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THE EXPLOITATION OF NITI-ALLOYS AS SOLID-STATE REFRIGERANTS OF AN ELASTOCALORIC SYSTEM

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ABSTRACT

The most recent information made available to the scientific community claims that a prototype elastocaloric device provides a number of benefits over conventional systems based on vapor compression. Greater energy efficiency is one of the key benefits, as the elastocaloric device method uses less energy than conventional systems. This is accomplished without the use of chemical refrigerants thanks to the elastic deformation of a solid substance utilized as a heat transfer medium. Despite the many benefits, the technology is still in its infancy, and further investigation is required to answer worries about prices, efficiency, and scalability. In general, this technology exhibits potential as a viable and alluring replacement for conventional refrigeration systems. Through an accurate two-dimensional model of an elastocaloric system, the exploitation of Ni.Ti alloys as solid state refrigerants is tested. This study presents an optimized geometric configuration of the device that maximizes the energy performance. Along with preliminary performance numbers for cooling power and coefficient of performance, the findings are reported in terms of temperature, velocity, and pressure.

KEYWORDS: Nitinol; Shape Memory Alloys; Device; Solid State Cooling

1. INTRODUCTION (Details for Submitting Extended Abstract)

According to the International Energy Agency [1], approximately 20% of the global electricity consumption is attributed to cooling residential buildings. Currently, the predominant method used in traditional refrigeration is Vapour Compression (VC). Space cooling contributes to annual CO_2 emissions of 1130 million tonnes. This is the outcome of both the direct impact, caused by the release of refrigerant gas with a high Global Warming Potential (GWP) into the atmosphere, and the indirect impact, caused by the energy consumption of the system, on global warming. Developing a sustainable alternative to VC in the air-conditioning industry has emerged as a top priority for contemporary society due to the need to decrease greenhouse gas emissions. The elastoCaloric Cooling (eCC) is considered one of the most promising alternative refrigeration technologies due to its potential to achieve great efficiency without using environmentally damaging refrigerants. eCC is a type of refrigeration technology that uses solid-state refrigerants. It has several advantages: it does not use greenhouse gases, operates quietly, can recycle its components, and has the potential for 50-60% greater energy efficiency compared to traditional refrigeration systems [2]. The U.S. Department of Energy and the European Commission acknowledge eCC as the most auspicious substitute for VC and Elastocaloric has been classified as number 7 of the Top Ten Emerging Technology by the World Economic Forum [3]. eCC bases on the elastocaloric effect, a physical phenomenon where a mechanic stress forcing a solid-state elastocaloric material like Shape Memory Alloy (SMA) generates a temperature change. Since 2012, almost 20 experimental prototypes have been constructed in research laboratories around the world and are currently documented in the literature [4]. These prototypes can be categorized into two groups based on the type of heat transfer mechanism utilised

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with the solid refrigerant, either convective or conductive. The first category includes prototypes that involve direct contact between two solid materials (solid-to-solid). The prototypes mentioned are primarily compact and employed in small cooling systems or for the purpose of cooling electronic components. The second category involves the utilization of a secondary fluid, such as water or air, to facilitate the transfer of heat with the solid refrigerant. These devices can be loaded using either compression or tension mechanisms. The prototypes that use air as a secondary fluid are suitable for applications in the macro-scale field, as determined by tensile stress. Two rotary prototypes have been created using this operational approach, however, there is a lack of substantial experimental data that has been made public. At the Heat Transfer Laboratory (HTL) of the University of Naples Federico II an experimental elastocaloric prototype for air conditioning has been developed within the SUSSTAINEBLE project. The outcomes of SUSSTAINEBLE project involve the forthcoming deployment of an elastocaloric device, which is the responsibility of the University of Naples Federico II, and a magnetocaloric device, which is assigned to the University of Genoa unit whereas the development of performing solid-state refrigerants is a National Research Council responsibility. The prototype is designed in a rotating manner to ensure a continuous flow of hot or cold air. A two-dimensional model was constructed to properly measure the dimensions of the prototype by simulating the actual rotation of the device. An energy performance study is conducted to identify the most promising elastocaloric materials from a range of options. The investigation reported in this paper introduces several innovations. Firstly, it involves the design of an environmental conditioning device that outperforms traditional systems. Secondly, it presents a two-dimensional model that accurately replicates the device's rotation using a rotary dynamic meshing technique. Lastly, it creates an energy performance map for various NiTi SMAs to identify the most promising option.

