COMPARATIVE PERFORMANCE ANALYSIS OF SELECTED WORKING FLUIDS IN A LOW TEMPERATURE ORGANIC RANKINE CYCLE FOR WASTE HEAT RECOVERY APPLICATION.

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CERTIFICATION

This is to certify that COMPARATIVE PERFORMANCE ANALYSIS OF SELECTED WORKING FLUIDS IN A LOW TEMPERATURE ORGANIC RANKINE CYCLE FOR WASTE HEAT RECOVERY APPLICATION was carried out by **BENAYEI CLEMENT**, **JOSEPH A. ESHIOLESE**, and **OGHENEVWEDE F. AVWEROSOUGHENE** in the Department of Mechanical Engineering, Faculty of Engineering, University of Benin, Benin City.

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DEDICATION

This project work is dedicated to God Almighty who made everything possible. To God be the glory for His infinite mercy and giver of wisdom. We would like to thank our parents for their undying love, support and care.

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We would like to take this opportunity to acknowledge our project supervisor, Prof. O.O. IGHODARO who in his fatherly position gave us guidance and corrected every possible mistake, before completing this project. With gratitude in our heart, we say thank you sir.

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ABSTRACT

Comparative Performance analysis of Selected Working Fluids in a low temperature organic Rankine Cycle for Waste Heat recovery Application.

The global imperative to improve energy efficiency necessitates the effective recovery of low-grade waste heat, a challenge perfectly addressed by the organic Rankine Cycle (ORC) technology. This project undertakes a comprehensive comparative analysis of selected candidate organic working fluids – including Ethanol, Toluene, Cyclopentane, R245fa, R1233zd(E) and R152a, drawn from the categories of dry, wet and isentropic fluids, within a low-temperature ORC system designed for industrial waste heat recovery. The primary goal is to identify the optimal fluid that maximizes thermodynamic performance under a specified heat source temperature (e.g 206^{0}C to 123.7^{0}C).

A thermodynamic model was developed to simulate the cycle's performance. The selected fluids are evaluated against key metrics such as network and thermal efficiency.

Initial simulation results reveal significant variability in cycle performance, depending on the fluid's critical temperature, boiling point and condensation temperatures and pressures.

The findings provide a data driven basis for selecting a working fluid that not only achieves higher power generation but also minimizes system's complexity and investment cost, thereby accelerating the deployment of sustainable low temperature waste heat recovery systems.

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CHAPTER ONE

INTRODUCTION

1.1 Background

The population of the world has been on a constant and continuous increase which has led to increase in the demand of electrical energy. It is also imperative to significantly look at the environmental impact as in the case of global warming and the world carefully discuss on the possible torture it will impose on to humanity if not properly handled and has otherwise being a topic of debate for decades. Renewable energy technologies need to be developed and this concept requires new technology.

There are a lot of sectors that need energy for one purpose or the other and in the cause of energy consumption, there is ever an even unavoidable occurrence of waste heat dissipation. This wasted heat comes at varying thermal temperatures. The industrial waste heat absolutely has a temperature high enough that enable the direct delivery to the district heat grid. The profitability and undeniable competition in line with high electricity thus, this available waste heat has woken up an old technology. This technology is based on converting industrial waste heat into electrical energy with an attractive payback price. This new approach gives birth to the Organic Rankine Cycle. The wasted heat is used to heat up organic working fluids. Majority of these organic working fluid such as ethanol, cyclohexane, R245fa, R1233zd(E), R152a have their boiling points lower than water and can be easily evaporated at low temperatures. This evaporated working fluid is then expanded in a turbine where the turbine drives an electric generating generator.

The reliance on primary energy source like the fossil fuel for over the years has ever being on an exponential rise due to modernization and technology. The severe impact on the environment as a result of the end use of electric power by heavy industries, conventional and residential buildings has scale up to a tremendous increase.

Many west African countries like Nigeria, organizes its energy mix around energy sources that are abundant within its boundaries. Hydropower and gas fired power plants have been the predominant energy mix in Africa's most populous country. Hydro is largely seen as clean means of power generation. On the other hand, gas has been given green credentials by the European Union due to the less polluting nature than coal and since labeled a transition fuel. The grid emission factor of the power generating systems in Nigeria is based on the energy source are in relatively good stead.

The power generating plants connected to the national grid in Nigeria with different installation capacity are 23 in number. The installed capacity is 10396MW and available capacity of 6056MW. Of this, gas powered plants accounts for 8457MW with available capacity 4966MW while the rest is hydropower with installed capacity of 1038.4MW and available capacity of 1060MW. A great deal of the country's power generation is ideally gas fired.

Generation of electricity carried out from the primary energy sources fossil fuel through numerous ways, and one of it, the most common way of harvesting electrical energy from thermal energy is vapour power cycle.

Table 1.1: Top Six Thermal Power Plants in Operation in Nigeria

POWER PLANTS	LOCATION	CAPACITY
Egbin thermal power station	Lagos	1320MW
Sapele power plant	Delta	720MW

Ughelli power plant	Delta	964.68MW
Alaoji power plant	Abia	1074MW
Afam power station	Rivers	987.20MW
Olorunsogo II power plant	Ogun	750MW

The vapour power cycles are actually classified into steam engines and power plants. The steam engines are mobile while the power plants are stationary. Thus, the generation of electric power by using the vapour power cycles is largely driven by non-renewable energy sources. Talking about the vapour power cycles, the ideal cycle is the Rankine cycle. The Rankine cycle is the main cycle that converts heat energy into electrical and it is used to drive all vapour power machines. But, due to the current hot debates on the negative impacts to the environment by the continuous use of the fossil fuel, the use of low-grade heat sources are considered in this study. The low-grade heat sources are renewable and in higher energy consuming countries. These energy sources such geothermal, biomass or solar are largely carried out. Therefore, the vapour power cycle that uses low grade heat to produce heat energy along with organic working fluids is the Organic Rankine Cycle. The ORC study in this project is slightly different from the conventional Rankine cycle that uses water as its working fluid but, through the Rankine Cycle, ORC is studied.

In the design of power systems that low temperature heat source, there is need for a working fluid that will transfer the energy gained from either the combustion of fossil fuel, renewable energy sources or heat sources into useful work. The Rankine Cycle uses water that has low molecular mass (18kg/kmol) but a higher boiling point(100^{0}C) as its working fluid while the Organic Rankine Cycle makes use of working fluids that have lower boiling points but, higher molecular mass. Example of some as organic working fluids are toluene, cyclohexane, cyclopentane, R245fa, R1233zd(E), R152a, R143a, R22, R134a etc.

1.2 Problem Statement

The boiling point of water is 100^{0}C and is heated up to its vapour phase by using a high-grade heat source. The heated water is passed through the boiler for turbine power generation. The selection criterion of water as a working fluid for vapour power cycle is based on some factors. It is chemically inert, abundant in earth, not prone to attacking the pumps, pipes, turbine blades, or other equipment. Because water needs high grade heat source to vapourize, it becomes a thing of concern as it cannot be heated up to vapour phase by low grade heat sources, hence the need for Organic Rankine Cycle with working fluid that a low-grade heat source can easily vapourize. These ORC working fluids have high molecular mass and low boiling point. The selection criterion for the proper organic working fluids is significant and it is the main objective. For instance, R245fa, R1233zd(E) and toluene are types of organic working fluids. The thermophysical properties for the ORC working fluids are density, latent heat of vaporization, specific heat capacity, thermal conductivity, specific volume, molecular mass, normal boiling point, critical temperature, critical pressure.

In this project we also consider mechanical parameters like work net, efficiency and back work ratio for better performance evaluation for the selected ORC working fluids.

1.3 Purpose of the study

The core purpose of this project can be broken down into these key aspects:

1. Waste Heat utilization: to effectively utilize readily available low-grade waste heat, (e.g

from industrial processes) that would otherwise be rejected into the environment.

2. Performance optimization: To identify the specific working fluid that maximizes the net power output and thermal efficiency of the ORC system under fixed operating condition (e.g heat source temperature)
3. Informed selection: to offer a data driven recommendation for engineers and designers on the optimal working fluid selection for low – temperature ORC application, considering not only performance but also safety, environmental impact (GWP, ODP) and cost.

1.4 Aim of the project

The primary aim of this project is to evaluate and compare the thermodynamic and heat transfer performance of selected organic working fluids (e.g Ethanol, Toluene, Cyclopentane, R245fa, R1233zd (E) and R152a) in a low temperature organic Rankine cycle (ORC) designed to recover waste heat, ultimately identifying the optimal working fluid that maximizes the net power output and efficiency under specific heat source conditions.

1.5 Objectives

Replacement of water with high molecular mass working fluid, also known as organic working fluid, is the main approach being carried out in this project. Objective of this project is given below:

1. To select candidate working fluids from the three categories of dry, wet and isentropic fluids; based on criteria such as low boiling point, high critical temperature and environmental impact
2. To develop the thermodynamic model of the low temperature ORC system using Cool Prop library.
3. To perform the thermodynamic analysis of the fluids and compare their thermodynamic metrics in terms of network and efficiency.

