Quantum Thermodynamics

Enhancing The Performance Of Quantum Thermal Devices At Small Scales

Alicia R.Mobbs* (220673002) ,a.mobbs3@newcastle.ac.uk, BSc Theoretical Physics with Hons

Introduction

The study of quantum thermodynamics is focused on the thermodynamic phenomena in the quantum world and allows the design of quantum thermal devices to effectively manipulate the heat in quantum systems (Guo et al., 2022). One such quantum thermal device is a quantum heat engine, which converts heat into mechanical work.

An approximation to any heat engine process can be made via looking at different thermodynamic cycles that describe the relationship between heat and work such as:
Carnot Cycle – An idealised model of a thermodynamic cycle for a heat engine
Otto Cycle - An approximation of an internal combustion engine

The aim of this project is to utilize quantum thermodynamic effects on a heat engine to achieve the following objectives:

- **I. Deriving the efficiency equations of the quantum engine for different working mediums (single/two-particle).**
- **II. Identification of best engine performance at high and low temperature regimes as well as different adiabatic parameters.**
- **III. Determining if quantum symmetry of fundamental particles affects performance.**

Quantum Otto Cycle

The engine working medium is a quantum harmonic trap with one or two particles. This engine cycle consists of four consecutive steps as follows:

Isentropic Compression – The frequency is varied from ω_1 to ω_2 during time τ_1
Hot Isochore – Coupled to a hot bath during time τ_2 to get temperature to increase to β_2
Isentropic Expansion – The frequency is changed back to ω_1 from ω_2 during time τ_3
Cold Isochore – Coupled to a cold bath during time τ_4 to get temperature to decrease to β_1

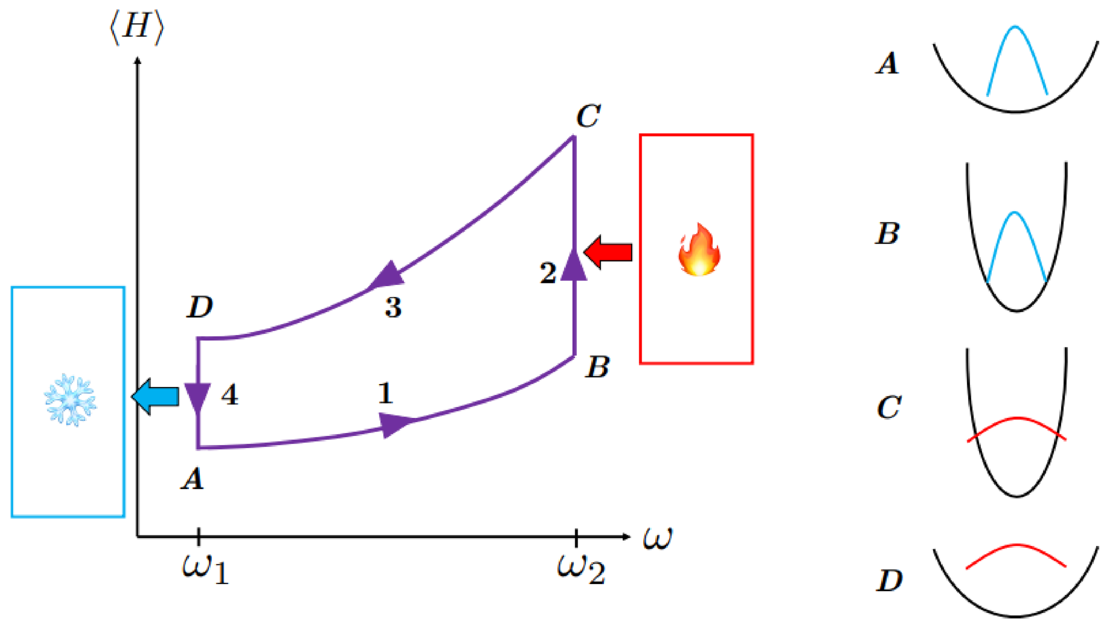

Figure 1. The quantum Otto cycle represented as a diagram of energy as a function of frequency with representation of the stroke's trapping potential (Myers and Deffner, 2020)

The efficiency of this quantum engine, is defined as the ratio of the total work per cycle and the heat received from the hot reservoir and is given by the following equation:

$$\eta = -\frac{\langle W_1 \rangle + \langle W_3 \rangle}{\langle Q_2 \rangle}$$

where $\langle W_1 \rangle$ is the average work done during the first stage, $\langle W_3 \rangle$ is the average work done during the third stage and $\langle Q_2 \rangle$ is the average heat exchanged with the hot bath during the second stage.

