AIMS Materials Science

http://www.aimspress.com/journal/Materials

AIMS Materials Science, 6(6): 1135–1152.
DOI: 10.3934/matersci.2019.6.1135
Received: 30 September 2019
Accepted: 20 November 2019
Published: 25 November 2019

Short review

Elastocaloric cooling: roadmap towards successful implementation in the built environment

Giulia Ulpiani[1,*], Gianluca Ranzi[1], Florian Bruederlin[2], Riccardo Paolini[3], Francesco Fiorito[4], Shamila Haddad[3], Manfred Kohl[2] and Mat Santamouris[3]

[1] School of Civil Engineering, The University of Sydney, Sydney, New South Wales, Australia
[2] Institute of Microstructure Technology, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[3] Faculty of Built Environment, University of New South Wales, Sydney, New South Wales, Australia
[4] Department of Civil, Environmental, Land, Building Engineering and Chemistry-DICATECh, Polytechnic University of Bari, Bari, Italy

* **Correspondence:** Email: giulia.ulpiani@sydney.edu.au; Tel: +61481600997.

Abstract: In the pursuit of ever more efficient built environments, able to resiliently respond to the many implications of climate change, near room-temperature caloric cooling could be a game changer from multiple standpoints. In this paper, perspectives and challenges of successful implementation of elastocaloric devices in the built environment are explored by contrasting the current readiness level with the envisaged potentiality. Material-level and device-level criticalities are identified and potential solutions are discussed. The roadmap towards an informed and efficient use of this environmentally friendly technology is eventually proposed aiming at an increase of building's energy efficiency, but also at counteracting the urban heat island effect.

Keywords: elastocaloric effect; solid state cooling; built environment; energy; urban heat island; climate resilience; shape memory alloy; advanced materials; integrated design; short-lived climate pollutants

Abbreviations: AC: Air Conditioning; A_f: Austenite finish temperature; BTO: Building Technologies Office; CCD: Charged Coupled Device; CFC: Chlorofluorocarbon; COP: Coefficient of performance; DIC: Digital Image Correlation; DOE: U.S. Department of Energy; eCE:

Elastocaloric effect; EERE: Office of Energy Efficiency and Renewable Energy; GHG: Greenhouse gas; GWP: Global warming potential; HCFC: Hydrochlorofluorocarbon; HFC: Hydrofluorocarbon; HTF: Heat transfer fluid; HVAC: Heating, Ventilation and Air Conditioning; IPCC: Intergovernmental Panel on Climate Change; IR: Infrared radiation; ORC: Organic Rankine Cycle; SLCP: Short-lived climate pollutant; SMA: Shape Memory Alloy; UHI: Urban heat island

1. Introduction

According to the latest IPCC report [1], the window for curbing climate-changing emissions and staying within the 2 °C global warming guardrail over preindustrial levels is dauntingly approaching closure. It is universally acknowledged that fast and forceful CO_2 abatement is key, but much less publicized is the role of SLCPs (short-lived climate pollutants), whose reduction represents the most effective countermeasure in the near term [2]. SLCPs include black carbon, methane, tropospheric ozone, and hydrofluorocarbons, which are extremely powerful climate forcers, responsible of about one third of the current total GHG burden [3]: they persist in the atmosphere for few days up to 15 years, much less compared to the millennial lifetime of carbon dioxide. Despite this, their GWP is up to thousand times higher.

There is room to prevent up to 90% of SLCPs' predicted warming effect within a decade by a significant curtailment of their usage [4]. Indeed, curbing the emission of all four pollutants could avoid up to 0.6 °C global average warming by 2050 [5]. This would tremendously reduce the risk of setting off irreversible and self-amplifying feedback mechanisms that accelerate climate change and global warming.

Hydrofluorocarbons (HFCs) are the fastest growing SLCPs, doubling every decade [6]. They are largely used in buildings refrigeration in lieu of ozone-depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), phased out by the Montreal Protocol. Their warming impact significantly varies among different chemicals. For instance, the GWP-100 of HFC-134a is 1300 while that of HFC-23 is about one order of magnitude higher (12400) [7].

In order to fade out HCFCs, effective alternatives must be guaranteed, by intensifying the research and industrial effort into cutting-edge technologies and by spurring the spread of low-cost, low-temperature dissipative techniques [8]. For instance, an active research focus is on climate-friendly cooling agents (such as CO_2, water, ethanol, etc.) that can be used in absorption, potentially self-sustained, heat pumps [9–11]. These technologies could work as a short-term substitute to conventional refrigerants, while long-term alternatives are on their way towards commercialization.

In 2017, the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy's (EERE's), Building Technologies Office (BTO) published the updated characterization and technology assessment of heating, ventilation, and air-conditioning (HVAC) systems, notably for commercial buildings [12]. The authors screened out over 300 technology options (membrane cooling systems, metastable critical-flow cycles, caloric cooling systems, S-RAM heat pumps, Turbo-Compressor-Condenser-Expander heat pumps, electrochemical heat pumps, etc.) and ranked them according to their technical energy-savings potential, development status, upfront cost, operational complexity, non-energy benefits, and other factors. A final, omni-comprehensive score was assigned to each option to obtain a prioritized list.

Elastocaloric heat pump technologies emerged as the most promising caloric solution with the highest final score. They also reached the greatest technical energy savings, with 0.41 Quads/year against 0.26 of electrocalorics and 0.21 of magnetocalorics.

Indeed, despite elastocaloric devices lag behind many other alternative technologies in terms of readiness level, their enormous potential is driving several laboratory studies, demonstrators and proof-of-concept prototypes. According to Scopus Database, the term "elastocaloric" featured in the title, abstract or keywords of 247 peer-reviewed scientific papers since 1962. As shown in Figure 1, the interest has been skyrocketing over the last decade with 97% of papers published from 2008 on. The trend points to a stable exponential rise.

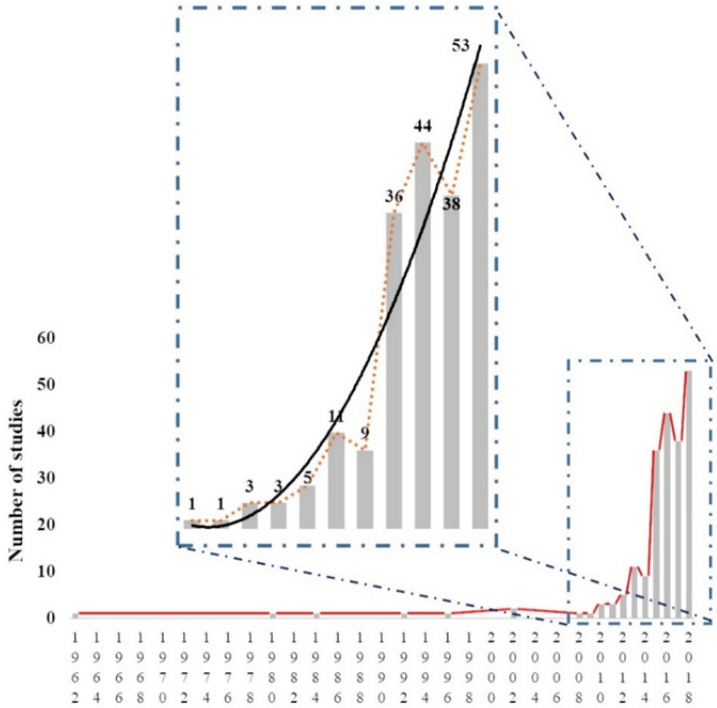

Figure 1. Number of Scopus-indexed papers focused on the elastocaloric effect from 1962 to date. Additional 36 papers have been published in the first months of 2019.