1.6 Importance of ORC as a Project.

- **Waste Heat Recovery**:

ORC systems can recover waste heat from industrial processes, such as those in cement and metal plants, which would otherwise be lost. By converting this waste heat into electricity, ORCs can significantly improve the overall energy efficiency of industrial operations.

- **Renewable Energy Integration**:

ORCs can utilize heat from renewable sources like geothermal and solar thermal energy, which are often available at lower temperatures.

This allows for the decentralized and sustainable generation of power, especially in locations with limited access to conventional energy sources.

- **Low-Temperature Applications**:

ORCs are well-suited for utilizing heat sources at lower temperatures (e.g., below 150°C) compared to traditional steam Rankine cycles.

This expands the range of potential heat sources that can be used for power generation, including some geothermal and solar applications.

- **Small-Scale Power Generation**:

ORC systems can be designed for various power output levels, making them suitable for both large and small-scale power generation.

This flexibility allows for decentralized power generation, which can be particularly useful in remote areas or for specific industrial applications.

- **Environmental Benefits**:

ORCs can reduce reliance on fossil fuels by utilizing waste heat and renewable energy sources.

This can lead to lower greenhouse gas emissions and contribute to climate change mitigation efforts.

- **Economic Viability**:

ORC technology is becoming increasingly competitive, especially with advancements in working fluids and system design. The ability to utilize low-cost heat sources and the potential for modular designs make ORC systems economically attractive in various applications.

1.7 Scope of the study

This research project work on **Comparative Performance Analysis of Selected Working Fluids in Low Temperature Organic Rankine Cycle Waste Heat Recovery Application** is carried out by identifying and understanding the various classifications and types of the working fluids. The essence is to harnessed the industrial waste heat having a temperature as low as 206^0C as its source to the turbine temperature zone and to the condensing temperature of -40^0C. For easy evaluation, working fluids that have their boiling point greater than -53^0C are selected and they are classified into dry, isentropic and wet. Some dry fluids are: toluene, cyclopentane, cyclohexane, R600, R600a. isentropic fluids are: R1233zd (E), R245fa, while wet fluids are: ethanol, R152a and R143a etc.

CoolProp is a thermodynamic modelling software used for this project. Lastly, the selection of materials, performance of the heat transfer of either the evaporator or condenser, component configuration for the design of the power plant are not considered in this research work.

CHAPTER TWO

LITERATURE REVIEW

2.1. Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is a prototype of the original Rankine cycle. The Rankine cycle was invented by W. Rankine in the 1850's and is widely used for boiler steam power generation systems. The modification of the Rankine Cycle is done by the replacement of the working fluid – water to organic working fluids. The replacement becomes so imperative that the ORC system is operated at lower temperature heat source as compared to water. ORC working fluids are capable of producing higher thermal efficiencies despite the fact that the working fluid is at lower temperature than water. In the ORC system, the mass flow rate, the quantity of heat needed by the system, the power generated by the system the work net are some crucial properties that greatly influenced the thermal efficiency of system. The ideal ORC working fluid has a low boiling point that can easily vapourize at low heat source and low freezing point so that it will not become solid throughout the cycle.

The heat exchanger is better used as a machine for an ORC system to convert low temperature heat energy sources into electrical power instead of the boiler. One of the major advantages of ORC system is that virtually, it can exploit any external thermal energy sources with the temperature differences between the thermal sources and the sink ranging from -40^{0}C to 206^{0}C. After the invention of the steam cycle, the thought of organic working fluids instead of water gave birth. The idea remained plain until the second haft of the 20th Century. It was the research work carried out by Physicist, Harry Zvi Tabor and Engineer Lucien Bronicki that led to the construction of the first working ORC installation in 1961. The curiosity to harvest and convert more solar energy, a cycle suitable enough for recovering low temperature heat source was developed.

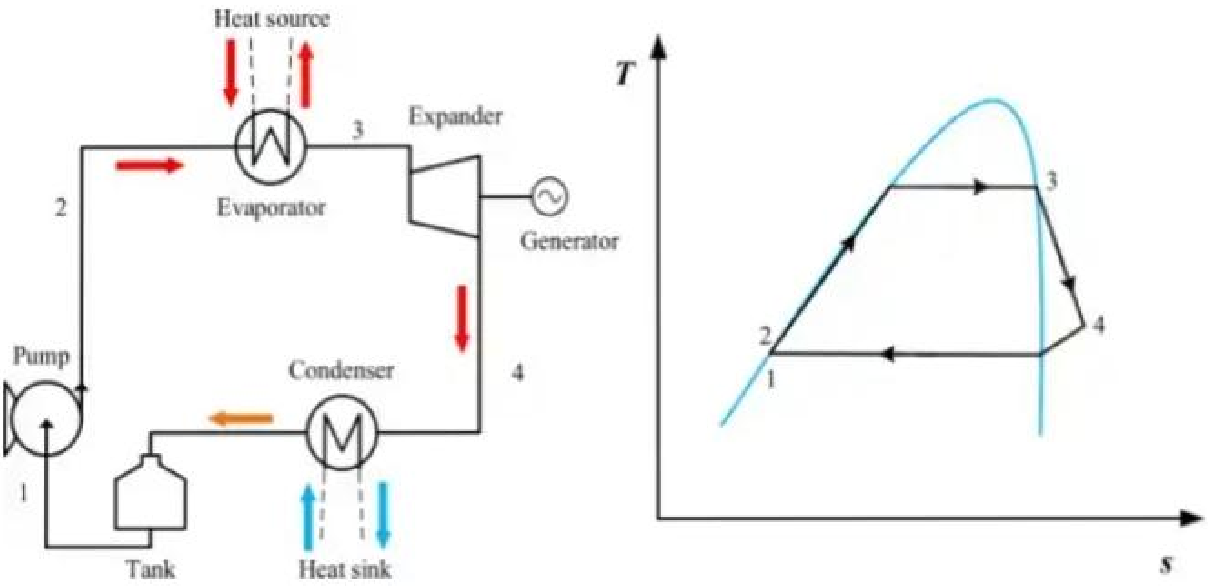


Fig.2.1. Block layout and T – s plot of a Simple Organic Rankine Cycle

2.2 Low Grade Heat Sources

The fossil fuel is one of the primary energy sources, that is of a great demand up till now. It is widely needed for the generation of electrical energy and heat energy for human activities. This research work examines the possibility of utilizing low temperature industrial waste heat resources as part of the sustainable energy supply to developing countries like Nigeria. Approach to low grade heat sources like industrial waste heat (cement industry), biomass, geothermal, solar energy, are explained and its usage in ORC are significant.

Apart from this, the industrial waste heat discharged PRESCO Plc, in Edo State during the vegetable oil refining is 206^0C is sufficient enough to set up ORC plant. It is a smaller scale system therefore; it is suitable for small scale demand. The ORC technology is cost effective and it is of a rapid increase due to its low carbon emission.

Besides that, solar energy is one of the vital sources used for ORC system. The primary of all energy, sun's energy, is extracted through solar system and has been common in nowadays world. Development of solar powered ORC has become significant and many modifications have been done. Low grade heat energy of below 300˚C is viable through ORC for generation of electrical energy.

Furthermore, recovery heat, waste heat is the best method of controlling excessive non-renewable energy usages. The demand for waste heat recovery is continuously growing under the rising commitment of the industry to reduce energy consumption, operational costs and carbon emissions. Stated that usage of waste heat recovery ORC has return of investment (ROI) 2 years less than conventional one. Development of waste recovery ORC that gives higher output power 2MW using medium temperature level 300˚C is manufactured by Siemens and is commercially used.

2.3 Working Fluids

The working fluids of an ORC systems are classified into dry, isentropic and wet and this clearly illustrated on the slope of saturated vapour curve on a T-s diagram, shown in Figure 2.2. As the gradient of the slope shows positive, it simply means the working fluid is dry, example is cyclopentane. If the gradient of the slope that gives approximate zero that is a vertical gradient, it is basically an isentropic fluid like R245fa and for negative gradient it is wet fluids like water. From our test, the result shows that with the usage of R1233zd(E) as the working fluid over a medium temperature range, 45.6kW of electrical power is generated. The working fluid must provide an adequate chemical stability in the desired temperature range.

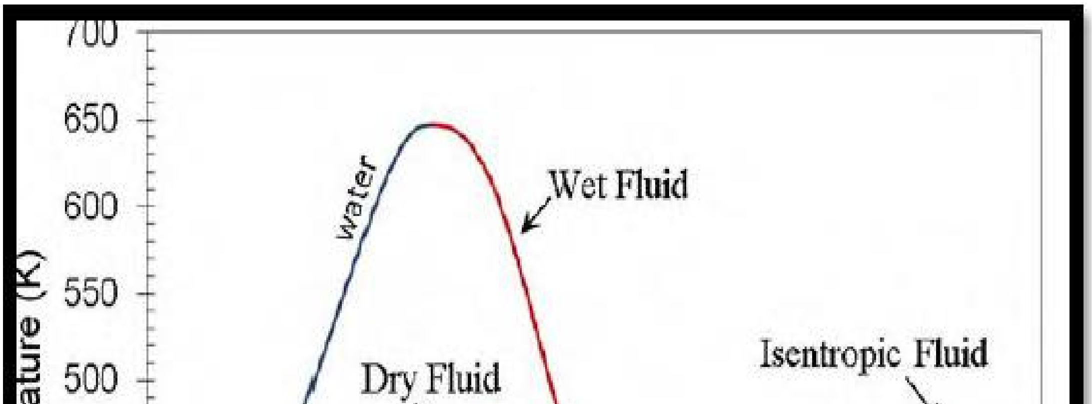


Figure 2.2: T-s diagram for Wet, Isentropic and Dry fluids.