The efficiency depends on how fast the frequency is changed, characterised via the adiabatic parameter Q^*. The two extreme cases of Q^*, which are analytically solvable, were chosen to determine the impact on efficiency.

$$Q^* = 1 = Q^*_{ad} \quad \text{This is an adiabatic (slow) process}$$

$$Q^* = \frac{(\omega_1^2 + \omega_2^2)}{2\omega_1\omega_2} = Q^*_{SS} \quad \text{This is a sudden switch (extremely fast) process}$$

The adiabatic process is hard to achieve experimentally, whereas the sudden switch process is a more realistic behavior that occurs experimentally, thus both processes are considered.

Results

Numerical analysis was successfully completed for the high and low temperature regimes, with variation to both the working medium (single/two particle harmonic trap) and the adiabatic parameter Q^* ($Q^* = Q^*_{ad}/Q^* = Q^*_{ss}$).

For the two-particle trap, comparisons between the two fundamental classes of particles, fermions or bosons was also made, to determine if quantum symmetry does indeed effect efficiency.

High Temperature case -

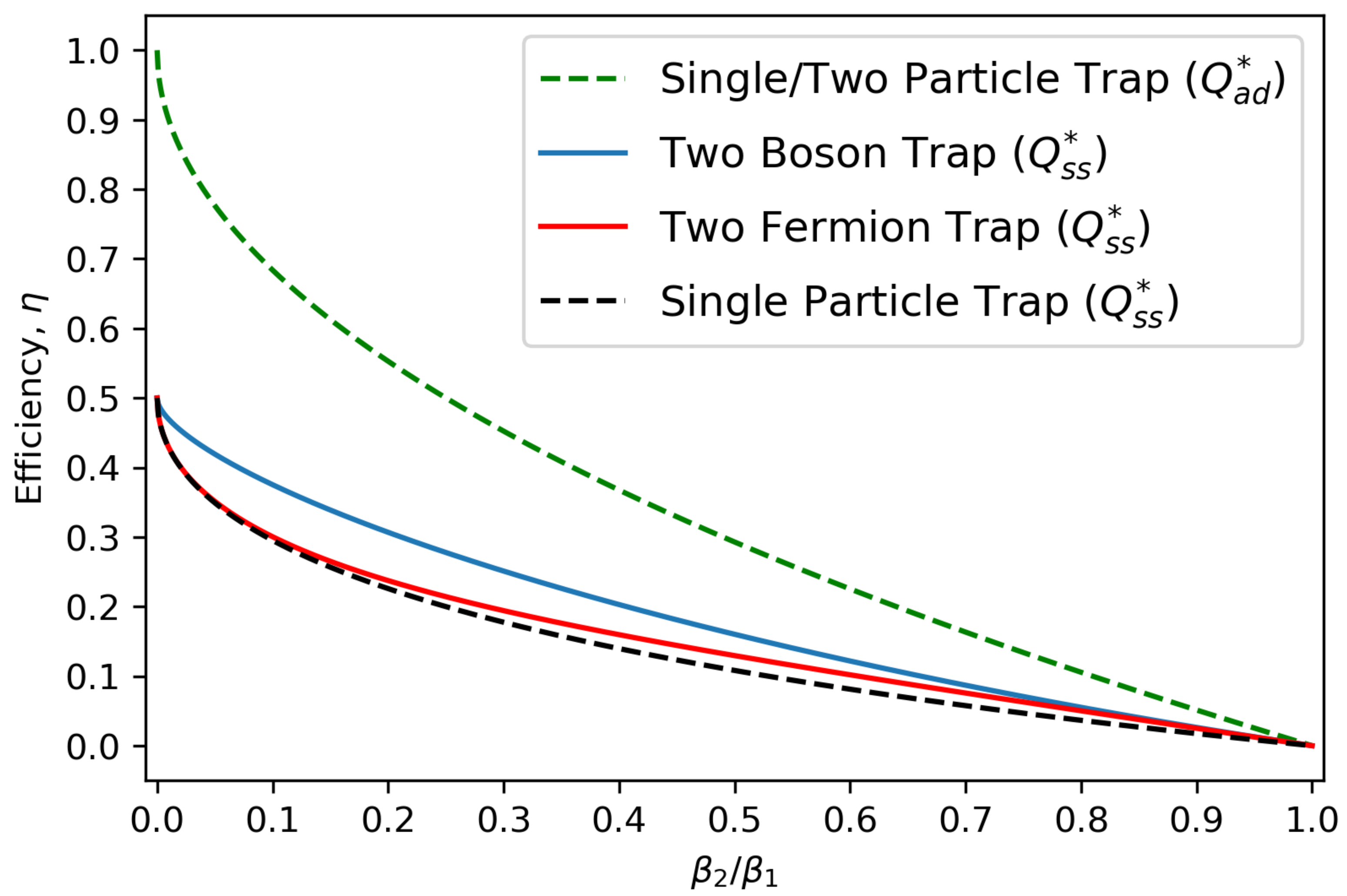

Figure 2. Efficiency at maximum power in the high temperature regime ($\beta_i \hbar\omega_i \ll 1$) as a function of the ratio of the two inverse temperatures β_2 and β_1 for a bosonic, fermionic and single particle engine with different adiabatic parameters.

