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DEVELOPMENT OF A SHAPE MEMORY BASED AIR CONDITIONING SYSTEM

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ABSTRACT

The following contribution presents a new concept of an air conditioning device based on the elastocaloric cooling effect of shape memory alloys (SMA's). This technology provides an energy efficient and environment friendly alternative to conventional vapor compression based cooling principles. Starting from the thermodynamic investigation of the elastocaloric cooling process, a continuous operating elastocaloric air cooling device is developed. The device enables an optimized thermodynamic process control under various operating conditions as well as large temperature spans. This work presents the design process of such a system starting from SMA based heat engines to a thermodynamically optimized design of an elastocaloric air conditioning device.

1. INTRODUCTION

Shape memory alloys (SMA's) have been known for biocompatibility, high energy density and self-sensing properties. In addition elastocaloric cooling has recently started to attract interest as a further possible application for SMA's and is currently being investigated as part of the German Science Foundation (DFG) Priority program SPP 1599 Ferroic Cooling [1].
Elastocaloric cooling is a pioneering cooling technology which has the potential to become an environmentally friendly alternative to the conventional vapor compression based process[2]. The advantage of this technology is that the use of ozone-depleting refrigerants can be avoided. Elastocaloric materials, especially SMA's based on Ni-Ti, show large latent heats [3] [4] and require a small work input which results in an efficient cooling process. The latent heats of the material can be accessed by loading and unloading the SMA sample. Fast adiabatic loading leads to a phase transformation from austenite to martensite and a temperature increase of the material whereas fast adiabatic unloading leads to a temperature decrease and a reverse transformation.[5] Based on this material behavior, elastocaloric cooling processes can be developed and implemented in a SMA based cooling device. The first thermodynamic devices based on SMA technology are heat engines. The operation principle of these systems are similar to the operation principle of a cooling system, the thermodynamic cycle is just inverted. To realize an air cooling device, a continuous heat flux is needed. A parallel, time-staggered sequence of multiple discontinuous processes generates a continuous heat flux from a discontinuous process. This is equivalent to the requirements of an SMA based heat engine.

1.1 Heat engine

In the literature different mechanical principles of heat engines are described to transfer a discontinuous SMA based heat conversion process into a continuous one. Heat engines generates mechanical energy from thermal energy, the underlying mechanical configuration can also be used for the reversed process of the cooling applications. Below three promising concepts are specified:

Myung, et al. [6] describe a concept in which the SMA samples are arranged between two planar placed counter rotating disks, as shown in Figure 1. A vessel with hot fluid is placed at the lower part of the disks (6). The SMA sample contract as soon as it is in contact with the liquid and extend at ambient air, which results due to the lever arm in to a rotational movement of the disks. This principle was investigated by Kaneko and Enomoto [7].

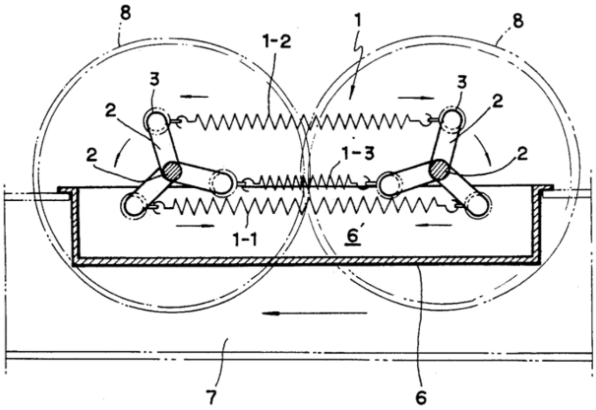

Figure 1: Schematic side view of the TWIN-CRANK TYPE HEAT ENGINE by Myung, et al. [6]: Components: Power elements (SMA) formed into tightly (1), two crank shafts (2), sliding bearings (3), hot water vessel (6), hot water passage (7), crack shaft (8).

