# CHAPTER I INTRODUCTION

## 1.1 Background of The Study

Global energy demand continues to increase due to population growth and technological development. According to the International Energy Agency (2024), global energy consumption has increased approximately 15% in recent years, with fossil fuels still accounting for nearly 80% of total energy usage in 2023. This heavy reliance presents serious challenges, as current reserves are projected to meet global demand only until around 2060. Moreover, fossil-fuel-related $CO_2$ emissions contribute approximately 89% of total anthropogenic greenhouse gas emissions (Chen et al., 2019; Friedlingstein et al., 2024; Pambudi et al., 2023). These concerns highlight the urgent need for the development of more efficient and sustainable energy technologies, to support achieve Net Zero Emissions (NZE) by 2060 (Prasodjo, 2023; Zahira and Fadillah, 2022) and the objectives of the Sustainable Development Goals (SDGs) (Santika et al., 2020).

Cooling technologies represent a significant contributor to global energy consumption. Such systems are essential for applications ranging from vaccine preservation and precision optical instrumentation to high-performance computing and quantum information processing (Aamir et al., 2025; Cengel et al., 2011; Myers et al., 2022a). Despite their widespread use, conventional cooling technologies based on gas-compression cycles remain fundamentally limited in both energy efficiency and environmental sustainability. Many classical refrigeration systems employ synthetic refrigerants, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), that cause ozone layer depletion and the enhancement of the greenhouse effect (Galka et al., 2012; Kim et al., 2024; Zhao et al., 2015). Furthermore, classical refrigeration processes are inherently non-ideal and subject to thermodynamic irreversibility, leading to substantial energy losses, particularly in low-temperature regimes (Abah et al., 2020; Çengel, 2008).

These limitations become increasingly pronounced as modern technologies demand precise and stable temperature control, especially in advanced systems such as high-sensitivity sensors, sophisticated optical devices, and quantum computing platforms that are extremely sensitive to thermal fluctuations (Manikandan et al., 2020; Tabatabaei and Jahangiri, 2024). In many cases, reliable operation is only achievable at ultra-low temperatures. However, classical cooling systems experience severe efficiency degradation under such conditions due to dominant irreversible processes (Deffner and Campbell, 2019; Kosloff and Rezek, 2017; Myers et al., 2022a; Zhang, 2020). This inadequacy highlights the necessity of alternative approaches that extend beyond classical thermodynamic frameworks. In this context, quantum physics offers a promising foundation, as quantum systems exhibit discrete energy spectra and microscopic energy-exchange mechanisms that differ fundamentally from their classical counterparts. Indeed, several studies have demonstrated that quantum refrigerators can operate close to the Carnot efficiency limit at ultra-low temperatures ($T < 1$ K) (Cleri, 2024; Kaur et al., 2025; Singh and Abah, 2020; Zhang et al., 2023).

In the study of quantum thermal machines, system operation is commonly described using thermodynamic cycles such as Carnot (Altintas, 2025; Belfaqih et al., 2015; Contreras-Vergara et al., 2024; Fei et al., 2022; Zhang et al., 2023), Stirling (Cruz et al., 2023; Getie et al., 2020; Yin et al., 2017), and Otto cycles (Abah and Lutz, 2016; Behzadi, 2024; Jiao et al., 2021; Kaur et al., 2025; Sutantyo et al., 2024; Wiedmann et al., 2021). In this work, the Otto cycle is adopted due to its relatively simple structure while still capturing the essential features of energy conversion in quantum systems (Chen et al., 2023). Although the Otto cycle originates from classical thermodynamics, the incorporation of quantum working media has been shown to significantly enhance system performance. Under certain conditions, quantum thermal machines may even exceed classical Carnot efficiency bounds (Myers et al., 2022b). Beyond the choice of thermodynamic cycle, the selection of the working substance plays a crucial role in determining operational characteristics. Previous studies have explored a variety of working media, including classical gases, single ions, fermionic systems, and bosonic systems, with bosonic media exhibiting particularly favorable performance in low-temperature regimes (Cohen-Tannoudji et al., 2019; Myers et al., 2022b; Setyo and Latifah, 2018; Sutantyo et al., 2024; Van Horne et al., 2020; Zettira et al., 2024).

