Mechanocaloric Effect Cooling Concept Development

Liaison: Cliff Edwards. cliff.edwards@envisioninglabs.com

MECH 45X – Capstone Design Project Proposal for Stacked Mechanocaloric Effect Cooling

Introduction

During investigation into the Global Cooling Prize challenge [1] we uncovered a potential approach to meet the open innovation challenge requirements and improve the sustainability of room air conditioning (and other heat pump applications) globally.

Interior space air conditioning (A/C) is estimated to use almost 9% of global energy demand [2] or 17% of global electricity demand [3], and is projected to increase dramatically by mid-century if innovative low energy A/C is not adopted. A/C, and other refrigeration, cause a problematic positive feedback loop. They use a lot of energy which produces a lot of atmosphere harming emissions, and use refrigerants that when leaked cause global warming. Yet, as the world warms, more and more people will need (not just want) AC and refrigeration [4]. The current status quo of A/C and refrigeration systems is the vapour compression cycle, using a refrigerant with appropriate phase change properties, cycled through a compressor, condenser, expansion valve, and evaporator. Evaluations of technology improvements [5] and potential new technologies [3] estimate that climate effects of A/C can be reduced at least five fold, if not significantly more [1], over current vapour compression systems which go back at least 165 years.

Note that both vapour compression and mechanocaloric cooling are reversible heat pump cycles, supporting heating as well as cooling with simple design consideration.

Researchers studying mechanocaloric materials, such as elastocalorics and barocalorics [1], have discovered materials with properties highly favorable to cooling innovation. We believe to move beyond the limits of vapour compression, mechanocaloric materials, in particular, present the most promising path forward. It seems novel engineering may be all that separates us from the advantages of radically better cooling technology, and not enough effort is going into developing it (see Figure 1 for typical features that should be considered).

[1] “The mechanocaloric effect refers to the reversible thermal response of a solid when subjected to an external mechanical field, and encompasses both the elastocaloric effect, corresponding to a uniaxial force, and the barocaloric effect, which corresponds to the response to hydrostatic pressure.” [https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201603607]