Banks developed a principle in which the SMA wires are arranged radially in one plane, as shown in Figure 2 [8]. The outer ends of the wires are attached radially on a ring with a fixed diameter (12), while the inner ends are connected to an eccentrically-mounted ring (19). Below this wheel, two semicircular liquid vessels at different temperature levels are placed (20, 21). While the rotation of the wheel the SMA passing the vessel thus the SMAs generates as a result of the contraction and extension the rotational movement.

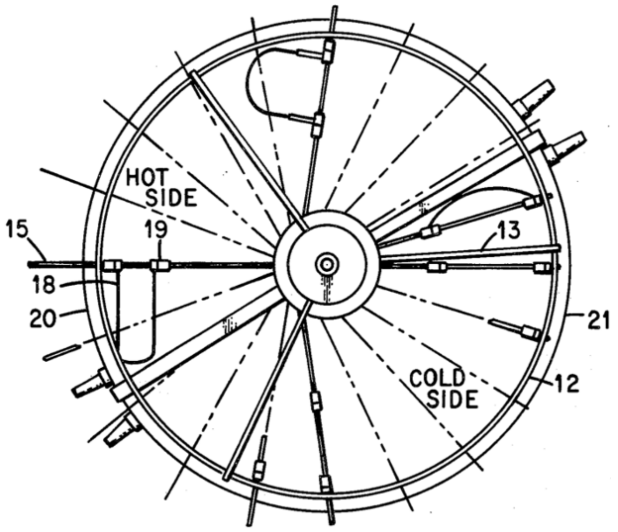

Figure 2: Schematic top view of the ENERGY CONVERSION SYSTEM by Banks [8]:
Components: Ring member (12), ring spider (13), rod members (15), fixed shaft (16), thermally responsive elements (SMA) (18), engage fixed means (19), semicircular vessel (20), containing water at a temperature-above the critical temperature, semicircular vessel (21), containing water at a temperature below said critical temperature.

Cory developed a mechanical concept (see figure 3) in which the SMA samples (190) are arranged axially around the circumference between two co-rotating disks (186) [9]. At least, one of these disks is inclined. Additionally to the sketch a vessel with tempered fluid has to be arranged axially, to generate a heat source and heat sink. While the passing of the heat source and the heat sink the SMA sample contracts and expands which results in to a rotational movement. This concept was investigated by Glasauer (1996) and Gümpel et al. (2001) [10]. Comparable to the concept from Banks (1975) as mentioned before, is this the axially everted version.

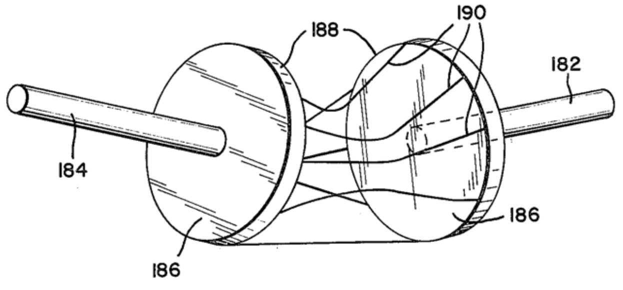

Figure 3: Schematic view of the SOLID STATE HEAT ENGINE by Cory [9]:
Components: Axes (182, 184), disk (186), peripheral portions (188), bending or flexing of strings 190.

The concept of co-rotating disks seems due to the mechanical arrangement of the wires best suited for the elastocaloric air conditioning unit in terms of the system complexity, -size and -efficiency.

1.2 Elastocaloric Cooling devices

In addition to the SMA based heat engine first SMA based cooling devices has been developed in the past few years. In microscale technology Ossmer et al. developed and realized a SMA thin-film-based heat pump demonstrator [11]. The macroscopic technology can be divided by the load case, the geometry of the active material, the type of the heat exchange and the medium. A summary of the research activities in alternative cooling technologies based on ferroic materials is given by Kitanovski et al. [12]. Additionally Qian et. al. gave an overview of recently developed cooling devices [13]. Tušek et al. present a discontinuous working active elastocaloric regenerator based on the convective heat exchange between planar stacked SMA plates [14]. Qian et al. developed an elastocaloric cooling demonstrator based on compression loaded SMA tubes packets, surrounded by a fluid [15]. The convective heat exchange produces with control valves a discontinuous heat flux.

