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Controlling and maximizing effective thermal properties by manipulating transient behaviors during energy-system cycles☆

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ABSTRACT

Transient processes generally constitute part of energy-system cycles. If skillfully manipulated, they actually are capable of assisting systems to behave beneficially to suit designers' needs. In the present study, behaviors related to both thermal conductivities (κ) and heat capacities (c_v) are investigated. Three major findings validated by COMSOL simulations and micro-Hamiltonian-Oscillator analyses are reported: (1) effective κ and effective c_v can be controlled to vary from their intrinsic material-property values to a few orders of magnitude larger; (2) a parameter, tentatively named as "nonlinear thermal bias", is identified and can be used as a criterion in estimating energies transferred into the system during heating processes; (3) For bodies of fluids confined by a cold bottom and a hot top, it may be feasible to install a propeller that can be turned by a weak buoyancy force induced by the top-to-bottom heat conduction via the propeller, provided that densities of the propeller and the fluid are similar. Such a turning motion serves double purposes of performing the hydraulic work and increasing the effective κ of the propeller. Hence, hot-top-and-cold-bottom fluid-filled enclosures (e.g., oceans) that induce nearly no buoyancy flows may now, in principle, become energy-harnessing sources.

1. Introduction

Heat conduction and convection are mechanisms that govern thermal behaviors of various energy-related devices, including bi-segment thermal rectifiers with the thermal conductivity of the system depending on the temperature [1,2], a thermal diode model coupling two nonlinear 1D lattices for a wide range of system parameters [3], thermoelectric modules with thermal energy being converted into electricity [4,5], low-temperature waste heat thermoelectric generator systems optimized and modified [6], photovoltaic films with solar energy being converted into electricity [7,8,9], and light-emitting diodes with the electricity being converted into both thermal energy and the light [10,11]. On the basis of the first law of thermodynamics, temperatures of these solid energy systems are governed by (see Appendix A.1)

$$\kappa\nabla^2 T = \rho c_v \frac{\partial T}{\partial t} - \left(\frac{\partial \kappa}{\partial T}\right)\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] - Q_g, \tag{1}$$

where Q_g denotes the volumetric energy generation (or depletion). The Laplacian term in the left-hand side of Eq. (1) physically stands for diffusive heat flux gradients. In principle, its value can be ubiquitously influenced by all terms, namely, energy storage rate, temperature-dependent κ, and energy generation in the right-hand side. When the second term and the third terms are manipulated, energy systems are known as those devices aforementioned, respectively. In the literature, however, manipulations of the first transient term for beneficial applications appear to have been rarely reported. Buoyancy-driven convective flows in enclosures [12] can be regarded as a close analogy to the present rod-flipping problem. In the former, the rising flow along the hot vertical wall and the sinking flow along the cold vertical wall behave like two ends of a flipping rod. To the best of our knowledge and surveying efforts, even though the idea (that circulating flows enhance the heat transfer more efficiently than stagnant fluids do) is simple and obvious, the extension of this idea to flipping solid rods has not been reported.

Possible applications of maximizing or controlling effective κ abound. They include areas of micro-electro-mechanical systems (MEMS) [13,14], thermal signals, thermostats, among others. High thermal conductivities for single-walled nanotubes based on MD simulations are reported, promising efficient thermal managements in nanotube-based MEMS devices [15].

Another possible application of transient-behavior manipulations is to enhance the effective c_v of the system. In taking advantage of the

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Nomenclature

$\vec{v}$	flow velocity, $u\vec{i}+v\vec{j}+w\vec{k}$ (ms^{-1})
$\vec{g}$	gravitational acceleration (ms^{-2})
A	area of the house (m^2)
$a_1, \ldots, a_4$	randomly generated numbers (dimensionless)
A_c	cross-sectional area (m^2)
Bi	Biot number defined as hL/κ (dimensionless)
bi	small Biot number defined as $h\Delta x/\kappa$ (dimensionless)
c_1	a convenient parameter defined as $hA/(mc_v)$ (s^{-1})
c_p	heat capacity with pressure kept constant $(Jkg^{-1}K^{-1})$
c_v	heat capacity with volume kept constant $(Jkg^{-1}K^{-1})$
$d_1, \ldots, d_5$	coefficients that appear in Eq. (8) (various dimensions)
f	frequency (s^{-1})
h	heat transfer coefficient $(Wm^{-2}K^{-1})$
J	heat transfer (or heat flow) rate (W)
k	spring constant $(kg\ s^{-2})$
NTB	nonlinear thermal bias (K)
nx	number of grid intervals (dimensionless)
p	pressure (Nm^{-2})
P_i	momentum of the i th particle $(kgms^{-1})$
Q	heat transfer (or energy) (J or kJ)
Q_g	heat generation (Wm^{-3})
R	overall thermal resistance (m^2KW^{-1})
r	aspect ratio, $\alpha\Delta t/(\Delta x)^2$(dimensionless)
S	entropy (JK^{-1})
T	temperature (°C or K)
t_o	the flipping period (s)
x_i	the displacement of the i th particle (nm)

