Finite-time quantum measurement cooling beyond the Carnot limit

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We proposed the finite-time cycle model of a measurement-based quantum cooler, where invasive measurement provides the power to drive the cooling cycle. Such a cooler may be regarded as an alternative thought experiment of Maxwell’s demon. The measurement-feedback information is capable of moving heat from the cold to hot bath without any work input and even making the maximum coefficient of performance larger than the Carnot limit. The causes that this seemingly paradoxical result does not violate the laws of thermodynamics can be clearly explained through the derivation of a generalized Clausius inequality including the mutual information.

For a classical system exchanging heat with two external baths and undergoing a thermodynamic cycle, Clausius’s inequality reads $-\langle Q_h \rangle / T_h - \langle Q_c \rangle / T_c \geq 0$, where $\langle Q_\alpha \rangle (\alpha = h, c)$ represents the amount of heat flowing into the system from bath $\alpha$ with temperature $T_\alpha$ \cite{1}. The inequality indicates that it is impossible to construct a self-acting machine, unaided by any external agency, to transfer heat from a cool bath to a hot bath. Meanwhile, all thermal machines between two heat baths are less efficient than the Carnot cycle.

Nevertheless, quantum thermodynamics points to new amazing discoveries. Nonequilibrium thermal reservoirs, including quantum coherent \cite{2,3} and squeezed thermal reservoir \cite{4,8}, are expected to be the resources for a quantum machine beyond the thermodynamic bound of its standard counterpart. Niedenzu et al. revealed an efficiency bound for the quantum engine with a non-thermal bath by deriving a tight inequality between the entropy change of the system and the energy exchanged with the bath \cite{9,10}. Watanabe revealed that quantum statistics yields the enhancement of work of thermal machine through many cycles and multiple work resources \cite{11,12}. Shirai et al. considered the non-Markovian effect in a quantum Otto engine and stated that Carnot’s theorem is consistent with a definition of work including the energy of the system-reservoir interaction \cite{13}. Micadei et al. experimentally demonstrated that quantum correlation between the qubits allows the reversal of heat flow \cite{14}. For a time-dependent system in a non-adiabatic quantum evolution, both Brandner and Su found that quantum coherence plays an important role in heat and work \cite{15,16}. The concept of fluctuating efficiency has been introduced, because quantum-scale engines are subjected to thermal and quantum fluctuations \cite{17,18}. Pietzonka and Seifert showed that power fluctuations determine the bounds on the power and efficiency of a class of quantum machines through a universal trade-off relation among the power, efficiency, and fluctuation \cite{19,20}.

More interestingly, quantum measurement allows us to create a variety of ingenious energy conversion processes. There exist two standard ways of designing thermal machines with quantum measurement. The first case is characterized the noninvasive measurement, which does not alter the internal energy for the measured system because of the fact that the measurement basis corresponds to the energy eigenbasis of the Hamiltonian $H$ of the system \cite{21,22}. In general, the measurement acquires information about the state of the working substance, followed by a feedback control evolution depending on the measurement outcome. Based on the thought experiments of Maxwell’s demon \cite{23}, Dong et al. translated Szilard’s classical engine \cite{24,25} into a quantum version by using the noninvasive interaction between the measuring apparatus and the system \cite{26}. Quan et al. designed a Maxwell’s demon assisted thermodynamic cycle, where the measurement is implemented through a controlled-NOT gate operation and does not increase the entropy \cite{27}. Manzano et al. assessed the roles of classical and quantum correlations in the optimal work extraction from a bipartite system by performing a measurement on the ancilla unit \cite{28}. Employing an effective nonselective projective measurement in the energy basis of the $^{13}C$ nuclear spin, Camati et al. provided an experimental evidence of the trade-off between the information and the entropy production \cite{29}. Experimental observations of the role of the noninvasive measurement in the work extraction and the fluctuation have been conducted in superconducting quantum circuits as well \cite{30,31}. The second case is characterized by the invasive measurement, where the internal energy of the observed system is changed if the measurement basis is not identical to the eigenstate of $H$. Jacobs showed that this additional energetic difference leads to a tight version of bound on the extractable work from a system initially in thermal equilibrium \cite{32}. Brandner et al. obtained a natural definition for the efficiency of information to work conversion by extending this bound to feedback-driven quantum engines running periodically \cite{33}. Elouard et al. proposed efficient quantum measurement engines where work is directly extracted from the measurement channel instead of a heat bath \cite{34,35}. The average work and efficiency of four-stroke quantum engines alternately interacting with a measurement apparatus and a single heat bath have

