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# *Parametric Sensitivity Analysis of Organic Rankine Cycle for Waste Heat Recovery*

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# *Abstract*

This study aims to evaluate and improve the performance of the Organic Rankine Cycle (ORC) as an effective means of recovering wasted heat in industrial applications that rely on low to medium temperature heat sources. The focus was on selecting the most suitable organic fluid and analyzing the impact of key operational variables on the cycle's yield. The Aspen Plus thermal simulation software was used to assess the performance of four different organic fluids: benzene, cyclohexane, toluene, and acetone. The sensitivity analysis results showed that increasing the evaporation pressure (30 bar) significantly improves net power output, with benzene achieving the highest value (2294 kW). Lowering the condenser pressure (1 bar) also enhances performance, with benzene recording the highest yield. The turbine efficiency (0.85) greatly contributes to increasing power production, with output rising from 1698 to 2443 kW for benzene. In contrast, pump efficiency had a relatively lower positive impact, with benzene's performance ranging from 2265 to 2299 kW. The analysis established that benzene is the best-performing fluid among the tested options, followed by cyclohexane, while acetone showed the weakest yield. This study contributes to improving thermal energy recovery efficiency and highlights the importance of precise operational adjustments and suitable fluid selection for high energy performance.

**Keywords:** ORC, WHR, Simulation, Sensitivity analysis**,** Aspen Plus**,** Working fluid, Efficiency.

# ملخص

تهدف هذه الدراسة إلى تقييم وتحسين أداء دورة رانكين العضوية (ORC) كوسيلة فعالة لاسترجاع الحرارة المهدورة في التطبيقات الصناعية التي تعتمد على مصادر حرارة منخفضة إلى متوسطة، تم التركيز على اختيار السائل العضوي الأنسب وتحليل تأثير المتغيرات التشغيلية الأساسية على مردود الدورة، تم استخدام برنامج المحاكاة الحرارية Aspen Plus لتقييم أداء أربعة سوائل عضوية مختلفة: البنزين، السيكلوهكسان، التولوين، والأسيتون. أظهرت نتائج تحليل الحساسية أن زيادة ضغط التبخير (30 بار) تحسن بشكل كبير من صافي الطاقة المنتجة، حيث حقق البنزين أعلى قيمة (2294 كيلوواط). كما أن خفض ضغط المكثف (1 بار) يعزز الأداء، مع تسجيل البنزين لأعلى مردود، تساهم كفاءة التوربين (0.85) بشكل كبير في زيادة إنتاج الطاقة، حيث ارتفعت القدرة من 1698 إلى 2443 كيلوواط للبنزين في المقابل، كان لكفاءة المضخة تأثير إيجابي أقل نسبيًا، حيث تراوح أداء البنزين من 2265 إلى 2299 كيلوواط، أثبت التحليل أن البنزين هو السائل الأفضل أداءً من بين الخيارات المختبرة، يليه السيكلوهكسان، بينما أظهر الأسيتون أضعف مردود، تسهم هذه الدراسة في تحسين كفاءة استرجاع الطاقة الحرارية وتبرز أهمية الضبط الدقيق للمعطيات التشغيلية واختيار السائل المناسب لتحقيق أداء طاقوي مرتفع.

**الكلمات المفتاحية :** دورة رانكين العضوية، استرجاع الحرارة المهدورة، محاكاة، تحليل الحساسية، برنامج Aspen Plus، مائع عمل، الكفاءة.

# *Dedication*

To the children of Gaza…
To the students who lost their schools and dreams under the rubble, yet still cling to knowledge as light in the darkness of war.
﴿وَقُلِ ٱعْمَلُواْ فَسَيَرَى ٱللَّهُ عَمَلَكُمْ﴾ – التوبة105

To the one who departed but remains alive in my heart — to my father… may Allah bless your soul and grant you paradise.
To my mother, heartbeat and strength of spirit…
To those who loved me, supported me, and walked beside me,
And to myself — the pride and hope of this achievement.
**Rouissi Roukaia**

To my mother and father, my sisters, and my friend Amira — thank you for your support and love, which were the reason I reached this moment.
My graduation is the fruit of your support; this joy is mine and yours alike.
**Hadj Ammar Ichrak**

Praise be to Allah for His love, kindness, and generosity.
Praise be to Allah for every blessing He has granted me  the greatest being the gift of Islam, the most beautiful being my parents and family, and the kindest being the blessing of righteous companions.
I do not dedicate this effort or work to you, but rather a sincere prayer from my heart. May Allah protect you all for me.
And this, O my soul, is only the beginning.
**Cheggouri Chourouk**

# *Acknowledgments*

All praise is due to Allah who granted us strength, wellness, and success. We thank Him for easing our path and granting us the patience and perseverance to complete these years dedicated to seeking knowledge.

We extend our sincere gratitude and appreciation to our supervisor, **Dr. Redjeb Youcef**, who generously shared his knowledge and provided valuable guidance throughout the preparation of this thesis. His continuous support, constructive feedback, and patience had a profound impact on shaping and refining this work. His professionalism, scientific dedication, and commitment to our academic growth will always be deeply appreciated.

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Our thanks also go to everyone who supported us, encouraged us, and stood by our side, especially our families and friends. Special thanks go to **our class representative, Lotoufa Salah Eddine**, for his dedication and sense of responsibility. May Allah reward him abundantly and grant him continued success.

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**ORC:** Organic Rankine Cycle

**CSP:** Concentrated Solar Power

**CHP:** Combined Heat Power

**HP:** High Pressure

**LP:** low Pressure

**ODP:** Ozone Depletion Potential

**GWP:** Global Warming Potential

**WHR:** Waste Heat Recovery

# *General Introduction*

# General Introduction

In light of the increasing challenges associated with modern technological changes, it has become essential to seek effective solutions for recovering and utilizing waste heat in various industrial processes, including turbine exhaust heat, solar energy, and biomass energy. These thermal sources are often low to medium grade and cannot be efficiently exploited using conventional systems.

In this context, the Organic Rankine Cycle (ORC) has emerged as a promising technological solution for converting this waste heat into electrical energy. The Rankine cycle began its journey in the 19th century when the Scottish scientist William John Macquorn Rankine developed it as a means to convert thermal energy into mechanical energy using steam. Initially, it was used to power steam engines in trains and factories, relying on water as the working fluid and high temperatures. As it evolved, this technology began to utilize organic fluids with suitable thermodynamic properties. The ORC has gained widespread adoption in recent years, with increasing research and practical applications in several developed countries. However, the efficiency of the cycle heavily depends on the selection of the appropriate working fluid, which requires consideration of a set of criteria, including thermal properties, safety, and environmental impact.

