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Performance analysis of a quantum heat-pump using spin systems as the working substance

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Abstract

The performance of a quantum-mechanical heat pump using many non-interacting spin-1/2 systems as the working substance and consisting of two isothermal and two isomagnetic field processes is investigated, based on the quantum master equation and semi-group approach. The inherent regenerative losses in the two isomagnetic field processes are calculated and the influence of non-perfect regeneration on the performance of the cycle is analyzed. Expressions for some important performance parameters, such as the coefficient of performance, heating load, power input, and rate of the entropy production, are derived. Several interesting cases are discussed and, especially, the optimal performance of the cycle at high temperature is discussed in detail. Some important characteristic curves of the cycle, such as the heating load versus coefficient of performance curves, the power input versus coefficient of performance curves, the heating load versus power input curves, and so on, are presented. The maximum heating-load and the corresponding coefficient of performance are calculated. Other optimal performances are also analyzed. The results obtained here are further generalized, so that they may be directly used to describe the performance of the quantum heat-pump using spin-J systems as the working substance.

1. Introduction

Heat pumps are important devices for saving energy and have been used widely. Like heat engines and refrigerators, the optimal design of a heat pump is also a

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Nomenclature

B	Magnetic field
E	Internal energy of the spin system
H	Hamiltonian
L	Lagrangian function
M	Magnetic moment
P	Power input
P_{m}	Power input at maximum heating-load
Q_1	Amount of heat exchange between the working substance and the heat sink under high-temperature isothermal-process
Q_2	Amount of heat exchange between the working substance and the heat reservoir under low-temperature isothermal-process
Q_{bc}	Amount of heat exchange between the working substance and the regenerator under isomagnetic-field process $\omega = \omega_2$
Q_{da}	Amount of heat exchange between the working substance and the regenerator under isomagnetic-field process $\omega = \omega_1$
S	Angular momentum
T_c	Temperature of the heat reservoir
T_p	Temperature of the heat sink
T'	Temperature of the working substance
t	Cycle period
t_1	Time of the high-temperature isothermal-process
t_2	Time of the isomagnetic-field process with ω_2
t_3	Time of the low-temperature isothermal-process
t_4	Time of the isomagnetic-field process with ω_1
W	Work input
β	$=1/T$
β_{c}	"Temperature" of the heat reservoir
β_{p}	"Temperature" of the heat sink
β_1	"Temperature" of the working substance under high-temperature isothermal process
β_2	"Temperature" of the working substance under low-temperature isothermal process
β_{1r}	"Temperature" of the regenerator under isomagnetic field process with ω_2
β_{2r}	"Temperature" of the regenerator under isomagnetic field process with ω_1
σ	Rate of the entropy production
σ_{m}	Rate of the entropy production at maximum heating load
ω	Equivalent magnetic-field intensity
ψ	Coefficient of performance
ψ_c	Coefficient of performance of a reversible Carnot heat-pump
ψ_{m}	Coefficient of performance at maximum heating load
ψ_r	$= \psi_c - 1$
Π	Heating load
$\Pi_{\max}$	Maximum heating-load