As a solid-state cooling technology, environmentally harmful and health-threatening volatile liquid refrigerants do not come into play, thus reducing direct ozone-depleting emissions [13]. Also, compared to other caloric effects, eCE (elastocaloric effect) can reach giant magnitude (temperature change reportedly over 30 K [14,15]), with no need for strong magnetic or electric fields, but just a relatively small mechanical work input. Therefore, material-level coefficients of performance (COP) could go as high as 20 [16,17], exceeding 80% of the thermodynamic maximum [18,19]. Also, no rare earth materials are involved, which are not just expensive but also prone to supply shortages [20].

Nonetheless, looking at costs and operational complexity, eCE-based devices could prove cumbersome: despite the simple functional principle, mechanocaloric devices are quite challenging when it comes to cycling stability and maintenance. A moderately high upfront cost is thus expected. Nonetheless, under mass production, the cost premium could be significantly reduced to be almost on par with vapor-compression systems [12]. Moreover, disposal would be much more straightforward compared to conventional refrigerants.

The building sector will especially benefit from elastocaloric advancements, as air conditioning currently accounts for nearly 40% of building energy consumption [21]. On top of that, according to recent statistics, about 1.6 billion new AC units will be in service by 2050 worldwide [22] to accommodate the needs of an ever more growing population, an ever more rapid urbanization and ever more intense climate change. Santamouris estimated that the mean cooling energy demand of the residential and commercial buildings in 2050, will increase up to 750% and 275%, respectively, considering an average development scenario, accounting for world population growth, floor area per person increase, climate change exacerbation, penetration and optimization of the air conditioners and global improvement of the energy performance of buildings [8]. It is also worth mentioning, that climate change hampers the potential of passive cooling techniques, notably those based on natural ventilation, thus boosting the use of active cooling technologies [23].

The projected space cooling saving by elastocaloric over conventional AC systems could reach 40% [12]. As residential refrigeration and cooling cover 45% of the global electricity demand for cooling (much more than the industrial and tertiary sectors, taken individually), near-room temperature applications with moderate temperature spans constitute the main target [24].

In addition to AC systems, a whole novel spectrum of integrated devices is currently under study. These researches aim not just at enhancing the efficiency of traditional cooling systems used for building applications, but also at reducing the contribution of structural and architectural components to the urban heat island effect (UHI). Accordingly, elastocaloric implementations are expected to reduce (i) the anthropogenic heat release due to AC systems (when used in heat pumping mode), which together with indirect solar heating, is the main cause of UHI [25]; (ii) the amount of incoming heat/cold when incorporated in building envelopes; (iii) the acoustic pollution by eliminating the need for compressors. Indeed, elastocaloric units lend themselves to a plethora of potential applications, not just for their scalability, but also for the simultaneous production of heat and cold obtained by thermal switching between the hot reservoir (heat sink) and the cold reservoir (heat source). Accordingly, they could either provide cooling power directly indoors (while generated heat could be used to feed pre-heating circuits, to name one possibility) or provide shielding from outdoor heat gains, such as solar gains, e.g. by working as “active” cool roofs. Despite this, many material-level and device-level issues must be tackled to guarantee successful implementations in the built environment and, eventually, usher in a new wave of promising commercial sectors.

In the following paragraphs, the reader is introduced to the physical principles of elastocaloric cooling, to frame advantages and disadvantages compared to conventional vapor-compression systems. The main challenges and opportunities are discussed, focusing on the material scale first and the device scale afterwards, to point out the key questions to be addressed in order to reduce the lag time to commercialization. Finally, a proposal for widening the range of applications in building integrated systems is presented.

2. Perspectives and challenges

Shape Memory Alloys (SMAs) are named after their ability to “memorize” a pre-defined shape (imprinted by annealing in the austenitic phase), apparently lose it under quasi-plastic deformation and recover it upon heating. This heat-induced, reversible phase transformation from low-temperature martensitic phase with, e.g. orthorhombic (B19) or monoclinic (B19') lattice, to the cubic austenitic phase (B2), is the basis for SMA actuation.

On the other side, when the transformation is stress-induced, pseudoelastic effects manifest, providing the physical basis for elastocaloric cooling.

The cycle starts with the material in stress-free state (or moderately prestrained) at a temperature slightly above austenitic finish temperature (A_f). Upon application of an uniaxial force, the stress increases elastically with slope equal to the austenite's Young modulus, until an abrupt flattening occurs. At this critical stress, the material transforms exothermically to martensite, undergoing a diffusionless, first-order phase transition with latent heat release, as a result of the entropy difference between the two co-existing phases. If sufficiently fast (near adiabatic conditions), this process leads to significant self-heating. The stress remains quite constant over the transformation, being used to reconfigure the lattice to fully detwinned martensite. At this point, if stressed further, the material enters a new elastic region, sloped according to the martensite's Young modulus. Heat transfer with a sink is used to bring the SMA back to ambient temperature during the holding phase at constant strain. In this way, when, the reverse, endothermal phase transformation occurs during the unloading phase, the SMA temperature can go considerably below ambient, especially under fast adiabatic release. This time, the stress plateaux are at a lower level compared to the forward transformation, thus a mechanical hysteresis is observed. To close the cycle, the external force is completely removed and the SMA elastically re-approaches a stress-free austenitic state. The release and holding phases can be used for heat transfer between the SMA and a heat source.

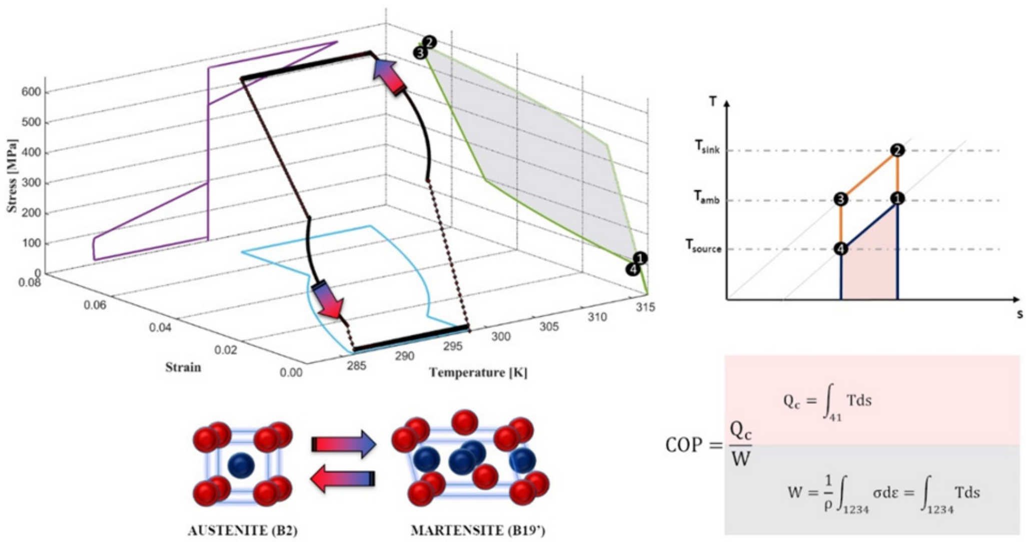

Figure 2. Three-dimensional trajectory of the elastocaloric cycle in the strain-temperature-stress space (strain-controlled tensile test, 10 s holding time), T-s diagram and COP equations. Numerator and denominator are highlighted in the graphs by colored areas.