2. THE SELECTION OF THE NITI ALLOYS

The selection of an elastocaloric material for use as an eC heat pump's refrigerant in residential applications is contingent upon a number of criteria, such as the particular demands of the application, the material's thermal characteristics, safety, longevity, and energy efficiency. A further important consideration when choosing elastocaloric materials for solid-state refrigeration is to confirm the material's long-term stability and resilience to repeated cycles of elastic deformation and relaxation. Furthermore, it is important to consider market availability and, by extension, the cost of procurement as well as manufacturing. The economic viability of experimental prototypes and possible large-scale commercialization would be greatly impacted by the availability of a particularly rare or, worse, costly elastocaloric material. However, as no material can truly satisfy every need at once, selecting a respectable material requires making a good compromise. It is possible to define the COP of the material (COP_{mat}), which measures the energy conversion efficiency through the properties of the elastocaloric materials, under the assumption of an ideal refrigeration cycle on net work required to show the effect, i.e. the area enclosed in the hysteresis loop associated with the loading and unloading operation.

The thermodynamic characteristics of the most promising candidates, which is also the subject of the comparison in this research, are compiled in Table 1: $Ni_{55.9}Ti_{44.1}$, $Ni_{45}Ti_{47.2}Cu_{5}V_{2.75}$, $Ni_{50}Mn_{30}Ti_{20}$, $Ni_{50.8}Ti_{49.2}$, and $Ni_{50}Mn_{31.5}Ti_{18.5}$ are the alloys. When used as solid-state refrigerants, the majority of the recommended materials have very promising energy performances due to their exceptionally high COPmat values.

Table 1 Characteristics of the elastocaloric materials.

Material	**ρ (kg m^{-3})**	**c (Jkg^{-1}K^{-1})**	**k (Wm^{-1}K^{-1})**	**ΔT_{ad} (K)**	**COP_{mat}**	**w (J g^{-1})**	**Af (K)**	**Δσ (MPa)**
$Ni_{50.8}Ti_{49.2}$	6500	550	18	17.8/14.7	6.99/5.78	1.4	273	450
$Ni_{55.9}Ti_{44.1}$	6500	430	18	24/17	26.8/18.9	0.385	266	900
$Ni_{45}Ti_{47.2}Cu_{5}V_{2.75}$	7340	460	25	21/20	19.2/18.4	0.5	278	400
$(Ni_{50}Mn_{31.5}Ti_{18.5})_{99.8}B_{0.2}$	7587	470	10	26.9/31.5	21.9/25.7	0.577	269	700
$Ni_{50}Mn_{30}Ti_{20}$	7340	470	10	20/23.7	19.2/16.5	0.870	273	1070

3. THE SUSSTAIN-EL DEVICE AND THE NUMERICAL MODEL

The elastocaloric device, known as SUSSTAIN-EL, is designed to deliver two uninterrupted air flows (one cold and one hot) for air conditioning purposes. This is achieved using a revolving configuration. When two cylinders

with different diameters (inner diameter = 120 mm; outer diameter = 135 mm) and a length of 300 mm are stacked on top of each other, the device is designed to accommodate 600 wires with a diameter of 0.5 mm and a length of 30 cm each. These wires allow air to flow between them, serving as a heat transfer fluid.
The device is a cutting-edge elastocaloric cooler specifically engineered for household use. Its primary objective is to deliver effective and environmentally-friendly cooling or heating. The system's core comprises 600 SMA wires that exhibits exceptional elastocaloric capabilities. Electronically controlled pistons exert a cyclical force on each group of SMA wires, causing them to undergo cycles of elastic loading and relaxation. While loading, the temperature of the SMA rises due to the elastocaloric action. Additionally, an air flow system is used to heat up the air drawn through the channel. During the relaxation phase, the elastocaloric material undergoes cooling. The device allows air from the external environment to enter and come into touch with the elastocaloric materials for the purpose of cooling. The device is capable of guaranteeing a constant flow of hot or cold air, which can be utilised for cooling during the summer and heating during the winter.
A 2D rotative numerical model, experimentally validated in previous investigations [5] was utilized to design and test the experimental device mounting different materials. The numerical model is mathematically described by: i) the air mass continuity equation; ii) the air momentum equation; iii) the air energy equation; iv) the SMA energy equation that are reported below (1-4):

