Elastocaloric Cooling

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The use of the vapor compression cycle (VCC) has resulted in unpredicted environmental damage such as depleting the ozone layer and promoting global warming when its refrigerant leaks into the atmosphere. One way to tackle this problem is to develop cooling cycles using solid-state refrigerants: the caloric materials. The main characteristic of caloric materials is that it is possible to induce a phase transition in solid phase with the application of an external field, which translates in an adiabatic temperature increase or an isothermal entropy change. In this work, we present the main steps to use this caloric effect for cooling and two system integration possibilities for elastocaloric cooling systems.

Introduction

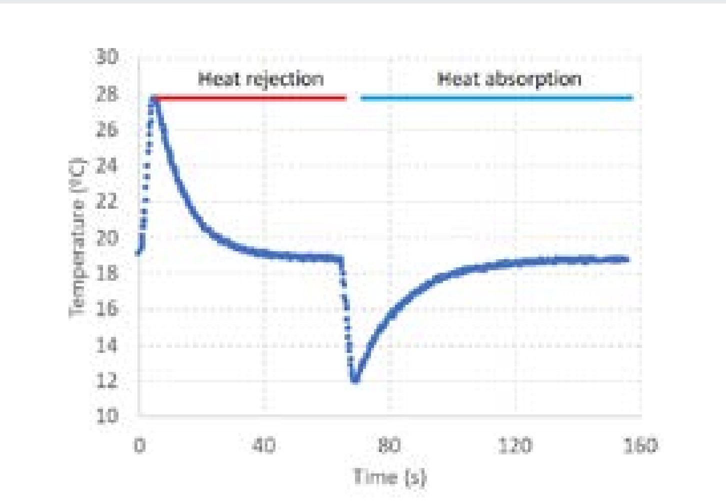
The vapor compression cycle (VCC) has been developed and optimized over the last hundred years to provide cooling in residential and industrial buildings, and vehicles. However, its usage has resulted in unpredicted environmental damage such as depleting the ozone layer and promoting global warming when its refrigerant leaks into the atmosphere. Because of this, it is important to replace VCC by developing a superior alternative cooling technology, without the environmental cost. One way to tackle this problem is to develop heat pumping cycles using solid-state refrigerants since a solid is incapable of leaking into the atmosphere. Caloric materials can be used as solid-state refrigerants. It is also desirable to make these new systems more energy-efficient than VCC. The grand challenges are to keep developing materials with better performance and, just as important, to integrate these materials into systems efficiently.

Generally speaking, the main characteristic of caloric materials is that it is possible to induce a phase transition in a solid phase with the application of an external field. The particular characteristics of this phase transition depend on the material, but it always involves a significant change in entropy. The entropy change manifests itself as a temperature change of the material when the external field is applied or removed adiabatically and as a heat exchange between the material and the surroundings under the constant external field.

Based on the type of external field to which the caloric materials respond, they are classified as magnetocaloric (the phase change is induced by a magnetic field), electrocaloric (the phase change is induced by an electric field) and elastocaloric materials (the phase change is induced by a stress field). This last category is the one that we are focusing on in this report.

Development of Elastocaloric Cooling Technology

A commercially available elastocaloric alloy was used in this study. Conceptually, in order to use it as a solid-state refrigerant it is necessary to apply the following four processes (see Figure 1).



1) **Loading:** A stress is applied adiabatically to the material and its temperature increases.
2) **Heat rejection:** While maintaining the stress, the material cools down to its original temperature by rejecting its heat to a heat sink.
3) **Unloading:** The stress is removed adiabatically from the material. The phase transformation is reversed, and its temperature decreases below its room temperature.
4) **Heat absorption:** The material absorbs heat from a heat source and increases its temperature back to the original one, and the cycle can begin again. During this step of the process, the material supplies cooling.

Fig. 1: Temperature variation during loading and unloading of the elastocaloric alloy.

The main purpose of a cooling cycle is to pump heat from a low temperature level to a high temperature level. In a power cycle, it is necessary to supply heat to produce work output. The heat pump cycle is a reverse power cycle. Therefore, the heat pump cycle and the power cycle can be analyzed in very similar manners. The elastocaloric material can be integrated into a system in different configurations.

