CHAPTER 1 INTRODUCTION

1.1 Background

The breakthrough of quantum physics in modern era at the present moment has revolutionized the world's understanding by the failure of classical mechanics to explain various microscopic phenomena (Zettili, 2009), which mostly formulated in the basic form of equation in the late nineteenth century (Dimock, 2011). According to Longair (2013), the discovery of thoroughly contrast world of quantum mechanics, has introduced the ideas of probabilistic, superposition, and the energy discretization which leads the way into the understanding of quantum thermodynamics (Deffner and Campbell, 2019) and nano thermodynamics (Chamberlin, 2015). These fields were implemented into the study of quantum heat engine (Bender et al., 2000; Paul, 2020; Sutantyo, 2020; Yin et al., 2017) as pioneered by Scovil and Schulz-DuBois (Scovil and Schulz-DuBois, 1959). Quantum heat engine is a device that converts quantum particles in the form of heat as thermal energy into work as mechanical energy by using quantum effect in order to improve the energy conservation (Santos, 2018). Quantum heat engine can be a guidance to develop the study of wealth exploration, especially in the study of energy stored and transferred in the microscopic regime. However, the quantum heat engine still provide the essential connection between theoretical concept and the substantial physical phenomena (Geva and Kosloff, 1994).

The arrival of quantum heat engine has reorganized human's perspective over energy utilization and continues to evolve in order to obtain high performance and the ability to regenerate itself. Quantum heat engine relies on the quantum matters to produce work and requires classical thermodynamics cycle to accomplish maximum efficiency (Quan et al., 2007), where the classical system replaced by the relevant quantum system. Some of the quantum heat engines which had been studied are Otto engine (Zettira et al., 2023), Carnot engine (Gardas and Deffner, 2015), Diesel engine (Singh and Rebari, 2020), Ericsson engine (Enock et al., 2020), Lenoir engine (Fahriza et al., 2022), Brayton engine (Lin and Chen, 2003; Singh, 2020), Stirling engine (Das et al., 2023; Raja et al., 2021) and many others. Theoretically, Carnot engine established as the highest limit of heat engine (Carnot, 1824), which has become a benchmark through the years.

In reality, the realization of Carnot engine is still not feasible in practice, since reversibility can only achieved once after an infinite amount of time which is known as the quasistatic condition (Gemmer et al., 2009). According to the second law of thermodynamics, this condition is necessary for the terms of reversible circumstances in consequence of the entropy remain constant from the beginning to the end of the process (Borgnakke and Sonntag, 2020). The quasistatic will surpass into the quasi equilibrium (Morales-Rodriguez, 2012), where the rate change in thermodynamics such as expansion, compression, heating, cooling, and any other transformations occurs extremely slowly. The very slight difference between the internal and external forces together with the tiny shift in the external forces, leads the process to reverse eventually (Helrich, 2009). This concept becomes the basis of the endoreversible model (Gonzalez-ayala et al., 2020), which assumed the internal process of the system is fully reversible and irreversible solely occurs at the interfaces between the system and the environment. Within endoreversible model, the system operates close to real-world order, by considering the outside interactions between the system and the reservoir. An Engine with endoreversible cycle exhibits lower efficiency than Carnot engine due to the temperature gradient of heat induces irreversibility, whereas Carnot engine is completely reversible both internally and externally. There will be a temperature gradient between the temperature of system and reservoir. As consequence, the Fourier's conduction law is needed to linked both temperatures.