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been revealed [38, 39]. Measurement-driven machines were extended to composite working substances. For a two-stroke two-qubit cooler, the singlet-triplet basis maximizes the energy extraction [10]. An alternate scheme introduced a two-qubit engine powered by entanglement and local measurements [11]. Quantum discord has been related to the quantum feedback cooling by controlling the state of the system through the measurement on ancillas [12].

Note that the invasive measurement changes not only the internal energy but also the entropy of the system. Most quantum thermodynamic cycles, such as Carnot and Otto cycles, consider connecting cooling and heating processes via adiabatic processes. In this Letter, we adopt a different approach by replacing the adiabatic processes with the invasive measurement. The energy offered by the measurement process will be regarded as the work for pumping heat from a cold to hot bath. It would be interested to know if this new configuration has a stable limit cycle. By including the information gain in the measurement, it will be revealed whether a generalized Clausius inequality leads to an unusual bound on the performance for this cycle. Particularly, attention will be paid to create a measurement assisted cooler with a coefficient of performance (COP) larger than the Carnot limit even for finite-time scale.

**Results.** For a quantum system alternately contacting with thermal baths at temperatures $T_h$ and $T_c$ as shown in Fig. 1(a), the measurement-based feedback control results in the inequality

\[
\langle \sigma \rangle = \langle I \rangle - \frac{\langle Q_h \rangle}{T_h} - \frac{\langle Q_c \rangle}{T_c} \geq 0, \tag{1}
\]

where $\langle \sigma \rangle$ is the total amount of entropy production, and $\langle I \rangle$ denotes the mutual information associated with the measured system that has been obtained by measurement. $\langle S \rangle = -\frac{\langle Q_h \rangle}{T_h} - \frac{\langle Q_c \rangle}{T_c}$ is interpreted as the average entropy change of the two baths. When $\langle Q_c \rangle = -\langle Q_h \rangle > 0$, the information offers the possibility of cooling without needing an energy input.

The bound on the COP $\varepsilon$ of a cooler could be established by rearranging the inequality [1], i.e.,

\[
\frac{\varepsilon}{\varepsilon_C} \leq 1 + \frac{T_h \langle I \rangle}{\langle W \rangle} \tag{2}
\]

where $\varepsilon_C = T_c / (T_h - T_c)$ is the reversible COP of a Carnot cycle, and the cooler is driven by energy $\langle W \rangle = -\langle Q_h \rangle - \langle Q_c \rangle$ ($\langle Q_h \rangle \neq -\langle Q_c \rangle$) provided by the invasive measurement. Equation (2) gives rise to a new limit of the COP that incorporates the information $\langle I \rangle$. A main consequence of this new bound is that a quantum measurement cooler may have a performance beyond the Carnot limit. If $\langle I \rangle = 0$, Eq. (1) reduces to the traditional Clausius inequality and $\varepsilon$ is then bounded by the Carnot COP.

**Model.** As an application of this concept, we consider a two-level system as the working substance. The Hamiltonian is assumed as the form

\[
H_S = \frac{\hbar \omega}{2} \sigma_z, \tag{3}
\]

where $\hbar \omega > 0$ is the energy spacing between the excited state $| e \rangle$ and the ground state $| g \rangle$, and the Pauli operator $\sigma_z = | e \rangle \langle e | - | g \rangle \langle g |$. The control protocol of the cooling cycle is illustrated in Fig. 1(b). The two-level system is prepared in an arbitrary initial state $\rho_0$. In the first stroke, the system interacts with a measurement apparatus, projecting the system onto the basis $\{| \psi_+ \rangle, | \psi_- \rangle \}$. If the state vector after measurement is $| \psi_k \rangle (k = +, -)$, the state of the system is updated to $\rho_k = \pi_k \rho_0 \pi_k^\dagger / Tr \{ \pi_k \rho_0 \pi_k^\dagger \} = | \psi_k \rangle \langle \psi_k |$ [37, 43, 44], where $\pi_k = | \psi_k \rangle \langle \psi_k |$ represents the orthogonal projector associated with the measurement basis.

