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Future prospects for elastocaloric devices

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Abstract

Elastocaloric cooling is an alternative cooling technology that has been identified as having the potential to be more efficient than vapor compression systems. It is based on the elastocaloric effect, which is a change in temperature coupled to an applied uniaxial strain in materials such as NiTi alloys. Although elastocaloric cooling is a promising technology for energy savings in the future, there are still challenges to be addressed if it is to be commercially successful. This paper gives a summary of the state of the art and recent developments in the area as well as perspectives on the most important challenges that must be met to make the technology commercial.

Keywords: Elastocaloric refrigeration, regenerator, superelastic

1. Introduction

Refrigeration and air conditioning currently account for approximately 17 % of total global electricity consumption [1] and approximately 40 % of building energy consumption [2], with that amount predicted to grow as emerging markets continue to adopt air conditioning and due to increased urbanization of larger cities [3]. According to the International Energy Agency, the world may soon face a "cold crunch" as increases in cooling demand begin to stress electrical grids and drive energy consumption higher. Clearly, efficient refrigeration and space cooling technologies are an essential aspect of the future energy outlook. According to the International Institute of Refrigeration, residential refrigeration and cooling account for 45 % of electricity demand for cooling while the remaining electricity is used by industrial and tertiary sectors. This indicates that the most important applications for alternative cooling technologies are near room temperature and with moderate temperature spans, as can be used for space cooling and refrigeration as well as for industrial applications.

Although there is a variety of cooling technologies, vapor compression has essentially 100 % of the cooling market near room temperature, with thermoelectric (Peltier) coolers and Stirling cycles occupying a small market [4]. Vapor compression technology relies on the compression and expansion of a gaseous refrigerant and is proven for both stationary and transportation applications. However, the vapor compression cycle suffers efficiency losses associated with superheating of the refrigerant upon compression, expansion loses in the throttle valve, compressor losses, and other losses due to practical issues such as mixing of the refrigerant with lubricants for the compressor [5]. Additionally, leakage of the refrigerant can reduce efficiency during the device's lifetime and increase its environmental impact [6]. Despite the

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known loss mechanisms and drawbacks of the cycle, vapor compression remains the market leader because it is a mature technology, has a relatively high efficiency, is inexpensive and is generally reliable.

Due to the large market for new cooling and refrigeration equipment and the potential to build more environmentally friendly cooling cycles, there is a large research effort to develop high-efficiency and environmentally friendly alternative cooling cycles for application near room temperature, such as absorption, thermoacoustic, desiccant, thermoelectric and caloric cooling [7, 4]. Caloric cooling is based on the change in temperature of a solid refrigerant when subjected to an external magnetic field (magnetocalorics), an electric field (electrocalorics), an applied pressure (barocalorics) or a uni-axial strain (elastocalorics) and each effect has been suggested for use in a thermodynamic cycle [8]. In 2014 a U.S. Department of Energy (DOE) report determined that elastocaloric cooling (EC)is the most promising non-vapor compression technology, with the potential to save approximately 790 TWh of energy per year [9]. EC can also be more environmentally friendly than vapor compression systems because they use a solid refrigerant with a water-based heat transfer fluid and there is no environmental impact associated with leakage of the refrigerant. The DOE report and an article suggesting that NiTi wires in tension can be used to build efficient elastocaloric cooling devices [10] have greatly increased research interest in the technology in the last years [11]. While elastocaloric cooling is a promising technology, it is still in the early stages of development and the prototypes and demonstrators reported thus far are not commercially viable for residential or commercial cooling applications. This perspective article is written from the standpoint of how elastocaloric cooling can become a successful commercial technology and fulfill its promise of large energy savings in the future.

