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THERMODYNAMIC AND SUSTAINABILITY ANALYSIS OF AN ORGANIC RANKINE CYCLE SYSTEM FOR TURBOFAN ENGINE

NUR ATHIRAH BINTI MOHD NASIR

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By

NUR ATHIRAH BINTI MOHD NASIR

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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July 2020

Chair : Syamimi Saadon, PhD
Faculty : Engineering

With the advancement of aviation industry, the use of energy has increased and its environmental consequences have become more significant. The energy efficiency of the aircraft has been the major interest to restrain the energy consumption increment. Since the energy prices are rising worldwide, the idea of increasing energy efficiency is a continuous challenge for the industry. This is the reason why waste heat recovery (WHR) process is chosen to improve the energy efficiency of aircraft engine. By reusing this waste heat from the engine, the fuel consumption was reduced. Due to its unique features, Organic Rankine Cycle (ORC) is a powerful potential for this purpose. This thesis focused on the analysis of the Organic Rankine Cycle (ORC) from thermodynamics and sustainability aspects. The performance analysis was divided into two conditions of fluid which were subcritical and supercritical by including preheater or superheater. The new ORC system was then integrated to an aircraft turbofan engine. For a set of values of the initial parameters, the thermodynamic cycle of the system was solved in the MATLAB software to attain the net power output, thermal efficiency and the mass flow rate of working fluid. The integration of ORC to a turbofan engine was performed and the Thrust-Specific Fuel Consumption (TSFC) along with the fuel burn were evaluated. From the results, it was noted that a better fuel consumption could be accomplished by applying the ORC system to the turbofan engine with the aid of superheater at both subcritical and supercritical conditions which were noted as Case B and Case D. Taking into account the extra weight that can be added to the engine, the fuel burn reduction were 7.68% for Case B and 10.74% for Case D. The exergetic sustainability index has emerged to be a crucial method in determining the sustainability of a system. From this study, the two best cases, Case B and Case D demonstrated exceptional exergetic sustainability index at 0.474 and 0.470 respectively. The greater the value of sustainability index, the better it is for the practical applications. Both of the cases B and D showed a percentage improvement of 2.16% and 1.29% respectively compared to the turbofan engine without ORC system. By

analyzing the thermodynamic performance and sustainability index of the system, this research indicated that ORC as waste heat recovery system is compatible and beneficial to the turbofan engine, as it improves the engine's fuel consumption and overall performance.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