Low Temperature case -

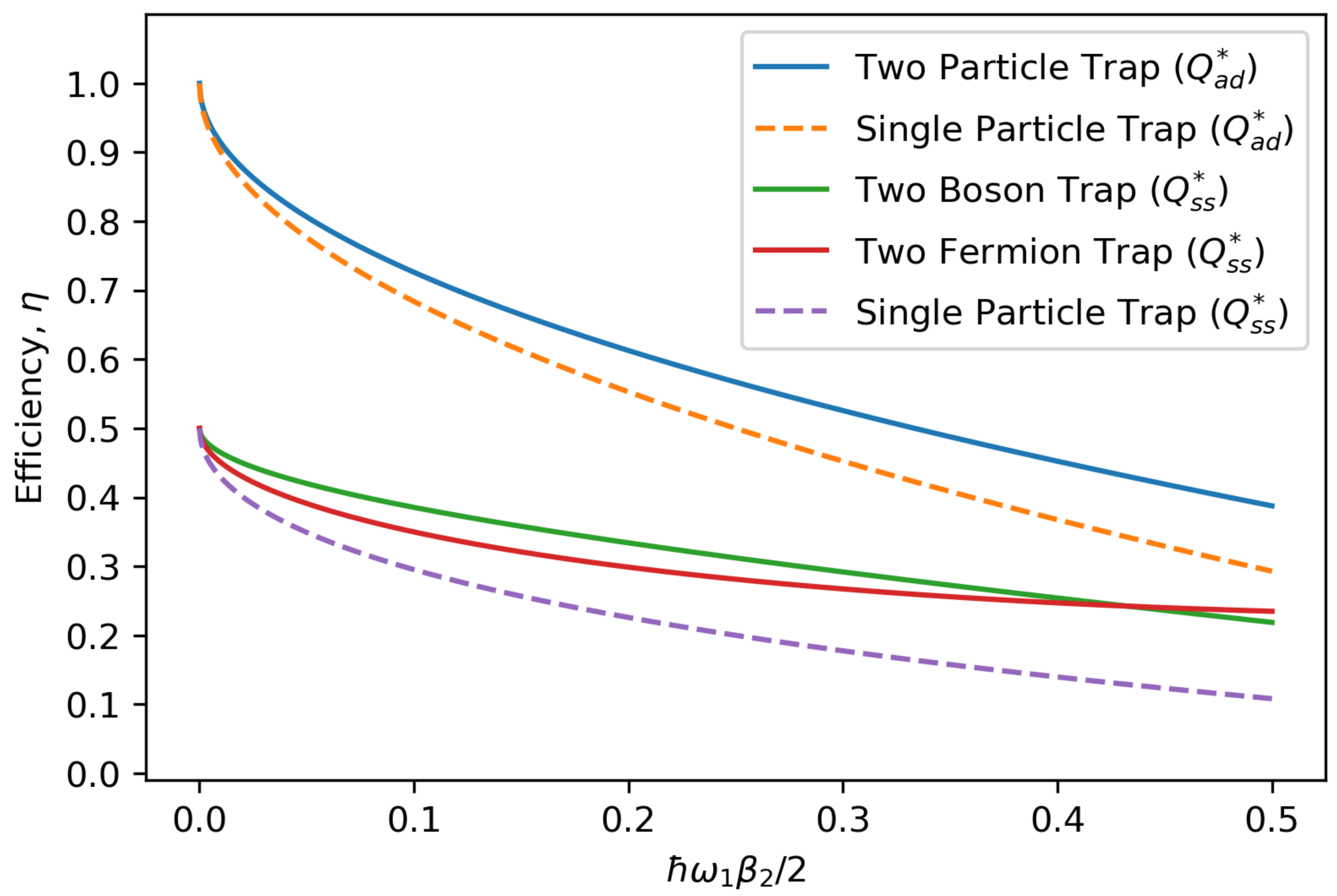

Figure 3. Efficiency at maximum power in the low temperature regime ($\beta_i \hbar\omega_i \gg 1$) as a function of the inverse of the hot bath temperature β_2 (in units of quantum energy) for a bosonic, fermionic and single particle engine with different adiabatic parameters.

Discussion

In general, how fast or slow the frequency is changed (characterised via the adiabatic parameter) effects the efficiency of the quantum heat engine irrespective of the nature of the working medium.

High Temperature Regime – In the adiabatic case (Q^*_{ad}), the single-particle trap is the most efficient at all values. For sudden switch case (Q^*_{ss}), the two-particle trap is most efficient, yielding higher efficiencies at intermediate values of inverse temperature than the single-particle trap. More specifically, the two-Boson trap is the most efficient two-particle trap comparative to the two-Fermion trap .

Low Temperature Regime – In the adiabatic case (Q^*_{ad}), initially the single and two-particle trap yield the same efficiency, however the two-particle trap is most efficient at all values after this. For the sudden switch case (Q^*_{ss}), the two-particle trap is most efficient in this case, yielding higher efficiencies at intermediate values of inverse temperature than the single-particle trap. More specifically, the two-Boson trap is the most efficient two-particle trap comparative to the two-Fermion trap .

Two Particle Trap – When comparing the two fundamental classes of particles over both temperature regimes, the difference can be seen when the adiabatic parameters are set to Q^*_{SS}. The two-boson trap in both cases yield the most efficient working medium especially for the intermediate inverse temperatures.