2. State of the art

EC is built upon materials that exhibit the elastocaloric effect (eCE), which is defined as the isothermal change of entropy or the adiabatic change in temperature of a material subjected to a uniaxial strain [12]. For superelastic materials such as NiTi, the eCE is caused by the martensitic phase transformation, which is a first-order diffusionless structural transformation. The transformation is reversible; the original shape is restored by heating from the martensitic state or by releasing the applied strain. The causes of the eCE and analysis of available materials are discussed in more detail in Ref. [13, 14]. The entropy change associated with the eCE can be calculated according to measured mechanical properties [12].

$$\Delta S(0 \rightarrow \varepsilon) = -\int_0^{\varepsilon} \left(\frac{\partial \sigma}{\partial T}\right)_{\varepsilon} d\varepsilon \tag{1}$$

where $\Delta S(0 \rightarrow \varepsilon)$ is the entropy change from the relaxed state to strain ε. For first-order materials, the effect is associated with a latent heat associated with the phase transition. This results in a large change in energy at a constant stress across the transition. In the transition region, the entropy change can be calculated from the Clausius-Clapeyron equation by assuming that that $dT_{\mathrm{t}}/d\sigma$ is constant across the transition [12].

$$\Delta S_{\mathrm{t}} = -\frac{\Delta \varepsilon}{dT_{\mathrm{t}}/d\sigma} \tag{2}$$

where ΔS_{t} is the entropy change associated with the martensitic transition and T_{t} is the transition temperature. Larger transitions and latent heat associated with the transition give a higher refrigeration potential of the material. However, there is generally hysteresis associated with the first-order transition, where the austenite to martensite occurs at a higher stress than the reverse [11]. Hysteresis effects reduce

Table 1: Summary of elastocaloric material properties for material families that are considered most attractive for implementing in devices near room temperature. Values are representative and specific material properties will vary.

Material family	ΔS_{t} (J/kg-K)	Hysteresis (MPa)	Critical stress (MPa)
NiTi	-33	100	400
CuNzAl	-17.9	30	250
FePd	-2.2	˜0	200

material performance and cycle efficiency. For elastocaloric materials (eCMs), the properties are often given relative to the material's austenitic finish temperature, A_f. Below A_f the material does not exhibit attractive eCE properties as the transition is not fully reversible [11]. However, as the temperature continues to rise above A_f the stress required to induce the martensitic transformation increases and the eCE decreases [11]. It is therefore a good practice to operate always above but still close to A_f when applying eCEs in a device.

The most studied eCMs are NiTi based alloys, Cu-based alloys, and Fe-based alloys. The NiTi based alloys have been extensively studied for their shape memory properties and are also the most popular eCM for use in devices because of their commercial availability, durability and large eCE. Their transformation temperatures, A_f, can be tuned by varying the composition or by creating alloys by introducing other elements, such as Cu, Pd, Co, among others [15]. Recently an ultralow-fatigue eCM based on NiTiCu that allows over 10 million transformation cycles under isothermal conditions was reported [16], indicating that the materials can exhibit excellent fatigue life. Cu-based alloys are also of interest due to their lower cost in comparison with Ni based eCMs and lower forces to generate the eCE. For example, under adiabatic conditions CuZnAl requires an applied stress of approximately 250 MPa compared to 400 MPa for NiTi. CuZnAl alloys can achieve an outstanding refrigerant capacity due to their entropy change over a broad temperature range, which is reproducible upon cycling [17]. Fe-based alloys are considered less promising because of their lower latent heat. Nevertheless, they avoid brittleness issues and may be attractive, considering their fatigue life [11]. Most of the data in the literature were obtained by applying strain in tension, but Ref. [18] studied different eCMs (CuZnAl, NiTi, NiTiCu, Ni_2FeGa and $NiTiHf_{13.3}$) under both tension and compression. They found that NiTi lifetime in tension was 165 cycles, while in compression it was more than 10,000 cycles. A brief summary of the primary eCMs is given in Table 1. Only material families that can have A_f values suitable for room temperature applications are listed. In Table 1, the hysteresis is defined as the difference in stress in the martensitic transition zone between stress application and release under isothermal conditions. The critical stress is the stress applied to achieve an effectively adiabatic strain application. The values in Table 1 are temperature dependent and can vary for specific compositions so values are only representative.

At the same time, a number of demonstrators has been reported that prove the concept of EC but still do not represent commercially relevant systems. These include systems based on a single ribbon or foil of eCM that is periodically strained and released and alternately put in thermal contact with hot and cold reservoirs. Systems can be built from single ribbons or a cascade of ribbons to increase the overall system temperature span. These "one shot" demonstrators have been reported in several configurations and with several NiTi based alloys [19, 20] and are discussed in more detail in Ref. [21]. These systems use a solid eCM refrigerant that directly cools a small thermal reservoir, usually in the form of a metal block. Other systems employ a porous refrigerant in the form of an array of wires [22], a stack of plates [23] or a bundle of tubes [24] that interacts with thermal reservoirs via a secondary heat transfer fluid, usually water or air. To some extent, the refrigerant and heat transfer fluid in all of these porous

Table 2: Summary of reported elastocaloric cooling demonstrators.