In this framework, this study aims to analyze the Organic Rankine Cycle from both theoretical and practical perspectives by providing a historical overview of its development, studying its structure and various technologies, and reviewing the criteria for selecting working fluids. We also focus on the utilization of waste heat in the industrial context as a practical entry point for applying the cycle. To achieve this, a thermal simulation of the cycle was conducted using Aspen Plus software to evaluate its performance and propose improvements to the design and operating conditions to enhance the energy efficiency of the system. The study also includes an analysis of the obtained results, along with a discussion of the economic aspects and technical recommendations that contribute to supporting the application of this technology in the industrial reality.

# *Bibliographic Part*

# *Chapter I*

# *The Organic Rankine Cycle*

# I. The Organic Rankine Cycle

## I.1. Introduction

The generation of energy from medium and low-grade thermal sources is garnering considerable focus in research and development to improve sustainability, given its great potential in the global energy market. The Organic Rankine Cycle (ORC) system is recognized as an effective technique for transforming low-grade heat into electricity or mechanical energy.

The Organic Rankine Cycle (ORC) resembles the conventional Rankine steam engine in its fundamental principle, functioning as a closed thermal cycle in which the working fluid experiences multiple phases: compression, evaporation, expansion, and condensation. The distinction resides in the type of working fluid employed, rather than water, an alternative fluid is utilized in the ORC [1].

ORC systems function utilizing organic molecules characterized by low boiling points and elevated molecular weights, enabling efficient operation at low and medium temperatures and low to medium grade thermal energy. These systems can utilize many heat sources, including solar energy, geothermal energy, combustion heat from fuels (such as biomass or biogas), and waste heat [2].

The Organic Rankine Cycle (ORC) is a novel technique for producing sustainable energy and enhancing energy efficiency. It is distinguished by its superior efficiency, operational adaptability, and minimal expenses. Notwithstanding many limitations, it is anticipated to assume a crucial role in the future of sustainable energy.

## I.2. History

### I.2.1. Evolution of the Rankine Cycle

Over the years, the Organic Rankine Cycle (ORC) has evolved considerably, with engineering advancements enhancing efficiency and broadening its application in power production. This advancement can be comprehended by monitoring the stages it has undergone, which have consistently enhanced its performance.

- In 1823, researcher Humphry Davy presented a device that functioned as an alternative to the steam engine. He elucidated that a swiftly evaporating liquid may be converted into vapor by the waste steam, which could potentially provide a greater quantity of energy [3].

- In 1824, the Frenchman Sadi Carnot published a book discussing the enhancement of heating and cooling processes at constant pressures by heat exchange at constant volumes or temperatures. Carnot established the efficiency of a heat engine predicated on isothermal heating, isentropic (adiabatic) expansion, isothermal cooling, and isentropic compression [4].
- In the mid-19th century, the Scottish scientist William Rankine formulated a practical implementation of Carnot's concept. The Rankine cycle was engineered to be more applicable for practical uses, especially in thermal power plants [5].
- In 1859, physicist William Rankine wrote "A Manual of the Steam Engine," in which he formulated the theory of phase shift of steam in heat engines. He substituted water with an organic fluid (including hydrocarbons, refrigerants, ethers, and siloxanes) and delineated the thermodynamic cycle that is referred to as the "Rankine Cycle". Ethers were initially utilized as a working fluid for motors in 1826. In the early 20th century, endeavors were undertaken to advance Organic Rankine Cycle (ORC) technology by utilizing solar and geothermal energy[6].
- In 1883, Frank W. obtained a patent for a naphtha engine that functions on a closed cycle and utilizes naphtha as the working fluid instead of water [ 3].

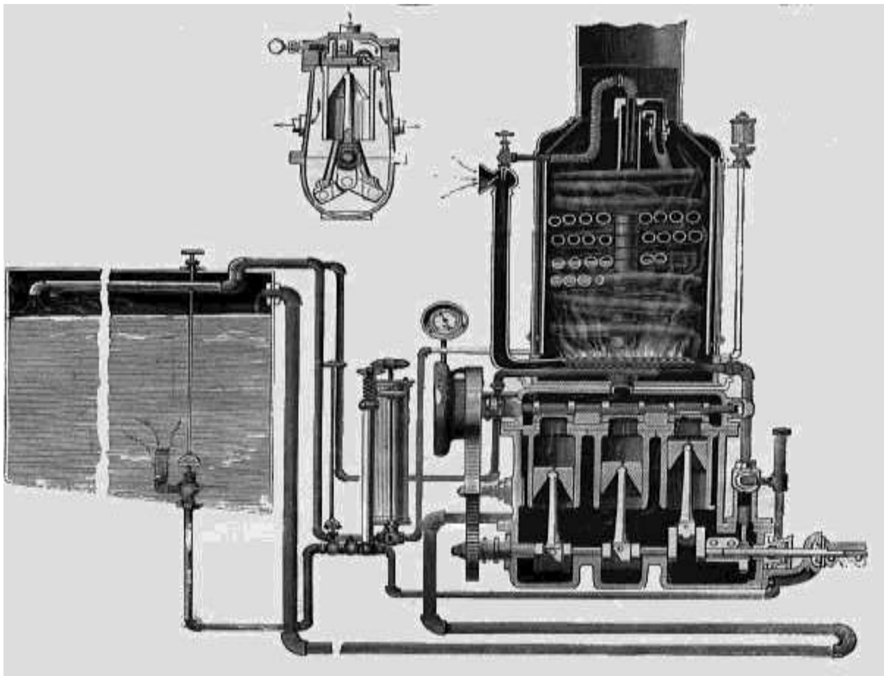


***Figure I.1.*** *Ofeldt naphtha launches Engine*

- Tito Romagnoli designed a series of Rankine engines utilizing methyl chloride as the working fluid from 1923 to 1930 [3].
- In 1967, Russia inaugurated a geothermal power plant with a functional capacity of up to 670 kilowatts [7].
- In the 1970s, Gianfranco Agelino, Ennico Macchi, and Mario Gaia invented and enhanced a cycle with a productivity of 3 kilowatts, which facilitated the establishment of the business Turboden in 1980.
- During the 1980s, Turboden predominantly manufactured units for energy generation from biomass sources, with a capacity of 300 kilowatts.
- During the 1990s, Ormat had notable advancements in harnessing energy from geothermal sources through the ORC cycle [3].

### I.2.2. Main Applications of ORC

Following examples illustrate multiple applications where the Organic Rankine Cycle can be efficiently employed to provide electrical power or mechanical work.