ANALISIS TERMODINAMIK DAN KEMAMPANAN KITARAN RANKINE ORGANIK UNTUK ENJIN TURBOFAN

Oleh

NUR ATHIRAH BINTI MOHD NASIR

Julai 2020

Pengerusi : Syamimi Saadon, PhD
Fakulti : Kejuruteraan

Seiring dengan kepesatan industri penerbangan, penggunaan tenaga meningkat dan juga kesannya kepada alam sekitar lebih ketara. Kecekapan tenaga pesawat menjadi keutamaan dalam mengekang kenaikan penggunaan tenaga. Memandangkan berlakunya peningkatan harga tenaga di seluruh dunia, cadangan untuk meningkatkan kecekapan tenaga adalah cabaran berterusan bagi industry penerbangan. Oleh itu, pemulihan haba sisa (WHR) adalah penting bagi meningkatkan kecekapan tenaga enjin pesawat. Dengan menggunakan semulasumber haba dari enjin ini, penggunaan bahan api dapat dikurangkan. Disebabkan oleh ciri-ciri uniknya, Kitaran Rankine Organik (ORC) berpotensi tinggi untuk tujuan ini. Tesis ini bertujuan untuk menganalisis Kitaran Rankine Organik (ORC) dari aspek termodinamik dan kemampanan. Subkritikal dan superkritikal adalah dua keadaan yang dikaji dengan cara memasukkan prapemanas atau pemanas lanjut. Sistem Kitaran Rankine Organik yang baru diintegrasikan kepada enjin turbofan pesawat. Bagi satu set nilai untuk parameter awal, kitaran sistem termodinamik diselesaikan menggunakan perisian MATLAB untuk mencapai hasil kuasa bersih, kecekapan haba dan kadar jisim bendalir bekerja. Integrasi antara enjin turbofan dan sistem ORC telah dilaksanakan dan Penggunaan Bahan Api Khusus Tujahan (TSFC) bersama-sama dengan bahan api terbakar telah dinilai. Kesimpulannya, penggunaan bahan api yang lebih baik boleh dicapai dengan menggunakan sistem ORC bersama enjin turbofan dengan bantuan pemanas lanjut dalam kedua-dua keadaan iaitu subkritikal dan superkritikal yang diklasifikasikan sebagai Kes B dan Kes D. Mengambilkira berat tambahan yang ditambah kepada enjin, pengurangan pembakaran bahan api adalah sebanyak 7.68% untuk subkritikal, Kes B dan 10.74% untuk superkritikal, Kes D. Indeks kemampanan eksergi telah muncul sebagai kaedah penting untuk menentukan kemampanan sistem. Daripada kajian ini, kedua-dua kes terbaik iaitu Kes B dan Kes D menunjukkan indeks kemampanan bertenaga yang luar biasa masing-masing pada 0.474 dan 0.470. Jika nilai indeks kemampanan semakin tinggi, maka aplikasi praktikal akan menjadi lebih baik. Kedua-dua

Kes B dan D menunjukkan peningkatan peratusan sebanyak 2.16% dan 1.29% berbanding enjin turbofan tanpa sistem ORC. Dengan menganalisa prestasi termodinamik dan indeks kemampanan sistem, kajian ini membuktikan bahawa ORC sebagai sistem pemulihan haba sisa adalah bersesuaian dan bermanfaat kepada enjin turbofan, kerana ia memperbaiki penggunaan minyak enjin dan keseluruhan prestasi enjin.

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This thesis is dedicated to my husband, my daughter and both of my families, who have been there during my struggles, who always believe in me and give their endless support. Thank you for making who I am.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Syamimi Saadon, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abd. Rahim Abu Talib, PhD
Professor Ir. Ts.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____
ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

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LIST OF ABBREVIATIONS

A	area (m^2)
C	heat capacity rate (kJ/(K.s))
C_p	specific heat capacity (kJ/(kg.K))
ch	chemical
cond	condenser
cri	critical
CO_2	Carbon Dioxide
CC	combustion chamber
en	energy
evap	evaporator
ex	specific exergy (kJ/kg)
exh	exhaust
exp	Expander / turbine
$\dot{E}_x$	exergy (MW)
$\dot{F}$	fuel exergy (MW)
h	enthalpy (kJ/kg)
hf	Hot fluid
HPC	high pressure compressor
HPT	high pressure turbine
HV_{fuel}	fuel heating value (kJ/kg)
i	Component point

ICE	Internal combustion engine
in	inlet
IP_i	exergetic improvement potential (%)
LPT	low pressure turbine
$\dot{m}$	mass flow rate (kg/s)
max	maximum
min	minimum
NTU	number of heat transfer unit
ORC	Organic Rankine Cycle
OTEC	Ocean Thermal Energy Conversion
out	outlet
P	pressure (MPa)
$\dot{P}$	product exergy (MW)
ph	physical
R	gas constant (J/(mol.K))
r_{eef}	environmental effect factor
r_{re}	recoverable exergy
s	entropy (kJ/kg.K)
sup	superheater
T	Temperature (K)
$\dot{T}$	Thrust power (kN)
TSFC	Thrust Specific Fuel Consumption (g/(kN.s))

U	Overall heat transfer coefficient (W/(m^2.K))
UAV	Unmanned Aerial Vehicle
UPM	Universiti Putra Malaysia
V	Speed (m/s)
wf	Working fluid
WHR	Waste Heat Recovery
W	Power (kW)
X	Mole fraction
i	segment
ε	effectiveness
η	efficiency
θ_{esi}	Exergetic sustainability index
γ	Specific heat ratio
0	Ambient condition