In the second stroke, an isochoric process is executed through the feedback control. The Lindblad master equation will be introduced to treat the time evolution of the system interacting with a thermal bath [44]. The feedback operator $V_k$ is performed with probability $p_k = \langle \psi_k | \rho_0 | \psi_k \rangle$, leading to the evolved density matrix $\rho_k = V_k \rho_k V_k$. The first case is characterized by the postmea-
measurement state vector $|\psi_+\rangle$, where the system is put in contact with a cold bath. For the outcome with the state vector $|\psi_-\rangle$, the system interacts with a dissipative hot bath. Let $\tau_c$ ($\tau_h$) be the time interval during which the system is brought in thermal contact with the cold (hot) bath. The density matrix at the end of the feedback control serves as the initial state of the succeeding cycle.

The two thermodynamic processes are carried out alternately until the measurement outcomes reach a steady distribution. For the two state system, the constant probability $p_+$ of the state vector $|\psi_+\rangle$ has the form (Supplementary I)

$$p_+ = \frac{q_{[+|-]} - q_{[+|+]} + 1}{q_{[+|-]} - q_{[+|+]} + 1},$$

where $q_{[k'|k]}$ represents the conditional probability of the measurement outcomes $|\psi_\prime\rangle$ in one cycle and $|\psi_k\rangle$ in the previous cycle, i.e.,

$$q_{[k'|k]} = \langle \psi_\prime | \rho_k | \psi_k \rangle = \langle \psi_\prime | \mathbf{V}_k | | \psi_k \rangle | | \psi_k \rangle.$$  \hspace{1cm} (5)

By considering $p(k', k) \equiv q_{[k'|k]} p_k$ as the probability of two consecutive measurement outcomes $|\psi_k\rangle$ and $|\psi_k\prime\rangle$ and the sum rule $\sum_k p_{[k'|k]} = 1$, the average work performed by the measurement

$$\langle W \rangle = \sum_k p_k \langle \psi_k | H_S | \psi_k \rangle - Tr \{ H_S \tilde{\rho}_k \}. \hspace{1cm} (6)$$

The average entropy change of the system per cycle associated with the measurement reads

$$\langle \Delta S^m \rangle = k_B \sum_k p_k Tr \{ \tilde{\rho}_k ln \tilde{\rho}_k \}. \hspace{1cm} (7)$$

After the measurement, the system has the probability $p_+$ to contact with the cold bath. The average heat extracted from the cold bath

$$\langle Q_c \rangle = p_+ \{ Tr \{ H_S \tilde{\rho}_+ \} - Tr \{ H_S \rho_+ \} \}. \hspace{1cm} (8)$$

Similarly, the system gets in touch with the hot bath at the probability $p_-$, resulting in the average heat extracted from the hot bath as

$$\langle Q_h \rangle = p_- \{ Tr \{ H_S \tilde{\rho}_- \} - Tr \{ H_S \rho_- \} \}. \hspace{1cm} (9)$$

Note that $\langle Q_c \rangle + \langle Q_h \rangle + \langle W \rangle = 0$ satisfying the first law of thermodynamics. The more detailed calculations of Eqs. (6-9) are presented in Supplementary II.

