Collisional model-based quantum heat engines

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Introduction

In the framework of **Quantum Thermodynamics**, this work starts from the collisional model to conceive quantum heat engines. These engines are studied in the continuous time and discrete time (stroke-based) regimes, and a link between them is found.

In the end the continuation of this work is set: fluctuation relations.

Collisional Model

A schematic representation of this model[1] can be seen in Fig. (1). Its main idea is to consider the environments as flywheels of thermal state units which interact for a very short time with the system, taken in the limit to 0. A central idea of this model is to consider the interaction V_i to scale with $1/\sqrt{\tau}$.

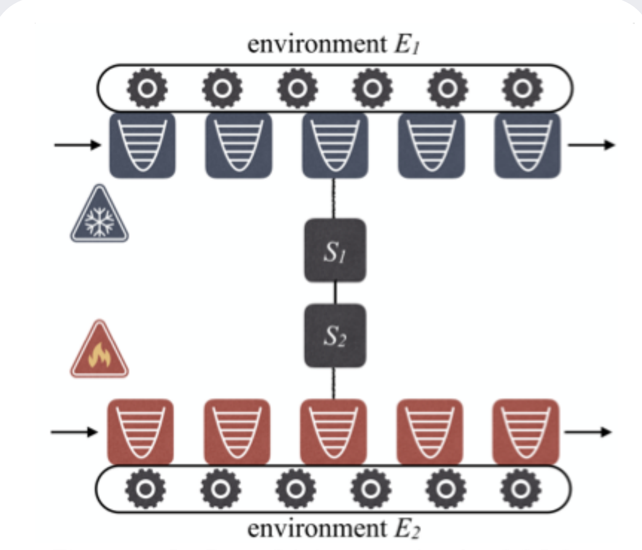

Figure 1: De Chiara et al., 2018

Environment: thermal state units + $\tau \to 0$ = Local Master Equation (LME)

$$\frac{d\rho_S}{dt} = -i\,[H_S, \rho_S] + \sum_{i=1}^{2} D_i(\rho_S) \qquad (1)$$

With: $D_i = -\frac{1}{2} Tr_{E_i}\left\{\left[V_i, [V_i, \rho_S \otimes \rho_{E_i}]\right]\right\}$

Expanding these dissipators, it can be seen that they have a Lindblad dissipator form.

Quantum Heat Engine

The operation of a quantum heat engines containing 2 or more subsystems (this work considers 2), can only be understood looking at the interaction between the parts and also local and global detailed balance.

Local detailed balance holds:

$$[H_{S_i} + H_{E_i}, V_i] = 0 \qquad (i = 1,2)$$

But **global** detailed balance **does not hold**:

$$[H_S + H_{E_1} + H_{E_2}, V_1 + V_2] = [H_I, V_1 + V_2] \neq 0$$

$$\dot{W}_{ext} \neq 0 \qquad (2)$$

$$\frac{d\langle H_S\rangle}{dt} = \dot{W}_{ext} + \sum_{i=1}^{2} \dot{Q}_i$$

1st Law of Thermodynamics

Continuous Time Engine

Within the collisional model, we can expand in power series the average energy of the system and obtain:

$$\frac{d\langle H_S\rangle}{dt} = -\frac{1}{2}\sum_{i=1}^{2}\langle [V_i, [V_i, H_S]]\rangle$$

Steady-state

$$\dot{W}_{ext} + \sum_{i=1}^{2} \dot{Q}_i = 0 \qquad (3a)$$

$$\Pi = -\sum_{i=1}^{2} \frac{\dot{Q}_i}{T_i} \quad \text{(Entropy production)} \qquad (3b)$$