The boiling point of most of the organic fluids are very low when compared to water as mentioned earlier in Problem Statement. This factor makes organic fluid need a lower heat source temperature to evaporate the ORC working fluid into the turbine inlet. Figure 2.3 below shows the T-s diagram for water and some organic working fluids for ORC. The positive and infinite slopes have enormous advantages for turbo machinery expanders. These working fluids leave the expander as superheated vapour and eliminate the corrosion risk in case of using turbo machinery expanders.

Furthermore, there is no need for overheating the vapour before entering the expander, and a smaller and cheaper heat exchanger can be used.

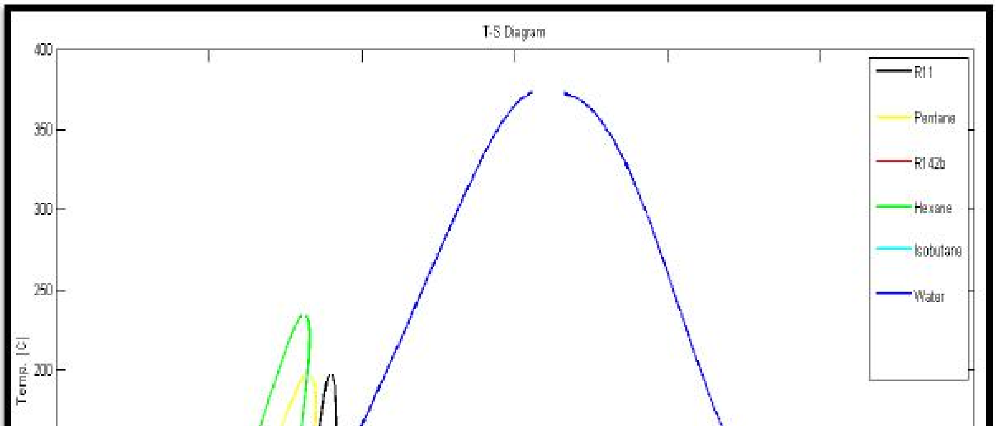


Figure 2.3: T-s diagram for water and some organic working fluids for ORC

There are several factors to consider when selecting working fluids. The low level of toxicity as a working fluid needs to be chosen. The compatibility with materials in contact and the chemical stability, Organic Rankine Cycle working fluids undergo chemical decomposition and deterioration at higher temperature. The maximum operating temperature must be limited as per stability is concerned. In addition to this, the boiling temperature of the ORC working fluids is also important. Given a very low boiling temperature requires a suitable condenser as it requires lower condenser temperature and high boiling temperature requires high heat input from boiler. Besides that, flash point criterium is vital, as higher flash point should be selected to avoid flammability. Apart from that, lower specific heat and higher latent heat should be selected for low load for the condenser and to raise efficiency of heat recovery. Ozone depletion potential (ODP), global warming potential (GWP) and atmospheric lifetime (ALT) factors, needed controlled at safe zone for environmental aspects of working fluids.

Table 2.1: Thermophysical properties of the selected ORC working fluids.

Working fluids	Toluene	Cyclo pentane	R245fa	R1233zd(E)	R-152a	Ethanol
Chemical formula	C_7H_8	C_5H_{16}	$C_3H_3F_5$	$C_4H_2F_6$	$C_2H_4F_2$	C_2H_5OH
Molecular mass (kg/kmol)	92.123	70.13	134.045	130.5	66.05	46.07
Critical temperature (°C)	318.60	238.57	154.1	166.6	113.3	240.8
Critical pressure (bar)	41.263	45.71	45.17	35.31	45.2	61.48
Normal boiling point	110.60	49.4	15.05	18.26	-24.02	78.4
Thermal stability (°C)	300	Appr. 300	250	270	250	300
Fluid type	Dry	Dry	Isentropic	Isentropic	Wet	Wet
ODP	0	n.a	0	0	0	0
GWP (100-year)	0	n.a	950	1	138	Low
Latent Heat of Vaporization (kJ/kg)	361.8	389	196	195.52	329.4	854
Density of fluid (kg/m^3)	862.2	751	5.718	1321.3	1013	789
Specific Heat	1.707	1.75	1.293	1.205	1.625	2.5

Capacity (KJ/kgK)						
Freezing Point ^{0}C	-95	-94	-107	-107	-117	-114.6

The table above shows some thermophysical properties of wet, isentropic dry ORC working fluids as listed in the scope of this project. The tabulated data is imported into this Final Year Project to ease the study on the selection of working fluids suitable for the ORC operation. Besides, CoolProp software, and sources from the internet were used to generate the thermophysical data for various refrigerants.

2.4 Characteristics of ORC Working Fluids for Low Temperature Sources

The chosen working fluids having different properties have a significant impact on the performance of the ORC. Ultimately appropriate thermodynamic properties can result in higher cycle performance and low cost. In other to achieve a successful ORC process, the ideal working fluid should have the following general characteristics.

- Small heat content (low enthalpy).
- Low heat latency.
- Low environmental impact.
- Non - flammable, corrosive or toxic.
- Inexpensive to avoid high overall system cost.
- High molecular weight.

High critical pressure and temperature to allow engine operating temperature to absorb all the heat available up to that temperature.

Low operating pressure to avoid danger of explosion or rupture and avoid negative impact on the reliability of the cycle.

Small specific volume of fluid in its gaseous state to avoid the need of large and costly turbines, evaporators and condensers.

Has higher pressure inside condenser to air inflow into the system.

The least toxic of fluids are the refrigerant and they also exhibit good material compatibility and stability limit. The fluids chosen as the subject of the work belong to the class refrigerants developed to have no Ozone Depletion Potential (ODP) and small Global Warming Potential (GWP). Also, they have thermodynamics properties that make them suitable for use with low temperature heat source.

2.5 Thermodynamics Analysis of the ORC Cycle.

An ORC can be depicted schematically in Fig. 2.4. The cycle is entirely in the sub – critical region of the T-S chart utilizing phase change heat transfer processes to both energy addition and rejection. The cycle consists of an evaporator (4-1) in which the energy from the industrial waste heat source is transferred to the ORC working fluid. The fluid leaves the evaporator in the dry saturated condition and enters the expansion device (1-2). The expansion process drives an electric generator. On leaving the expander, the fluid is fully condensed (2-3) leaving the condenser as a low temperature, low pressure liquid. It is then compressed to the evaporator pressure and the cycle is repeated.

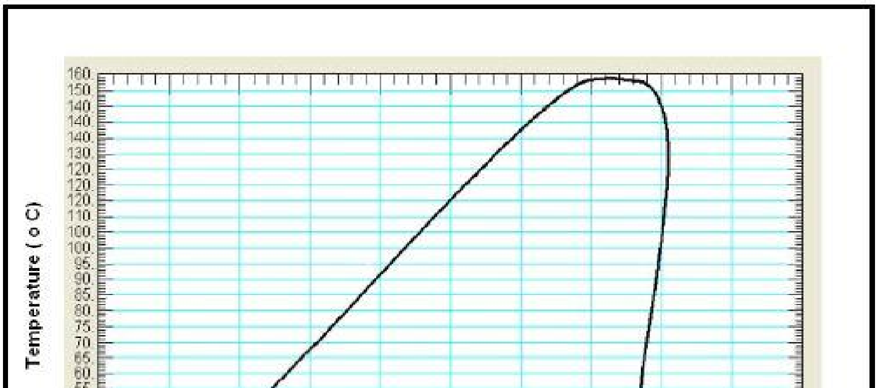


Fig. 2.4 T-s diagram for the ORC cycle.

1 → fluid state after the boiler and before the turbine.

2 → fluid state after the turbine.

3 → Fluid state after the condenser and before the pump.

4 → fluid state after the pump.

2.6 Previous Research.

In 1976, Patel and Doyle [5] recovered the exhaust waste heat of a Mack 676 diesel engine in a long-haul truck by an ORC using Fluorinol-50 as the working fluid. The operating temperature was between 650 °F (343.3 °C) at turbine inlet and 158 °F (70 °C) at condenser exit. They claimed a 13% increase in maximum power output along with a 15% improvement in fuel economy [1].

In 1985, Badr [6] documented a working fluid selection process for a Rankine cycle engine producing a low power (<10 kW) and operating between 40 °C and 120 °C. 67 prospective working fluids were evaluated, among which three superior candidates were R-11, R-113, and R114, while R-11 was identified to be unstable at temperature above 120 °C [1].