CHAPTER 1

INTRODUCTION

Overview

Nowadays, the engineering industries are demanding to decrease the emissions of greenhouse gas and enhance the efficiency of the sites. This is due to the increasing in fuel prices along with the rising concern on the global warming. Therefore, the waste heat recovery is identified as one of the approaches to solve the matter of energy savings. Here, the proposed waste heat recovery method is the Organic Rankine Cycle (ORC). As an overview, the waste heat recovery concept and its advantages will be first introduced, including some examples which are currently being developed by research across the globe. Then, to ensure the sustainability of the proposed waste heat recovery method, the system will be evaluated through an exergy analysis, which will be briefly at the end of the chapter.

1.1 Research Background

1.1.1 Energy and Environment

In general, one third of energy consumption is charged to the industrial sector, including more than fifty percent eventually wasted as heat [1]. The waste heat is hard to be detected and evaluated in the areas of quality and quantity, as it is not clearly noticeable as material waste. Due to the responsibility for the global energy interests and in opposition to the rising consumption and decreasing energy-rich fossil-based fuels, the future aims to contribute to energy price increment.

In conjunction with the interest in this energy saving issue, the Waste Heat Recovery method has been introduced. Fundamentally, the concept of energy recovery is that the energy is never consumed, but it is being transformed into another form where it is exploiting as an energy supply.

Waste heat is described as the unused heat generated during the phase of chemical reaction or combustion process that is drained into the atmosphere instantaneously. There are a lot of benefits of a conversion of exhaust heat into useful power such as enhancing fuel consumptions, improving engine power density, further decreasing carbon dioxide (CO_2) and other harmful exhaust emissions subsequently.

Waste heat can be dismissed at unspecific temperature. Typically, the quality of waste heat recovery increases when the temperature increases. Therefore, it is crucial to classify the greatest quantity of recoverable waste heat from a process and to obtain the greatest efficiency of the system of waste heat recovery.

The advantages of the waste heat recovery are as follows:

I. Decreases energy costs

This is because the purchased energy instantly restored by waste heat that have been recovered.

II. Decreases capital equipment costs and operating costs

The heat recovery cost can be saved because it requires smaller energy conversion equipment capacity.

III. Decreases environmental impact

Since the waste heat recovery instantaneously restores purchased energy, the environmental impact on water and air can be decreased.

IV. Decreases Green House Gas (GHG) emissions

This process helps to decrease the emission of GHG related to industrial operation.

Table 1.1 below shows the type of waste heat recovery along with the temperature and examples:

Table 1.1: The types of waste heat recovery

Types of waste heat recovery	**Temperature (℃)**	**Examples**
Low grade	< 100	Bricks and ceramics industries glass, iron and steel, nonferrous metals.
Medium grade	100 – 400	Food and drink and other process industries, building utilities and chemicals
High grade	> 400	Hot water system and ventilation

Most of the heat is recovered from and passed to material in a gas or liquid phase due to its difficulty to recover heat from solid materials. Hence, the temperature and material phase play important roles when selecting the heat exchanger.

With the advancement of aviation industry, the energy use and environmental consequences have increased. The energy efficiency of the aircraft has been the major interest to restrain the energy consumption increment. Aircraft designers and engineers have taken steps to increase fuel efficiency by modifying aircraft structures and fuel types. The reduction in fuel usage gives advantages to the economy and also helps to improve the environment.

Since the energy prices are rising worldwide, the concept of rising energy efficiency is a continuous challenge for industry. By 2030, in conjunction with the National Transformation 2050, the National Green Technology Master Plan (GTMP) intends to decrease the CO2 emissions to 192.3 million tonnes eq/year. This is the reason why waste heat recovery (WHR) is significantly improves heating efficiency by reusing this heat sources, which resulting in lower fuel used. Due to its unique features, Organic Rankine Cycle (ORC) is a powerful potential for this purpose.