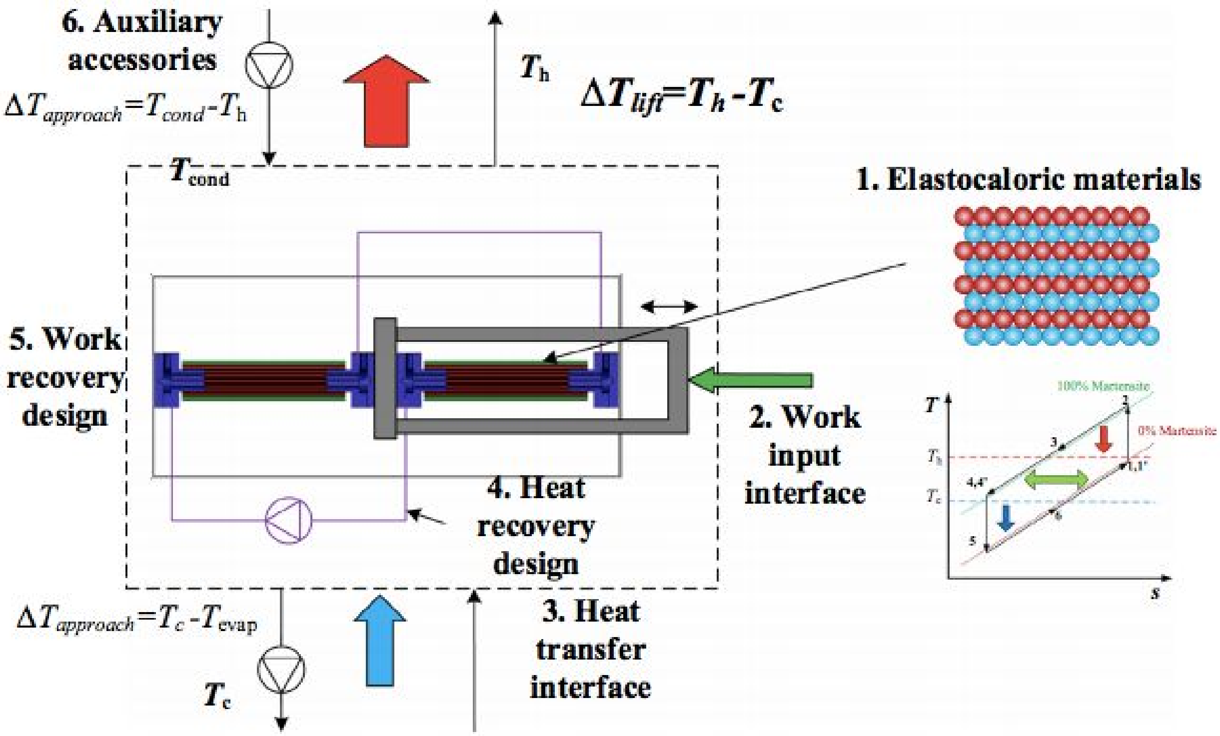

Figure 1: Illustration of the typical features of an elastocaloric cooling system [Source: 6]

Brief Project Description

We have identified several different types of mechanocaloric materials, materials that absorb and reject heat under mechanical forces, to evaluate. These materials have been found to have so-called “giant” or “colossal” elastocaloric and barocaloric effects. Similar to magnetocaloric cooling systems, much of the engineering to make viable solutions goes into achieving the appropriate temperature range or span of the cooling with enough temperature lift and power density to achieve a significant and useful cooling effect. This can be done by tuning regenerators to different operational temperature bands, stacking them to get appropriate lift, and including enough material mass to get the required cooling power. Similarly, elasto and baro calorics can have their phase transition temperature and pressure tuned to produce regenerators that work at different operating temperatures, as diagrammed in Figure 2 below. These stacked regenerators can then fit into a heat pump system design as shown in Figure 3.

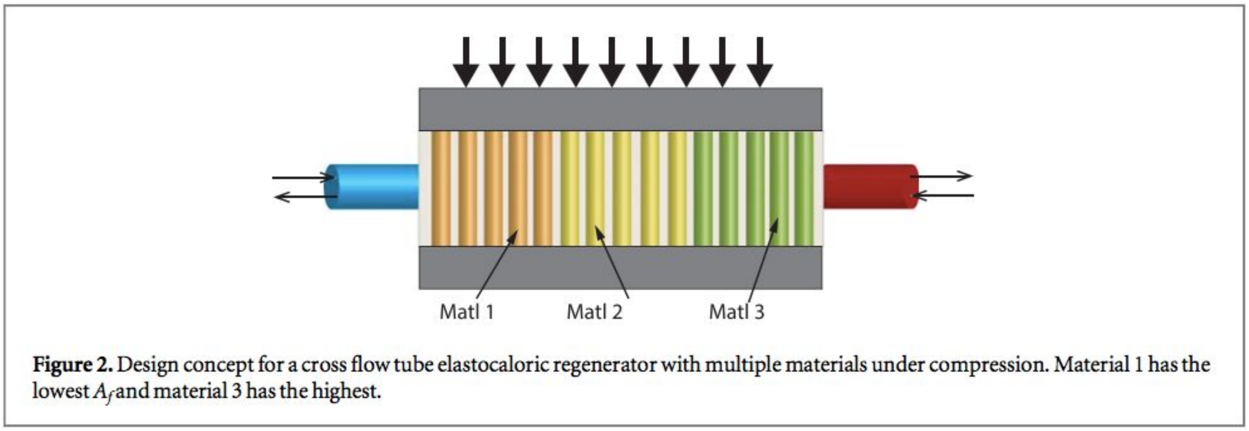

Figure 2: Example stacked regenerator showing Nitinol tubes compressed between two plates [Source: 2]

