Transactions on Environment, Energy and Earth Sciences
ISSN: 2960-1924, eISSN: 2960-2300 | Volume 5
EMCEME 2025

Exploration of the Improvement of Shape Memory Alloys for Elastocaloric Refrigeration

Qiyuan Luo *

School of Chemical Engineering, Ocean and Life Sciences, Dalian University of Technology, Dalian, China

* Corresponding Author Email: luoqiyuan@ mail.dlut.edu.cn

Abstract. Elastomeric cooling, an emerging solid-state cooling technology that uses the reversible phase transition between austenite and martensite in shape memory alloys (SMA) under stress for cooling, has advantages such as high COP and environmental friendliness, and is expected to replace traditional cooling methods. This paper systematically presents the basic principles of elastocaloric refrigeration, the methods for characterizing material properties and the progress of equipment research. The fatigue life, elastocaloric effect and cooling efficiency of SMA were significantly enhanced through material modification (such as element doping, concentration gradient design, and nanocrystalline structure regulation) and structural optimization (such as thin-walled tubes, thin-film multilayer coupling, tilt, and roller drive design). Despite the current challenges of fatigue life, equipment compactness and energy utilization efficiency, elastomeric cooling technology shows broad application prospects in low-carbon environmental protection and efficient cooling. Although it still faces challenges such as fatigue life, equipment compactness and energy utilization efficiency at present, elastomer cooling technology shows broad application prospects in the fields of low-carbon environmental protection and efficient refrigeration.

Keywords: Shape memory alloys; Elastocaloric; Efficient refrigeration.

1. Introduction

Conventional refrigeration models, such as refrigerators, rely on chemical reagents like chlorofluorocarbons through gas compression to cycle phase changes, using latent heat exchange in the process to achieve cooling. However, with the widespread use of such traditional refrigeration equipment, its drawbacks have gradually emerged: the leakage of refrigerants damages the ozone layer and intensifies the greenhouse effect; Air conditioners consume a lot of electricity and make a lot of noise. As a result, people are focusing on new ways of cooling. The current mainstream new research directions are: magnetocaloric effect, elastocaloric effect, comprescaloric effect and electrocaloric effect, which are respectively driven by different external forces for cooling. In contrast, elastocaloric cooling, which uses the cycle between austenite and martensite in shape memory alloys under different stress conditions, has a simple mechanism, a significant temperature drop, a higher COP and is more environmentally friendly. There has been considerable progress in the study of the mechanism of elastocaloric refrigeration and the design of elastocaloric refrigeration equipment in various countries. Yang Rui and others from the Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences have designed a new elastocaloric refrigeration system that uses low-grade heat to drive the engine to achieve the effect of improving energy utilization [1]. Ahcin et al. have designed a shell-and-tube projectile cooling system with a temperature variation of up to 31.3K and a maximum power of over 60W [2]. However, the current application of elastomeric cooling is still limited by the SMA metal fatigue effect, the carbon emissions during the operating period have not been reduced, the prototype structure of the cooler is unreasonable, and there is still room for improvement in energy utilization.

This article will first outline the basic principles and several important performance parameters of elastocaloric refrigeration and then outline and evaluate several common ways to improve the performance of elastocaloric refrigeration equipment.

2. The principle of elastocaloric refrigeration

In the 21st century, Quarini et al. and Bonnot et al. have successively reported the huge elastocaloric effect of Ni-Ti and Cu-Zn-Al shape memory alloys (SMA) [3][4], and as a result, the use of SMA for elastocaloric cooling has been widely studied and attempted as a highly promising cooling method. The thermal-elastic effect is a physical phenomenon in which the temperature of SMA changes significantly when it is subjected to external stress. Essentially, it is caused by the heat absorption and release of the cyclic phase transition between martensite and austenite in response to the stress of SMA.

Initially, SMA is a cubic lattice of austenite; When stress is applied, SMA transforms into monoclinic lattice martensite, the system entropy decreases, and heat is released to raise the temperature; When the stress is removed, SMA reverts to austenite and absorbs heat, causing the temperature to drop, and then returns to its initial state. This process is called the Brayton cycle[5].