Geometry	Configuration	Material family	Temperature span	Thermal cycle	Ref.
Single ribbon	Tension	NiTi	7	one shot	[19]
Single ribbon	Tension	NiTi	4.2	one shot	[27]
Two-stage ribbon	Tension	NiTiFe	13	cascade	[28]
Single ribbon	Tension	NiTiCuCo	14	one shot	[21]
Tube bundle	Compression	NiTi	1.5	regenerative	[24]
Tube bundle	Compression	NiTi	14	regenerative	[29]
Stack of plates	Tension	NiTi	19.9	regenerative	[25]
Array of wires	Tension	NiTi	under development	regenerative	[22]
Cascaded tube bundles	Compression	NiTi	under development	cascade	[26]

structures are subjected to a temperature gradient and these systems can be considered regenerative. A schematic of the regenerative elastocaloric cycle is shown in Fig. 1. In the cycle, there is a temperature gradient along the flow direction, which is the same direction of strain application. When the material is strained, it heats up due to the eCE. Then fluid flows from the cold reservoir at temperature T_c to the hot reservoir while the material is still under strain, cooling the material. The strain is then released and the material's temperature falls due to the eCE. Fluid then flows from the hot reservoir at temperature T_h to the cold reservoir, accepting a cooling load at the cold reservoir and bringing the system back to its original temperature. The processes need not necessarily occur consecutively and the flow periods can overlap with the application and release of strain [25]. The design of a continuously rotating system using a radially arranged array of wires has been recently described [22]. In that system, the wires are continuously strained and released while air flows over them, thus creating hot and cold air flows. Another elastocaloric cooling configuration based on a cascading series of tube bundles in direct contact with a two-phase heat transfer fluid has also recently been described [26]. the tube bundles are arranged in a series of beds and each bed is compressed consecutively. The heat released during compression boils the heat transfer fluid, which is then transported to the next tube bundle, which operates at a higher temperature. By arranging the bundles in a cascade, the system is able to operate over a temperature span that is significantly higher than the temperature change in a single tube bundle. The system may also be able to operate at high frequency. A summary of reported demonstrators and their performance is given in Table 2. For the most part the systems that have been reported so far use either mechanical testers or hydraulic systems that are designed to ensure accurate loading of the eCM and adequate force. Their efficiencies are generally not reported and are likely low, as they are not designed specifically for the EC application or with high efficiency in mind.

3. Challenges for elastocaloric cooling

Caloric cooling has seen fast development recently, with devices being reported with steadily increasing performance and complexity and new materials with promising properties being developed. However, the technology is still not mature and is not commercially available. The following perspectives are all from the standpoint of elastocaloric cooling being implemented on a large scale in the built environment, such as residential or commercial space cooling or refrigeration. These areas are the most important if the technology is to realize the energy savings predicted by the DOE [9] and to make a serious reduction in energy consumption. Elastocaloric cooling has been suggested for miniature scale applications [21] and