2. DEVELOPMENT PROCESS

Below the development process of the actuation mechanism and the heat exchange concept for the elastocaloric cooling device are described.

2.1 Inclined Disk

The basic concept of the elastocaloric air conditioning device is derived from a SMA heat engine, which has been adapted to the requirements of cooling systems. A schematic of the derived device is shown in Figure 4.

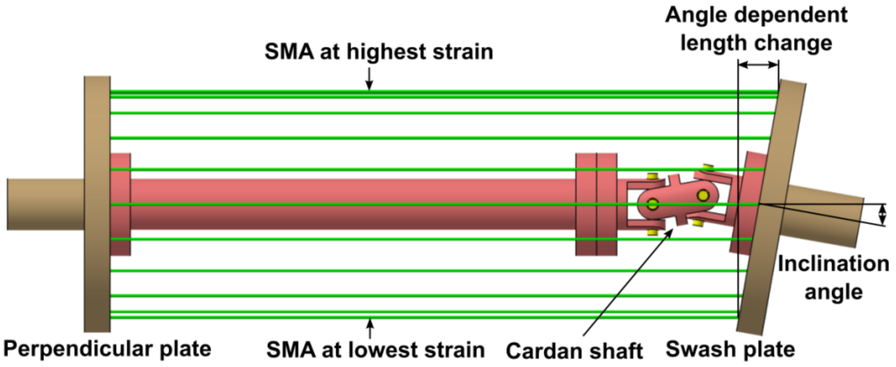

Figure 4: Side view of the schematic mechanical setup for the proposed elastocaloric cooling device. The swash plate converts the rotary motion into linear movement. Variation of the inclination angle allows adjusting the SMAs strain during the rotation [16].

The major advantages of this concept in relation to other concepts are the stationary heat sink and source as well as the use of a rotary drive for energy efficient operation. Furthermore the design offers the potential to place a large amount of active SMA material in a small assembly space. Numerous superelastic SMA wires can be arranged around the circumference of the two circular plates. Both ends of each wire has to be guided synchronously corresponding to the perpendicular and the inclined disk, therefore the two disks are connected by a Cardan shaft to allow the angular tilt.

While the rotation of the disks the swash plate converts the rotary motion due to the inclination angle to a linear distance change. This mechanism loads and unloads the SMA wires continuously. The maximum temperature change of the wires depends on maximum strain of the wires, which can be adjusted by the inclination angle of the swash plate. Due to the increasing strain during rotation the martensitic transformation results in an increasing temperature during loading. During subsequent unloading the transformation to austenite leads to a temperature decrease. The cyclic loading and unloading induces a temperature profile along the circumference of the device. In order to efficiently use the resulting heating and cooling capacity an appropriate heat transport mechanism is required.

The heat exchange can be achieved by a transversal air flow. The large number of individual wires in various stages of transformation around the circumference generates a continuous process that enables a uniform heating or cooling (see Figure 5).

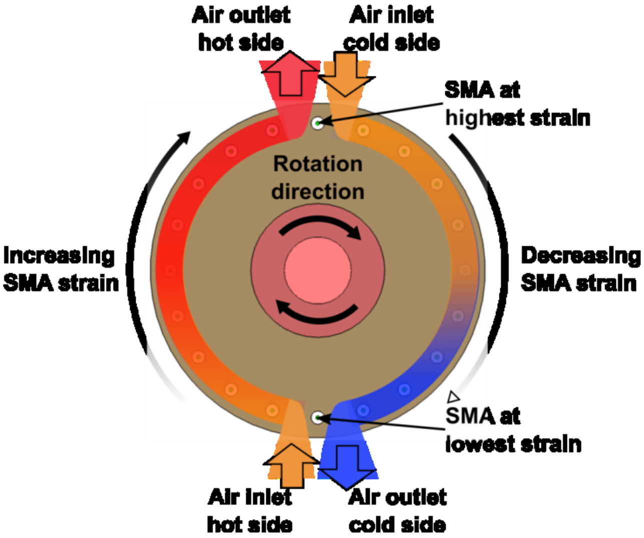

Figure 5: Schematic cross section of the temperature distribution in the proposed elastocaloric cooling device with continuous operation. The rotary motion of the device leads to continuous loading and unloading of the SMA wires. The cold SMA elements absorb heat from the cold side air stream, while the air stream on the hot side cools the hot SMA elements [16].