The common effects currently used for cooling include magnetocaloric, electrocaloric, thermocaloric and elastic-thermic effects. The magnetocaloric effect is typically driven by a magnetic field of about 1.93T, with a temperature variation of only 7.3K and it is difficult to control the magnetic field to stabilize. The thermocaloric effect requires 260MPa to produce an extremely low temperature variation of 4.5K, which is the smallest of the four effects. The thermocaloric effect, although it can achieve a relatively large temperature variation of 12K, requires a voltage of 25V. The first three effects are difficult to achieve due to their high requirements for the applied magnetic field, electric field, and pressure, and the cooling amplitude is not as high as that of the extremely high 15K temperature change[6] of elastocaloric cooling; thus, the practical application is limited.

Whether a shape memory material can be applied to elastocaloric refrigeration primarily depends on the intensity of the elastocaloric effect and COP of the material, which are inherent properties of the material and directly determine the performance of the elastocaloric refrigeration equipment. However, other performance indicators such as operating temperature, fatigue life and other parameters can only be measured experimentally. Commercially, SMA cycles are typically required to be more than 107cyc cycles and be easy to process.

3. Improvements to thermal cooling equipment

3.1. SMA modification

Vanaei's team studied improvements to the properties of NiTi shape memory alloys by doping elements such as copper, vanadium, cobalt, manganese, and boron [7]. The study shows that adding Cu, Co, or V to binary NiTi alloys increases fatigue life but typically reduces adiabatic temperature rise, with COP rising from around 5 to about 20 but adiabatic temperature rise dropping by about 5 degrees Celsius; When Fe is added, it mainly affects the phase transition, microstructure and mechanical properties, and has a relatively higher and wider coefficient of action; Mn can increase pressure changes when the load is removed; Cu can reduce hysteresis pressure. Meanwhile, the team examined the impact of factors such as geometry, applied stress, and operating frequency on SMA performance. It was found that the thinner the alloy, the larger the surface area and volume, and the stress was closer to 1% for the cooling performance of SMA

Meanwhile, the Vanaei[7] team applied additive manufacturing to the production of elastocaloric cooling equipment, using this technology to create thin-walled SMA tubes with different phase transition temperatures, enhancing the performance of NiTi tubes with thermal gradients. The design arranges thin-walled SMA tubes with different austenite end temperatures in sequence, using the phase transition temperature gradient to reduce the impact of the temperature distribution of the SMA on heat transfer in actual operation, thereby maintaining stable pressure operation in practical applications.

Huang et al. conducted in-situ cyclic tensile experiments on nanocrystalline NiTi SMA with different aspect ratios (10:1,4:1,2:1,1:1) [8]. They observed the axial strain field and temperature field of the specimens using DIC and infrared cameras and found that as the aspect ratio decreased, the adiabatic temperature change of nanocrystalline NiTi SMA gradually decreased. The performance system of the material increased, and the cycling stability was enhanced. When the aspect ratio L/W is greater than 4, the elastic-thermal effect and its cycling stability are gradually reduced in dependence on the aspect ratio.

Xu et al. manipulated the concentration gradient of Ni in NiTi SMA to construct a function model of the martensite transition initiation temperature with respect to Ni concentration [9], and the simulated evolution equation is as follows:

$$\frac{1}{L}\emptyset = -[A(T-T_c)\emptyset - B\emptyset^3 + C\emptyset^5] + \beta\nabla^2\emptyset + \sigma_{ij}\varepsilon_{ij}^0 \tag{1}$$

The simulation results show that through the optimized design, COP can be increased by an order of magnitude to 125.57 compared with the traditional coarse-grained NiTi alloy (~3-15), while ΔTad remains considerable (21.54K), but this material has not yet been developed and manufactured, and further research and development are needed.