$$\frac{\partial \rho}{\partial t} + \nabla\left(\rho \vec{u}\right) = 0 \tag{1}$$

$$\rho \frac{\delta \bar{u}}{\delta t} + \rho(\bar{u} \cdot \nabla)\bar{u} = \nabla \cdot \{-p\bar{I} + (\mu + \mu_T)[\nabla\bar{u} + (\nabla\bar{u})^T]\} \tag{2}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\bar{u}(\rho E + p)] = \nabla \cdot \left[k_{eff}\nabla T + \tau_{eff} \cdot \bar{u}\right] \tag{3}$$

$$\rho_{SMA} c_{SMA.p} \frac{\partial T_{SMA}}{\partial t} = k_{SMA}\left(\frac{\partial^2 T_{SMA}}{\partial x^2} + \frac{\partial^2 T_{SMA}}{\partial y^2}\right) + g''' \tag{4}$$

where g''' represents the elastocaloric effect (a positive term during loading, negative during unloading) and it can be evaluated with the following equation:

$$g''' = \rho_{SMA}(\Delta H + w)\dot{\xi}_M \tag{5}$$

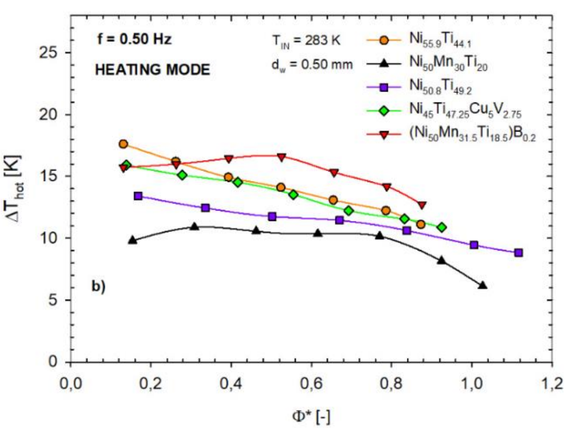
and w is the required net work:

$$w_{net} = w_{load} - w_{unload} \tag{6}$$

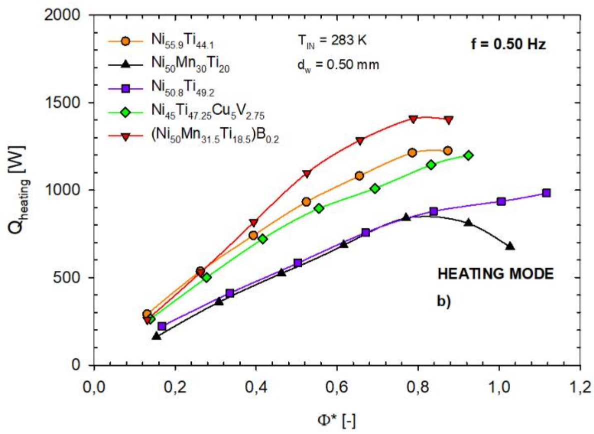
4. RESULTS

Numerical simulations have been carried out and the energy performances have been evaluated while the prototype mounts the SMA listed in Table 1 and it works in heating mode at 0.5 Hz as rotation frequency with an inlet temperature of 283 K.
In Figure 1 the (a) temperature span on hot side; (b) the heating power; (c) the Coefficient Of Performance (COP) and (d) the COP on COP_{mat} ratio are shown as a function of the utilization factor, evaluated as:

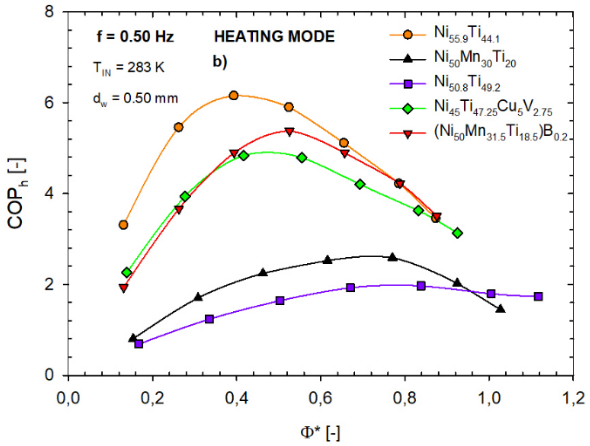
$$\Phi^* = \frac{\dot{m}_{air} c_{air} t_{channel}}{m_s c_s} \tag{7}$$