In 1995, Larjola [7] used an ORC with prototype high-speed oil free turbogenerator-feed pumps to recover heat from a 425 °C source. Among the several working fluids that he tested; toluene showed the best suitability. The toluene-based ORC had 26% efficiency compared to the 11-19% efficiency achieved by a steam Rankine cycle [1].

In 1997, Hung [8] evaluated the performance of six working fluids, benzene, ammonia, R-11, R12, R-134a, and R-113, by modeling to determine the maximum Rankine cycle efficiency at different turbine inlet temperatures. The result showed that benzene had the highest efficiency from 500-550 K (227 °C – 277 °C) [1].

In another work published four years later, Hung [9] investigated the potentials of benzene, toluene, p-xylene, R-113 and R-123 to recover waste heat from a 10 MW source at 600 K (327 °C) in an ORC. P-xylene showed highest cycle efficiency when a constant 15 °C temperature difference between the turbine inlet and the waste heat source existed. Refrigerants showed better performance as the source temperature decreased [1].

In 2005, El Chammas and Clodic [10] configured an ORC for WHR from the cooling circuit and exhaust of a 1.4 L spark ignition engine in a hybrid vehicle using a 55 °C condensing temperature. They tested water, isopentane, R-123, R-245ca, R-245fa, butane, isobutane, and R152a as the working fluids. The results indicated that water gave the highest efficiency, followed by R-123, isopentane, and R-245ca [1].

In 2007, Mago et al. [11] investigated the performances of R-134a, R-113, R-245ca, R-245fa, R123, isobutane, and propane as the working fluids in an ORC operating at low temperatures. R113 showed highest system thermal efficiency at temperature around 450 K (177 °C) [1].

In the same year, Quoilin [12] described optimization of a small-scale ORC through computer simulations. He indicated that R-123 operated efficiently with source temperatures between 100 and 200 °C [1].

In 2009, Ringler et al. [13] found that water was the most appropriate working fluid for an ORC that works with a four-cylinder engine to recover heat from exhaust gas only [1]. The investigation was facilitated by a Dymola modeling tool, thus the engine performance directly linked to the vehicle speeds [1].

In 2010, Espinosa et al. [14] studied the optimal ORC configuration for WHR on commercial trucks. In addition to the optimal configuration discussion, he used computer models to evaluate three working fluids, water, ethanol, and HFC-R-245fa. R-245fa was deemed as the most suitable working fluid [1].

In 2011, Roy et al. [15] parametrically optimized the performance of an ORC using R-12, R-123, R-134a, and R-717 as the working fluids. R-123 demonstrated the highest efficiency for both a constant hears source temperature of 550 K (227 °C) and a variable heat source.

In 2012, Seher, Lengenfelder, Gerhardt, Eisenmenger, Hackner and Krinn [16] compared WHR power produced by an ORC in connection with a diesel engine for a heavy-duty commercial vehicle using water, toluene, MM, ethanol, and R-245fa. The results obtained by both simulations and experiments indicated that water or ethanol is the suitable working fluid.

In 2013, Bao and Zhao [4] reviewed working fluid selections for ORC. They summarized selection criteria based on thermodynamic and physical properties, such as latent heat and boiling temperature. They proposed a table of recommended fluids for different applications, working conditions and performance indicators. Over the heat source temperature range of 320 - 500 K (47-227 °C), 24 working fluids were recommended in their work.

In short, previous researchers have done large amount of work on the ORC used in connection with internal combustion engines. However, the assumed operating conditions of the ORC and the results in their works vary largely. No single working fluid is suitable for all conditions.

Therefore, rather than a further detailed study on why the results of these literatures vary largely, a simple statistical summary is more helpful to narrow down the working fluid selections. Based on this consideration, I summarized that the working fluids that were frequently investigated in the literatures are R-11, R12, R-113, R134a, R123, R-245ca, R-245fa, isobutane (R-600a), toluene, benzene, ethanol and water. The working fluids that have demonstrated the highest system efficiencies in the literatures are R-11, R-113, R-114, R-123, R-245fa, toluene, benzene, p-xylene, ethanol and water. Note that R-123 showed the best performance in three studies ([10], [12] and [15]).

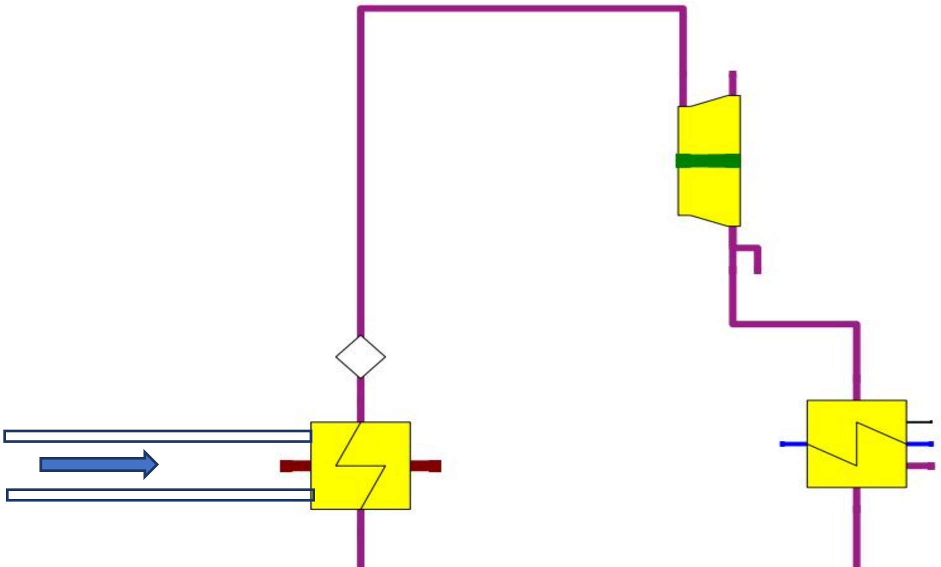
CHAPTER THREE

METHODOLOGY

In this study, variation of the properties with the variation of the different working fluids, condenser and evaporator pressures have been studied. The fundamental equations have been used to simply analyze the performance of different working fluids. During the study, the frictional losses of the fluids flowing in the pipes were neglected and hence operating the conditions have been assumed in the processes of isobaric heat supply at the evaporator, expansion at the turbine, isobaric heat rejection at the condenser and compression at the pump. The information of relevant operating conditions and input parameters are displayed in the table below. The modelling was carried out by using CoolProp software.

Table 3.1 Conditions for ORC systems for verification.

Parameters	H.E inlet temp. (^{0}C)	H.E exit temp. (^{0}C)	C_p (kJ/kg)	m (kg/s)	Q_{in} (KW)	L.H.V (KJ/kg)	T_c (^{0}C)	T_e(^{0}C)	P_c (bar)	P_t (bar)	$_t$	$_p$ (%)
Water	206	123.7	4.184	1.5	516.4542							
Toluene	206	123.7	1.707	1.0	516.4542	361.8	20	110.6	0.02926	0.99543	95	90
Cyclopentane	206	123.7	1.75	1.17	516.4542	389	20	49.4	0.346118	1.0332	95	90
R245fa	206	123.7	1.293	1.93	516.4542	196	-40	15.05	0.0584	1.0132	95	90
R1233zd(E)	206	123.7	1.205	1.94	516.4542	195.52	-40	18.26	0.0570	1.0133	95	90
R152a	206	123.7	1.625	1.45	516.4542	329.4	-40	-24.02	0.4721	1.0133	95	90
Ethanol	206	123.7	2.5	0.516	516.4542	854	20	78.4	0.058724	1.0011	95	90



Condenser

Cooling water from oil refinery (206^{o}C) Heat Exchanger

Pump

Figure 3.1 Schematic layout of ORC system

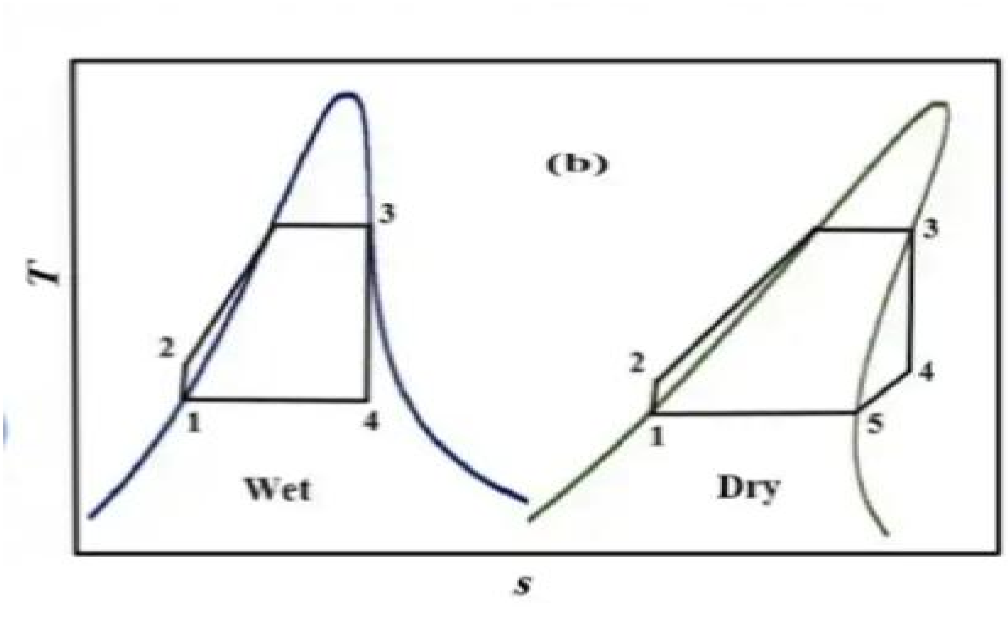


Figure 3.2 T-s plot for dry and wet ORC fluids.