The entropy productions of both types of control evolution are always positive, resulting in the average entropy production (Supplementary III)

$$\langle \sigma \rangle = \sum_{k'} p_{k'} Tr \{ \tilde{\rho}_{k'} \ln \tilde{\rho}_{k'} \} + k_B \sum_k p_k Tr \{ \rho_k \ln \rho_k \} - \frac{\langle Q_h \rangle}{T_h} - \frac{\langle Q_c \rangle}{T_c} \geq 0 \hspace{1cm} (10)$$

The sum of the first two terms can be interpreted as the average mutual information $I$ describing the information about the measured system that has been obtained by measurement \[30\,37\]. Therefore, the quantum cooler satisfies the inequality Eq. (11). Once the periodically measurement-driven refrigerator is established, information may become a source of energy to move the heat from the cold to hot bath.

**Discussion.** For the first stroke, we choose the measurement bases $|\psi_k\rangle$ associated with measurement operator $\pi_k$ as $|\psi_\prime\rangle = \cos \frac{\vartheta}{2} |e\rangle + e^{i\varphi} \sin \frac{\vartheta}{2} |g\rangle$ and $|\psi_-\rangle = e^{-i\varphi} \sin \frac{\vartheta}{2} |e\rangle - \cos \frac{\vartheta}{2} |g\rangle$, where $\vartheta$ and $\varphi$ represent, respectively, the colatitude with respect to the $z$-axis and the longitude with respect to the $x$-axis in the Bloch sphere representation. In the feedback control process, a two-level system that is damped by interacting with the radiation field in thermal equilibrium at temperature $T_\alpha$ is adopted. The Hamiltonian $H_\alpha$ of bath $\alpha$ and the interaction Hamiltonian $H_{S-\alpha}$ between the system and the bath are given in Supplementary V. With the Born-Markov approximation, one obtains the evolution of the system under the feedback control $\mathcal{U}_\alpha$ in the Kraus representation (Supplementary V), where we have defined the Plank distribution of the cold bath $n_c = \{ \exp [\hbar \omega / (k_B T_c)] - 1 \}$, the coupling parameter $\gamma_c$, and $\Gamma_c = \gamma_c (2 n_c + 1)$. The evolution of system under the feedback control $\mathcal{R}_- = \mathcal{U}_- [\rho_-]$ is obtained by replacing the subscript $c$ with $h$.

Fig.2 (a) indicates that the average entropy change of the baths $\langle S \rangle$ (blue dash-dotted line) may be less than zero and the COP of the cooler is larger than the Carnot COP, i.e., $\varepsilon / \varepsilon_C \geq 1$ (green dash-double-dotted line). A consideration of the mutual information $I$ (red dash line) guarantees that the entropy production $\langle \sigma \rangle \geq 0$ (black solid line). In the case of $\langle S \rangle = 0$, the definition of $\langle S \rangle$ results in $\varepsilon = \varepsilon_C$ (the crosspoints between the blue dash-dotted line and the green dash-double-dotted line). When the colatitude $\vartheta = \pi$, the measurement bases reduce to the eigenstates of $H$, i.e., $|\psi_\prime\rangle \propto |g\rangle$ and $|\psi_-\rangle \propto |e\rangle$. The measurement does not change the internal energy of the system. However, heat flows from the cold to hot bath without any work input, i.e., $\langle W \rangle = 0$ [Eq. (4)], leading to an infinitely large COP $\varepsilon \to \infty$. The measurement is likely to prepare the system in the ground state $|g\rangle$ before contacting with the cold bath and in the excited state before getting in touch with the hot bath. Therefore, energy is always extracted from the cold bath and released to the hot bath. In fact, the cycle acts as a cooler driven by purely information, representing an alternative thought experiment of Maxwell’s demon.