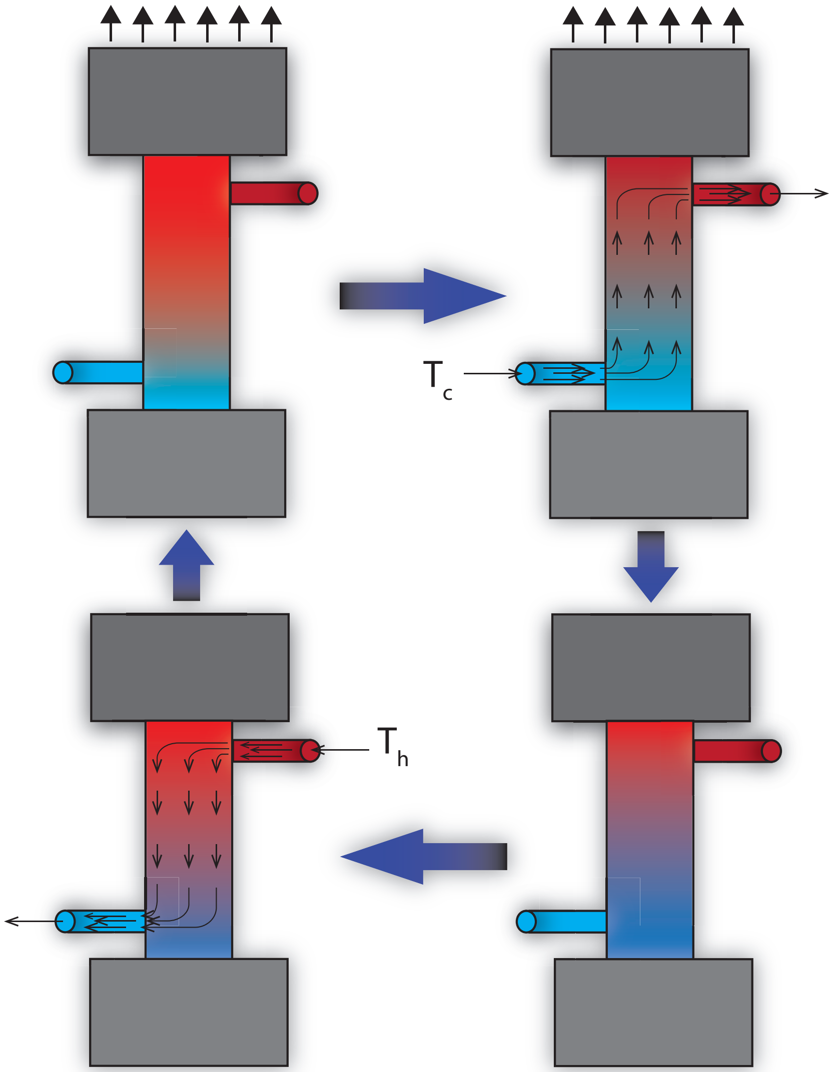

Figure 1: A schematic of a regenerative elastocaloric cooling cycle where the material is in tension. The material is a stack of eCM plates and operates with a temperature gradient in the fluid flow direction (indicated by the color) in steady state operation. The four steps of the cycle are strain application, fluid flow from cold to hot reservoirs, strain release, and fluid flow from hot to cold reservoirs.

cryogenic applications may also pose opportunities for energy savings [30], but those are not discussed here. In order to enter the space cooling market an idealized temperature span for the elastocaloric cooler is from 10 °C to 35 °C [4] and for refrigeration the span can be considered from -10 °C to 30 °C [31], although the actual numbers can vary significantly based on application and geography. It should be noted that the elastocaloric system must operate over a larger temperature span than the span from ambient to the cooled space in order to allow an approach temperature for the heat exchangers. A target temperature span of 40 °C is then reasonable for the technology to be considered as a serious alternative to vapor compression. A 40 °C temperature span also opens up heat pump applications, with additional potential energy savings. The definition of a means of comparing elastocaloric systems to benchmark vapor compression in a way that accounts for the operating conditions of each is also important. As suggested by Ref. [4], the second law efficiency is a useful means of comparing efficiency when the operating temperatures are not the same.

$$\phi = \frac{COP}{COP_{Carnot}} = \frac{Q_{\mathrm{c}}/W}{\frac{T_{\mathrm{c}}}{T_{\mathrm{h}}-T_{\mathrm{c}}}} \tag{3}$$

where COP is the coefficient of performance, Q_c is the cooling power accepted by the device, W is the total work input (including mechanical and pump work) to the system, T_{c} is the cold reservoir temperature as shown in Fig. 1, and T_{h} is the hot reservoir temperature.