3.2. Elastic heat cooling equipment optimization

One of the current bottlenecks in commercializing elastocaloric refrigeration equipment is the compactness of the equipment. Based on this, Chen et al. adopted a special inclined design that uses the inclined screw to drive the SMA to slide and accelerate its exchange with the heat exchanger [10], thereby reducing the volume of the equipment. The picture below shows the structure of the equipment and how the equipment works. As shown in fig 1, the design is a compact independent elastocaloric cooler using an inclined single-motor scheme and a solid-solid contact device. Using polycrystalline NiTi shape memory wire as the refrigerant, the ratio of the refrigerant alloy to the total weight of the equipment can reach 2.56 $\times 10^{-3}$, which is more than 90% higher than the reported data, and the volumetric work efficiency can be increased by 20%.

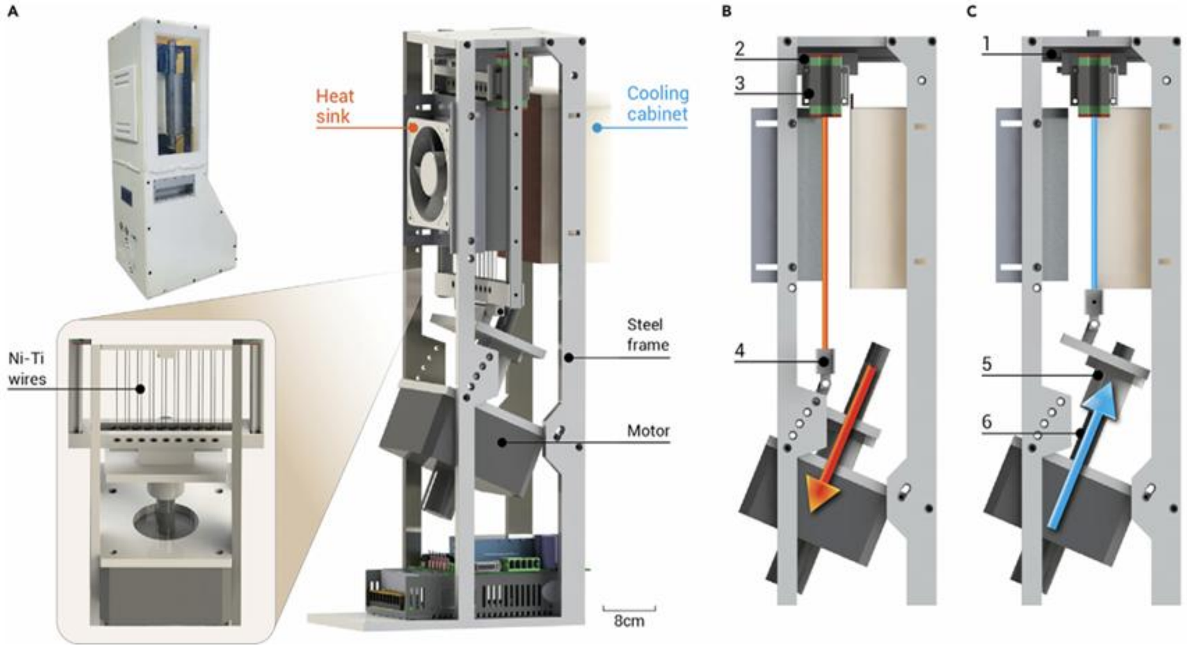

Fig 1. Schematic diagram of the compact elastic thermal cooler.

Meanwhile, the Yao team used a roller-driven dual SMA combined cooling design to avoid errors caused by rotational phase and recover kinetic energy generated during SMA deformation,in fig 2 [11], successfully increasing the adiabatic temperature variation of the material by 1.1 times and the no-load temperature span of 25.4K. The diagram below shows the relationship between strain and time, as well as stress and strain, when the roller is in different positions.

