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Performance optimization of quantum Brayton refrigeration cycle working with spin systems

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Abstract

The new model of a quantum refrigeration cycle composed of two adiabatic and two isomagnetic field processes is established. The working substance in the cycle consists of many non-interacting spin-1/2 systems. The performance of the cycle is investigated, based on the quantum master equation and semi-group approach. The general expressions of several important performance parameters, such as the coefficient of performance, cooling rate and power input, are given. It is found that the coefficient of performance of this cycle is a close analogue of the classical Carnot-cycle. Some performance characteristic curves relating the cooling rate, the coefficient of performance and power input are plotted. Further, for high temperatures, the optimal relations between the cooling rate and the coefficient of performance are analyzed in detail.

Keywords: Spin systems; Quantum refrigeration cycle; Performance parameters; Optimization analysis

1. Introduction

In recent years, the optimal analysis of the performance characteristics of thermodynamic cycles has been extended to the regime of quantum cycles. The performances of quantum Carnot, Ericsson and Stirling cycles have been intensively studied [1–14]. Many novel conclusions have been obtained. Besides, the investigations have also dealt with the performance of quantum Brayton refrigeration cycle [7,15], such as the behaviour of the

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Nomenclature

$\mathbf{B}$	magnetic field (T)
E	internal energy (J)
$\hat{H}$	Hamiltonian (J)
h	Planck's constant (J s)
$\mathbf{M}$	magnetic moment (J T^{-1})
P	power input (J s^{-1})
Q	amount of heat (J)
Q_c	amount of heat absorbed by the working substance from the hot reservoir (J)
Q_h	amount of heat released to the hot reservoir from the working substance (J)
R	cooling rate (J s^{-1})
$\mathbf{S}$	spin angular momentum
S_1	mean value of the spin angular momentum in one adiabatic process
S_2	mean value of the spin angular momentum in another adiabatic process
T	absolute temperature (K)
T_c	temperature of cold reservoir (K)
T_h	temperature of hot reservoir (K)
t	cycle period (s)
t_c	time of isomagnetic field process (s)
t_h	time of isomagnetic field process (s)
W	work per cycle (J)
β	inverse of temperature (T^{-1})
β_c	inverse of temperature of cold reservoir (T^{-1})
β_h	inverse of temperature of hot reservoir (T^{-1})
ε	coefficient of performance
ε_c	coefficient of performance of the Carnot refrigeration cycle
μ_B	Bohr magneton (J T^{-1})
Γ_c	thermal conductivity of cold reservoir material (s^{-1})
ω	magnetic-field (J)
ω_1	high magnetic-field (J)
ω_2	low magnetic-field (J)
ω_c	the upper bound of low magnetic-field (ω_2) (J)
ω_h	the low bound of high magnetic-field (ω_1) (J)
Γ_h	thermal conductivity of hot reservoir (s^{-1})

molecular refrigerators toward attaining ultra-low temperatures and three-level laser refrigeration [11]. In fact, the Brayton cycle is an important cycle in engineering thermodynamics. The investigation relative to Brayton cycles has continuously attracted a good deal of attention [16–18]. It has some distinctive merits, which are noteworthy in theory and practice.

In classical thermodynamic cycles, there are the Stirling cycle, Ericsson cycle, Brayton cycle, etc., besides the Carnot cycle. The performance of the Carnot cycle is independent of the property of the working substance, while the performances of other cycles are, in general, dependent on the property of the working substance [19,20]. Quantum-mechanical