In order for elastocaloric cooling to become commercially relevant and to realize its energy saving potential, I see the following major challenges that must be overcome, in descending order of importance:

- Increasing system temperature span from less than 20 °C today to at least 40 °C
- Increasing fatigue life of eCEs in devices to over 1 million cycles
- Finding a practical solution to applying the strain on the refrigerant
- Demonstrating high efficiency
- Increasing the cooling capacity to match final applications
- Coupling the elastocaloric cooler to external components such as heat exchangers and efficient fluid circulators
- Devising control schemes and cycle fine tuning
- Designing a cost-effective and efficient system

In the list above, I consider realizing a commercially relevant temperature span as the most important challenge because maintaining a specific low temperature is the most fundamental function that a cooler provides. As shown in Table 2, devices reported so far are still well below the target of 40 °C, but recent publications have demonstrated significant progress in improving the temperature span and modelling suggests that higher temperature spans are possible [32]. Ways to improve the temperature span are discussed below. Fatigue life is an important challenge that must also be addressed before the technology can be considered for commercialization. I have listed over 1 million cycles as a goal because there are indications that eCMs that can withstand even 100,000 cycles may have infinite fatigue life [33]. If we consider a 20,000 hr lifetime operating at 1 Hz, the required lifetime will be 72,000,000 cycles. In operation as an EC, eCE lifetimes on the order of hundreds of cycles [21] to between 5000 and 6000 cycles [25] have been reported for materials in tension. Perhaps the most promising path to achieving a useful fatigue life is by operating the material in compression rather than tension, and it has been shown that a range of eCMs show high eCE in compression along with potentially much higher fatigue life [34]. The potential benefits of operating in compression are discussed in Ref. [34] and several reported devices are currently operating in compression, but their fatigue life has not yet been reported. Other methods to improve fatigue life include implementing advanced materials [16] and applying the strain in tension at the middle of the superelastic region rather than at a fully relaxed state [33]. Another solution to the fatigue challenge is to develop new, more resilient materials or to improve fatigue properties by controlling hysteresis [35]. I expect eCM research to continue to generate higher performance materials [11] but current materials show promising properties and the challenges listed above can be addressed in parallel to materials research.

The stress required to induce the eCE is approximately 470 MPa for NiTi near its A_f [36], which can lead to high required forces in a device. The system must also apply a strain of approximately 3 %. For the devices reported to date, the force has been applied by a laboratory mechanical tester or a hydraulic system. For practical systems it will be important to develop a compact mechanical system that can apply the high forces and moderate strains as well as external components and housings that can withstand the operating conditions. One way to reduce the necessary force on the system is to use materials with lower transition stresses such as CuZnAl [17], with a required strain near 250 MPa, or operating as close to the material's A_f as possible. In principle, a mechanical system with an efficiency higher than 0.9 should be possible [37], excluding the motor efficiency, which indicates that the mechanical system need not be a major loss mechanism. Another solution to reduce required forces that has been demonstrated is to use an applied magnetic field on a magnetic shape memory alloy [38]. Once a useful temperature span can be achieved with a practical system, it will be important to demonstrate high efficiency on a laboratory scale. Again, it is important to compare second law efficiency as defined in Eq. 3 and to give meaningful comparisons that account for external equipment in an equivalent manner. Aspects of high efficiency operation are discussed below. Achieving cooling powers that match specific applications is only necessary once EC proven that it can meet temperature requirements and operate efficiently. Scaling up cooling power is discussed below in more detail. The final challenges involve implementing elastocaloric cooling into existing applications currently occupied by vapor compression. This includes selecting components such as pumps, motors and heat exchangers and designing a control scheme for the entire system. One major difference between elastocaloric and vapor compression systems is that elastocaloric systems use a single phase fluid at low pressure. This allows the use of cheaper plastic piping and lighter construction heat exchangers, which can be an advantage for EC. Finally, if EC is to gain market share, it must be produced at a competitive cost. However, until the first challenges are met and the size and design of potentially commercial devices are known, the price of such a system cannot be determined with any accuracy.