1.1.2 Organic Rankine Cycle

One form of WHR, the Organic Rankine cycle, operates on the Rankine Cycle theory, where a working fluid is rotated through four basic parts in a closed-loop system. This enables the waste heat to convert into mechanical or electrical power. While ORC has many limitations, like the fluids used in ORC cycle are flammable, and in the case of leakage, an environmental issue could occur, and despite that ORCs are more costly, compared to the steam cycle, the use of organic fluids over water adds a number of benefits to the system. Based on their thermophysical characteristics, such as low boiling temperature, low critical point, and high molecular mass, the probability of turning low temperature heat into usable electrical energy is high and can be effective. Below shows the advantages of the ORC system:

- Conducive to apply in lower temperature
- Does not require operators due to its compatibility and automated
- The flexibility of the design with the alternative to exploit the mostproductive working fluid available
- The correlated costs are low
- The simplicity and reliability of system maintenance
- Less heat is needed during the evaporation process
- The evaporation process takes place at lower pressure and temperature

There are four basic components of Rankine Cycle which are working fluid pump, a condenser, an evaporator, and a turbine as illustrated in Figure 1.1.

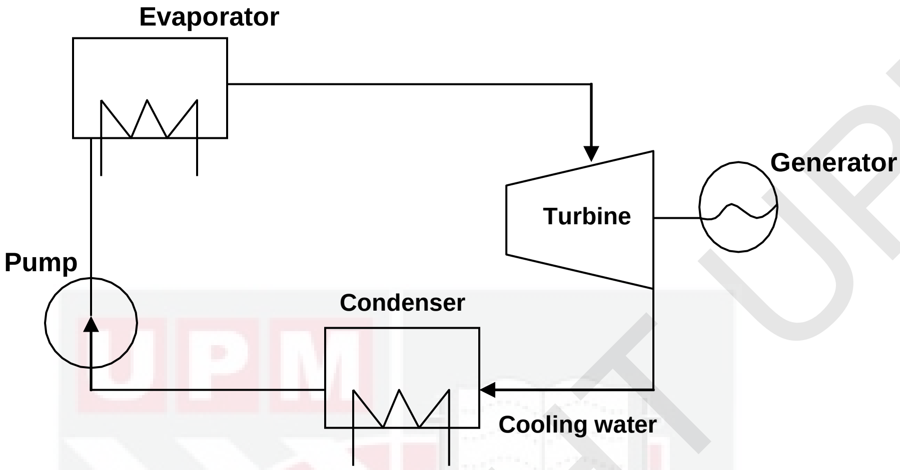

Figure 1.1: The schematic diagram of ORC

Figure 1.1 shows the process of Organic Rankine Cycle. The cycle begins from the condenser where the liquid organic working fluid is pumped into the evaporator and then it is transformed into saturated or superheated vapor. Then, the organic vapor expands in the turbine to generate power. Afterwards, the generator converted the power into electricity. Then, in condenser, the exhaust gas from the turbine is condensed to liquid through cooling water to start the process again.

In subcritical ORC, the saturated working fluid is stimulated to the heat exchanger. Here, it is heated, vaporized, even superheated by a heat source. Then, the vapor at saturated or superheated state is passed into the turbine linked with an electrical generator, where the electricity is produced. At the turbine exit, the working fluid is cooled down and condensed by a heated sink in the condenser before entering the pump to complete and start again the cycle.

In supercritical ORC, the vapor is expanded in the turbine at saturated or slightly superheated condition. In spite of that, the study of supercritical fluid parameters is crucial. Higher efficiencies have been demonstrated to be more attractive for waste heat applications [2].