Two semicircular ducts divides the airflow into two air streams. The left air stream is heated through the exothermic phase transformation during loading of the SMA wires and the right air stream is cooled by the endothermic phase transformation during unloading. The advantage of this system is the use of air, eliminating the need for an additional heat exchanger and thus the associated efficiency losses.

The investigations of the process parameters shows a strong strain rate dependency of the temperature change in the SMA [17]. The strain rate can be adjusted by the rotational frequency.

The strain rate is only one of numerous control parameters influencing the process variables: work, heat, coefficient of performance and cooling power. A systematic variation of the control parameters is required in order to develop an optimal SMA based air conditioning device. To this end, a scientific test setup has been developed which enables an independent investigation of the influence of each control parameter to the process variables [18] [19]. In addition to the strain rate, the influence of the maximum strain [20], the process control [17], the thermal boundary conditions, the material [21] as well as the elastocaloric cycle itself [16] has been investigated. One of the mayor findings was that an advanced thermodynamic cycle with a combination of an adiabatic and an isothermal cycle shows the best performance [22]. This has also been shown for other caloric materials showing the magnetocaloric effect, which confirms the results [23]. The concept of the inclined disk, only provides a continuous sine-wave formed loading and unloading which does not allow for advanced process control like adiabatic isothermal combined cycles.

To overcome the disadvantages of this concept, enabling an efficient cooling device with high cooling power, a new mechanical concept is needed, which allows the control of the thermodynamic cycle.

2.2 Cam disk

In the new mechanical design, an advanced stroke concept with a cam disk is developed [24]. The cam disk converts rotary motions into linear motions. In Figure 6 the mechanical concept of the cam disk is shown. The cam follower is guided by the cam profile and generates a linear axial movement.

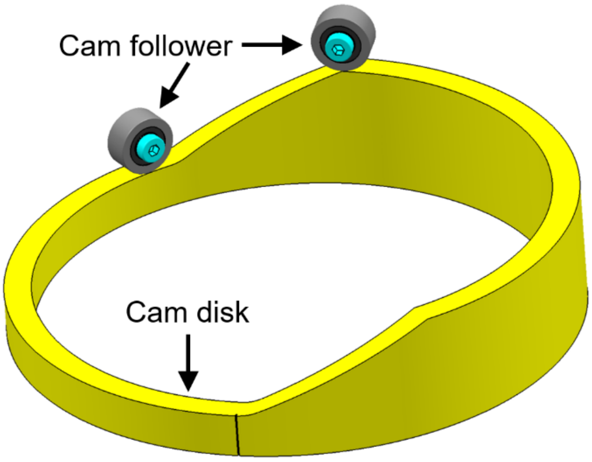

Figure 6: Isometric view of a Cam disk with two cam followers.

The motion function of the cam follower and thus the load profile of the active element can be adjust with the cam profile to the desired thermodynamic cycle. The cam profile enables further the addition of holding phases in the cycle for heat exchange with air.
A side view of the schematic mechanical setup for the advanced elastocaloric cooling device is shown in Figure 7.