3.1. Lessons from magnetocaloric research

Elastocaloric systems share many thermodynamic and design aspects with magnetocaloric systems, which have been the subject of much more study [13], making magnetocaloric research a good place to look for solutions to challenges facing EC. Both technologies use a solid refrigerant in contact with an aqueous heat transfer fluid that is subjected to a time-varying external field. Magnetocaloric cooling was first studied at low temperature using a "one shot" cooling cycle and an electromagnet to cool a small reservoir from 1.5 K to 0.25 K [39] and the technique has evolved to industrial scale devices based on permanent magnets [40]. By using a regenerative cycle, the active magnetic regenerator (AMR), the temperature span could be increased from 1.25 °C to approximately 24 °C [41]. More recent devices have shown that they can absorb cooling loads above 2 kW [42] and achieve temperature spans above 30 °C using much lower magnetic fields than earlier devices [43]. I consider EC device research to now be at approximately the same stage as magnetocaloric research was in the 1990s, where system performance was starting to increase but electromagnets, which are not practical for residential or commercial applications, were still being used. This is analog to the recent improvements in system design while still using large mechanical systems to actuate the eCM. The trend in system design has been to move from the first demonstrators that were used single regenerators and electromagnets to more practical systems based on permanent magnets, regenerator beds made from multiple materials and continuously rotating regenerators based on multiple regenerator beds [42, 43, 44]. These systems have also demonstrated that cooling power generally scales directly with the mass of refrigerant for a fixed applied magnetic field, and it is expected that cooling power in EC devices can also be easily scaled by increasing the mass of eCM.

The thermodynamic cycle for EC is the same as for magnetocaloric cooling and therefore much of the modeling and experimental conclusions from magnetocaloric cooling can be applied to elastocalorics. Magnetocaloric materials exhibit a temperature change of magnetization of only a few degrees in permanent magnet fields [45] whereas eCMs can show temperature changes above 20 °C [11]. Therefore, magnetocaloric systems rely more heavily on regeneration than elastocaloric coolers do to reach the same system temperature span. It has been shown by a range of devices that the regenerative cycle can achieve relatively high temperature spans and efficient operation [8] and I see the regenerative elastocaloric cycle as the most promising cycle configuration for achieving high performance ECs. It has been shown that high heat transfer in the AMR systems is critical for high performance through AMR modeling [46, 47]. AMRs with small hydraulic diameters of the regenerator geometry generally have higher performance experimentally as well [48]. It has been shown that maximizing COP for a given operating condition requires a geometry that has a combination of high heat transfer performance and low pressure drop, as pump work can significantly increase work input [48, 47]. Therefore, ECs, just as magnetocaloric systems, will require regenerator geometries with high heat transfer and low pressure drop. Magnetocaloric materials exhibit a large magnetocaloric effect over a relatively small temperature range. It has been shown that by building an AMR from multiple materials where each material is chosen to exhibit the largest magnetocaloric effect in its operating temperature range, AMR performance can be greatly increased [49, 50]. Using multi-material systems could be an attractive way to increase performance or possibly fatigue life of EC systems. System design aspects that have been shown to reduce efficiency of magnetocaloric coolers that are also relevant for EC devices include parasitic heat losses [51, 44] and heat capacity of the regenerator housing [52, 46]. Efficient EC designs will need insulation included in the foundation of the system design and should have housings with low thermal mass.

3.2. Multicaloric effects

Some caloric materials exhibit multicaloric effects, where the change in temperature of the material can be induced by a change in uniaxial stress coupled to another external field, such as a magnetic field [53]. Multicaloric effects in elastocaloric materials have been reported in magnetic fields (magnetic shape memory alloys) [54] or in electric fields [55]. A multicaloric cooling system can be realized by combining a mechanical load with a magnetic field or electric field and gives the possibility of increased solid refrigerant performance [56] or additional novel implementations of caloric cooling devices [57]. It has been shown that by applying a small magnetic field of 0.16 T, the required stress to induce the eCE can be reduced [38]. The application of an external field could possibly increase fatigue life of eCE materials. The use of the multicaloric effects is a promising path to improving EC performance or to add the eCE to, for example, magnetocaloric devices. The potential drawbacks of using multicaloric effects are increased complexity, size and cost of the system.