Greek symbols

α	thermal diffusivity, $k/(\rho c_v)$ (m^2s^{-1})
β	strength of the on-site potential $(kgm^{-2}s^{-2})$
η	intermediate variable in Hamiltonian-oscillator formulation (N)
κ	thermal conductivity $(Wm^{-1}K^{-1})$
λ	damping factor (kgs^{-1})
μ	viscosity $(kgm^{-1}s^{-1})$
ρ	density (kgm^{-3})

Superscript

α	the valley temperature in the quasi-steady state
β	the peak temperature in the quasi-steady state
a	assembly (reservoirs + the system)
c	cold, or cross-sectional
cap	heat capacity
$cond$	thermal conductivity
eff	effective
h	hot
i	i th node or i th particle, or at the initial state
qs	quasi-steady state
Rc	cold reservoir
Rh	hot reservoir
s	at the left surface of the rod system
ss	steady state
sys	system

energy-storage rate in Eq. (1), the mass, flipping frequency, heat transfer coefficient, or surface area of the system can be manipulated such that the effective c_v also increases by a few orders of magnitude over the intrinsic counterpart.

2. Theoretical concepts

2.1. Four-stroke heating and cooling transient-phase cycles

Analyses of transient multi-dimensional problems generally require numerical simulations. The description of theoretical concepts, however, is best facilitated by considering transient 1D heat conduction phenomena within a rod system insulated circumferentially, sandwiched, and flipped between two thermal reservoirs, as shown in Fig. 1(a). Mathematically, flipping the rod system while maintaining reservoir temperatures unaltered is similar to keeping the rod stationary while altering reservoir temperatures. Both step-varying and continuously-varying boundary conditions are considered. In the steady state, the heat transfer rate can be readily obtained as

$$J = A_c(T_{Rh} - T_{Rc})/R, \tag{2}$$

where T_{Rh} denotes the temperature of the hot reservoir on the left; T_{Rc} the temperature of the cold reservoir on the right; A_c the cross-sectional area of the system; and R the overall resistance, derived to be equal to $1/h_h + L/\kappa + 1/h_c$, where h is commonly known as the heat transfer coefficient such that, at the left end,

$$h(T_{Rh} - T_s(t)) = -\kappa(dT/dx)_{x=0}, \tag{3}$$

with T_s being the temperature on the left end of the system. A similar condition applies to the right end. Furthermore, when a system is

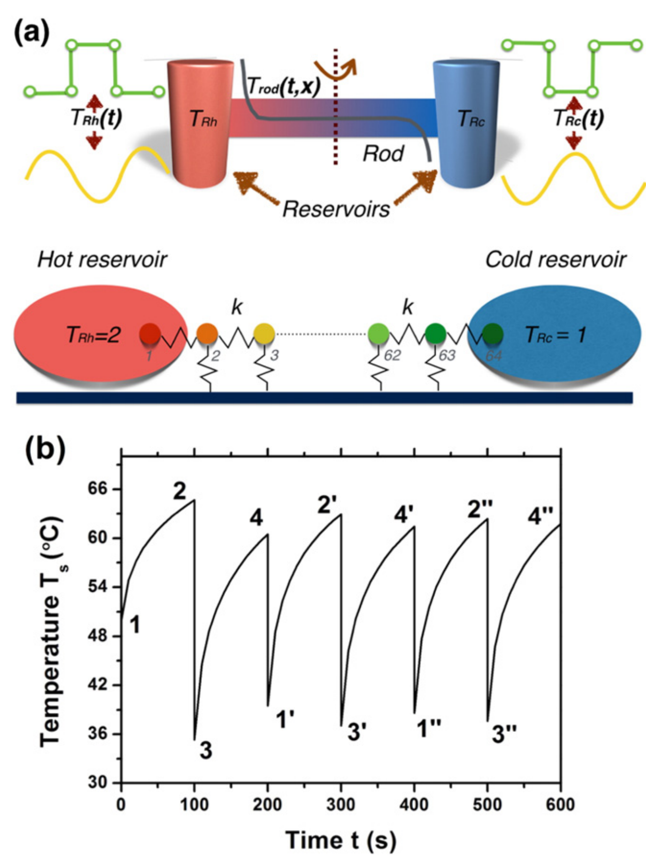

Fig. 1. The assembly that consists of the rod (or slab) system and two thermal reservoirs. (a) The schematic of the assembly and the flipping system. In most cases, the rod system flips and reservoirs are stationary. For sinusoidal boundary conditions, the rod also stays stationary. Also shown are 1D Hamiltonian oscillators for calibration purpose; (b) the temperature at the left end of the rod, T_s, as a function of time. The single prime denotes the second cycle; the double prime denotes the third cycle. Note that $T_{Rh}=100$°C and $T_{Rc}=0$°C.