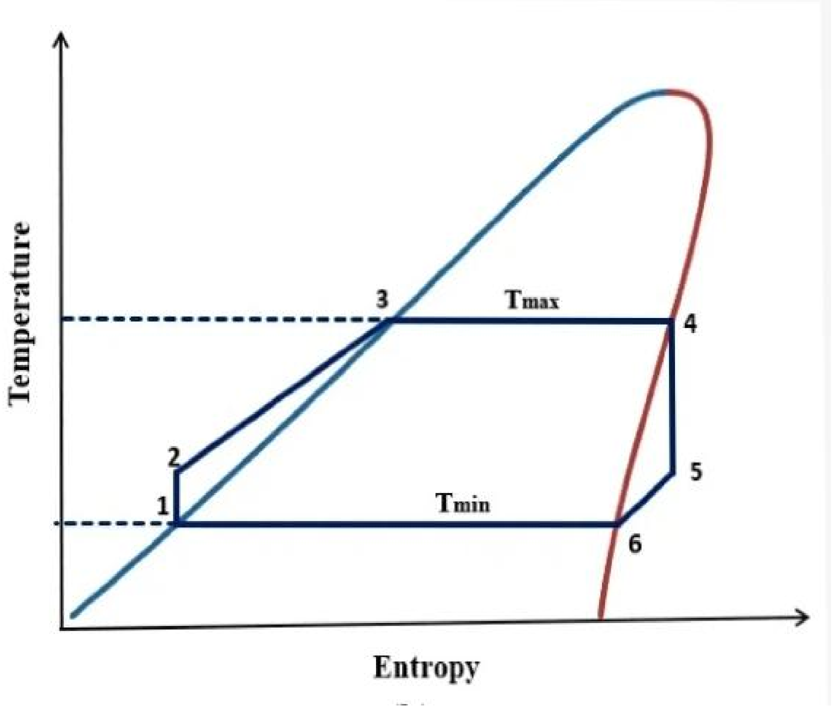


Figure 3.3 T-s plot for the ORC.

Process 1-2, isentropic compression of pump

Process 2-4, isobaric evaporation of which means no pressure drop in the boiler. In the boiler, the fluid undergoes three processes.

Process 2-3, steam preheating.

Process 3-4, steam evaporation from liquid phase to saturation vapour.

Process 4-5, isentropic expansion

Process 5-6 isobaric condensation from superheated steam to a saturated vapour.

Process 6-1 sub-cooling from saturated vapour to saturated liquid.

Note that these series undergo processes bearing in mind that this is an ideal cycle isentropic expansion adiabatic conditions, no losses, no pressure drops etc.

3.2 Thermodynamic Modelling.

The principal processes of the ORC system are illustrated in the fig3.1a above which shows the schematic and temperature-entropy diagram of the thermodynamic cycle. The common components of the ORC plant should consist of pumps, evaporator, expander and the condenser. By observing their pressure and temperature on each individual component in the Organic Rankine Cycle system to evaluate thermodynamic properties of the working fluids.

3.3 Steam Quality

The statement that the dryness fraction of an Organic Rankine Cycle is always greater than 1, is incorrect. The dryness fraction being the measure of the mixture of the saturated liquid and vapour and it ranges from 0 to 1. ORC often use fluids that are classified as ‘dry’ or ‘isentropic’, meaning that an isentropic expansion in the turbine keeps the fluid out of the two-phase region resulting a dryness fraction greater than 1.

3.3.1 Dry Fluids:

Many organic fluids are dry with a positive slope on a T-s diagram and naturally becomes superheated after expansion through the turbine. This means the fluid remains in a gaseous state throughout the expansion avoiding condensation and the potential for liquid droplets to damage the turbine blade. For these fluids the dryness fraction at the turbine outlet will be greater than 1 indicating that the fluid has become a superheated vapour. Examples of dry organic fluids are: cyclopentane, toluene, R600, R600a, benzene, isobutane etc.

3.2.2 Isentropic Fluids.

Isentropic working fluids for an Organic Rankine Cycle are organic fluids that do not need superheating because during the adiabatic expansion, they stay in the saturated vapour region and condensation does not occur at the turbine outlet. These fluids have nearly vertical saturation curve a temperature – entropy (T-s) diagram making them ideal for ORCs with no risk of blade corrosion from fluid droplets. Examples of isentropic fluids are: R245fa, R1233zd(E), R11, R123 etc.

3.3.3 Wet Fluids.

If a wet fluid like water is used, an isentropic expansion will lead to a two-phase mixture with a dryness fraction less than 1. In a temperature – entropy (T – s) diagram, these fluids have a negative slope for their saturation vapour curve. That simply means their saturation temperature decreases as their entropy increases. When a wet organic fluid expands isentropically from a saturation vapor state, it enters the wet vapour region. Fluids with simpler molecular structure tend to behave as wet fluids. Example of the wet organic fluids are ethanol, R152a, R134a. These fluids typically require superheating before expansion to prevent liquid droplet from damaging the turbine blade.

3.4 Mathematical Modelling

Mathematical approach to calculate the efficiency of the ORC system is vital.

Work input in pump and output in turbine is important to determine the back-work ratio. Figure 3.1b is chosen as the reference assuming ideal cycle.

Below are the various formulae used for the calculations.

Heat Transfer Equation:

The heat transfer equation is used to determine the quantity of heat from the waste heat source to heat up the ORC working fluids to the vaporization temperature.

$$Q = m(h_{in} - h_{out}) = mC_p(T_{in} - T_{out}) = m_f C_{pf}(T_e - T_c) + m_f L_v \quad (1)$$

Dryness Fraction:

The dryness fraction is a key parameter used to characterize the state of the working fluid and optimize the performance of the expander and the entire ORC system, ensuring both efficiency and operational reliability. The dryness of the working fluid is critical in selecting the right fluid for the ORC. Dry fluid maintains their vapour phase during expansion which is often preferred for ORCs using standard turbine. The function below is used to determine the dryness fraction of an ORC working fluid.

$$x = \frac{s_{g4} - s_{f1}}{s_{fg}} \quad (2)$$

Temperature at superheat

$$s_4 = s_6 + c_p log_e \frac{T_5}{T_6} \quad (3)$$

Enthalpy value at superheat.

$$h_5 = h_6 + c_p(T_5 - T_6) \quad (4)$$

Actual enthalpy value at superheat

$$h_5 = h_4 - \eta(h_4 - h_5) \quad (5)$$

Actual enthalpy of pump

$$h_2 = h_{f1} + \frac{h_2 - h_{f1}}{\eta} \tag{6}$$

Specific enthalpy value (for wet fluid only)

$$h_2 = h_{f1} + xh_{fg} \tag{7}$$

Turbine work:

The turbine is the prime mover device that converts the heat energy of the system into motion energy that can be used as a generator rotor for power generation. The steam turbine power can be determined by using the equation below.

$$w_T = m(h_4 - h_5) \tag{8}$$

Pump work:

The pump functions to create pressure on the working fluid in the ORC by converting mechanical energy into kinetic energy so that the fluid can circulate. From the thermodynamic analysis, the equation below is used to determine the pump work.

$$w_p = m(P_e - P_c) = m\left(h_2 - h_{f1}\right) \tag{9}$$

Preheater:

In the preheater, the working fluid receives heat from the saturated liquid.

Quantity of heat supplied

$$Q_{in} = m(h_4 - h_2) \tag{10}$$

Quantity of heat rejected

$$Q_{re} = m(h_5 - h_{f1}) \quad (11)$$

Net work

$$w_n = w_T - w_p \quad (12)$$

The essential parameter to equate the efficiency is when the work done by turbine need to be calculated. The overall efficiency of the system is given as well.

Overall efficiency

$$\eta_{Th} = \frac{w_n}{Q_{in}} \quad (13)$$

Back work ratio parameter is also considered to be an evaluation of the ORC performance and the formula as follows:

Back work ratio

$$Bwr = \frac{w_T}{w_p} \quad (14)$$

In addition to the mathematical approach of the system, a thermodynamic modelling via a proper series of equation is important, involving actual and ideal Organic Rankine cycle. Before that, modelling of such thermodynamic system involves certain constraint that needed to be fixed. Below are the constraints to be fixed:

1. Selection of working fluids which has boiling point above 220K, the reason is to have a clear and efficient way of comparing its performance on ORC system.
2. The condensing temperature is fixed at -40˚C, also known as the lowest temperature TL of fluids with lower boiling point used in this project work. The system temperature ranges between boiler

exit and turbine exit can be from 90°C to -30°C for industrial waste heat. Generally, the maximum pressure range that a boiler operates is between 0.057bar to 1.0133bar. The scope is smaller than the boiling temperature above, thus consideration of boiling pressure is vital.