In this way, also the temperature returns to its initial state and cooling is provided. Under ideal, fatigue-free conditions, start and end points perfectly coincide. The 3D schematic trajectory in Figure 2 displays a simplified model of the reverse Brayton cycle (alternation of adiabatic isentropic and isobaric tranformations), considering the experimental performance of a 40 μm cold-rolled NiTiFe foil, strained at a strain-rate of 0.1 s^{-1} in tensile mode. The temperature-entropy diagram is reported alongside, together with the equations for the COP calculation. Quotient of absorbed heat and applied work, the COP is graphically determined as the integral over the four process steps divided by the integral over the end and start step of the temperature-entropy curve.

It is assumed that the unloading work is fully recovered, which is an ideal case. However, depending on method, part of the mechanical energy can be recovered. This is attained, for instance, by introducing a piezoelectric or electromagnetic generator to use the mechanical energy for producing electricity, but a much more common strategy is to couple the SMA elements in antagonistic pairs, so that mechanical work can be inter-transferred between two counter-moving elastocaloric elements during the cycle [26].

The cooling capacity of elastocaloric devices largely relies on the intensity and cyclic stability of the latent heat. Furthermore (i) the material's behavior is thermo-mechanically coupled, thus the stress-strain curve is strongly temperature and process-dependent [27], (ii) strain-rate plays a pivotal role [28,29] by arbitrating the balance between self-heating/cooling and heat transfer to the environment. Finding the right balance is the major complicacy hindering progress in commercialization. To overcome such disadvantages effective solutions and strategies to harmonize material, device and cycle optimization must be identified.

3. Material-level challenges

The quest for easily manufacturable, high-performance elastocaloric materials is no trivial matter. A dedicated consortium, CaloriCool® [30], was established in 2016 by the U.S. DOE to accelerate the discovery of advanced caloric materials and boost the technological transfer for rapid scale-up.

Over 1000 systems were assessed during the first year of CaloriCool operation. Despite this, the "perfect" material is still unrevealed. This is because several specific properties need to coexist in the same material to respond to all critical design requirements: (i) large latent heat of phase transformation, (ii) high adiabatic temperature change, (iii) low mechanical hysteresis, (iv) good thermal conductivity, (v) low structural and functional fatigue [31,32].

Latent heat and adiabatic temperature change are strictly connected. Indeed, the theoretical maximum temperature change (adiabatic) is the quotient of latent heat of transformation and material's heat capacity. Reportedly, NiTi alloys can reach as high as 35 J/g playing around with stoichiometry, carbon and oxygen content [33]. Additionally, a strong correlation exists between specific latent heat (J/g) and A_f (see Figure 10 in [32]). This entails that the highest latent heats can be deployed only at high transformation temperatures, making it harder to guarantee good performances in buildings applications.

Guaranteeing sufficient operative window around ambient temperature is necessary for large-scale implementation in the built environment. Ideally, to operate between 10 °C to +35 °C and seriously compete with vapor-compression systems, elastocaloric devices should guarantee a temperature span of about 20–40 °C, closely above A_f [24,34]. This temperature can be tuned by altering the composition or by alloying additional elements, such as Cu, Co and Pd [35], while widening the temperature span could be attained at device-level by connecting multiple elements in series, each working in a different temperature window. To provide an updated example, in 2019, Bruederlin et al. conceptualized a three-film cascaded demonstrator on the miniature scale, where the end units realize the heat transfer to the surroundings and the intermediate unit acts as a preheater/precooler. The temperature span doubled from 7.6 for a single unit up to 15 K for the cascaded assembly [36].

Once the unloading work is recovered, the goal is to reduce the work input, thus the mechanical hysteresis (or equivalently the thermal hysteresis, being directly proportional [32]). This is dictated by composition [37] and microstructure [38], which in turn, profoundly impact on phase transformation reversibility and fatigue life. Here comes another crucial compromise: for NiTi based SMAs a proportionality exists between specific latent heat and thermal hysteresis width (see Figure 11 in [32]) hence a trade-off must be established to narrow down the hysteresis without eroding a potentially large latent heat. An extraordinarily promising material is NiTiCuV [15]: despite moderate latent heats (approximately 9.2 J/g versus 14.6 J/g for binary NiTi), the combination of low A_f temperature and very small input work results in an extremely high COP value of 20 (four times higher than that of binary Ni-rich Ni–Ti), complemented by excellent functional stability.

Indeed, elastocaloric devices have to withstand millions of load cycles to be used in building applications. The key players towards a long and stable service life are (i) crystallographic compatibility between austenite and martensite variants and (ii) manufacturing (including surface treatments, cutting techniques, etc.). The former impacts on functional fatigue, namely on the degradation of recoverable strain and latent heat as it arbitrates the accumulation of defects, while the latter affects structural fatigue, namely the tendency to mechanical failure by cracks initiation and propagation upon cycling.

Alloy composition determines the microstructural compatibility: this is established by looking at the transformation strain tensor U between austenite and each martensite variant. Volume conservation is the primal condition to respect (detU = 1), but supercompatibility (and therefore fully reversible phase transformation) is achieved when three additional subconditions (cofactor conditions) are met (i) unitary middle eigenvalue (meaning that austenite is compatible with one single martensite variant), (ii) low energy transition layers in austenite/martensite interfaces for every volume fraction and (iii) infinite number of compatible interfaces between austenite and finely twinned martensite [39]. Under the cofactor conditions, crystals with both austenite and martensite exhibit numerous zero energy (or near zero energy) modes of motion [40]. Recent studies by Chen et al. [41,42] have additionally demonstrated that, by introducing intermediate B19 martensite phase and nanocrystalline structures, lattice compatibility between the parent and martensite phases improves, thus beneficially impacting on fatigue behavior and stress hysteresis.

Yet, even if supercompatibility is satisfied, premature fatigue-driven failure might derive from inhomogeneous and crack-sensitive surface conditions. Surface finish largely impacts on fatigue life: polishing (electro or fine mechanical polishing) and etchings are the most recommended treatments [43,44]. They could remove most of cracks from the edges of the sample and significantly reduce the maximum valley depth on the other surfaces [45].

Overall, the best case would be uniform texture, fine-grained polycrystalline materials, smooth polished surfaces and absence of heat transfer fluids (as they might trigger electrochemical reactions at the surface) [18].

Ti-rich TiNiCu films are reknown ultra-low fatigue elastocaloric materials, withstanding several million cycles without any degradation [46,47], indeed, they closely fulfill all three supercompatibility conditions. Nonetheless, these materials operate at relatively high A_f (≅65 °C), thus requiring transformation temperature adjustments to be used as elastocaloric cooling agent. Quaternary Co and Fe alloying can reduce the transformation temperature by 42 and 22 K at%$^{-1}$ [46]. In this vein, the University of Kiel developed sputter-deposited samples of quaternary NiTiCuCo (thickness of about 20 µm, thus very interesting for microcooling applications) which could withstand ten million pseudoelastic loading cycles without any signs of fatigue [46].