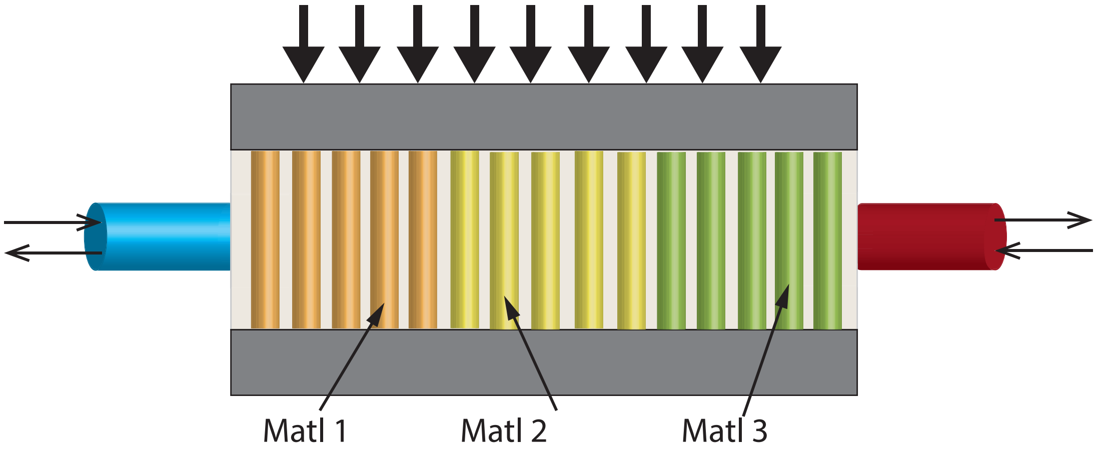

Figure 2: Design concept for a cross flow tube elastocaloric regenerator with multiple materials under compression. Material 1 has the lowest A_f and Material 3 has the highest.

3.3. Elastocaloric system design suggestion

Based on the challenges laid out above and building on research from the field of magnetocalorics, a suggestion for an elastocaloric cooler design is described in Fig. 2. It addresses the required temperature span by using a regenerative cycle based on staggered cylinders in cross flow. The cylinder size and spacing will need to be chosen to achieve adequate heat transfer, probably with a hydraulic diameter on the order of 0.1 mm. A multi-material regenerator is used to reduce the force required to strain the regenerator, to maximize the eCM in each material, and to keep each material operating near its A_f. By arranging a number of regenerators in a parallel flow circuit with a valve system and continuously operating pump (in the same manner as existing AMR systems), a compact industrial system could be constructed. Provided that the system uses efficient components, is well insulated and uses an adequate eCM, the system may be able to achieve a high second law COP. This is just one possible implementation of a high performance elastocaloric cooler and based on systems that are already proposed or reported, I am confident that more innovative designs will be reported in the future.

4. Outlook

Elastocaloric cooling is a promising technology for realizing energy savings through higher efficiency cooling devices and lower environmental impact because the refrigerant is a solid with no risk of leaking gaseous refrigerants to the environment. Current systems are not yet commercially relevant but recent years have shown improvements in reported system performance and new designs presented. Major challenges to commercialization are currently being addressed by researchers across a range of disciplines. The temperature span of systems is increasing through development of new system configurations [21] and new materials [14]. The fatigue life of the refrigerant is being addressed through ultralow fatigue materials [16] and through operating in compression [34]. The high forces required to induce the eCE in NiTi can be addressed by using a magnetic shape memory alloy with a small applied field [38] or by implementing materials with lower required stresses, such as Cu-based alloys. Modelling has shown that by using eCMs with small hydraulic diameters EC based coolers can achieve high efficiency [32]. In addition to these already reported solutions, additional research is still needed. As systems become more industrially relevant it is important to give meaningful comparisons between newly reported results and benchmark existing systems. The second law efficiency gives a good method of comparison, as it takes different operating temperatures into account. It is also important to consider external components in an equivalent way to give a meaningful comparison. When comparing EC devices to vapor compression, consideration must be given to the over 100 years of development vapor compression has been afforded. It is unrealistic that laboratory systems will beat highly optimized commercial systems on performance and the goal should be to demonstrate high efficiency in the laboratory, with the hope that industrial development can bring future efficiencies higher.

The two most critical challenges of increasing system temperature span and fatigue life were suggested in this article. Achieving these goals will likely require a regenerative cycle with improvements in heat transfer between the eCM and heat transfer fluid. High efficiency EC regenerators will require geometries with high heat transfer but relatively low pressure drop, as is also required for magnetocaloric systems. Concepts such as operating in compression or using advanced eCMs to meet the challenge of improving fatigue life are promising but have not yet been proven. If these challenges can be met, I am hopeful that EC devices can become a commercial, energy efficient technology.

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