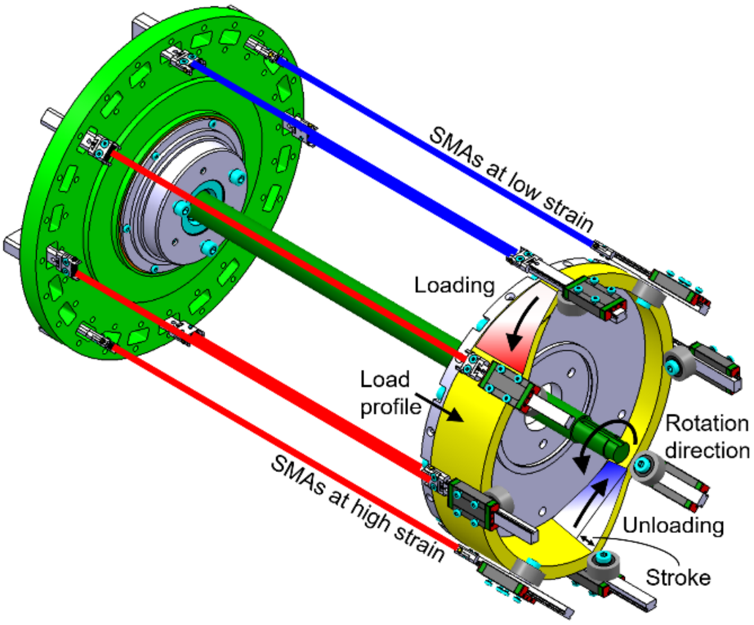

Figure 7: Isometric view of the schematic mechanical setup for the advanced elastocaloric cooling device. The cam disk converts the rotary motion into linear movement. The motion function of the cam follower, thus the load profile of the active element can be adjust with the cam profile to the desired thermodynamic cycle.

The SMA wires are attached on the cam follower. The loading force of the SMA depends on the applied strain, which is controlled by the cam profile. To minimize the friction and increase the system efficiency the cam follower is engineered as a roller. A further advantage of the cam disk is that the disk provides a pure axial loading to the wire in contrast to the inclined disk, where the wire is bending near to the clamp. The pure axial load increases the lifetime of the wires. The convective heat transfer, should take place with a surrounding fluid. To guide the fluid across the wires, ducts are used, as shown in Figure 8 equivalent to the initial design concept.

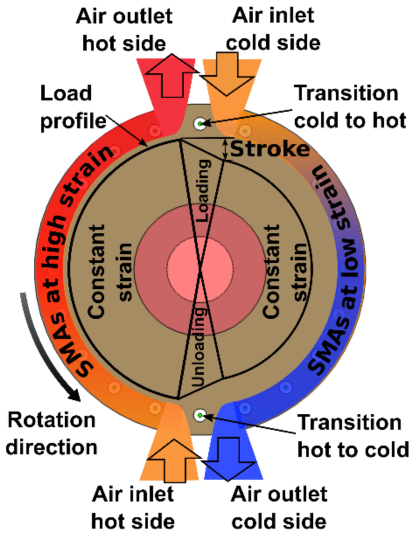

Figure 8: Schematic cross section of the temperature distribution in the advanced elastocaloric cooling device with continuous operation. The rotary motion of the device leads to loading and unloading of the SMA wires defined by the load profile.

The left side in figure 8 shows, the load profile of the rotating wires. The wire temperature change during loading and unloading, due to the latent heats and fulfill a heat exchange with the surrounding fluid. The resulting temperature profile over the circumference is illustrated in Figure 8.

The required mechanical work during the cooling process and thus the overall efficiency strongly depends on the wire temperature as a result of the heat exchange during phase transformations as well as the strain rate during the loading and unloading phase [17]. Airflow and air velocity are control parameters influencing the heat exchange of the wires during the rotation .Fine tuning these parameters enable to match the operating point to the highest efficiency. The variation of the airflow and air velocity affects the temperature development in the material due to the phase transformation in a similar way as a variation of the strain rate.

3. Conclusion

In this work, an advanced mechanical concept of a continuously operating elastocaloric air cooling device is presented. Starting from the first concept, derived from a heat engine principle, the mechanical actuation mechanism is improved. The new cam disk based concept enables an optimized thermodynamic process control under various operating conditions as well as large temperature spans. In detail, it allows optimized combinations of adiabatic and isothermal transitions for loading and unloading, as well as increased heat transfer time at constant strain to improved heat exchange with the air. This improves the system performance significantly.

Additionally the concept of the heat exchange between SMA wires as cooling medium and air as heat transport medium is introduced. The cooling unit absorbs heat from the indoor air without the need for an additional heat exchanger. All these optimization approaches will improve the efficiency as well as the cooling power of the future elastocaloric air cooling unit. The system design enables a straight forward adaption to the required cooling power.

4. Acknowledgements

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