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Thermodynamics cycle analysis and numerical modeling of thermoelastic cooling systems

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ABSTRACT

To avoid global warming potential gases emission from vapor compression air-conditioners and water chillers, alternative cooling technologies have recently garnered more and more attentions. Thermoelastic cooling is among one of the alternative candidates, and have demonstrated promising performance improvement potential on the material level. However, a thermoelastic cooling system integrated with heat transfer fluid loops have not been studied yet. This paper intends to bridge such a gap by introducing the single-stage cycle design options at the beginning. An analytical coefficient of performance (COP) equation was then derived for one of the options using reverse Brayton cycle design. The equation provides physical insights on how the system performance behaves under different conditions. The performance of the same thermoelastic cooling cycle using NiTi alloy was then evaluated based on a dynamic model developed in this study. It was found that the system COP was 1.7 for a baseline case considering both driving motor and parasitic pump power consumptions, while COP ranged from 5.2 to 7.7 when estimated with future improvements.

Analyse de cycle thermodynamique et modélisation numérique des systèmes de refroidissement thermoélastique

Mots-clés : Alliage à mémoire de forme ; Elastocalorique ; Efficacité ; Nitinol ; Refroidissement à l'état solide

1. Introduction

Solid-state cooling technologies have been developed rapidly during the past few decades, including thermoelectric cooling (Sharp et al., 2006), magnetic cooling (Sarlah et al., 2006; Vasile and Muller, 2006; Zimm et al., 2006; Jacobs et al., 2014), electrocaloric cooling (Gu et al., 2013; Jia and Yu, 2012), thermoacoustic cooling (Reid et al., 1998; Swift et al., 1999; Yazaki et al., 2002), and most recently, thermoelastic cooling (Cui et al.,

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Nomenclature

Symbols

A	material constant related to hysteresis energy [J g^{-1}]
Bi	Biot number
COP	coefficient of performance
c_p	specific heat [J g^{-1} K^{-1}]
D	mechanical efficiency loss factor
e	strain
$\dot{e}$	strain change rate [s^{-1}]
F	cyclic loss factor
GWP	global warming potential
g'''	generation term in energy equation [W m^{-3}]
HR	heat recovery
HTF	heat transfer fluid
Δh	latent heat [J g^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
ID	internal diameter [m]
K	material constant related to elasticity [MPa]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg s^{-1}]
OD	outside diameter [m]
Q	heat transferred [J]
$\dot{Q}$	capacity [W]
q	capacity per unit mass [J g^{-1}]
RHS	right hand side
s	specific entropy [J g^{-1} K^{-1}]
SMA	shape memory alloy
sec	second
T	temperature [°C]
ΔT_{ad}	adiabatic temperature span [K]
t	time, or duration [s]
t^*	heat recovery coefficient
u	fluid mean velocity [m s^{-1}]
u^*	internal energy [J g^{-1}]
$\dot{V}$	volumetric flow rate [m^3 s^{-1}]
W	work [J]
$\dot{W}$	work rate [W]
w	specific work [J g^{-1}]
VCC	vapor compression cycle
α	thermal diffusivity [m^2 s^{-1}]
δ	equivalent thickness [m]
ε	effectiveness
σ	stress [MPa]
γ	non-dimensional latent heat
η	efficiency
κ	thermal mass factor
ρ	density [kg m^{-3}]
ξ	martensite phase fraction
$\dot{\xi}$	martensite phase fraction change rate [s^{-1}]
Δ	material constant related to strain [–]

Subscripts

ad	adiabatic
AM	austenite to martensite
cyc	cycle
f	fluid
HT	heat transfer
init	initial
mat	material
mot	motor
MA	martensite to austenite
rec	recovery
s	solid, solid heat exchanger or bed
sat	saturation
trsm	transmission
+	loading
−	unloading

2012) (a.k.a. elastocaloric cooling). These solid-state cooling systems offer us alternatives to eliminate the emission of traditional high global warming potential (GWP) halogenated refrigerants used in the vapor compression cycle (VCC) systems. Compared with other alternative cooling methods, elastocaloric effect has a higher adiabatic temperature span, and therefore, it's possible to use a single stage cycle for typical air-conditioning and refrigeration applications. A more sophisticated ranking of solid-state materials also indicates that thermoelastic cooling materials are better than materials used for magnetic cooling (Qian et al., 2015) in terms of the material level performance. Therefore, from thermodynamics perspective, thermoelastic cooling can be easily applied to cooling systems as compared to its competitive technologies.

Thermoelastic cooling technology uses shape memory alloy (SMA), which is a group of metal alloys with significant elastocaloric effect. They can be used for power cycle, or applied reversely for thermoelastic cooling/heat pump cycles. In a power cycle, the driving potential is the temperature difference. While in a heat pump cycle, the applied stress induces the cooling and heating. In a cooling/heat pump cycle, the useful cooling/heating effect is the result of the associated latent heat released during the stress-induced martensitic phase change process, which makes the material transits between the martensite phase and austenite phase. As shown in Fig. 1 (a), when the SMA is subjected to an external stress exceeding the phase change stress σ_{sat}, austenite crystal starts to transform to martensite crystal, and meanwhile releases the latent heat to raise SMA's temperature at the same time. The cooling effect takes place when the external system stress is less than the σ_{sat}. As the stress decreases below the threshold, the material transits back to the "parent" state, the austenite state, and absorbs ambient heat. The SMA was famous for its unique mechanical property that it "remembers" an original "trained" shape, and can return to this pre-deformed shape upon heating above a transitional temperature. NiTi alloy and copper based alloys are most widely used as engineering functional materials for a variety of applications, including automotive, aerospace, mini actuators and sensors, biomedical, and orthopedic surgery (Jani et al., 2014). As the market of SMA grows, the cost of SMA reduces and it is now possible to use them for power generation and