4. Device-level challenges

The roadmap towards high-performance elastocaloric materials is well paved. Giant/large/colossal/enhanced eCE features in the title/abstract or keyword of a growing number of scientific papers (Figure 3) with China and Spain as leading countries. 6 new studies were published in the first half of 2019.

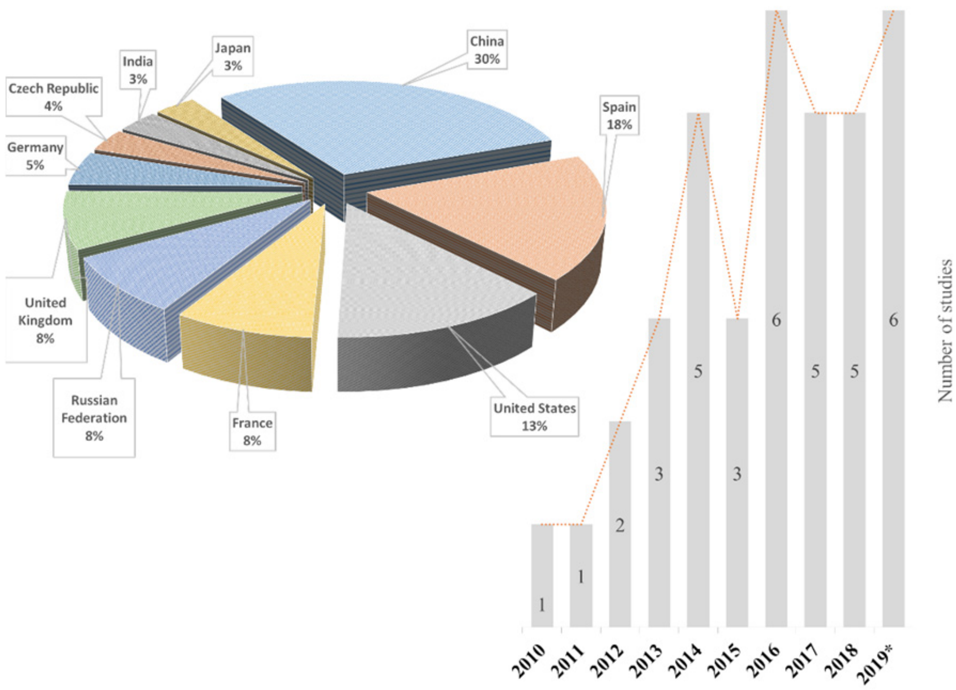

Figure 3. The quest for giant elastocaloric effect over the last 10 years of publications.

Beyond materials science, mature eCE technologies heavily depend on device-level challenges. A number of device parameters influence the useful temperature change, the COP and the cooling power: strain rate and maximum strain [28], thermal boundary conditions and cooling cycle [48] are among the main players.

Several studies [19,32] point to an optimum thermodynamic cycle, given by hybrid adiabatic-isothermal loading/unloading. This is achieved by a fast, no-contact initial phase transformation which only contributes to self-heating/cooling, followed by a near constant temperature step where the SMA is in contact with the heat source or sink. The graphical method, developed by Schmidt et al. [48] provides a quick demonstration of the work input reduction. Additionally, since the material doesn't heat up to its maximum, the stress increment, described by the Clausius–Clapeyron coefficient, is limited, thus reducing the risk of exceeding the yield limit.

Despite the theoretical benefit of such hybrid cycle has been demonstrated, no experimental data are available to date. Also, the identification of the optimal adiabatic/isothermal process ratio has never been addressed—it is expected that by changing the contact point for heat exchange, both the cooling power and the heat source and heat sink temperatures could be tuned. Further insight will arise from the brand-new prototype described by Kirsch et al. [32]. They developed a novel, patent-pending stroke-concept based on a rotary cam track which could be used to govern the load profile of the elastocaloric process cycle in a quite limitless fashion. Among possible parameterizations, more sections can be added to mimic an adiabatic-isothermal hybrid process and collect experimental evidence of the potential benefits. This prototype upgrades the concept of Schimdt et al.'s [48], in which superelastic SMA wires were arranged in circle, with the ends attached to two co-rotating disks, one being a swash plate and responsible of the conversion from rotary to linear motion for loading/unloading.

For a detailed description of all conceptualized design solutions for elastocaloric cooling, the reader is referred to Qian's 2016 review [19], while the most recent prototypes are described in [32,49]. Device-level COP also depends on the loading type [50], as a rule of thumb, compression is associated with lower hysteresis widths, which translate into higher COPs. Also cracks initiation and propagation are much less likely to occur, compared to tensile mode [51]. Nonetheless, compression-based devices require bulkier SMA elements to avoid buckling, which may annul the overall advantage, in tensile mode, the surface-to-volume ratio can be made considerably larger, thus significantly improving heat transfer and cooling capacity scalability [32].

In 2014, a first study was conducted on a single lot of superelastic NiTi tubes to compare the performance under tension, compression, and pure bending modes [52]. Uniaxial tension systematically led to localized transformation fronts, while under uniaxial compression, uniform strain fields were observed. The strain fields in bending combined the two phenomena, resulting in an energetic competition between preferred kinematics and a complex morphology of localization. In terms of fatigue, this reflected in non-monotonic constant life curves as a function of mean strain [53].

In 2018, Sharar et al. presented an innovative architectural concept for a continuous-loop eC cooler in bending mode, which reached comparable COP to that of uniaxial stress while taking advantage of a 6× reduction in force and a 2× reduction in actuation distance [54]. The drawback was the reduced endothermic temperature change, mostly due to the fact that, in bending mode, the material closest to the neutral axis is experiencing minimal stress and strain, without partecipating in the phase transformation. Similarly, Ossmer et al. exploited the potential of reduced actuator force and stroke by multiaxial loading/unloading at the miniature scale [55]. The authors developed a first-of-its-kind heat pump demonstrator, relying on out-of-plane deflection of film bridges, which could generate a temperature difference of 3.5 K within 13 s, due to the large surface-to-volume ratio and the reduced stroke, reaching device-level COP of about 3. Bending of ribbons was also investigated by Ulrich et al. [56]. Much rarer is the investigation of the torsional mode. In [57] the effect of applying both axial and torsional load on NiTi tubes was simulated. It was found that the axial loading contributes far more than the torsional loading to the cooling power, in a large spectrum of axial elongations and angles of twist.

By and large, the loading type imposes the morphology of the SMA (wires, tubes, foams, ribbons, foils, films, etc.). The performance is comparable to a certain extent, for instance, a similar temperature change of 17 and 16 K was found for NiTi wires [58] and thin films [59], respectively.

Another knot to untangle is how to guarantee the efficiency of the heat transfer between SMA and heat source/sink. Many controversial points arise:

-Is using a heat transfer medium a winning strategy?

-What is the number and typology of actuators to ensure accurate loading and adequate contact force? How to minimize their impact in the building structure?

-What are the potential advantages of control logics applied to govern the actuation stroke?

These questions still lack bold answers in literature.

