plans: To guide MCR research, an analytical model of an MCR was derived to describe the heat transfer in the regenerator. Based on the analytical model, a numerical model was developed to reveal the system performance and as a guide to approach an optimal design. The numerical model predicts that a 16-stage regenerator can provide a COP as high as 84% of Carnot cycle COP, as shown in Figure 22 (Zhang et al. 2017).

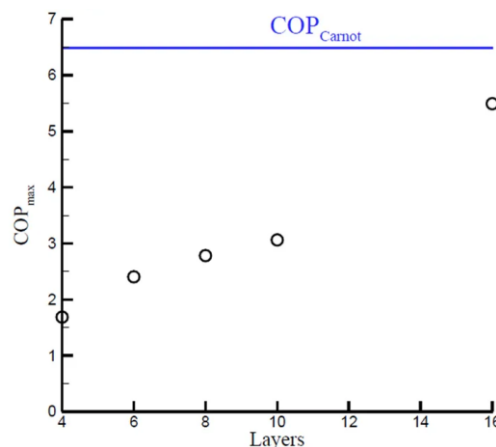


Figure 22: MC cycle COP vs. the number of stages

Prototypes will be built to test the solid-state MCR approach and the multistage MCR approach.

Project References:

Zhang M., Abdelaziz O., Momen A. M., et al. 2017. "A Numerical Analysis of a Magnetocaloric Refrigerator with a 16-Layer Regenerator," *Sci. Rep.* Vol. 7, p. 13962. doi:10.1038/s41598-017-14406-9.

Zhang M., Momen A., and Abdelaziz O. 2016. "Preliminary Analysis of a Fully Solid State Magnetocaloric Refrigeration," *International Refrigeration and Air Conditioning Conference*, paper 1758. <http://docs.lib.purdue.edu/iracc/1758>.

Appendix—Overview of Annex 53 Tasks

Task 1: Identify cooling/refrigeration focus areas for Annex technical contributions

Participants will describe the current development status of their candidate technologies and target applications.

Task 2: Perform modeling/simulation and lab evaluations of advanced AC/refrigeration technologies

This task constitutes the main part of the Annex. Country reports will describe the advances in the development of candidate technologies, including comparison to VC technologies and realistic estimates of cost potential.

Task 3: Identify the next steps for developing and deploying advanced AC/refrigeration systems

This task aims to evaluate design optimization and advancement on the life cycle climate performance (LCCP) reduction.

Task 4: Report and information dissemination

This task aims to report the works conducted and the disseminating information developed in this Annex.



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