#### *I.2.2.1. Waste heat recovery*

Waste heat recovery is the process of capturing heat that is lost or wasted, especially in industrial processes, and converting it into energy. To utilize the heat directly, waste heat recovery boilers are used to convert it into steam, which is then used to generate electricity. Heat exchangers (recuperator and regenerators) are also employed to transfer the waste heat to other processes that require heating [8].

#### *I.2.2.2. Concentrated solar power (CSP )*

Concentrated solar power (CSP) is a technology in which sunlight is concentrated through a solar collector and transferred to a high-temperature fluid. Through a thermal cycle, the thermal energy is converted into electricity. There are two designs for solar power plants that use the Organic Rankine Cycle (ORC) which can be distinguished by the maximum temperature of the working fluid:

- Medium-temperature power plants (less than 250°C).
- Low-temperature power plants (greater than 100°C) [3].

### I.2.2.3. Geothermal power

Geothermal energy is the heat emitted from the depths of the earth. It is considered a source of clean and renewable energy because the heat released from the earth's depths is largely unlimited. The geothermal system relies on three factors: heat, permeability, and water. A geothermal reservoir is formed when hot water or steam accumulates in permeable rocks under an impermeable rock layer. Geothermal heat is used for generating electricity and for heating purposes in commercial, industrial, and residential areas. Currently, there are several models for geothermal power plants:

- Single flash steam power plants.
- Double flash steam power plants.
- Dry steam power plants.
- Binary cycle power plants [3].

### I.2.2.4. Biomass power plants

Biomass is witnessing significant development in the market, as it is an inexpensive and sustainable energy source. It serves as an alternative to fossil fuels, which are costly and have a significant impact on the climate, contributing to global warming. Biomass is used in combined heat and power (CHP) generation, reducing carbon emissions because it returns the carbon it absorbed during its growth. Biomass sources include plants and trees, agricultural and industrial residues, and organic waste. Biomass fuel can be found in wood and its by-products, agricultural waste that can be burned, biogas, and black liquor [8].

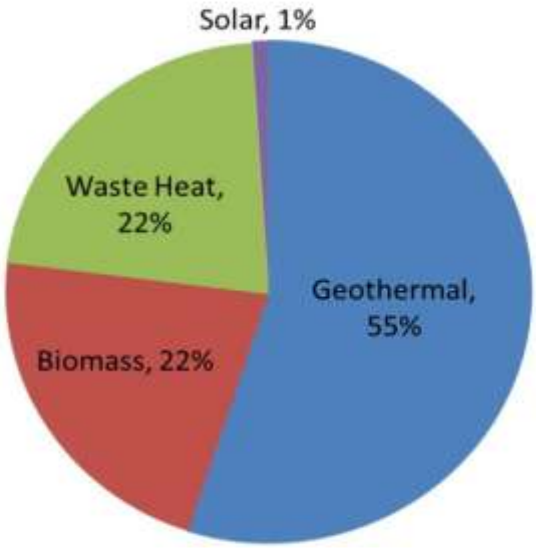


***Figure I.2.*** *Distribution of the main applications of the ORC system by installed electrical power [3]*

## I.3. Architectures

The common configurations of the Organic Rankine Cycle (ORC) can vary depending on the application, heat source, and performance objectives. Here is a description of the most commonly used architecture:

### I.3.1. Description of basic ORC (simple)

It consists of four main components: evaporator, turbine, condenser, and the pump. This is the simplest configuration of the cycle ORC, as shown in Figure 3

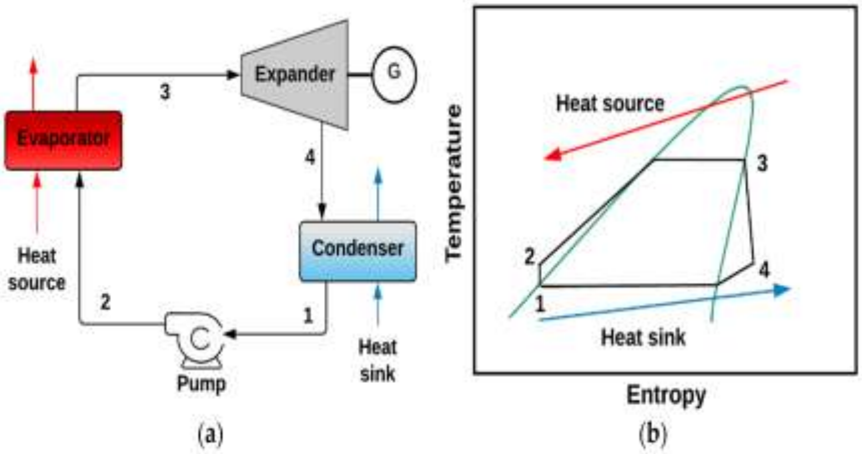


***Figure I.3.*** *Basic ORC (a) Schematic diagram; (b) T-s diagram [9]*

The pump increases the pressure of the saturated state (1) liquid by pumping it. After that, it goes into the evaporator (2), where heat energy is used to heat till it evaporates. The working fluid then exits the evaporator at point (saturated vapor) (3) and moves into the turbine, where it generates mechanical power while its pressure drops (4). The cycle is then repeated after the fluid travels to the condenser and condenses back into a liquid (1) [ 9].

### I.3.2. Description of Regenerative ORC

It is an improvement over the simple Rankine cycle, where a portion of the lost heat is recovered to enhance the thermal efficiency of the cycle. It relies on the use of an internal heat exchanger (sometimes called a regenerator or preheater). It consists of the evaporator, turbine, internal heat exchanger, condenser, and pump, as shown in Figure 4.