As regards the heat transfer, two leading concepts among elastocaloric demonstrators are gaining ground: one relies on the use of fluidic heat transfer mediums (convective-dominated cooling prototypes), the other on solid-to-solid heat transfer (conductive-dominated cooling prototypes).

The former concept includes the cutting-edge technology of active regeneration, whose main pro is the capability to outreach the adiabatic temperature span of the material at device level [60]. This entails that the temperature span of an elastocaloric cooler or heat pump can surpass the limits of its elastocaloric element and achieve the temperature lift required by most room temperature applications. Active regeneration is the result of the interaction between the elastocaloric material and a moving heat transfer fluid (HTF), pumped in such a way as to generate a temperature gradient along the material [61]. High temperature spans of up to 19.9 K could be reached with this technique, although fatigue failure occurred after few cycles (about 5000) [62]. Among other potential causes, this limited lifetime could be the result of surface reactions with the HTF, as previously discussed. Moreover, the performance enhancement comes at the expense of a much more complex architecture (fluidic channels, pumps, valves, etc.) and many additional key parameters at stake, such as the volume of liquid entrained in the system, the porosity and thus the volume fractions of active material in the regenerator, the pump control and timing, the handling of undesired heat flows along the regeneration units [62,63]. Also, pumping limits the cycle frequency of the system to just a few Hertz.

One potential solution is the passive approach presented by the researchers of the Fraunhofer IPM at the SYMPOSIUM TP01 on Caloric Materials for Highly Efficient Cooling Applications, held in November 2018 [64]. Their prototype consists of a bundle of Nitinol tubes in compressive loading. The heat transfer is efficiently realized by condensation and evaporation of the HFT (water or ethanol) in hermetically sealed tubes: the pressure gradient drives the opening of the valve in different directions, with no need for active pumping systems. Higher COPs are therefore expected since (i) there is no power required by the pump, (ii) the latent heat of evaporation/condensation can be as high as 100 $kW/(m^2K)$, which is many orders of magnitude higher than that achieved with convective-based systems, (iii) by combining latent heat and thermal diodes, heat can be transmitted at much higher frequencies (over 10 Hz). The reported temperature lift is 10 K, with the potential to achieve a pump capacity of 100 W, a temperature difference of 35 K and a COP of over 5 [65].

The second concept relies on the heat transfer by mechanical contact between elastocaloric SMA film and solid heat sink/source elements. Although much simpler than HTF-mediated demonstrators, the performance of the solid-to-solid concepts largely depends on the thermal mass (i.e. heat capacity) of heat source and sink with respect to the active elastocaloric material. The optimum is not straightforwardly determined and must be tailored to the intended application [18]—a lower thermal mass reacts more rapidly, but is more sensitive to parasitic heat flows because of the higher surface-to-volume ratio. Conversely, a greater mass restricts the observable temperature change. As a rule of thumb, for rapidly responding cooling applications, the heat sink should be much more massive than the source.

Another functional criticality of solid-to-solid heat transfer is the role played by contact resistance, which, in turn, depends on the roughness of the surfaces in contact, the contact area and the contact force. As a consequence, an efficient conduction-based device relies on high quality surfaces and very narrow tolerance on misalignments. High manufacture precision is thus required.

Imperfect heat transfer could be alleviated by the interposition of thermally conductive interface layers [66,67], yet no study has ever verified the actual benefit. In contrast, some researches point out that these coatings may introduce additional losses and complexities [68,69]. Another strategy could be to introduce bespoke compliant support structures to compensate for geometrical inaccuracies as well as plastic strain accumulation during cyclic operation. This pathway was chartered by Ossmer et al. in [26]: olymer springs consisting of meandering stripes with a thickness of 400 µm and a depth of 3 mm assured that the SMA bridges in their miniature demonstrator were pressed in a flat manner against the copper heat source and sink, thus guaranteeing good thermal contact.

Global, but especially local analysis of the evolution of the phase transformation is crucial for a better understanding of the impacts of each solution. A well-established experimental setup through which this analysis can be carried out is depicted in Figure 4, combined to the force-displacement measurements of the tensile testing machine, is the recording of the temperature evolution by means of high-spatial and high-temporal resolution IR camera. Samples are coated with a thin layer of graphite to accentuate thermal emissivity. Additionally, a CCD camera could be used simultaneously, to evaluate the local strain profiles by applying digital image correlation (DIC) algorithms. The graphite layer comes in handy again, as it creates a speckle pattern on the generally flat and featureless surface of the SMA sample, thus easing the identification of strain fronts [70].

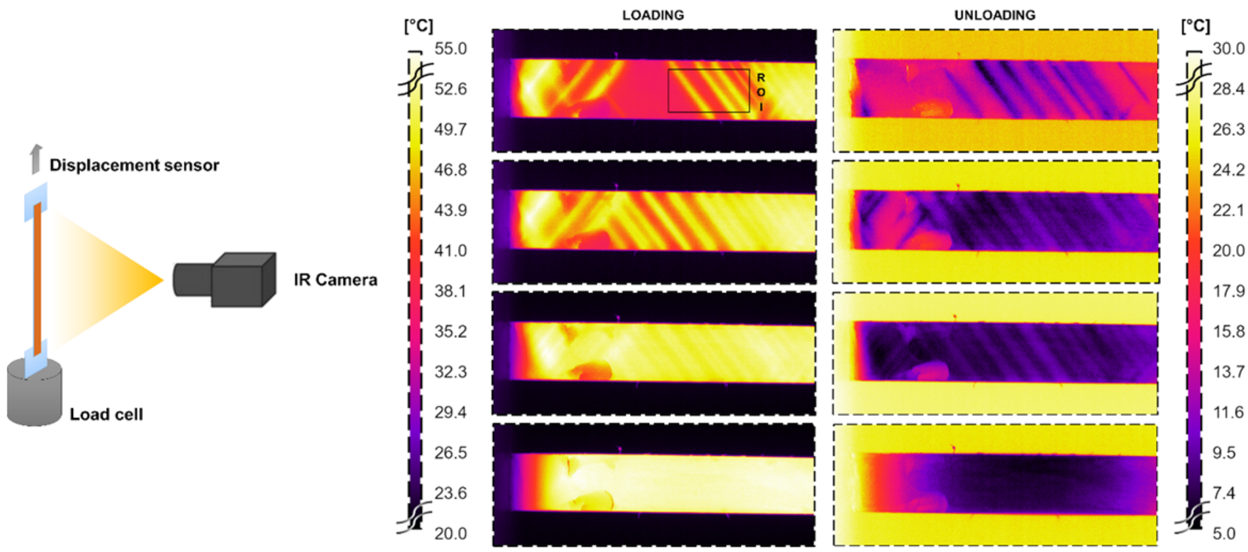

Figure 4. Analysis of the local thermal response of elastocaloric materials by means of tensile test rigs and IR cameras.

Another design detail to be defined in terms of heat transfer is whether to mechanically couple or decouple loading/unloading and thermal switch. Coupled systems require one single actuator to perform all the steps of the elastocaloric loop, but reduce the opportunities for optimized timing and hybridization of the thermodynamic cycles. Whichever case, since the power supply to the external actuator is included in the device-level COP, efficient technologies should be always preferred: the adoption of piezoelectric actuation plus strain amplification might be a viable solution, given the high efficiency of the capacitive operation principle, yet many other options might be explored. Also, smart control logic could optimize the actuation stroke to track a desirable contact force [63]. No study on such logics has ever been conducted in this field. As a general remark, there is a lack of experimental studies, aimed at a comprehensive analysis of elastocaloric devices considering all connected and connectable components, which undermine the validity of declared COPs.