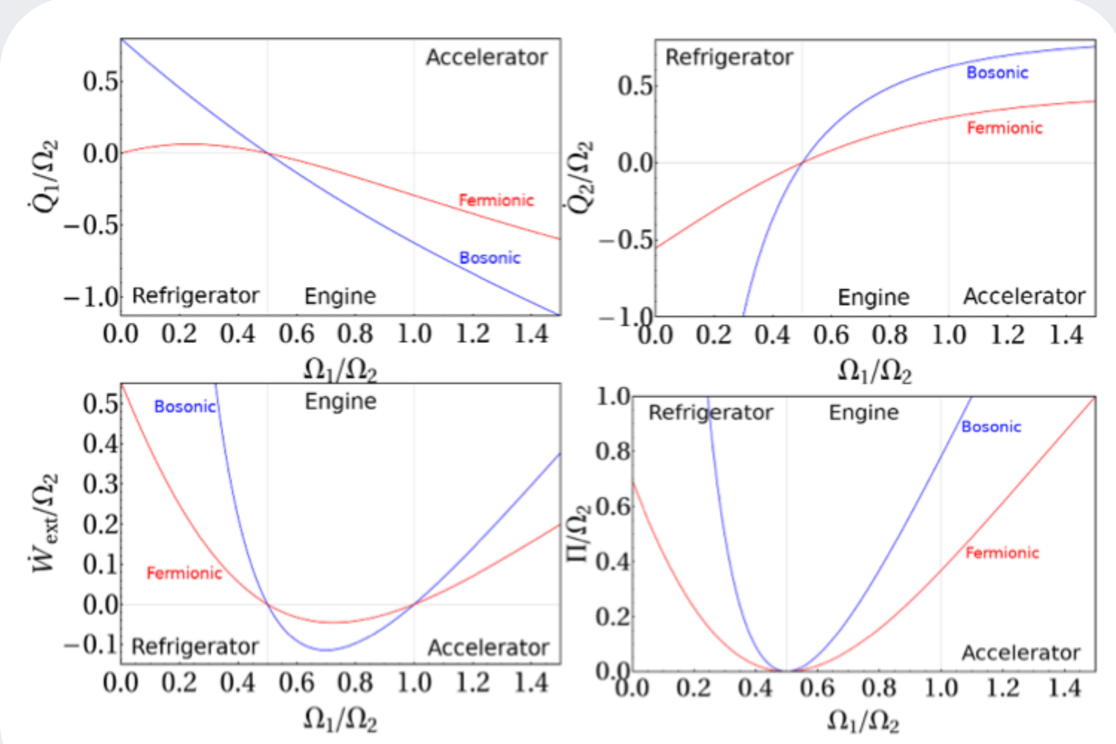

Figure 2

$$\eta = 1 - \frac{\Omega_1}{\Omega_2} \qquad \text{COP} = \frac{\Omega_1}{\Omega_1 - \Omega_2}$$

Otto cycle

The continuous time engine shows a **rectified** behavior, otherwise saying, it works as a refrigerator in just one way and not the other (while the heat engine and accelerator regimes are possible even when the subsystems are swapped).

Discrete Time Engine

All engines in essence are discrete time/stroke-based engines. Therefore, we look at the work and heat strokes separately and note that the system has a **stroboscopic** evolution[2].

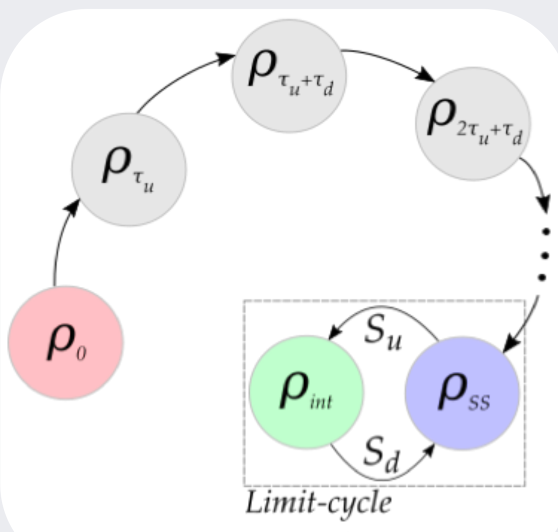

Figure 3

Steady-state approach

$$\mathcal{S}_d\mathcal{S}_u|\rho_S\rangle_{SS} = |\rho_S\rangle_{SS}$$

$$\eth \equiv \mathcal{S}_d\mathcal{S}_u$$

$$\to (\eth - I_{16})|\rho_S\rangle_{SS} = 0$$

$$|\rho_S\rangle_{SS} = \ker(\eth - I_{16}) \qquad (4)$$

Energy equations approach

Master equation at each stroke

Stroboscopic evolution

Linear system of equations of the energy

Both paths lead to equivalent thermodynamic quantities (work, heat and entropy production).

Looking for the connection

Expanding the thermodynamic quantities of the discrete time engine in power series, one can recover the continuous time engine if the following limiting conditions are considered:

Discrete time engine → $g\tau_u \ll 1$, $\gamma\tau_d \ll 1$, $\frac{\tau_d}{\tau_u} \approx \frac{4g^2}{\Delta^2}$ → Continuous time engine

$\Delta = \sqrt{\gamma^2 + 4g^2 + (\Omega_1 - \Omega_2)^2}$

g : strength of the interaction between subsystems

γ : strength of the interaction with the baths

Next step: fluctuation relations

As we deal with nonequilibrium steady-states, the thermodynamic quantities have stochastic distributions, which can be represented by fluctuation relations. So, as a next step of this work, relations of the following kind[3] will be studied:

$$\frac{P(N_W)}{P(-N_W)} = e^{(\beta_1\Omega_1 - \beta_2\Omega_2)N_W} \qquad (5)$$

Conclusion

This work shows that the collisional model is compatible with thermodynamics and that it is an interesting line of action to tackle the problem of modelling quantum heat engines operating at finite time.

The complete understanding of how heat engines work at the quantum regime and what are the advantages that can be obtained with respect to their classical counterparts are of utmost importance to the next generation of quantum technologies.

References

[1] G. D. Chiara, G. Landi, A. Hewgill, B. Reid, A. Ferraro, A. J. Roncaglia, and M. Antezza, "Reconciliation of quantum local master equations with thermodynamics," *New Journal of Physics*, vol. 20, p. 113024, nov 2018.

[2] S. Scopa, G. T. Landi, and D. Karevski, "Lindblad-floquet description of finite-time quantum heat engines," Phys. Rev. A, vol. 97, p. 062121, Jun 2018.

[3] M. Campisi, J. Pekola, and R. Fazio, "Nonequilibrium fluctuations in quantum heat engines: theory, example, and possible solid state experiments," New Journal of Physics, vol. 17, p. 035012, mar 2015.

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