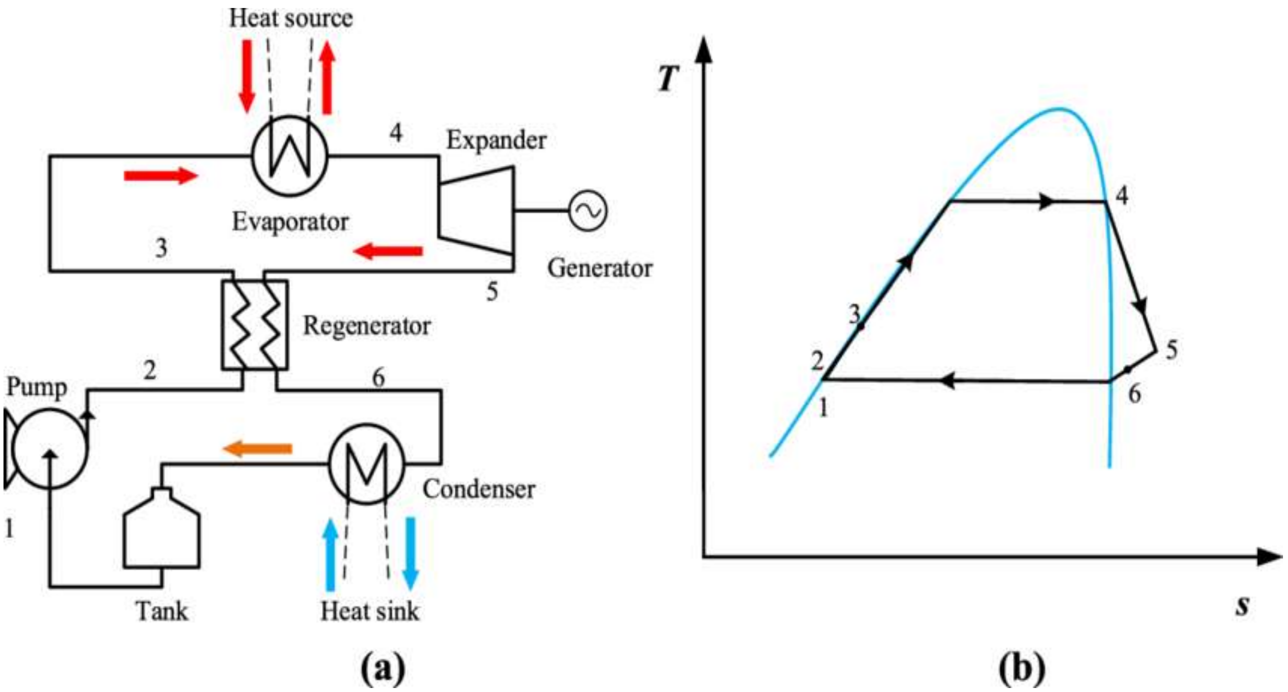


***Figure I.4.*** *Regenerative ORC (a) schematic diagram; (b) T-s diagram [37]*

The working fluid is pumped by the pump to increase its pressure. It then passes through an internal heat exchanger (regenerator), where it is heated using heat from the steam extracted from the turbine. The heated fluid enters the evaporator, where it is further heated and converted into high-pressure and high-temperature steam.

The steam enters the turbine, where it expands and produces mechanical energy. The steam exits the turbine and enters the condenser, where it is condensed back into a liquid. The liquid then returns to the pump, and the cycle repeats [10].

### I.3.3. Description of Recuperative ORC

This kind of thermal cycle is employed to increase waste heat recovery's effectiveness. The thermal load is decreased by preheating the working fluid before it enters the evaporator using a recuperators, an additional heat exchanger [9] .

Its main components are: the heat exchanger, the turbine, the condenser, the pump, and the recuperator, as shown in Figure 5.

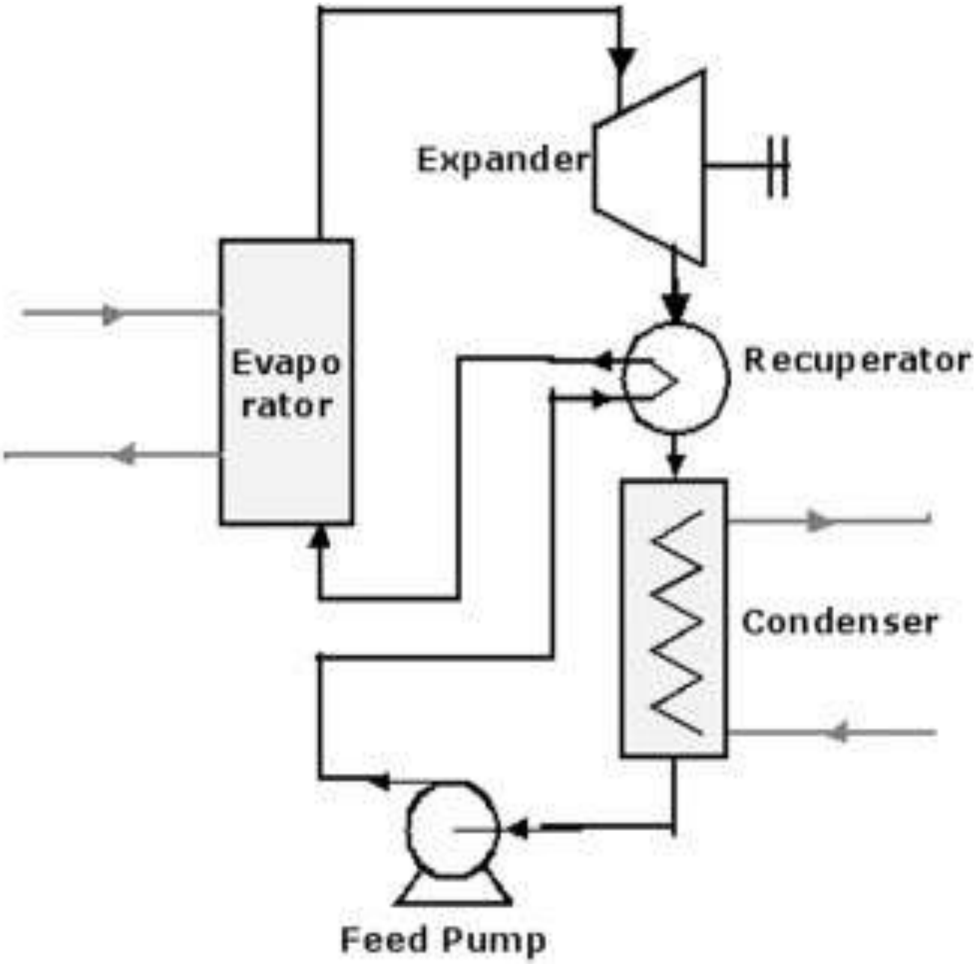


***Figure I.5.*** *Recuperative ORC schematic diagram [38]*

### I.3.4. Description of Dual-Pressure, Subcritical ORC

The dual-pressure cycle is an advanced version of the Organic Rankine Cycle (ORC) designed to enhance heat source utilization and improve efficiency. It operates at two pressure levels (high pressure and low pressure) in a subcritical condition. It consists of a high-pressure (HP) and low-pressure (LP) boiler, a high-pressure and low-pressure turbine, a heat source, the organic fluid, an air-cooled condenser, a high-pressure heater, a high-pressure loop (HP Loop), and a low-pressure loop (LP Loop), as shown in the Figure 6.

Evaporation occurs at two different temperature levels, with the high heat being used to convert the fluid into vapor in the high-pressure loop, while the remaining heat flow is used to evaporate the working fluid in the low-pressure loop.