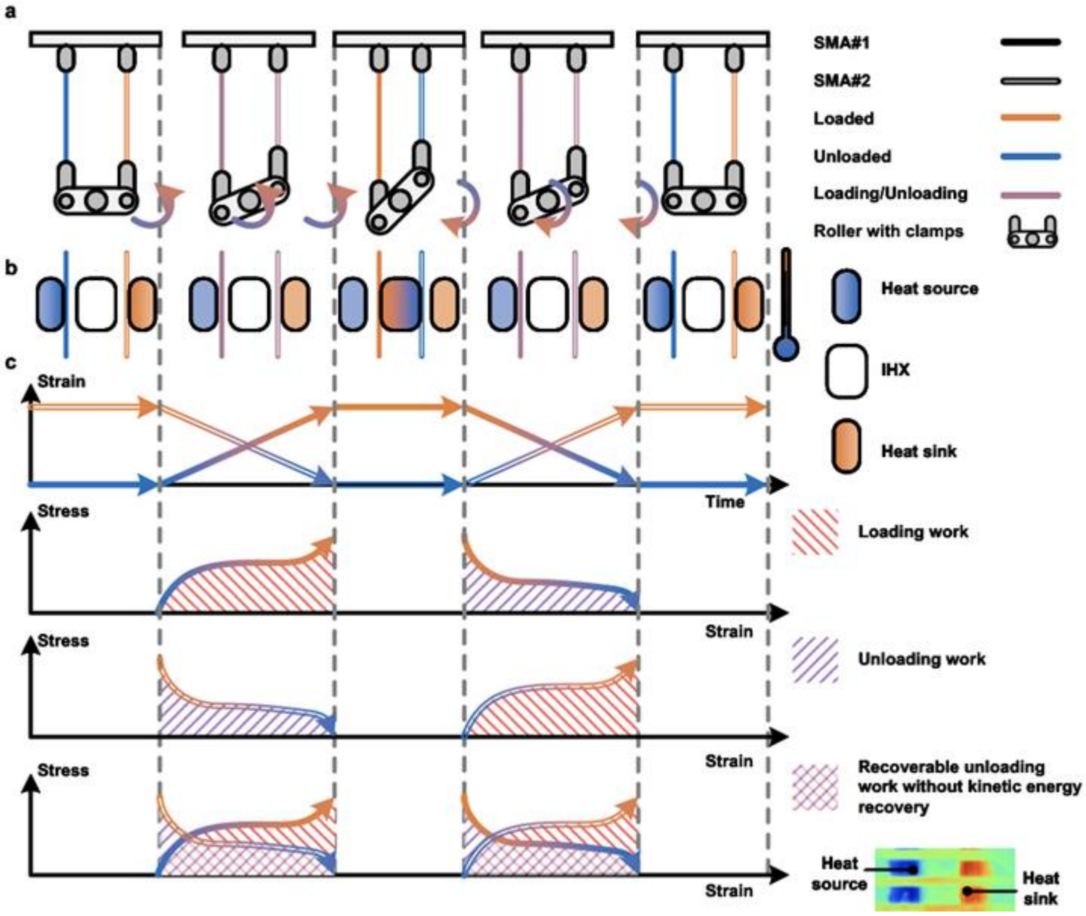

Fig 2. Schematic diagram of the roller-driven elastomeric cooling device.

4. Challenges and Developments

Projectile thermal cooling technology still faces multiple challenges in practical applications. First of all, the fatigue life of shape memory alloys is a major bottleneck restricting their commercialization. The material is prone to performance degradation under cyclic stress and is difficult to meet the demand for long-term stable operation. Secondly, the existing elastothermal cooling equipment is structurally complex and bulky, with insufficient compactness, which limits its application in miniaturized scenarios. In addition, the energy utilization rate of the system still needs to be improved. Although some materials theoretically have a high energy efficiency ratio, the loss in the process of energy conversion and transfer is still significant in actual operation. Complex manufacturing processes, high costs, and stability issues in system control and thermal management have further hindered the large-scale promotion of elastothermal refrigeration technology.

Future development will focus on the synergistic optimization of materials, structures and systems. Further enhance the elastothermal effect and cycling stability of shape memory alloys through means such as element doping, concentration gradient design and nanocrystalline structure regulation. In terms of equipment structure, innovative schemes such as inclined design, roller drive and thin-film multilayer coupling are expected to enhance heat exchange efficiency and energy recovery capacity and achieve higher adiabatic temperature variation and system compactness. At the same time, as green cooling and low-carbon goals are achieved, elastothermal cooling technology will show application potential in areas such as building energy conservation and electric vehicles. Ultimately, through the deep integration of industry, academic and research, promote the standardization and industrialization of material preparation and equipment manufacturing, and facilitate the transition of elastic thermal refrigeration technology from the laboratory to practical application, becoming a new generation of efficient and environmentally friendly refrigeration solutions.