At the exit of the condenser, the working fluid is directly pumped from saturated liquid to the supercritical pressure. Then, the heating process is performed in the higher temperature heat exchanger by heat absorption of working fluid from the heat source. In contrast to subcritical ORC, the healing process does not pass- through two-phase region. This results in a better thermal match in the heat exchanger with lower irreversibility.

In jet engine application, the ORC system is applied in between the low-pressure turbine and exhaust nozzle. The hot fluid from the exhaust nozzle will act as the heat source for this model and will exchange heat with the working fluid of the ORC which act as the cold fluid. The proposed idea of the implementation is using a small-scale ORC model for about 408 kg [3]. Here, the ORC is said to be the most promising solution due to its possibility to recover the engine's exhaust heat and reuse it to produce useful power.

1.1.3 Sustainability Analysis

As mentioned in the beginning of this chapter, due to the concern of sustainability of this waste heat recovery system, the ORC with the system integrated will be evaluated through an analysis based on their exergy performance.

Exergy analysis is a feasible approach to measure the worthiness of energy conversion or distribution process and system. The energy conversion system performance cannot be assessed precisely and efficiently with only an energy analysis. Hence, this exergy analysis will lead to enhance the energy analysis.

Exergy analysis identifies accurately the margin available to design more efficient energy systems by reducing inefficiencies. Many engineers and scientists suggest that the thermodynamic performance is best evaluated using exergy analysis because it provides more insights and is more useful in efficiency improvement efforts than energy analysis.

1.2 Problem Statement

The growth of the world's population has led to the increasing consumption of primary fossil fuels and extensive dismiss of pollutants which eventually the extending energy demands. Therefore, the energy shortfall and environmental destruction are the primary concerns that the world must face. It gives impact to the industries which waste a huge amount of energy. Recently, for these justifications, the consciousness of reusing the low and medium temperature heat sources has captivated many studies around the world.

With the advancement of aviation industry, the energy use and environmental consequences have increased. The energy efficiency of the aircraft has been the major interest to restrain the energy consumption increment. Aircraft designers and engineers have taken steps to increase fuel efficiency by modifying aircraft structures and fuel types. The reduction in fuel usage gives advantages to the economy and also helps to improve the environment. The Organic Rankine Cycle (ORC) is a powerful candidate to recover the waste heat from the turbofan engine core jet exhaust and uses it to produce electrical power due to its benefits.

However, according to some researchers, in order to allow more waste heat to be extracted, the performance of ORC has to be further improved. Therefore, to increase the output power produced by the ORC, research has to be done. For an aircraft engine, the main objective is not only to generate power, but also to reduce a considerable amount of fuel consumption.

One of the approaches to enhance this power and ultimately the engine's fuel consumption is to include extra heat exchanger device and to find this heat exchanger's best design configuration capability in the ORC system. Some of the studies done by previous researchers did not measure the additional fuel consumption due to the additional weight of the waste heat recovery units. There were also studies that perform work only with the additional preheater. Hence, the net power output is insufficient.

Another concern that may require to be discussed is that organic fluid mass flow rate used is normally higher than the mass flow rate of water or steam Rankine cycle. This will trigger the ORC to have a larger feed pump. This is why the analysis of supercritical fluid parameters is crucial. It is proven to perform higher efficiencies which are more attractive for waste heat application. In supercritical condition, the ORC thermal efficiency could be improved by 10-30% due to the increasing specific work output, since the heat is added to the working fluid at supercritical pressure [4- 6]. As a result, the loss in exergy will eventually become lower. However, the challenge lies in the unpredictable process of heat transfer in the evaporator since the properties of the fluid are variable to the temperature. Many researchers have done comprehensive work to boost the ORC's performance. Even so, the ORC design areas of additional heat exchangers and the use of organic fluids in supercritical condition have not yet been investigated and this part is the crucial elements of a waste heat recovery system to enhance the power output.

Lastly, based on previous studies, the main problem that causes loss of exergy in aircraft engine is found within the combustion chamber and exhaust nozzle and these parts have the highest improvement potential rate among all the core engine's components. However, the area related to the improvement of the exhaust nozzle component and the evaluation of aircraft engine's sustainability based on exergy are still very lacking.