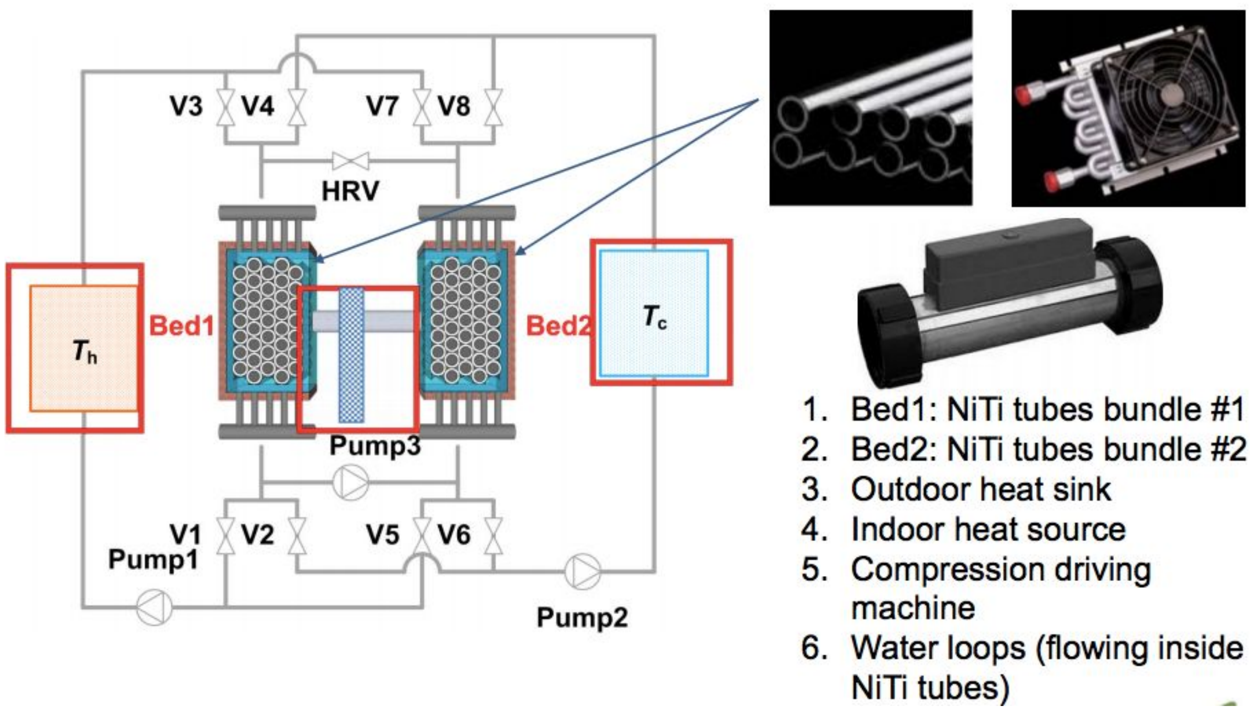

Figure 3: Example Nitinol tube system design from a research study into elastocaloric cooling [Source: 7]

Going beyond what has been considered before, we envision a mechanocaloric cooling approach that doubly stacks the regenerators, for example different materials are used together in each operational temperature section of the regenerator, and multiple of these sections are used to achieve appropriate temperature lift and power.

The identified materials consist of Nitinol tubes (elastocaloric), a liquid crystal barocaloric (diacylphosphatidylcholines12) that could fill the interior of the tubes, and a powdered barocaloric called Neopentylglycol (NPG) which could fill teflon spheres placed within the liquid crystal within the tubes. If these three materials, or a subset of them, can be made to work together, we may get enhanced cooling lift and power and various operating temperatures, supporting the concept of a viable multi-regenerator mechanocaloric heat pump.

One significant challenge is these materials all require significantly higher pressure and lower displacement compression than vapour compression. Achieving reasonable input energy (work) is sure to require a work recovery design, where a relaxing portion of the materials adds pressure to another portion being compressed (see Figure 4 for example approach from another elastocaloric prototype). SInce the pressures are high it’s likely a hydraulic conversion will be needed to take larger displacement lower pressure motion and produce small displacement high pressure compression. Our early conception considers a swashplate design to support these needs.