Example 1: Elastocaloric cooling cycle with internal heat recovery

As an example, an elastocaloric heat pump cycle was achieved by using the reversed Brayton thermodynamic cycle (Qian et al., 2015). The Brayton cycle represents the thermodynamic operation of a constant pressure heat engine for a power cycle. The reversed Brayton requires a net-work input in order to supply cooling. It comprises the four steps listed above, plus two heat recovery steps to improve the temperature lift that can be achieved. Figure 2, left, shows a schematic of the cooling system. Two sets of elastocaloric materials can be loaded and unloaded by moving the middle crossbar to the left and to the right. The left end of the elastocaloric bed #1 and the right end of elastocaloric bed #2 are fixed. When the crossbar is in the middle, both elastocaloric beds are compressed half way through. When the crossbar moves all the way to the left to fully compress bed #1, bed #2 is allowed to be fully relieved. When the crossbar moves all the way to the right to fully compress bed #2, bed #1 is allowed to be fully relieved. Since the beds are opposing each other, it is possible to recover the unloading work of one bed, and using this to assist the loading of the opposite bed, reducing the necessary amount of work that needs to be supplied in each cycle. By having two elastocaloric materials working in tandem it is also possible to exchange heat between them internally, to preheat and precool each bed before loading and unloading, using the thermal energy stored in them after the heat exchange steps. To further this concept, note that since the materials are solid, it is necessary to have a heat transfer fluid to exchange heat between the elastocaloric materials and the sink and reservoir. The orange tubing connects the elastocaloric materials to the heat sink, the light blue tubing connects them to the heat reservoir and and purple tubing connects the elastocaloric materials with each other. By opening or closing valves V1 to V8 and HRV it is possible to direct the heat transfer fluid to reservoir, sink or internal heat exchange during the correct step.

Figure 2, right, shows the representation of the different steps in an entropy-temperature plot. The state points related to the operating sequence are the following:

1. The cycle starts in state point 1, with the elastocaloric material bed #1 in the austenite phase with no stress applied to it. The material is then compressed until it reaches state 1'. That is the moment when the critical stress is reached and the martensitic transformation begins. Simultaneously, the elastocaloric material in bed #2 is in state point 4, and 4' when the reverse transformation begins upon unloading.

2. The increase in stress continues until the transformation is completed, reaching state point 2. During this process the heat of the transformation is released and the temperature of the elastocaloric material increases. Simultaneously the stress keeps decreasing for the elastocaloric material in bed #2, completing the reverse transformation, decreasing its temperature and reaching state point 5.

3. Valves 1 and 3 are open, pump 1 starts and flows heat transfer fluid through bed #1 towards the heat sink (valves 2 and 4 remain closed). The elastocaloric material in bed #1 cools down to reach state 3 while the stress is still applied. Simultaneously, valves 6 and 8 are open,

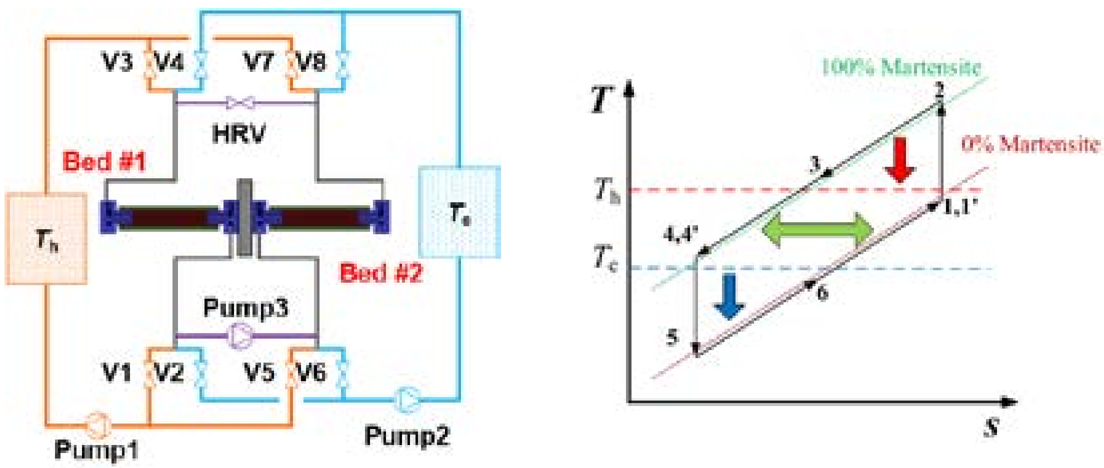


Fig. 2: Left: Schematic of the cooling system. Right: Thermodynamic representation of the reversed Brayton cycle applied to elastocaloric cooling