1.3 Hypothesis

The addition of the heat exchangers is expected to increase the power output thus aiding the turbofan engine to further recover waste heat and produce greater power than a simple ORC system. Due to increase in power output, the mass flow rate of ORC is affected. Working fluid in supercritical condition needs lower mass flow rate compared to in a subcritical condition. Thus, it is expected that less feed pump is needed when using supercritical fluid.

1.4 Research Objectives

- To analyze power output and efficiency of ORC by using preheater and superheater with subcritical and supercritical fluid.
- To investigate the effect of integrating ORC to a turbofan engine fuel consumption by calculating the Thrust-Specific Fuel Consumption.
- To evaluate the sustainability of waste heat recovery system using ORC by sustainability index analysis.

1.5 Research Questions

- What is the best technique of design configuration of heat exchanger in the ORC
- What is the effect of integrating ORC to the turbofan engine performance?
- How does this novel condition of ORC help the turbofan engine to generate more power and be sustainable for environment?

1.6 Scope of the Study

The crucial issues that the world must deal with are the energy shortage and the environmental deterioration. One of the factors comes from the transport sectors. The main focus in this study is on the airspace applications, specifically the civil aviation industry. The selected case study is the CFM56-7B27 turbofan engine which focused on the exhaust nozzle.

The study begins with the development of the Organic Rankine Cycle mathematical model and the data will be written in MATLAB programming. The thermodynamic analysis is done based on two main approaches, the energy analysis and the sustainability analysis. The performance analysis is divided into subcritical and supercritical conditions with the additional preheater and superheater.

The analysis tried to explore the heat transfer throughout the evaporator for the purpose of determining the ORC output power, and thermal efficiency, as well as the mass flow rate of the working fluid. Here, the effect of additional preheater or superheater to the ORC system is identified.

Finally, the ORC system will be integrated to turbofan engine performance by evaluating the Thrust-Specific Fuel Consumption (TSFC) as well as fuel burn. The sustainability analysis will be performed to ensure the waste heat recovery system using ORC gives better power output that can contribute to the environment and boost expansion of Malaysia's green technology sector.

1.7 Thesis Structure

Chapter 1 consists of the research background on the energy and environment, with the introduction of Waste Heat Recovery (WHR) along with its concept. Then, the ORC has been proposed as the WHR method that will be applied in this study. It includes the working principle. Besides that, there is also the introduction of the sustainability analysis. At the end of this chapter, the problem statements, research objectives, research questions, scope of the study and thesis structure are presented.

Chapter 2 represents the literature review from the previous researched which are related to ORC and sustainability analysis. The literature review includes the needs of WHR, the types of WHR, the applications of ORC from various fields, the optimization of ORC, and the sustainability analysis from previous studies. The summary of the literature review shows the parameters that will be used as the guidelines for this research.

Chapter 3 explains further the methods of doing this research. Firstly, it started with the flow chart of the research, followed by the introduction of the types of heat exchanger that will be used and also the types of ORC system along with the type of turbofan engine. Moreover, the calculating procedure of ORC is also presented in this chapter, together with the equations and parameters for energy analysis. For the sustainability analysis, the equations and parameters are also presented at the end of the chapters.

Chapter 4 shows the results of numerical solution for ORC system which have been validated with the previous studies. There are 4 cases studied in this research, with 2 conditions, which are subcritical and supercritical conditions. After the model is validated and verified, the results represented the variations of exhaust heat temperature against net power output, system thermal efficiency and mass flow rates of working fluids for 4 cases.

Chapter 5 shows the results of the sustainability analysis for the ORC system after integrated to turbofan engine. The results include the exergy efficiency, exergy destruction, improvement potential, recoverable exergy, environmental effect factor and exergetic sustainability.

Chapter 6 shows the conclusion and the recommendation for future work.

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