Bosons are particles or atomic nuclei that possess integer spin values $(0, 1, 2, \ldots)$ and obey Bose–Einstein statistics, in contrast to fermions, which have half-integer spin values $(1/2, 3/2, \ldots)$ and are subject to the Pauli exclusion principle. This fundamental distinction allows bosons to occupy the same energy state simultaneously, thereby giving rise to collective behaviors absent in fermionic systems (Deffner and Campbell, 2019). Such statistical properties directly influence the performance of quantum machines. Myers and Deffner (2020) demonstrated that boson-based systems can achieve superior thermodynamic performance symmetry expands the accessible state space. This phenomenon becomes particularly pronounced under ultra-low temperature conditions, where bosons undergo Bose–Einstein Condensation (BEC), a state in which a macroscopic fraction of particles accumulates in the ground state. BEC yields a highly ordered and analytically tractable energy distribution, enabling more stable thermal control and smoother responses to variations in quantum parameters. These properties make bosonic gases promising working media for quantum cooling machines.

Despite these advantages, many existing studies on bosonic quantum Otto engines continue to assume ideal thermal conditions during the isovolume processes, specifically full thermalization between the working medium and the heat reservoirs, even when the cycle is analyzed under finite-time conditions (Abah et al., 2020; Deffner, 2018; Kaur et al., 2025). This assumption implicitly requires sufficiently long contact times to ensure thermal equilibrium. In practical implementations, particularly in ultracold systems involving bosonic gases and BEC, the interaction time between the working medium and the reservoir is finite, while relaxation toward equilibrium proceeds relatively slowly (Kosloff and Rezek, 2017). Consequently, the system often undergoes only partial thermalization, resulting in final thermal states that deviate from ideal equilibrium distributions (Sutantyo et al., 2024; Zettira et al., 2024). This deviation leads to significant

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differences in the amount of heat absorbed and released during a cycle, thereby directly affecting cooling power and the coefficient of performance (COP).

Based on the above background, this study investigates the performance of a quantum Otto refrigerator employing a non-interacting Bose gas confined in a three-dimensional cubic potential, which is adopted to enable analytical treatment and to distinguish this model from previous studies that predominantly consider harmonic confinement; the analysis is conducted within an endoreversible framework, which improves tractability but also represents a limitation since internal dissipation and particle interactions are not explicitly included. The primary focus is on incorporating the effects of partial thermalization during the isovolume processes. Using the grand canonical ensemble approach, the main thermodynamic quantities are derived and subsequently utilized to evaluate the coefficient of performance (COP), cooling rate, power, and entropy production. This study is expected to provide a more realistic understanding of quantum refrigerator performance and to contribute to the development of practically applicable quantum cooling models at the microscopic scale.

## 1.2 Purpose of The Study

This study investigates a quantum Otto refrigerator employing a non-interacting bosonic gas in a three-dimensional cubic potential. This model is chosen to enable analytical treatment, isolate quantum statistical effects, and distinguish the present work from previous studies that predominantly consider harmonic confinement. The study focuses on the impact of partial thermalization during isovolume processes under finite-time operation. Thermodynamic quantities derived within the grand canonical ensemble are used to evaluate the coefficient of performance (COP), cooling rate, output power, and entropy production.

## 1.3 Benefits of The Study

This research enhances the understanding of quantum refrigeration systems employing a non-interacting bosonic gas in a three-dimensional cubic potential. By analyzing COP, cooling rate, output power, and entropy production under partial thermalization conditions, this study provides a more realistic description of quantum Otto refrigerators beyond ideal thermal equilibrium assumptions.

### 1.4 Research Scopes and Limitations

This study focuses on a quantum Otto refrigerator employing a non-interacting bosonic gas confined in a three-dimensional cubic potential. The choice of this working medium and trapping model is intended to highlight the role of discrete energy structure and finite-time thermalization on refrigerator performance.
The analysis is limited to:

1. An ideal bosonic working medium without particle interactions.
2. A cubic trapping potential with two fixed frequencies during isentropic strokes.
3. Finite-time heat exchange leading to partial thermalization and entropy production.
4. Evaluation of COP, cooling rate, and output power using grand-canonical thermodynamics and numerical calculations.

### 1.5 Hypothesis

It is hypothesized that a quantum Otto refrigerator based on an ideal non-interacting bosonic gas confined in a cubic potential exhibits tunable performance under partial thermalization. The COP, cooling rate, output power, and entropy production are expected to depend on the degree of thermalization and the trapping potential parameters.