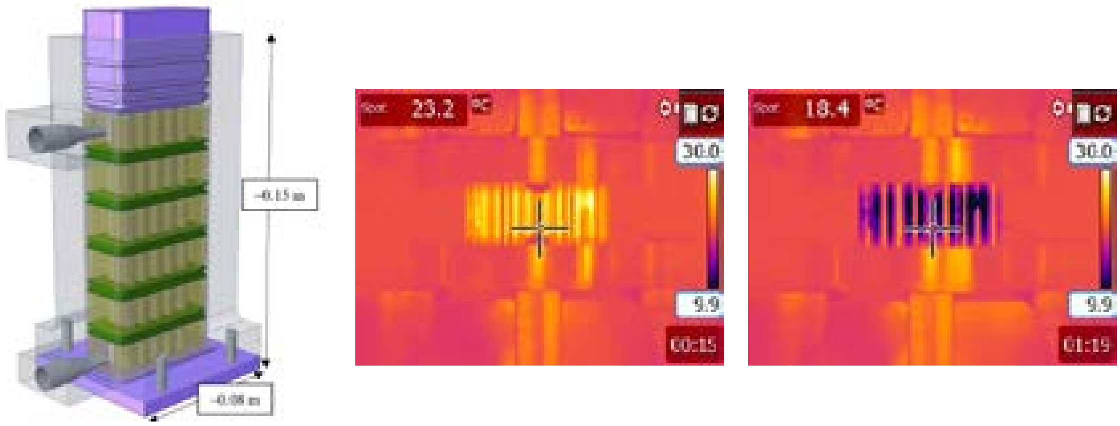


Fig. 3: Left: Regenerator diagram. Right: Proof of heating and cooling.

and pump 2 starts and flows heat transfer fluid through bed #2 towards the heat source (valves 5 and 7 remain closed). The elastocaloric material in bed #2 heats up to reach state 6, with no stress applied.

4. Before the stress is removed, the material in bed #1 can be further cooled down to state 4 by allowing it to exchange heat with the material in bed #2, which is at that moment in state 6. This is what the purple tubing is for. Valves 1 to 8 are closed, pump 1 and 2 are off, HRV is open, and the HR pump is turned on. Ideally, the material in bed #1 should reach the temperature of state 4 which could be equal to the one in state 6, and material in bed #2 should reach the temperature in state 1 which could be equal to the temperature in state 3.

5. The stress in bed #1 is removed, and upon unloading, the material reaches state 4', when the reverse transformation back to austenite begins, and later state 5, when the reverse transformation is completed. This results in a decrease of temperature of the elastocaloric material in bed #1. Simultaneously, the material in bed #2 should begin its loading process, reach state 1' when the forward transformation begins and finally reach state 2 when the transformation is completed. This results in an increase of temperature of the material in bed #2.

6. Valves 2 and 4 are open, pump 2 starts and flows heat transfer fluid through bed #1 towards the heat reservoir (valves 1 and 3 remain closed). The elastocaloric material in bed #1 heats up to reach state 6 still unloaded. Simultaneously valves 5 and 7 are open, and pump 1 starts and flows heat transfer fluid through bed #2 towards the heat sink (valves 6 and 8 remain closed). The elastocaloric material in bed #2 cools down to reach state 3, with no stress applied. After this, the heat recovery step brings everything to the original state and the cycle begins again.

Example 2, "active" elastocaloric regenerator

Another way to integrate the system is to make an active regenerator with the elastocaloric material (Tušek et al., 2016). A regenerator is a storage-type heat exchanger. Cold and hot fluids flow alternatively through the same flow passages, and hence the heat transfer is intermittent. When the hot fluid flows over the heat transfer surface the thermal energy from the hot fluid is stored in the regenerator wall, and thus the hot fluid is being cooled. As a cold fluid flows through the same passages later, the regenerator wall gives up thermal energy, which is absorbed by the cold fluid. During steady state operation, a temperature gradient is developed along the length of the regenerator, the high temperature end is connected to the heat sink and the cold end to the heat reservoir. It is called "active" elastocaloric regenerator, unlike "passive", because an elastocaloric material serves the dual function as heat storage medium and a heat source (or sink) when the forward (or reverse) transformation takes place.

The difference between the previous configuration (example 1) and this one (example 2) is that there is no dedicated heat recovery step. Moreover, a temperature gradient is developed along the regenerator as the hot and cold fluids flow alternatively through the passages. Significant enhancement of the materials capabilities in terms of temperature lift have been measured in magnetocaloric and elastocaloric materials. The largest temperature lift so far published is 19.9K (Engelbrecht et al., 2017) in a laboratory prototype. Another prototype at the early stage of development is currently under development at the University of Maryland (Emaikwu et al., 2019), and can be seen in Figure 3. The compression of a single stage of 23 tubes was achieved successfully, and the proof of heating and cooling can also be seen in Figure 3.

The regenerator design consists of layered stacks of short tubes of the elastocaloric alloy and the transformation is induced by compression. The flow pattern inside the regenerator is similar to the one that can be observed in a shell-and-tube heat exchanger. The length of the tubes is calculated such that buckling is prevented. The distance between tubes is one of the most important variables expected to influence the structural stability of the system, the heat transfer coefficient and the pressure drop.

Conclusions

Due to recent environmental concerns, the development of cooling technologies that do not use refrigerants with high global warming potential and ozone depletion potential and are more efficient than current vapor compression technology has become an important research topic. The development of elastocaloric cooling technologies is rather new, but progress has been made during the last few years. In this paper, two examples of system integration options have been presented: one with a dedicated heat recovery process and another one avoiding the heat recovery process by building a regenerator into the system. Even though the cooling capacity of the prototype systems is still far from the requirements of a commercial application, the temperature lift performance is growing and getting closer to the minimum requirements needed.

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