3. The efficiency of the turbine used in this project is set to 0.95. The reason is to find out the actual enthalpy, h_{5s} entropy at the turbine exit compares with the ideal one, given h_{5s} and S_{5s}. the formula for efficiency of turbine is equation 5.

4. The efficient of the pump is set to 0.90 as well, which is to find out the actual enthalpy, h2s given in equation 6.

5. The energy and work calculation throughout the system is based on specific energy and work done denoted as kJ/kg, thus mass flow rate is not ignored in the modelling but varied by taken cognizance 0f their boiling point with the available quantity of heat.

3.5 Thermodynamic modelling of ORC in CoolProp

Based on the equation on ideal ORC and actual ORC cycle from the constraints above, the series of equation is being written in the CoolProp software. The series of equations is used for all the 6 working fluids from three groups to generate the results on various parameters.

3.6 Cool Prop Library

Cool prop is an open-source, cross platform library that provides accurate thermophysical properties for a wide variety of fluids. It is often used as an alternative to proprietary databases like NIST REFPROP, offering high-accuracy reference equations of state and transport property correlations. Its free and flexible licensing (MIT License) makes it popular in both academic and industrial applications

It key features include: a comprehensive fluid database containing thermodynamic and transport properties for over 100 pure and pseudo-pure fluids, mixture capabilities for calculating mixture properties, humid air properties for high accuracy psychrometric analysis, cross platform with wrappers available for numerous popular programming languages and environments, has simple high level interface for quick property retrieval and has computational speed with high efficient methods, such as tabular interpolation for faster calculations.

CoolProp is widely used in projects related to: thermal systems design, energy systems, process engineering and system simulation.

3.7 Equations and Simulation Codes

Below are the equation code and its comment about the variables being used:

```
{Constraints"} s
{Turbine inlet/Boiler Outlet}
T_2 = 90 [C]                "Temperature inlet to turbine/ boiler exit"
P_2=1.033[bar]              "Pressure at turbine inlet"
{Quality is superheated}
eff_turbine = 0.95          "Efficiency of turbine fixed"
{Condenser inlet/Turbine Outlet}
P_3=0.057 [bar]             "Condensing Pressure"
{Pump Inlet/Condenser Outlet}
T_4 = -40 [C]               "Condensing Temperature"
P_4=P_3                     "Pressure on turbine exit is same throughout the
condensing process"
eff_pump = 0.90             "Efficiency of pump"
{Boiler inlet/Pump outlet}
P_1 = P_2                   "Pressure on pump exit is same as boiler exit"
```

```
"Organic Rankine Cycle modelling"
{Working Fluids}
import math
from typing import Dict, Any, List
import pandas as pd
import numpy as np
from CoolProp.CoolProp import PropsSI
import matplotlib.pyplot as plt
from matplotlib.backends.backend_pdf import PdfPages
# ===== Parameters (EDIT ME) =====
ETA_TURB = 0.95
ETA_PUMP = 0.90
MDOT = 1.0 # kg/s
SUPERHEAT_K = 10.0
SUBCOOL_K = 4.0

# Baseline setpoints for single/multi runs
BASE_Pe_bar = 35.0
BASE_Pc_bar = 1.06
BASE_Te_C = 205.0 #Heat Source Temperature
BASE_Tc_C = 50.0

# Sweep ranges
EVAP_T_RANGE = np.linspace(10, 205, 9) # °C
```

```
COND_T_RANGE = np.linspace(-40, 20, 10)  # °C
EVAP_P_RANGE = np.linspace(15, 40, 6)  # bar


# Fluid lists
FLUIDS_MAIN = ["Ethanol", "Toluene", "Isohexane", "R245fa", "R1233zd(E)", "R152a"]
FLUID_FOR_SWEEPS = "R152a"  # used in single-fluid sweeps


def orc_state_points(fluid: str,
        Pe_bar: float, Te_C: float, Pc_bar: float, Tc_C: float,
        superheat_K: float = 10.0, subcool_K: float = 4.0,
        eta_turb: float = 0.80, eta_pump: float = 0.70,
        mdot_kg_s: float = 1.0) -> Dict[str, Any]:
  Pe = Pe_bar * 1e5
  Pc = Pc_bar * 1e5
  T3 = (Te_C + superheat_K) + 273.15
  T1 = (Tc_C - subcool_K) + 273.15


  h3 = PropsSI("H", "T", T3, "P", Pe, fluid)
  s3 = PropsSI("S", "T", T3, "P", Pe, fluid)


  h4s = PropsSI("H", "P", Pc, "S", s3, fluid)
  h4 = h3 - eta_turb * (h3 - h4s)


  h1 = PropsSI("H", "T", T1, "P", Pc, fluid)
```

```
 s1=PropsSI("S","T",T1,"P",Pc,fluid)

 h2s=PropsSI("H","P",Pe,"S",s1,fluid)
 h2 =h1+(h2s-h1)/eta_pump

 Qin=mdot_kg_s*(h3-h2)
 Wt=mdot_kg_s*(h3-h4)
 Wp=mdot_kg_s*(h2-h1)
 Wnet=Wt-Wp
 eta_th=(Wnet/Qin) if Qin>0 else float("nan")

 return {
  "fluid": fluid, "Pe_bar": Pe_bar, "Te_C": Te_C, "Pc_bar": Pc_bar, "Tc_C": Tc_C,
  "superheat_K": superheat_K, "subcool_K": subcool_K,  "eta_turb": eta_turb, "eta_pump":
eta_pump, "mdot_kg_s": mdot_kg_s, "T3_K": T3, "p3_Pa": Pe, "h3_Jkg": h3, "s3_JkgK": s3,
  "h4s_Jkg": h4s, "h4_Jkg": h4, "T1_K": T1, "p1_Pa": Pc, "h1_Jkg": h1, "s1_JkgK": s1,
  "h2s_Jkg": h2s, "h2_Jkg": h2,  "Qin_kW": Qin/1000.0, "Wt_kW": Wt/1000.0, "Wp_kW":
Wp/1000.0, "Wnet_kW": Wnet/1000.0, "eta_th_%": eta_th*100.0
 }

def run_cases(cases: List[Dict[str, Any]]) -> pd.DataFrame:
 rows=[]
 for c in cases:
  try:
```

```
   rows.append(orc_state_points(**c))
  except Exception as e:
   c2 = c.copy()
   c2["error"] = str(e)
   rows.append(c2)
 return pd.DataFrame(rows)

# Baseline set of fluids
cases = [
 {"fluid": "Ethanol",  "Pe_bar": 1.0011, "Te_C": 78.4, "Pc_bar": 0.058724, "Tc_C": 20.0,
 "superheat_K": SUPERHEAT_K, "subcool_K": SUBCOOL_K, "eta_turb": ETA_TURB,
"eta_pump": ETA_PUMP, "mdot_kg_s": MDOT},
 {"fluid": "Toluene",  "Pe_bar": 0.99543, "Te_C": 110.6, "Pc_bar": 0.0296, "Tc_C": 20.0,
 "superheat_K": SUPERHEAT_K, "subcool_K": SUBCOOL_K, "eta_turb": ETA_TURB,
"eta_pump": ETA_PUMP, "mdot_kg_s": MDOT},
 {"fluid": "Cyclopentane", "Pe_bar": 1.0045, "Te_C": 49.4, "Pc_bar": 0.346118, "Tc_C": 20.0,
 "superheat_K": SUPERHEAT_K, "subcool_K": SUBCOOL_K, "eta_turb": ETA_TURB,
"eta_pump": ETA_PUMP, "mdot_kg_s": MDOT},
 {"fluid": "R245fa",  "Pe_bar": 1.0332, "Te_C": 15.05, "Pc_bar": 0.0584, "Tc_C": -40.0,
 "superheat_K": SUPERHEAT_K, "subcool_K": SUBCOOL_K, "eta_turb": ETA_TURB,
"eta_pump": ETA_PUMP, "mdot_kg_s": MDOT},
 {"fluid": "R1233zd(E)", "Pe_bar": 1.0132, "Te_C": 18.26, "Pc_bar": 0.0570, "Tc_C": -40.0,
 "superheat_K": SUPERHEAT_K, "subcool_K": SUBCOOL_K, "eta_turb": ETA_TURB,
"eta_pump": ETA_PUMP, "mdot_kg_s": MDOT},
```

```
 {"fluid": "R152a",  "Pe_bar": 1.033, "Te_C": -24.02, "Pc_bar": 0.4721, "Tc_C": -40.0,
 "superheat_K": SUPERHEAT_K, "subcool_K": SUBCOOL_K, "eta_turb": ETA_TURB,
"eta_pump": ETA_PUMP, "mdot_kg_s": MDOT},
]
df = run_cases(cases)
df_summary =
df[["fluid","Pe_bar","Te_C","Pc_bar","Tc_C","Qin_kW","Wt_kW","Wp_kW","Wnet_kW","
eta_th_%"]]
df_summary

# Plot 1: efficiency by fluid
fig1, ax1 = plt.subplots()
ax1.bar(df["fluid"], df["eta_th_%"])
ax1.set_ylabel("Thermal Efficiency [%]")
ax1.set_xlabel("Fluid")
ax1.set_title("ORC Efficiency by Fluid (baseline cases)")
plt.xticks(rotation=45)
plt.tight_layout()
plt.show()

# Evaporation temperature sweep
rows = []
for Te in EVAP_T_RANGE:
  rows.append(orc_state_points(FLUID_FOR_SWEEPS, BASE_Pe_bar, Te, BASE_Pc_bar,
```

```
BASE_Tc_C,
        SUPERHEAT_K, SUBCOOL_K, ETA_TURB, ETA_PUMP, MDOT))
sweep_evap=pd.DataFrame(rows)
sweep_evap[["fluid","Te_C","Wnet_kW","eta_th_%"]]

fig2, ax2=plt.subplots()
ax2.plot(sweep_evap["Te_C"], sweep_evap["eta_th_%"], marker="o")
ax2.set_xlabel(" Temperature Change [°C]")
ax2.set_ylabel("Thermal Efficiency [%]")
ax2.set_title(f"Efficiency vs Temperature Change — {FLUID_FOR_SWEEPS}")
ax2.grid(True)
plt.tight_layout()
plt.show()

# Condenser temperature sweep
rows=[]
for Tc in COND_T_RANGE:
 rows.append(orc_state_points(FLUID_FOR_SWEEPS, BASE_Pe_bar, BASE_Te_C,
BASE_Pc_bar, Tc,
        SUPERHEAT_K, SUBCOOL_K, ETA_TURB, ETA_PUMP, MDOT))
sweep_cond=pd.DataFrame(rows)
sweep_cond[["fluid","Tc_C","Wnet_kW","eta_th_%"]]

fig3, ax3=plt.subplots()
```

```
ax3.plot(sweep_cond["Tc_C"], sweep_cond["eta_th_%"], marker="o")
ax3.set_xlabel("Condenser (Cooling) Temperature [°C]")
ax3.set_ylabel("Thermal Efficiency [%]")
ax3.set_title(f"Efficiency vs Condenser Temperature — {FLUID_FOR_SWEEPS}")
ax3.grid(True)
plt.tight_layout()
plt.show()

# Evaporator pressure sweep
rows = []
for Pe in EVAP_P_RANGE:
 rows.append(orc_state_points(FLUID_FOR_SWEEPS, Pe, BASE_Te_C, BASE_Pc_bar, BASE_Tc_C,
         SUPERHEAT_K, SUBCOOL_K, ETA_TURB, ETA_PUMP, MDOT))
sweep_Pe = pd.DataFrame(rows)
sweep_Pe[["fluid","Pe_bar","Wnet_kW","eta_th_%"]]

fig4, ax4 = plt.subplots()
ax4.plot(sweep_Pe["Pe_bar"], sweep_Pe["eta_th_%"], marker="o")
ax4.set_xlabel("Evaporator Pressure [bar]")
ax4.set_ylabel("Thermal Efficiency [%]")
ax4.set_title(f"Efficiency vs Evaporator Pressure — {FLUID_FOR_SWEEPS}")
ax4.grid(True)
plt.tight_layout()
```

```
plt.show()
```