5. Conclusion

As a novel solid-state refrigeration technology based on the latent heat of phase change of shape memory alloys (SMA), elastomeric refrigeration has significant advantages such as high energy efficiency, environmental friendliness and low noise, and shows great potential to replace traditional refrigeration methods. This paper describes the development history and basic principles of elastothermal refrigeration and points out that performance can be characterized by key parameters such as isothermal entropy change, adiabatic temperature change, COP, operating temperature range and fatigue life. To improve the overall performance of elastothermal refrigeration equipment, studies have effectively enhanced the elastothermal effect intensity and cycling stability of SMA through methods such as element doping, metal concentration gradient design, nanocrystalline aspect ratio regulation, and additive manufacturing structure regulation. Meanwhile, the optimization of the structure of the elastothermal cooling equipment is the key to promoting the practical application of elastothermal cooling. Innovative designs such as inclined structures, roller drives, and thin-film multi-layer coupling not only enhance the compactness and heat exchange efficiency of the equipment but also achieve higher adiabatic temperature variation and energy recovery efficiency, providing possibilities for no-load temperature span and practical applications. Despite the current challenges in terms of fatigue life, manufacturing process and system integration, the advantages of elastothermal refrigeration in energy conservation, carbon reduction and green refrigeration have been initially verified. Future research should continue to focus on material-structure-system synergistic optimization to drive elastothermal refrigeration technology from the laboratory to large-scale application.

References

[1] Yang Rui, Yang Yupeng, Yu Guoyao, Wu Zhanghua, Luo Ercang. Elastothermal refrigeration system: CN 119492165 A[P].2023-08-21.

[2] Ahcin Z, Dall'Olio S, Zerovnik A, et al. High-performance cooling and heat pumping based on fatigue-resistant elastocaloric effect in compression [J]. Joule, 2022, 6(10): 2338-2357.

[3] Quarini J, Prince A. Solid state refrigeration: cooling and refrigeration using crystalline phase changes in metal alloys[J]. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2004, 218(10): 1175-1179.

[4] Bonnot E, Romero R, Mañosa L, et al. Elastocaloric effect associated with the martensitic transition in shape-memory alloys [J]. Phys. Rev. Lett., 2008, 100: 125901.

[5] Feng Danyang, Xiao Yicheng, and Liu Zunfeng. Advances in elastomeric cooling [J]. Laser & Optoelectronics Progress, 2023, 60(13).

[6] Xiao Fei, Chen Hong, Jin Xuejun. Research on the elastothermal cooling effect of shape memory alloys [J]. Acta Metallurgica Sinica, 2021, 57(1).

[7] Vanaei S, Mohajerani S, Rocco P, et al. Toward Advancing Elastocaloric Performance in Shape Memory Alloys Through Additive Manufacturing: Novel Conceptual Designs and Preliminary Insights [J]. Shape Memory and Superelasticity, 2025, 11(2): 115-151.

[8] Huang B, Xu B, Tang S, et al. Effect of aspect ratio on the elastocaloric effect and its cyclic stability of nanocrystalline NiTi shape memory alloy [J]. Journal of Materials Research and Technology, 2023, 25: 6288-6302.

[9] Xu B, Wang C, Wang Q, et al. Enhancing elastocaloric effect of NiTi alloy by concentration-gradient engineering [J]. International Journal of Mechanical Sciences, 2023, 246.

[10] Chen Y, Wang Y, Sun W, et al. A compact elastocaloric refrigerator [J]. Innovation (Camb), 2022, 3(2): 100205.

[11] Yao S, Dang P, Li Y, et al. Efficient roller-driven elastocaloric refrigerator [J]. Nat Commun, 2024, 15(1): 7203.