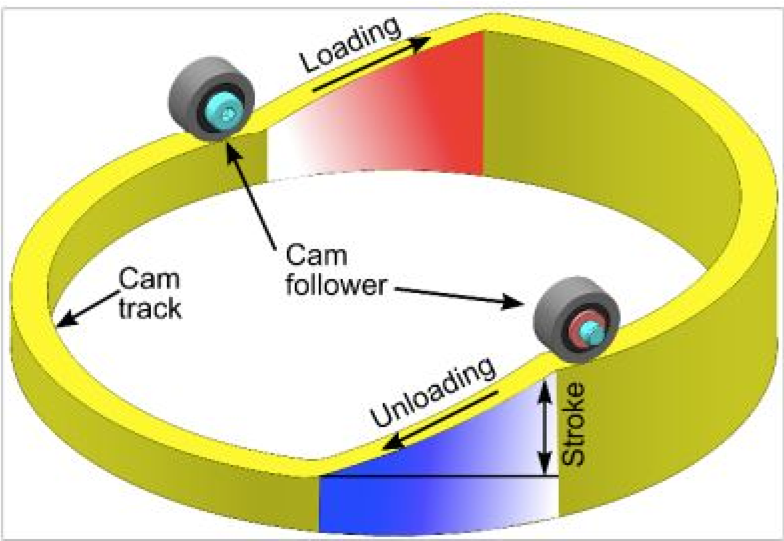

Figure 4: Example work recovery drive mechanism from unrelated elastocaloric prototype work, not as a design reference but just to show the kind of approach that can be taken [Source: 8]

Expected Outcomes

This project is intended as an early study of a conceptual new mechanocaloric material based cooling (heat pump) system. It will involve investigation into materials and their properties, heat pump cycles and their optimization, design concepts for a system, and into the design of proof-of-concept (PoC) prototype(s) to test aspects of the concept. We hope that after studying the background material the student team can investigate and report on the viability of the proposed concept, model some essential elements of the thermodynamics of the concept, and ideate and propose a conceptual engineering design for the system, and maybe even some designs for building one or more PoC prototypes. It will be up to the students if they want to or can go as far as physically building a first prototype to test an important aspect of the new concept. This concept is currently at low technology readiness level (TRL), based on science research but not integrated into a workable design, estimated at TRL 2. This project should help to lift the TRL to level 3.

Resources Available from the Customer

We envision the project cost may fall within the university provided budget for the Capstone. However, if the team is able to perform hardware prototyping we are willing to top up the budget by $1000 (or more) if need be to achieve even more from the project.

We will also allocate hours to the support of the team's project, including providing reference materials we've already discovered, clarifying vision and scope, answering questions through whatever means (phone, email, Slack channel, etc.) and regular meetings.

Customer Requirements

A) Must have:

1) **Engineering feasibility report:** Basing cooling system performance on the criteria established for the Global Cooling prize (to be shared), evaluate concept in an **initial engineering feasibility study** to clarify viability of concept, such as:
    - Do the identified materials make sense to use? (if not, can you find alternatives?)
    - Do they make sense to work together as proposed, mechanically and thermodynamically? (if not, can you envision another way to achieve objectives)
    - Can a mechanical system be envisioned to drive the applied forces with reasonable (according to Global Cooling Prize) input energy (work)?

2) Thermodynamic models: Modeling of the concept your evaluation has lead you to using appropriate system assumptions and constraints, and suitable modeling software.

3) Conceptual engineering design for overall system with supporting calculations

B) Nice to Have:

4) Designs for one or more PoC prototypes that will be needed to resolve technical uncertainty and risk in system development.

C) Solely based on team's capability

5) Development and test of one (or more) PoC prototypes
    a) Delivery of prototype(s)
    b) Delivery of design, assembly and test report(s)

References

[1] https://globalcoolingprize.org/
[2] https://economictimes.indiatimes.com/news/science/air-conditioning-is-the-worlds-next-big-threat/articleshow/69999842.cms?from=mdr
[3] https://iopscience.iop.org/article/10.1088/2515-7655/ab1573/pdf
[4] https://news.un.org/en/story/2019/06/1041201
[5] https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1794&context=iracc
[6] https://mse.umd.edu/sites/mse.umd.edu/files/documents/faculty/takeuchi/190_0.pdf
[7] https://docs.lib.purdue.edu/iracc/1411/
[8] https://onlinelibrary.wiley.com/doi/abs/10.1002/ente.201800152