According to the theory, Stirling engine has the capability to reach Carnot's efficiency in ideal condition, where Curzon Ahlborn efficiency as the model of endoreversible Carnot is not as efficient as the Carnot ideal model. This information could be a stepping stone for Stirling engine in the closer exploration to the quantum regime. Moreover, Stirling engine is considered to be superior among the engines due to its internal combustion unlikely any other conventional engine such as Otto and Diesel, which using direct combustion. This indirect combustion of Stirling engine only relies in heat transferred and makes it compatible for the quantum systems, where energy illegally exchange with the environment yet no particle exchange. Another key advance of the Stirling engine is the ability to incorporate the regeneration process, which is not possessed by other engines. During the operation, the heat produced by heating process is retained temporarily instead of disposing it into the environment. The heat is redirecting to the system and keep it in a particular element called regenerator. After the first cycle done, the heat is restoring back to the system in the next cycle, in order to reducing the heat supply from the hot reservoir. At the end, this process is capable to reduce energy waste and improve thermal efficiency. As realization, quantum Stirling engine examines flexibility in expressing the performance in finite time while using endoreversible model. It aligns well to involve in experimental essential, especially with particle trapped in general potential. This standpoint enables quantum Stirling engine to provides a strong justification, in order to understand the fundamental explorations of efficiency and power from the vision of quantum regime.

Quantum particles have a crucial role comprehending to the nature of energy and the process that take place when thermodynamics system is functioning in quantum level. Particles like boson and fermion exhibit distinct behavior within the system. Boson follows the Bose-Einstein statistic and has integer spin (0, 1, 2, 3, …) which makes it possible for some particles to be located in the same quantum condition. In the other hand, fermion follows the Fermi-Dirac statistic and has half integer spin (1/2, 3/2, 5/2, …) which makes it not possible to be located in the same quantum condition due to Pauli exclusion principle. Hence, the symmetrical characteristic has made Boson to dominated collective behavior which highly coherent, even though in an extremely low temperature. Consequently, it can be condensed to the ground state, as known as the Bose-Einstein Condensate (BEC). The new research explains an ultracold atom cloud based on quantum engine can be utilized on the properties of Bose-Einstein

Condensate (BEC) which can improve the efficiency of the thermodynamics cycle using Bose gas in 3D generic law potential effected the performance of the quantum heat engine (Koch et al., 2023). The 3D generic law potential is used to connect the microscopic with macroscopic properties to simplify the calculations.

Zettira (2023) studied an engine using two approaches, quasistatic and endoreversible cycle where in the quasistatic cycle it takes an infinite amount of time to reach thermal equilibrium, whereas in endoreversible cycle lasts for a finite amount of time. Sutantyo (2024) has deliberate about the partial thermalized quantum heat engine using Bose-Einstein Condensate (BEC) as working substance. Chatterjee (2021), examined Stirling engine using particle in infinite potential box as the working medium to show the efficiency at given frequency can be maximized the specific ratio of temperature for thermal reservoir. By implementing Bose-Einstein Condensate (BEC) into quantum Stirling engine could be much more powerful to enhance the efficiency of heat engine based on previous researches where Bose-Einstein Condensate (BEC) has proved to optimized the performance of heat engine.

Corresponding to previous studies, this research is using Bose-Einstein Condensate as working substance in 3D generic law potential to explore the efficiency of Stirling engine using endoreversible model. The physical world is represented by the 3D generic law potential which guarantees more realistic in practical and physical order. Boson has the capability to represent the working substance in quantum heat engine which allows transfer energy through an order of quantum excitation. At low temperature, Boson's collective behavior might impact the efficiency and performance of quantum heat engine which offers a strong basis for the creation of increasingly intricate models in the future.

1.2 Research Purpose

The purpose of this study is to develop a quantum Stirling engine using Bose-Einstein Condensate as working substance in 3D generic law potential; to determine how crucial the temperature and volume effected the efficiency; to perceive the effect of partial thermalization, and to formulated the expression of pressure, work, efficiency, and power output of quantum Stirling engine with endoreversible cycle.

1.3 Research Benefits

The model of quantum heat engine in this research hopefully has the ability to be a guidance for the development of enhance quantum Stirling engine and capable to be the comparison and foundation for further research.

1.4 Research Scope and Limitation

In order to avoid prevent expand of the study, this research will be focused on some following problems.

1. The thermodynamics cycle is using endoreversible Stirling cycle.
2. Boson particles used to generate the phenomenon of Bose-Einstein Condensate (BEC)
3. Boson particle is trapped in 3D generic law potential.
4. Modelling visualization and numerical calculations performed with *Mathematica 13.0*.