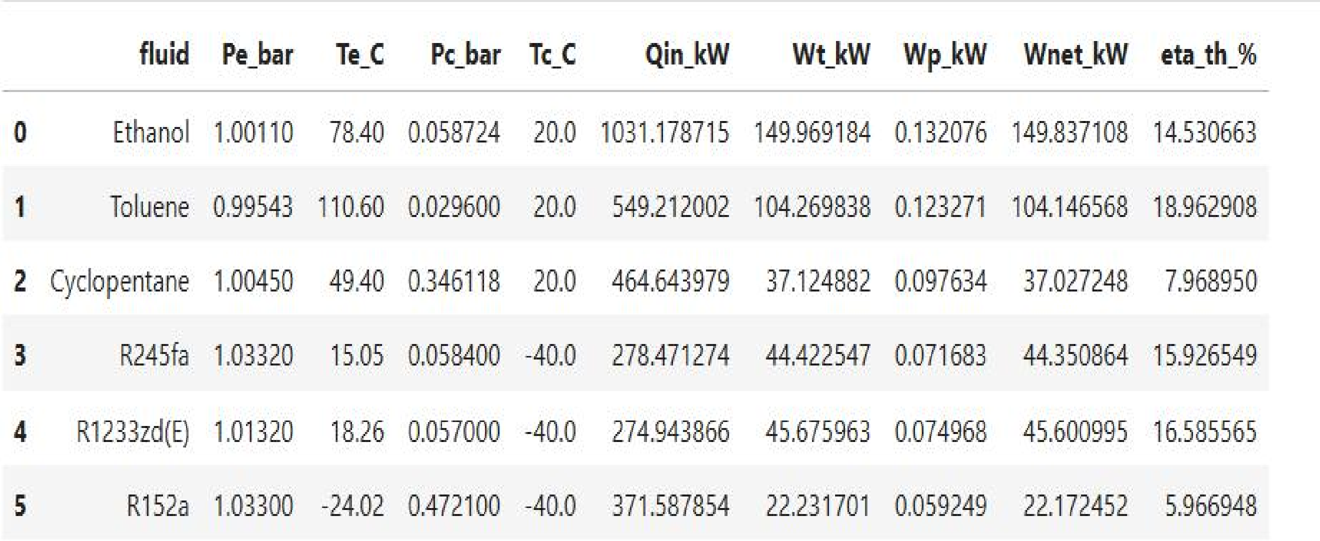
CHAPTER FOUR

RESULTS

4.1 Temperature dependent thermophysical Properties

Temperature dependent thermophysical properties were plotted using CoolProp software, with respect to the lowest temperature of -40°C, and 20°C, highest temperature of the system. But for higher temperature category of fluid chosen for this project work, the lower boiling point 20^0C and 110.6^0C. The corresponding pressures for low grade heat source are 1.0133bar at entry to the turbine, while at exit from the condenser is 0.0584bar. The results obtained from the CoolProp software is shown in the table below.

Table 4.1 Result obtained from CoolProp software.



	fluid	Pe_bar	Te_C	Pc_bar	Tc_C	Qin_kW	Wt_kW	Wp_kW	Wnet_kW	eta_th_%
0	Ethanol	1.00110	78.40	0.058724	20.0	1031.178715	149.969184	0.132076	149.837108	14.530663
1	Toluene	0.99543	110.60	0.029600	20.0	549.212002	104.269838	0.123271	104.146568	18.962908
2	Cyclopentane	1.00450	49.40	0.346118	20.0	464.643979	37.124882	0.097634	37.027248	7.968950
3	R245fa	1.03320	15.05	0.058400	-40.0	278.471274	44.422547	0.071683	44.350864	15.926549
4	R1233zd(E)	1.01320	18.26	0.057000	-40.0	274.943866	45.675963	0.074968	45.600995	16.585565
5	R152a	1.03300	-24.02	0.472100	-40.0	371.587854	22.231701	0.059249	22.172452	5.966948

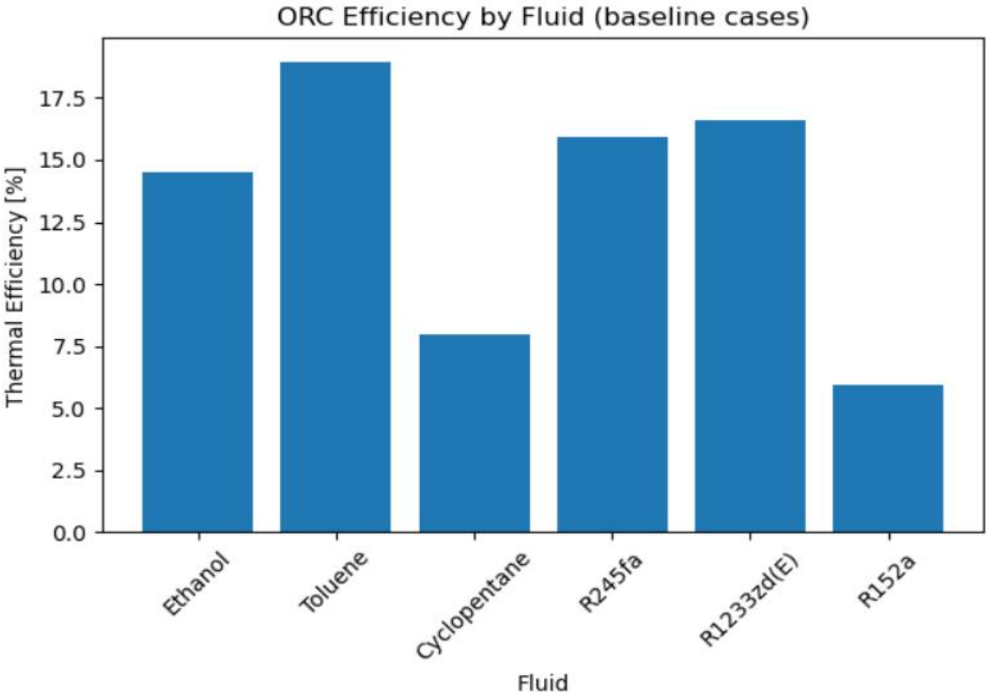


Figure 4.1 Bar chart showing efficiency and ORC fluids.