On top of that, no study aims at investigating how elastocaloric devices could be efficiently integrated within the building envelope through heat exchangers, radiant layers and other common components. A whole range of novel applications, dedicated to the built environment, are expected to arise: elastocaloric devices can be embedded or coupled to common structural typologies, such as metal claddings, concrete elements and pavements, hollow core members and ventilation ducts. The schemes in Figure 5 suggest how eCE-based devices could be implemented in new constructions and existing buildings. Prefabricated panels could be integrated into or fitted on both walls and floors. A double heat source, single heat sink configuration would be beneficial for both indoor cooling and outdoor anthropogenic heat mitigation. Besides, by using metallic elements as heat sinks (and thus solid-to-solid heat transfer), the waste heat could be recovered in a variety of fashions, from preheating circuitry to Organic Rankine Cycle (ORC) systems. Ventilation ducts would be also well suited for non-invasive implementation. The eCE component could be used to alternatively heat up or cool down the HTF (air). The thermal switch would be achieved by synchronous opening and closing of the hot air and cold air channels. The control logic behind timing and actuation would be crucial to reach high efficacy.

It should be stressed that, in heating-dominated climates, building energy sustainability is based on the "passive house" concept, relying on high thermal isolation and controlled ventilation. Elastocaloric devices could be harmoniously complemented with passive house technologies, e.g., if used as heat pumps directly integrated into cross-flow heat exchangers. In any case, having high-frequency oscillating cooling systems embedded in walls and floors tends to create a noisy, fault-prone and hard-to-maintain installation unless proper detailing is provided.

All things considered, a new wave of advanced solutions in the field of civil and mechanical engineering is expected to be ignited, in the pursuit of an ever more sustainable design paradigm, aimed at both tackling buildings energy needs and urban heat island intensity. Despite this, challenging precondition to achieve sizeable energy benefits is the identification of a solid methodology to determine the most appropriate heat transfer interactions: heat sinks and sources should be optimized in terms of thermal mass ratio, thermal conductivity, specific heat, geometry, configuration, roughness and emissivity of the interface materials [24,63]. Storage, pre-heating and pre-cooling options should be carefully investigated to enhance the overall efficiency. This is the roadmap towards an environmental-friendly cooling scenario for the built environment.

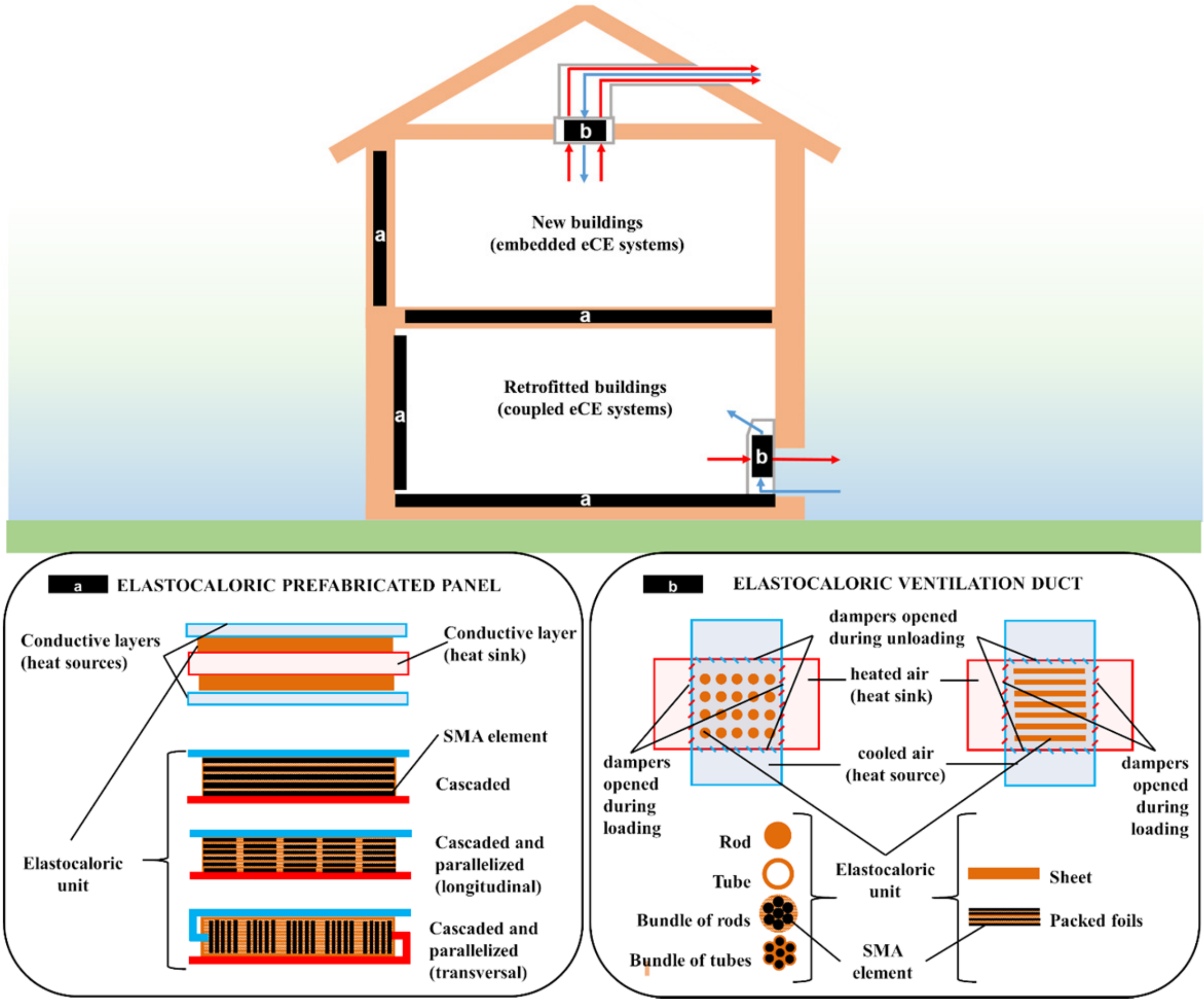

Figure 5. Examples of potential functionalities and arrangements of elastocaloric components integrated in the building structure.

6. Conclusions

This paper covers different aspects of elastocaloric cooling, devoted to near room temperature applications, with special attention to building integration. Fervent lines of research are discussed, together with open issues, cutting-edge proposals and future opportunities.

The need for more elaborated performance analysis of elastocaloric devices is particularly stressed, given that full-device COP values:

-Should include all power losses for better comparison of cooling demonstrators, which has never been attempted in the world of elastocaloric cooling [63];

-Should be calculated for specific temperature spans and thermal loads, to reveal the change of device temperature span as a function of applied thermal load to the heat source [63].

Additional parameterization should be investigated, to account for different boundary conditions and control techniques, by way of example. These analyses would require experimental settings designed for optimal observability as those in [71,72].