This cycle is a step closer to approximating the ideal Lorenz cycle, which utilizes an infinite number of pressure levels to achieve maximum efficiency [11].

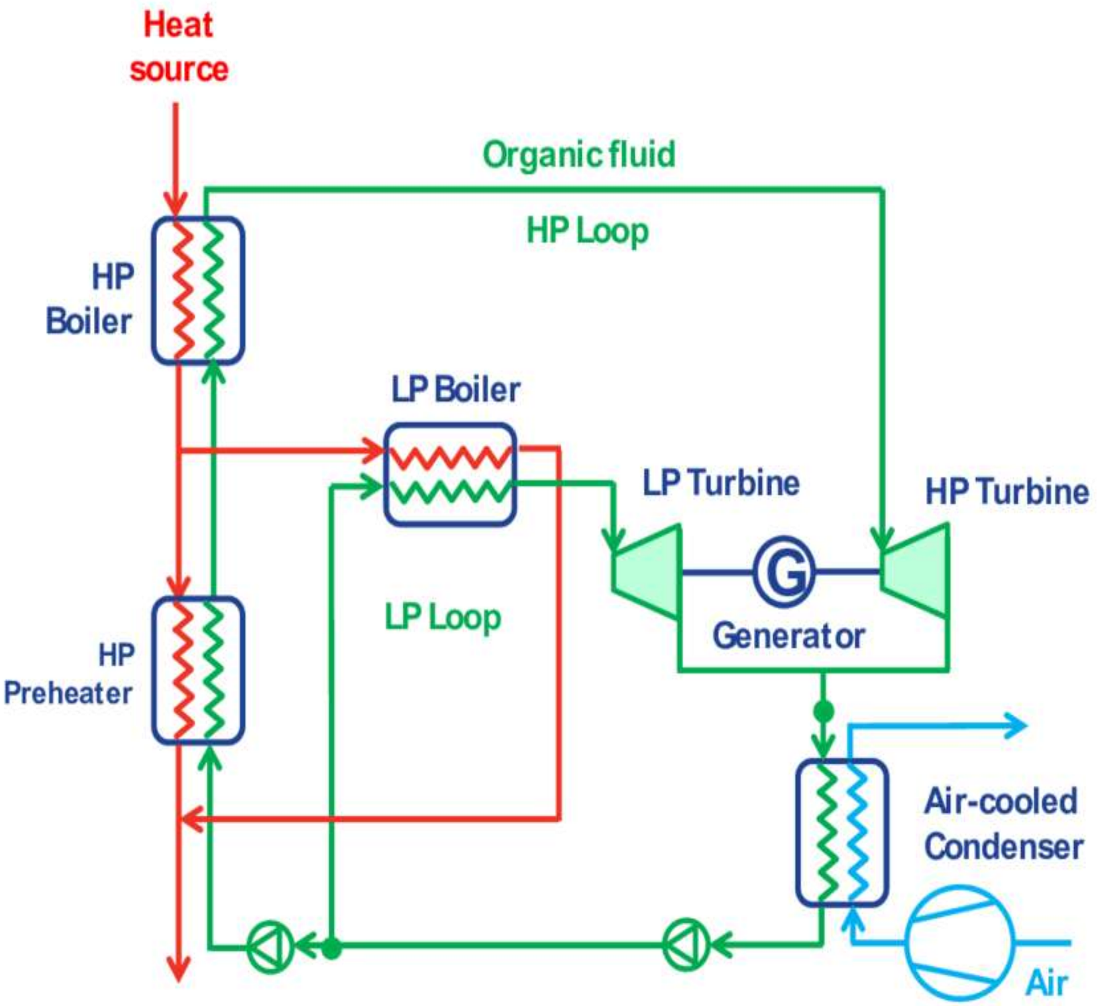


***Figure I.6.*** *Subcritical, dual-pressure organic Rankine cycle [11]*

## I.4. Working Fluids

The working fluid is a fundamental component in the Organic Rankine Cycle system, as its properties directly impact the system's efficiency and determine operating conditions such as temperature and pressure. When selecting the working fluid, environmental impact and economic balance should be considered [12].

### I.4.1. Criteria for selecting fluids

The selection criteria for working fluids in Organic Rankine Cycle (ORC) systems are of utmost importance for optimizing performance. The most important criteria to consider when selecting working fluids are as follows:

#### I.4.1.1. Thermodynamic selection criteria

- Vaporization Latent Heat

The increase in latent heat means a greater ability to absorb thermal energy during the evaporation phase, where fluids with high latent heat and high density are considered optimal choices in organic Rankine cycle systems. While high density leads to a reduction in specific volume and volumetric flow rate [12].

- Critical temperature

The critical temperature of the working fluid should be as high as possible and close to the maximum temperature of the heat source, to achieve better system performance [13].

- Critical pressure

The higher the critical pressure of the working fluid, the greater the ability to achieve high operating pressures in the cycle without reaching the supercritical state. This allows for more efficient utilization of low and medium-temperature heat sources.

- Saturation vapor line

One of the key characteristics to consider when selecting a working fluid is the slope of the saturation vapor curve on the temperature-entropy (T-S) diagram, as shown in Figure 7 [12] .The working fluids can be classified into three main categories based on the behavior of the saturation vapor curve:

- Dry fluids with $\frac{ds}{dT} > 0$

- Isentropic fluids with $\frac{ds}{dT} = 0$

- Wet fluids with $\frac{ds}{dT} < 0$

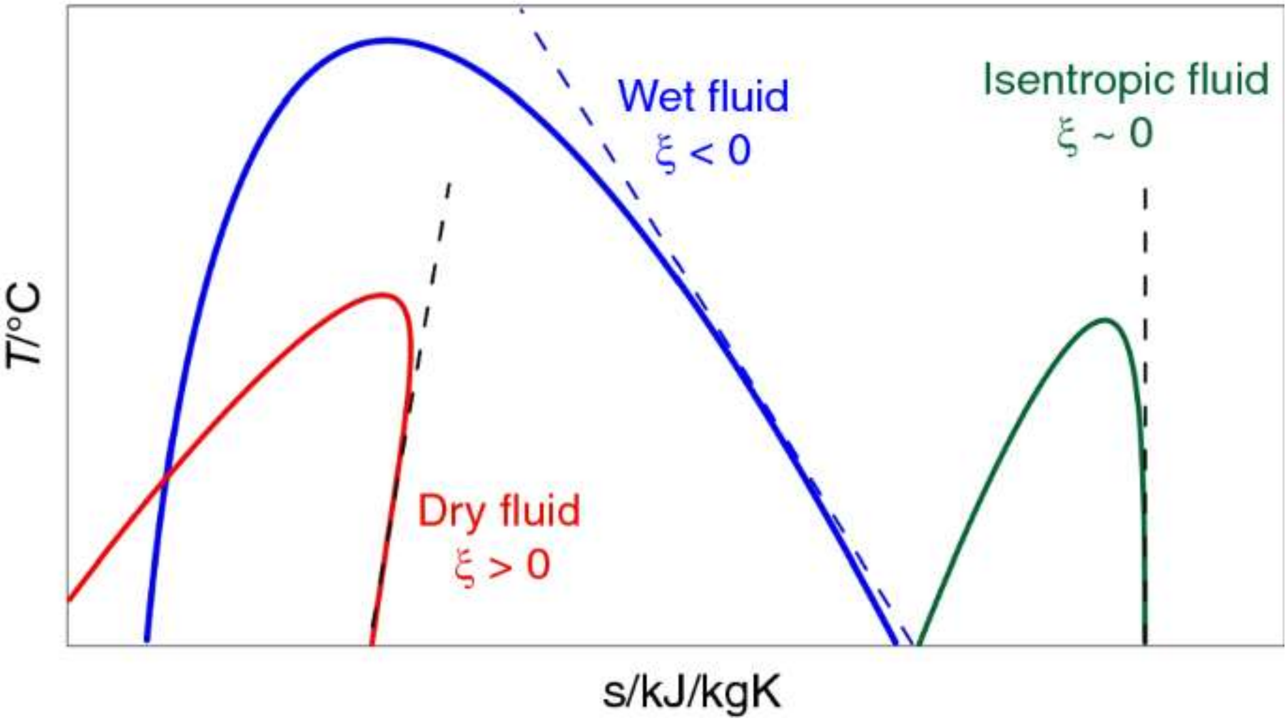


***Figure I. 7.*** *Types of working fluids (dry, wet, isentropic) based on saturation vapor curve [39]*

***Table I.1.*** *Thermodynamic Properties of Common ORC Fluids*

| *Fluid* | *chemical formula* | *critical temperature (°C)* | *Critical pressure (MPa)* | *vaporization latent heat(kJ/kg)* | *Type of Fluid* |
|---|---|---|---|---|---|
| R134a | $C_2H_2F_4$ | 101.1 | 4.06 | 215 | Isentropic |
| R245fa | $C_3H_3F_5$ | 154 | 3.65 | 196 | Dry |
| Isobutane | $C_4H_{10}$ | 134.7 | 3.62 | 360 | Wet |
| Toluene | $C_7H_8$ | 318.6 | 4.11 | 361 | Dry |
| Siloxane(D4) | $C_8H_{24}O_4Si_4$ | 313 | 1.33 | 142 | Dry |
| Ammonia | $NH_3$ | 132.4 | 11.3 | 1370 | Wet |
| Water | $H_2O$ | 374 | 22.06 | 2257 | Wet |
| Benzene | $C_6H_6$ | 288.9 | 4.075 | 394.96 | Dry |
| Pentane | $C_5H_{12}$ | 196.6 | 3.37 | 357.89 | Dry |

#### I.4.1.2. Environmental criteria

Environmental criteria are of great importance, as they focus on evaluating the impact of each fluid on the ozone layer and global warming. These impacts are determined using two main indicators:

- Ozone Depletion Potential (ODP)

It is a relative index of ozone depletion by working fluids with a reference value of 1 for R11 [14].

- Global Warming Potential (GWP)

It is a relative measure that compares the amount of heat trapped by the liquid gases in the air to the amount of heat absorbed by carbon dioxide, calculated over a period of 100 years [14].

#### I.4.1.3. Safety criteria

When selecting suitable working fluids, potential operational risks must be taken into consideration. Generally, it is preferable to use fluids that are non-toxic, non-flammable, and non-corrosive. However, in practice, it can be challenging to meet all these criteria simultaneously, so selecting a fluid that is relatively satisfactory is often sufficient during the selection process [13].

### I.4.1.4. Chemical and Thermal Stability

- Resistance to Thermal Decomposition: The fluid must be able to withstand high temperatures without undergoing chemical decomposition.

- Compatibility with System Materials: The fluid should be compatible with the materials used in the piping and other components to avoid corrosion or unwanted chemical reactions.

### I.4.1.5. Economic and Efficiency

- Cost**:** The fluid should be available at a reasonable cost.
- Thermal Conversion Efficiency**:** The fluid should have high efficiency in converting thermal energy into mechanical work.

## I.4.2. Thermophysical Properties

### I.4.2.1. Density

When dealing with fluids with extremely low condensation pressure, high vapor density is crucial, including silicone oils. When the density is low, the volumetric flow rate increases, which necessitates an increase in the size of the turbine and an increase in pressure within the heat exchangers [12].

### I.4.2.2. Viscosity

It is generally preferred that the viscosity be low for both the liquid and vapor phases to reduce pressure drop and enhance heat transfer**.**

### I.4.2.3. Specific Heat

In order to enhance the operational efficiency of the Organic Rankine Cycle system, the specific heat capacity of the fluid should be low to reduce energy consumption by the pump and improve performance indirectly [12].

### I.4.2.4. Thermal conductivity

To reduce the size of heat exchangers, especially the heat transfer area, it is preferable for the thermal conductivity rates to be high [13].

## I.5. Thermodynamic of the cycle

The Organic Rankine Cycle is a thermodynamic cycle used to convert low-grade heat into useful forms of energy, such as mechanical or electrical energy. It consists of a pump, an evaporator, a condenser, and a turbine, as shown in Figure 8.

It relies on four basic operations, illustrated in the (T-s) diagram**,** as shown in Figure 9.

- Process 1–2: Isentropic Compression The fluid is compressed in the pump isentropically, leading to an increase in its pressure.
- Process 2–3: Isobaric Heat Addition The fluid is heated at constant pressure to fully convert it into steam.
- Process 3–4: Isentropic Expansion in the Turbine The steam expands isentropically, converting its internal energy into mechanical work.
- Process 4–1: Isobaric Heat Rejection The steam is cooled at constant pressure in the condenser, where the heat is rejected to the surrounding environment and the steam is transformed into liquid, then it returns to the pump, and the cycle repeats [12].