Special Case – For the low temperature regime, when looking at the two-particle trap there is a limit where we can no longer consider the assumption ($\beta_i \hbar\omega_i \gg 1$) to hold. This causes the two-fermion case to suddenly start increasing in efficiency, even though this is non-physical and therefore after this point we can ignore the efficiency trend.

Conclusion

This project achieved its objects as follows:

- **I. Successfully derived the efficiency equations of the quantum engine for different working mediums.**
- **II. Determined the best engine performance at high and low temperature regimes for different adiabatic parameters Q^*_{ad} and Q^*_{SS}.**
- **III. Determined that due to the wavelike nature of particles, the symmetry of the fundamental particles does affect engine performance, with the symmetric wavefunction of bosons being more efficient for the engine than the antisymmetric wavefunction of fermions.**

Future Direction - Continuous research on different working mediums, thermodynamic cycles and the time dependency of the adiabatic parameters is consistently being carried out and new more efficient engines are being theorised or developed, which will help to make quantum technology more viable.

Acknowledgements

I would like to thank Dr Obinna Abah for supervising this opportunity to further explore the link between two important and relevant topics in physics.

This project was made possible via the 2024 Vacation Research Scholarship funding from Newcastle, George Brown Endowment, George Henderson Endowment and Florence Kirkby Endowment.

References

Guo, B., Zhou, N., Yang, C. and Yu, C. (2022). Multifunctional quantum thermal device with initial-state dependence. Physica E 142, pp.115275.

Myers, N.M. and Deffner, S. (2020). Bosons outperform fermions: The thermodynamic advantage of symmetry. Physical Review E 101, pp.012110.