Innovative frontiers towards embedded designs are eventually introduced and framed in the context of multifront counteraction of the urban heat island phenomenon (reduction of anthropogenic heat, shielding action against solar gains, etc.).

Overall, in view of the many potential applications of elastocaloric cooling in the built environment, the roadmap should include the following steps: (i) the development of an integrated theoretical framework aimed at structural and thermal optimization; (ii) the demonstration of integrated elastocaloric systems within common structural typologies; (iii) the collection of experimental data for rigorous benchmarking and iv) the definition of substantiated design criteria.

The building sector is expected to benefit enormously from elastocaloric advancements. If even just elastocaloric heat pumps reached the maturity stage, 0.41 Quads/year would be saved in commercial buildings [12]. To date, this is one of the most promising strategies against irreversible and mutual-empowering mechanisms that accelerate climate change, global warming and urban heat islands.

Acknowledgements

This research was supported by the Australian Government through the Australian Research Council's Discovery Projects funding scheme (project DP180101589).

Conflict of interests

All authors declare no conflicts of interest in this paper.

References

1. Pachauri RK, Meyer LA (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Switzerland: IPCC (International Panel on Climate Change).
2. Zaelke D, Borgford-Parnell N (2015) The importance of phasing down hydrofluorocarbons and other short-lived climate pollutants. *J Environ Stud Sci* 5: 169–175.
3. Ramanathan V, Xu Y (2010) The Copenhagen accord for limiting global warming: criteria, constraints, and available avenues. *PNAS* 107: 8055–8062.
4. UNEP (United Nations Environment Programme), Near-term climate protection and clean air benefits: actions for controlling short-lived climate forcers, 2011. Avaliable from: https://www.ccacoalition.org/en/file/914/download?token=dkVP64Ls.
5. Ullstein B (2011) *Integrated Assessment of Black Carbon and Tropospheric Ozone*, UNEP (United Nations Environment Programme), WMO (World Meteorological Organization).
6. Cross J-M, Pierson R (2013) *Short-Lived Climate Pollutants: why are They Important?* Washington: EESI (Environment and Energy Study Institute), 202: 628–1400.
7. Myhre G, Shindell D, Pongratz J (2014) Anthropogenic and natural radiative forcing, in: Stocker TF, Qin D, Plattner G-M, et al., *Climate Change 2013 Physical Science Basis. Contribution of Working Group I to Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York: Cambridge University Press, 659–740.

8. Santamouris M (2016) Cooling the buildings—past, present and future. *Energ Buildings* 128: 617–638.
9. Austin BT, Sumathy K (2011) Parametric study on the performance of a direct-expansion geothermal heat pump using carbon dioxide. *Appl Therm Eng* 31: 3774–3782.
10. Bellomare F, Minetto S (2015) Experimental analysis of hydrocarbons as drop-in replacement in household heat pump tumble dryers. *Energy Procedia* 81: 1212–1221.
11. Wang K, Abdelaziz O, Kisari P, et al. (2011) State-of-the-art review on crystallization control technologies for water/LiBr absorption heat pumps. *Int J Refrig* 34: 1325–1337.
12. Goetzler W, Shandross R, Young J, et al. (2017) Energy savings potential and RD&D opportunities for commercial auilding HVAC systems. DOE/EE-1703, Burlington: Navigant Consulting.
13. Takeuchi I, Sandeman K (2015) Solid-state cooling with caloric materials. *Phys Today* 68: 48.
14. Cui J, Wu Y, Muehlbauer J, et al. (2012) Demonstration of high efficiency elastocaloric cooling with large Δt using NiTi wires. *Appl Phys Lett* 101: 2–6.
15. Wieczorek A, Frenzel J, Schmidt M, et al. (2017) Optimizing Ni–Ti-based shape memory alloys for ferroic cooling. *Funct Mater Lett* 10: 1–8.
16. Li Y, Zhao D, Liu J (2016) Giant and reversible room-temperature elastocaloric effect in a single-crystalline Ni–Fe–Ga magnetic shape memory alloy. *Sci Rep* 6: 1–11.
17. Frenzel J, Eggeler G, Quandt E, et al. (2018) High-performance elastocaloric materials for the engineering of bulk- and micro-cooling devices. *MRS Bull* 43: 280–284.
18. Ossmer H (2016) Elastocaloric microcooling [PhD's thesis]. Karlsruher Institute of Technology, Germany, 1: 16159.
19. Qian S, Geng Y, Wang Y, et al. (2016) A review of elastocaloric cooling: Materials, cycles and system integrations. *Int J Refrig* 64: 1–19.
20. Bartekova E (2014) An introduction to the economics of rare earths, *UNU-MERIT Work Paper Series*, Maastricht: UNU-MERIT, #2014-043.
21. Vakiloroaya V, Samali B, Pishghadam K (2014) A comparative study on the effect of different strategies for energy saving of air-cooled vapor compression air conditioning systems. *Energ Buildings* 74: 163–172.
22. Shah N, Khanna N, Karali N, et al. (2017) Opportunities for simultaneous efficiency improvement and refrigerant transition in air conditioning. American: Lawrence Berkeley National Laboratory 18.
23. Santamouris M, Sfakianaki A, Pavlou K (2010) On the efficiency of night ventilation techniques applied to residential buildings. *Energ Buildings* 42: 1309–1313.
24. Engelbrecht K (2019) Future prospects for elastocaloric devices. *J Phys-Energ* 1: 021001.
25. Rizwan AM, Dennis LYC, Liu C (2008) A review on the generation, determination and mitigation of Urban Heat Island. *J Environ Sci* 20: 120–128.
26. Ossmer H, Wendler F, Gueltig M, et al. (2016) Energy-efficient miniature-scale heat pumping based on shape memory alloys. *Smart Mater Struct* 25: 085037.
27. Shaw JA, Kyriakides S (1995) Thermomechanical aspects of NiTi. *J Mech Phys Solids* 43: 1243–1281.
28. Schmidt M, Schütze A, Seelecke S (2016) Elastocaloric cooling processes: The influence of material strain and strain rate on efficiency and temperature span. *APL Mater* 4: 064107.