In Fig. 2(b), $\langle S \rangle$ (blue dash-dotted curve) is initially a decreasing function of the time interval $\tau_c$. After reaching a minimum value, $\langle S \rangle$ will increase with $\tau_c$. By implementing an external agent with measurement and feedback, it is no doubt that $\varepsilon$ goes beyond the Carnot limit $\varepsilon_C$ in the region of $\langle S \rangle < 0$. The mutual information $I$ (red dash line) ensures $\langle \sigma \rangle \geq 0$ (black solid line) in this area. Similar to Fig. 2(a), the point of $\langle S \rangle = 0$ coincides
Figure 2. (a) The total amount of entropy production \( \langle \sigma \rangle \), mutual information \( \langle I \rangle \), average entropy change \( \langle S \rangle \) of the hot and cold baths, and dimensionless COP \( \varepsilon / \varepsilon_C \) varying with the colatitude \( \vartheta \), where \( \tau_c = 0.5 \), the left vertical axis shows the values for \( \langle \sigma \rangle \), \( \langle I \rangle \), and \( \langle S \rangle \), and the corresponding scales of \( \varepsilon / \varepsilon_C \) is on the right vertical axis. Note that the performance of the cycle is independent on the longitude \( \varphi \). (b) The average entropy change \( \langle S \rangle \) of the hot and cold baths varying with the time interval \( \tau_c \), where \( \vartheta = 0.98 \pi \), the left vertical axis shows the value for \( \langle S \rangle \), and the corresponding scales of \( \varepsilon / \varepsilon_C \) is on the right vertical axis. The inserted figure presents \( \langle \sigma \rangle \) and \( \langle I \rangle \) varying with \( \tau_c \). The rest parameters \( \omega = 0.5 \), \( T_h = 0.2 \), \( T_c = 0.1 \), \( \gamma_h = \gamma_c = 0.01 \), \( \tau_h = 1 \), and \( \varphi = \frac{\pi}{2} \), where \( h = k_B = 1 \).

With that of \( \varepsilon = \varepsilon_C \).

When the times \( \tau_c \rightarrow \infty \) and \( \tau_h \rightarrow \infty \), or \( \gamma_c \rightarrow \infty \) and \( \gamma_h \rightarrow \infty \), thermal equilibrium states under the feedback controls \( V_+ \) and \( V_- \) are achieved. The conditional probabilities \( q[|+|] \) and \( q[|\tau|] \) are, respectively, simplified as \( q[|+|] = \frac{(1 + 2 \gamma_c - \cos \vartheta)}{2(1 + 2 \gamma_c)} \) and \( q[|\tau|] = \frac{(1 + 2 \gamma_h - \cos \vartheta)}{2(1 + 2 \gamma_h)} \). By using Eqs. (4), (8), and (9), the inequality \( \langle S \rangle \leq 0 \) can be equivalently expressed as

\[
- \frac{\langle Q_c \rangle}{\langle Q_h \rangle} = \frac{\gamma_h (n_h + \sin^2 \frac{\vartheta}{2}) (\cos^2 \frac{\vartheta}{2} + n_c \cos \vartheta)}{\gamma_c (n_c + \cos^2 \frac{\vartheta}{2}) (-\sin^2 \frac{\vartheta}{2} + n_h \cos \vartheta)} \geq \frac{\tau_c}{\tau_h}.
\]

(11)

As the colatitude \( \vartheta \) makes the ratio between the heat extracted from the cold bath \( \langle Q_c \rangle \) and that extracted from the hot bath \( \langle Q_h \rangle \) meet the condition given by Eq. (11), the COP \( \varepsilon \) will be greater than the Carnot limit \( \varepsilon_C \). Particularly, an algebra calculation shows that \( \langle Q_c \rangle / \langle Q_h \rangle = -1 \) at \( \vartheta = \pi \) and \( \gamma_h = \gamma_c \), leading to \( \varepsilon \rightarrow \infty \).

In conclusions, a general bound on the COP of quantum measurement coolers is presented. The mutual information obtained by measurement has the potential to improve the cooling performance. When the average entropy changes of the two baths are negative, the COP of the two-stoke cycle consisting of measurement and feedback surpasses the Carnot limit. The mutual information ensures that the entropy production is always positive, satisfying the second law of thermodynamics. In the case of a measurement basis corresponding to the energy eigenstates of the system, the feedback control makes heat flow from the cold to hot bath without any work input. The results derived from the present finite time model offer a broad configuration in the application of the fuel energy from quantum measurement and provide more instructive information to the development of experiments than those obtained by traditional time-independent models.

Acknowledgments

This work has been supported by the National Natural Science Foundation (Grants No. 12075197 and No. 11805159) and the Fundamental Research Fund for the Central Universities (No. 20720210024).

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