4.2 Discussion of Results

4.2.1 Pump Work

Work of pump is an important parameter when it comes to evaluating the back-work ratio and performance of the system. Identification of pump work eases by applying the equation (8) and getting the actual pump work. For low grade temperature fluids in this project the figure below shows their pump work generated by CoolProp. R152a(wet) has the lowest pump work while R1233zd(E) (isentropic) has the highest pump work, the same way for high temperature fluids, Cyclopentane(dry) has the lowest pump work while Ethanol (wet) has the highest pump work.

Table 4.2 pump work of low temperature ORC fluids.

R245fa (KW)	R1233zd(E) (KW)	R152a (KW)
0.071683	0.074968	0.059249

Table 4.3 pump work of high temperature ORC fluids.

Toluene (KW)	Ethanol (KW)	Cyclopentane (KW)
0.123271	0.132076	0.097634

4.2.2 Net Work

The difference between the work of turbine and the pump work yields another important parameter when selecting the best fluids. The figures below show the network for the low temperature and high temperature fluids selected for this project work.

From the table of the low temperature fluids R152a (wet) has the lowest work net while R1233zd(E) (isentropic) has the highest work net. But for the high temperature fluids cyclopentane (dry) has the lowest work net while ethanol (wet) has the highest work net.

Table 4.4 Work net of low temperature fluids.

R245fa (KW)	R1233zd(E) (KW)	R152a (KW)
44.350864	45.600995	22.172452

Table 4.5 Work net for high temperature ORC fluids.

Toluene (KW)	Ethanol (KW)	Cyclopentane (KW)
104.146568	149.837108	37.027248

Table 4.6 Work net for dry ORC fluids.

Fluid	Wt(KW)	Wp(KW)	Wn(KW)
Toluene	104.269838	0.123271	104.146568
Cyclopentane	37.124882	0.097634	37.027248

Table 4.7 Work net for Isentropic ORC fluids

Fluid	Wt(KW)	Wp(KW)	Wn(KW)
R245fa	44.422547	0.071683	44.350864
R1233zd(E)	45.675963	0.074968	45.600995

Table 4.8 Work net for wet ORC fluid

Fluid	Wt(KW)	Wp(KW)	Wn(KW)
Ethanol	149.969184	0.132076	149.837108
R152a	22.231701	0.059249	22.172452

Higher temperature in an ORC system generally leads to higher network output as increasing the heat source temperature, evaporation temperature and turbine inlet temperature boost performance. Conversely, lower temperature particularly a lower temperature difference between the source and the cold sink decrease the net power. A lower condensation temperature is beneficial for cycle performance and increases the network output because the temperature difference across the expander is larger. In addition to that, a higher ambient/condensation temperature decreases network and efficiency.

4.2.3 Efficiency

Efficiency is the most important parameter on selecting the right ORC fluids. From the graphs the overall best efficiency for the low temperature fluid is R1233zd(E) (isentropic) while the overall best efficiency of the high temperature fluids is toluene. Though ethanol (wet) seems to have the greater work net when compared with toluene (dry) but efficiency parameter is more prioritized if high grade heat source is used. Therefore, toluene from the dry group is chosen as the best working fluid. But for the low-grade heat source R1233zd(E) isentropic group is chosen as the best working fluid.

Table 4.9 Efficiency of low temperature ORC fluids.

R245fa (%)	R1233zd(E) (%)	R152a (%)
15.926549	16.585565	5.966948

Table 4.10 Efficiency of high temperature ORC fluids.

Toluene (%)	Ethanol (%)	Cyclopentane (%)
18.962908	14.530663	7.968950

Increasing the temperature difference between the heat source and the sink generally increases the efficiency of an Organic Rankine Cycle (ORC) system, as higher temperatures lead to greater power output. Specifically, higher heat source temperatures and higher turbine inlet temperatures are correlated with increased thermal efficiency, while factors like the working fluid and cycle configuration also play a significant role.

Increasing the turbine inlet pressure generally increases the overall efficiency of an ORC system by enhancing the turbine power output but, there are limits. However, this increase in pressure is not linear as it also increases the work required by the pump and can lead to reduced efficiency near the working fluid's critical pressure due to less efficient phase change process and mechanical limitations.

In an ORC system, the specific heat (C_p) of the working fluid has a complex and sometimes a conflicting effect on efficiency. A low specific heat capacity is generally favourable for thermal efficiency, while a high specific heat capacity can be beneficial for net power output. The overall system efficiency depends on the specific application such as temperature of the heat source.

The latent heat also affects the efficiency of the ORC system. The latent heat is the energy absorbed or released during a phase change, such as vaporization or condensation at a constant temperature. In the ORC system, working fluid with high latent heat of vaporization can significantly improve the efficiency by allowing the system to absorb more energy from the heat source to produce more power.

The thermal conductivity of ORC system working fluid significantly impacts the efficiency of the heat exchangers (evaporator and condenser) and the overall system's thermo – economic performance. Higher thermal conductivity is generally desirable for efficient heat transfer with a smaller temperature difference between the heat source/sink and the fluid. This smaller temperature in the evaporator reduces thermodynamic irreversibility which in turn leads to a better overall efficiency of the power output. The overall thermal efficiency of an ORC system is determined by a combination of factors, including operating conditions (temperature, pressures) and other thermophysical properties like critical temperature, latent heat of vaporization and specific heat capacity.

4.2.4 Back Work Ratio (Bwr)

A high back work ratio (Bwr) in an ORC system decreases net efficiency because more of the generated work is consumed by the pump, while low Bwr maximizes the network output. The Bwr is the ratio of the pump's power input to the expander's work output and minimizing it is crucial for performance which is achieved by choosing an appropriate working fluid and optimizing the system design, particular the expander's efficiency and expansion ratio.

CHAPTER FIVE

CONCLUSION

Organic Rankine Cycle is efficient cycle for energy production from low grade heat sources, like industrial solar and biomass using organic working fluids. Purpose of organic working fluids, is justified briefly over the conventional one, water. As water possesses higher boiling point than organic working fluids which is inefficient for Organic Rankine Cycle. The objective of this research project which is identifying the best working fluids for low grade heat sources, acting between the temperature of -40°C to 90°C, and between 100^0C to 200^0C is met by chosen suitable working fluid, R1233zd(E), under the isentropic fluid group. It has the highest work net of 45.60KW making it the highest among all the group of the low-grade heat source fluids. The efficiency of this fluid is 16.59%, being the highest in isentropic group. Lastly, the back-work ratio is also favorable giving the highest in the same group, thus R1233zd(E) is the best fluid. From the wet fluid group, R152a fluid among all the groups of working fluid has the lowest amount of work net by giving up to an efficiency of 5.83%. Among the dry fluids, toluene which happens to be a high temperature fluid is chosen as the best working fluids since it has higher work net of 104.57KWeven though its work net is less than ethanol as a wet fluid highest efficiency among its group giving up to 18.96%. Another significant observation made in the results is that, R245fa and R1233zd(E) have very close work net and efficiency.

5.2 LIMITATION OF ORGANIC RANKINE CYCLE

Possible limitations of Organic Rankine Cycle (ORC) include its low efficiency, constraints related to working fluids and high-cost relative to energy output. While highly effective for low to medium temperature heat sources, these limitation affects its overall performance. The efficiency of an ORC is directly dependent on the heat source temperature, its performance declines with low temperature.

The organic fluids used in ORCs can chemically degrade and decompose at high temperatures which limits the maximum temperature of the heat source that can be used. Many organic fluids used in ORCs are flammable, toxic or expensive. Flammability and toxicity create safety hazards that require design to prevent leaks, especially in a sub-ambient pressure condenser where air could leak in and form a flammable mixture.

5.3 RECOMMENDATIONS

In order to address the limitations of Organic Rankine Cycles, we recommend that engineers focus on cycle optimization, working fluid selection and component design,

This can be done through:

- Cycle configuration: employing advanced ORC configurations like recuperative, regenerative or reheated cycles to improve thermodynamic performance
- Fluid selection: prioritize fluids with high thermal stability to allow operations at higher temperatures. Nonflammable and low toxicity fluids will also help enhance safety and environmental compliance.
- Component selection: use simpler and less expensive machines like scroll expanders in small-scale ORC systems.
- Economic optimization: Employ multi-objective optimization (MOO) techniques during the design phase to simultaneously optimize for both thermodynamic performance and economic indicators

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