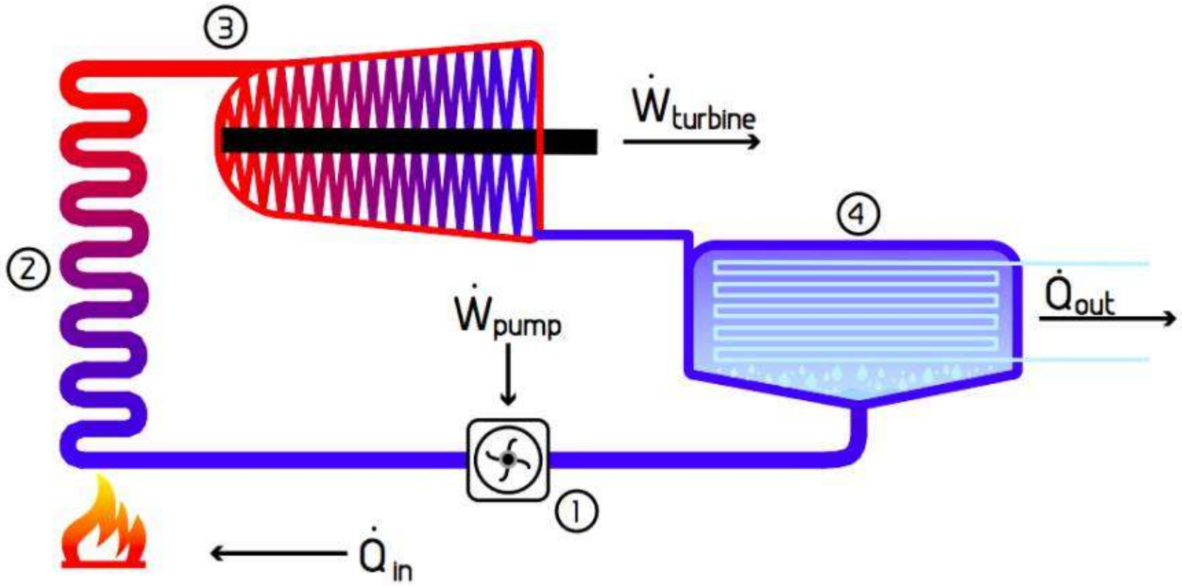


***Figure I.8.*** *Working Mechanism of the Organic Rankine Cycle*

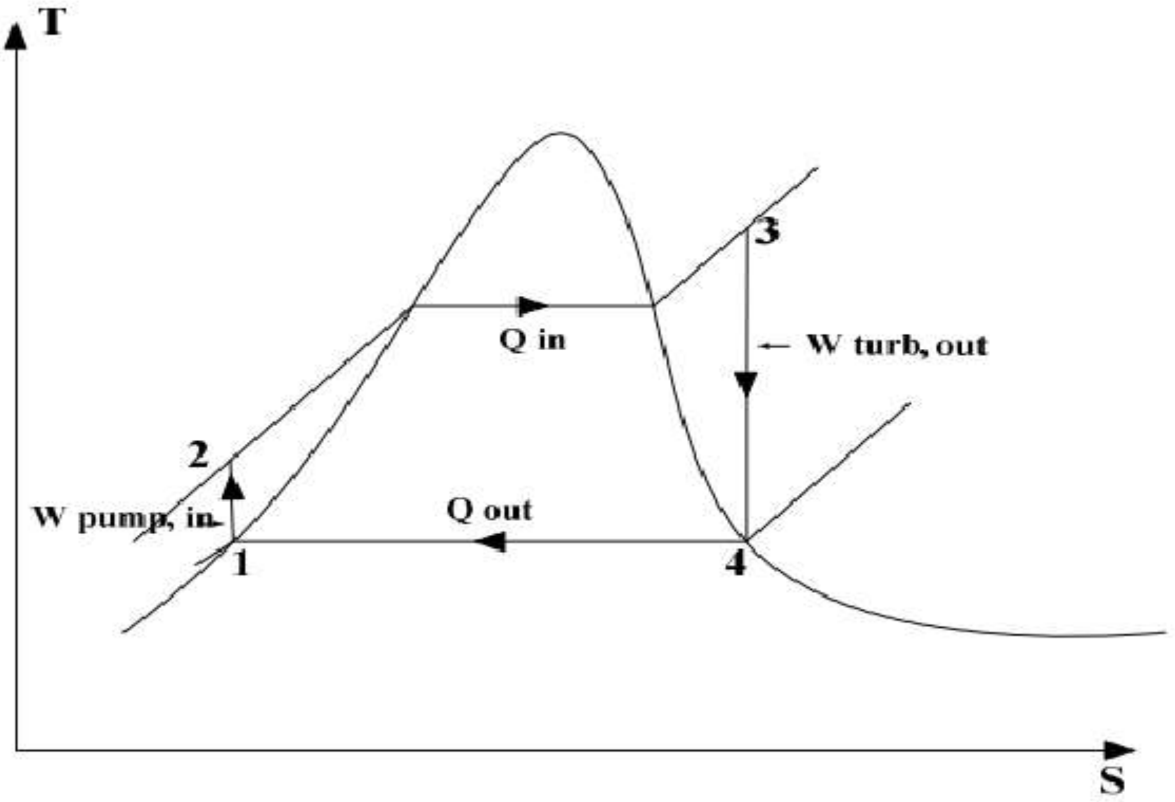


***Figure I.9.*** *Rankine cycle (T-s) diagram [40]*

Thermodynamic analysis within the scope of the Organic Rankine Cycle aims to evaluate the thermal efficiency of the system, study the mechanisms of heat transfer within its components, and the potential to generate energy efficiently by understanding the thermal and mechanical interactions between the working fluids and various components.

### I.5.1. Analysis of the thermal efficiency of the cycle

#### I.5.1.1. Definition of thermal efficiency

Thermal efficiency represents the ratio between the network produced by the cycle and the thermal energy absorbed in the evaporator [12]. It is calculated using the following equation:

$$\eta_{thermal} = \frac{Wnet}{Qin} \tag{1}$$

Where:

- $W_{net}$: The network produced by the cycle.

$$W_{net} = W_{turbine} - W_{pump} \quad (2)$$

$$W_{turbine} = \dot{m}\,(h_3 - h_4) \quad (3)$$

$$W_{pump} = \dot{m}\,(h_2 - h_1) \quad (4)$$

- $Q_{in}$: The thermal energy absorbed in the evaporator

$$Q_{in} = \dot{m}\,(h_3 - h_2) \quad (5)$$

$$\eta_{thermal} = \frac{Wturbine - Wpump}{Qin} \quad (6)$$

#### I.5.1.2. Determinants of efficiency

- The efficiency increases with the temperature of the heat source.
- Properties of the working fluid, including specific heat and boiling point.
- Enhancement of component efficiency: Optimizing the design of turbines and condensers.