29. Wendler F, Ossmer H, Chluba C, et al. (2017) Mesoscale simulation of elastocaloric cooling in SMA films. *Acta Mater* 136: 105–117.
30. Zarkevich NA, Johnson DD, Pecharsky VK (2018) High-throughput search for caloric materials: The CaloriCool approach. *J Phys D Appl Phys* 51: 024002.
31. Bruederlin F, Ossmer H, Wendler F, et al. (2017) SMA foil-based elastocaloric cooling: from material behavior to device engineering. *J Phys D Appl Phys* 50: 424003.
32. Kirsch SM, Welsch F, Michaelis N, et al. (2018) NiTi-Based elastocaloric cooling on the macroscale: from basic concepts to realization. *Energy Technol* 6: 1567–1587.
33. Otubo J, Rigo OD, Coelho AA, et al. (2008) The influence of carbon and oxygen content on the martensitic transformation temperatures and enthalpies of NiTi shape memory alloy. *Mater Sci Eng A-Struct* 481: 639–642.
34. Brown JS, Domanski PA (2014) Review of alternative cooling technologies. *Appl Therm Eng* 64: 252–262.
35. Otsuka K, Wayman CM (1998) *Shape Memory Materials*, Cambridge: Cambridge university press.
36. Bruederlin F, Bumke L, Quand E, et al. (2019) Cascaded Sma-film based elastocaloric cooling. *20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors XXXIII* 1467–1470.
37. Frenzel J, George EP, Dlouhy A, et al. (2010) Influence of Ni on martensitic phase transformations in NiTi shape memory alloys. *Acta Mater* 58: 3444–3458.
38. Cui J, Chu YS, Famodu OO, et al. (2006) Combinatorial search of thermoelastic shape-memory alloys with extremely small hysteresis width. *Nat Mater* 5: 286–290.
39. Gu H, Bumke L, Chluba C, et al. (2018) Phase engineering and supercompatibility of shape memory alloys. *Mater Today* 21: 265–277.
40. Chen X, Srivastava V, Dabade V, et al. (2013) Study of the cofactor conditions: Conditions of supercompatibility between phases. *J Mech Phys Solids* 61: 2566–2587.
41. Chen H, Xiao F, Liang X, et al. (2019) Giant elastocaloric effect with wide temperature window in an Al-doped nanocrystalline Ti–Ni–Cu shape memory alloy. *Acta Mater* 177: 169–177.
42. Chen H, Xiao F, Liang X, et al. (2018) Stable and large superelasticity and elastocaloric effect in nanocrystalline Ti–44Ni–5Cu–1Al (at%) alloy. *Acta Mater* 158: 330–339.
43. Robertson SW, Pelton AR, Ritchie RO (2012) Mechanical fatigue and fracture of Nitinol. *Int Mater Rev* 57: 1–36.
44. Tušek J, Žerovnik A, Čebron M, et al. (2018) Elastocaloric effect vs fatigue life: exploring the durability limits of Ni–Ti plates under pre-strain conditions for elastocaloric cooling. *Acta Mater* 150: 295–307.
45. Engelbrecht K, Tušek J, Sanna S, et al. (2016) Effects of surface finish and mechanical training on Ni–Ti sheets for elastocaloric cooling. *APL Mater* 4: 064110.
46. Chluba C, Ossmer H, Zamponi C, et al. (2016) Ultra-low fatigue quaternary TiNi-based films for elastocaloric cooling. *Shape Mem Superelasticity* 2: 95–103.
47. Bechtold C, Chluba C, Lima De Miranda R, et al. (2012) High cyclic stability of the elastocaloric effect in sputtered TiNiCu shape memory films. *Appl Phys Lett* 101: 091903.
48. Schmidt M, Kirsch SM, Seelecke S, et al. (2016) Elastocaloric cooling: from fundamental thermodynamics to solid state air conditioning. *Sci Technol Built Environ* 22: 475–488.

49. Greco A, Aprea C, Maiorino A, et al. (2019) A review of the state of the art of solid-state caloric cooling processes at room-temperature before 2019. *Int J Refrig* 106: 66–88.
50. Qian S, Geng Y, Wang Y, et al. (2016) A review of elastocaloric cooling: materials, cycles and system integrations. *Int J Refrig* 64: 1–19.
51. Hou H, Cui J, Qian S, et al. (2018) Overcoming fatigue through compression for advanced elastocaloric cooling. *MRS Bull* 43: 285–290.
52. Reedlunn B, Churchill CB, Nelson EE, et al. (2014) Tension, compression, and bending of superelastic shape memory alloy tubes. *J Mech Phys Solids* 63: 506–537.
53. Adler PH, Allen J, Lessar J, et al. (2007) Martensite transformations and fatigue behavior of nitinol. STP1481, ASTM International.
54. Sharar DJ, Radice J, Warzoha R, et al. (2018) First demonstration of a bending-mode elastocaloric cooling "loop". *17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems* 218–226.
55. Ossmer H, Chluba C, Kauffmann-Weiss S, et al. (2016) TiNi-based films for elastocaloric microcooling-fatigue life and device performance. *APL Mater* 4: 064102.
56. Ullrich SSJ, Schmidt M, Schütze A, et al. (2014) Experimental investigation and numerical simulation of the mechanical and thermal behavior of a superelastic shape memory alloy beam during bending, *Proceedings of the ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*.
57. Najib M (2016) Toward analysis of a cooling device using shape memory alloys [PhD's thesis]. University of Toledo, American.
58. Cui J, Wu Y, MuehlbauerJ, et al. (2012) Demonstration of high efficiency elastocaloric cooling with large Δt using NiTi wires. *Appl Phys Lett* 101: 2–6.
59. Ossmer H, Miyazaki S, Kohl M (2015) Elastocaloric heat pumping using a shape memory alloy foil device. *2015 Transducers-2015 18th Int Conf Solid-State Sensors, Actuators Microsystems*, 726–729.
60. Tušek J, Engelbrecht K, Eriksen D, et al. (2016) A regenerative elastocaloric heat pump. *Nat Energy* 1: 16134.
61. Tušek J, Engelbrecht K, Millán-Solsona R, et al. (2015) The elastocaloric effect: A way to cool efficiently. *Adv Energy Mater* 5: 1–5.
62. Engelbrecht K, Tušek J, Eriksen D, et al. (2017) A regenerative elastocaloric device: experimental results. *J Phys D Appl Phys* 50: 424006.
63. Bruederlin F, Bumke L, Chluba C, et al. (2018) Elastocaloric cooling on the miniature scale: A review on materials and device engineering. Energy Technol 6: 1588–1604.
64. Bartholome K, Fitger A, Mahlke A, et al. (2018) An elastocaloric cooling system based on latent heat transfer. *Symposium TP01: Caloric Materials for Highly Efficient Cooling Applications*. Avaliable from: https://www.mrs.org/docs/default-source/meetings-events/fall-meetings/2018/symposium-session-pdfs/symposium-tp01.pdf?sfvrsn=8c6ebb10_3.
65. Bartholome K (2017) Efficient elastocaloric heat pumps. Fraunhofer Reports AR 2016-17, 52–53. Avaliable from: https://www.ipm.fraunhofer.de/content/dam/ipm/en/PDFs/reports/ar-2016-17articles/AR-52-53-elastocaloric-heat-pumps.pdf.
66. Prasher R, Chiu CP (2016) Thermal interface materials. *Mater Adv Packag* 10: 511–535.
67. Prasher R (2006) Thermal interface materials: historical perspective, status, and future directions. *Proc IEEE* 94: 1571–1586.

68. Bahrami M, Yovanovich MM, Culham JR (2005) Thermal contact resistance at low contact pressure: effect of elastic deformation. *Int J Heat Mass Tran* 48: 3284–3293.
69. Gotsmann B, Lantz MA (2013) Quantized thermal transport across contacts of rough surfaces. *Nat Mater* 12: 59–65.
70. Ossmer H, Chluba C, Gueltig M, et al. (2015) Local evolution of the elastocaloric effect in TiNi-based films. *Shape Mem Superelasticity* 1: 142–152.
71. Schmidt M, Schütze A, Seelecke S (2015) Scientific test setup for investigation of shape memory alloy based elastocaloric cooling processes. *Int J Refrig* 54: 88–97.
72. Schmidt M, Ullrich J, Wieczorek A, et al. Experimental methods for investigation of shape memory based elastocaloric cooling processes and model validation. *J Vis Exp* 2016: 1–19.