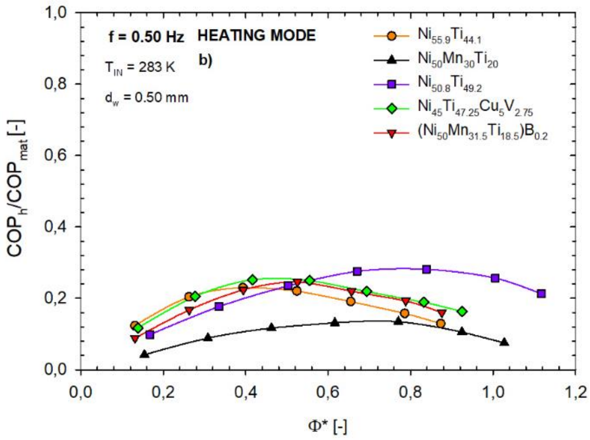
(a)



(b)



(c)



(d)

Fig. 1 (a) Temperature span on hot side; (b) heating power; (c) the Coefficient Of Performance (COP) and (d) the COP on COPmat ratio evaluated for different NiTi-SMA as a function of the utilization factor.

With the exception of $Ni_{45}Ti_{47.25}Cu_5V_{2.75}$ and $Ni_{55.9}Ti_{44.1}$, all materials show a similar pattern in the heating mode, with a maximum utilization factor below 0.2. The various behaviors can be attributed to an equilibrium between the latent heat of the SMAs that needs to be transferred and the optimum ideal duration required for complete heat transfer. The ideal point, which corresponds to the maximum of the curve, occurs at various utilization factors. The quaternary alloy $(Ni_{50}Mn_{31.5}Ti_{18.5})_{99.8}B_{0.2}$ is the most suitable material in terms of temperature range. It has values that range from 17.5 K (ϕ*=0.53) to 13.1 K (ϕ*=0.9) in heating mode. When operating in heating mode, none of the alloys are able to exceed heating power values of 1.5 kW, even under conditions of high utilization factor. The quaternary alloy $Ni_{45}Ti_{47.25}Cu_5V_{2.75}$ has the highest value, reaching 1.48 kW (ϕ*=0.8), which equates to a Specific Heating Power (SHP) of 5522 W kg^{-1}. Nevertheless, any configurations that demonstrate values over 1 kW can be deemed suitable for the prospective development of large-scale heat pump prototypes.

The COP values data as a function of the utilization factor exhibit parabolic-like tendencies and the maximum occurs at variable points for each material. When pressure drops increase dramatically, the fan's work and power consumption also increase because the COP values are affected at higher mass flow rates. Throughout the whole range of utilization factors, $(Ni_{50}Mn_{31.5}Ti_{18.5})_{99.8}B_{0.2}$ has higher COP values compared to all other materials. Indeed, the latter exhibits minimal hysteresis, as previously recorded. The maximum COP in heating mode is 5.3. The upper coefficients of performance for $Ni_{55.9}Ti_{44.1}$ and $Ni_{45}Ti_{47.2}Cu_5V_{2.75}$ in cooling mode are around 5. The COP values of $Ni_{50.8}Ti_{49.2}$ and $Ni_{50}Mn_{30}Ti_{20}$ are not competitive with those of conventional heat pumps. The maximum COP for $Ni_{50.8}Ti4_{9.2}$ is 1.8, while for $Ni_{50}Mn_{30}Ti_{20}$ it is 3.4. The substantial hysteresis weight negatively impacts the energy efficiency of $Ni_{50.8}Ti_{49.2}$. Figure 1 (d) presents the ratio between the coefficient of performance of the device and the COP of the material for different elastocaloric materials, as a function of the utilization factor. The ratio values represent the device's capacity to extract thermal energy from the elastocaloric substance. As general considerations we can observe the maximum falls at different ϕ*.

6. CONCLUSIONS

This study conducts a comparative investigation of NiTi-based shape memory alloys to determine their potential as refrigerants in an elastocaloric air conditioning system. The investigation was conducted using a two-dimensional rotating model. The performance characteristics, including temperature span, heating power, COP and COP on COP_{mat} were assessed. Our analysis has determined that the $(Ni_{50}Mn_{31.5}Ti_{18.5})_{99.8}B_{0.2}$ material is the most suitable for the SUSSTAIN-EL device since it guarantees the most improved energy performances.

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