### I.5.2. Heat transfer in the ORC cycle

The transfer of heat is a crucial component in the operation of the ORC cycle, mostly taking place in the evaporator and condenser.

#### I.5.2.1. the evaporator

The evaporator conveys heat from an external source, such as geothermal water, to the working fluid, facilitating its transformation from liquid to vapor state. The heat absorbed in the evaporator can be determined using the following equation:

$$Q_{in} = \dot{m}\,(h_3 - h_2) \quad (7)$$

Where:

- $\dot{m}$: the mass flow rate of the working fluid (kg/s).
- $h_2$: the enthalpy at evaporator inlet (J/mol).
- $h_3$: the enthalpy at evaporator outlet (J/mol).

### I.5.2.2. the condenser

The condenser transfers heat from the vapor of the working fluid to an external cooling medium (such as water or air), facilitating its conversion from vapor to liquid state. The heat expelled from the condenser to the ambient environment can be determined using the following equation:

$$Q_{out} = \dot{m}\,(h_4 - h_1) \qquad (8)$$

Where:

- $h_4$: the enthalpy at the exit of the turbine (J/mol).
- $h_1$: the enthalpy at the entrance of the pump (J/mol).
- $Q_{out}$: Heat Rejected in the Condenser (W or KW).

### I.5.2.3. Improving heat transfer

- Utilize high-efficiency heat exchangers, specifically plate or tubular types.
- Select organic fluids possessing appropriate thermodynamic characteristics (elevated vaporization heat, excellent thermal conductivity, etc.).

### I.5.3. Power generation

The power generation in the Organic Rankine Cycle refers to the conversion of heat into electricity using the turbine and the generator.

### I.5.3.1.The Turbine

The organic fluid vapor expands in the turbine, producing mechanical work. The generated mechanical work is calculated using the following equation:

$$W_{turbine} = \dot{m}\,(h_3 - h_4) \qquad (9)$$

### I.5.3.2. The Electric Generator

The mechanical work produced by the turbine is converted into electricity by the electric generator. It is calculated using the following equation:

$$P_{elect} = \eta_{gèn} . W_{turbine} \qquad (10)$$

$$P_{elect} = \eta_{gèn.} [\dot{m} (h_3 - h_4)] \qquad (11)$$

Were:

- $\eta_{gèn}$: is the efficiency of the electrical generator.

### I.5.3.3. Net electricity production

Net power is the difference between the electricity produced in the generator and the work consumed by the pump [15].

$$P_{(elect,\ net)} = P_{elect} - W_{pump} \qquad (12)$$

## I.6. Conclusion

The Organic Rankine Cycle (ORC) is an advantageous method for transforming thermal energy into electricity, especially at low to medium temperature ranges. It efficiently employs many heat sources, including solar energy, geothermal energy, and waste heat from industrial activities. A primary advantage of this technique is its adaptability in choosing working fluids (e.g., R245fa, R134a, or hydrocarbons). Furthermore, it possesses the capability to diminish greenhouse gas emissions, rendering it environmentally sustainable. The ORC exhibits reduced operational expenses relative to steam cycles.

However, the ORC encounters numerous obstacles. The preliminary expenses continue to be substantial, particularly for specialist apparatus such as heat exchangers. The system's sensitivity to fluctuations in heat sources is a concern, and thermal efficiency is generally lower, despite outperforming conventional cycles in some applications. Moreover, selecting the optimal working fluids that balance efficiency and environmental safety can be difficult. The technology also suffers from limited adoption due to a lack of technical expertise and competition from other energy recovery technologies.

Despite these challenges, the ORC remains a popular choice for energy transitions, provided that obstacles are addressed through improved system designs, more sustainable working fluids, and cost reductions to promote wider global adoption.

# Chapter II

# Waste Heat Recovery

# II.Waste Heat Recovery

## II.1. Introduction

In the early 2000s, some leading engine manufacturers began exploring more advanced methods of waste heat recovery; but today, in light of current environmental and economic challenges, coupled with the growing demand for energy in all its forms, there is a growing need for innovative solutions that support sustainability and reduce dependence on finite fossil fuels; Most low to moderate temperature renewable energy sources, such as solar, geothermal, biomass and industrial waste heat, are difficult to convert into electricity efficiently using conventional power generation technologies; Therefore, it is necessary to study several thermodynamic cycles, such as the RC, which has been extensively developed and can recover up to 30% of the wasted energy from both diesel engines and steam turbines; This energy is typically used to provide space and water heating in buildings such as hospitals and factories [16].

In this chapter, we have highlighted the most commonly used waste heat recovery methods and the most important practical applications of the organic Rankine cycle that utilizes this energy.

## II.2. Waste Heat

Waste heat is thermal energy that is dissipated into the environment without being harnessed to produce useful work, it is often medium or low grade, arises as a by product of industrial processes or human activities, increases proportionally with industrial technological infrastructure, in which therefore considered uneconomical to utilize [17].

The common understanding of the term ‘waste heat’ refers to heat that is released directly into the environment, and when considering the reuse of waste heat in industry, defining it as a potential primary energy alternative is critical to selecting appropriate waste heat recovery technologies [18].

While high temperature waste heat has already been reused in industrial processes, waste heat below 200°C and even more is still discharged to the environment [19].

However, in practice, industrial processes generate both avoidable and unavoidable waste heat, and due to the limitations imposed by the second law of thermodynamics, the distinction between avoidable and unavoidable waste heat must be made, which largely depends on system design and operational efficiency.

In terms of sustainable development and the fight against global warming, it is essential to recover and re-utilise this heat energy [20].

### II.2.1. Waste heat is categorised according to its carrier

- Flue gas (from combustion processes)
- Cooling fluids (water, oil, in cooling systems)
- Exhaust vapour (from turbines or industrial equipment)

### II.2.2. The importance of waste heat in the industrial context

The industrial sector is the most innovative in terms of energy efficiency, accounting for 21.7% of final energy consumption in Algeria; Recovering wasted heat in the Algerian industrial sector, particularly in the cement industry, is a significant step towards improving energy efficiency and reducing operational costs; An applied study in a cement factory in Algeria demonstrated the effectiveness of using organic and steam Rankine cycles to recover wasted heat, contributing to enhanced energy performance and reduced environmental impact. Therefore, focusing on recovering wasted thermal energy strengthens efforts and allows for the exploitation of new opportunities in the fields of innovation and energy saving, while also helping to revitalize the industry, thereby increasing competition among companies to improve their energy performance [21] [22] .

## II.3. Thermal energy recovery methods

Waste heat recovery methods involve capturing, converting and transferring waste heat into electrical, heat, or mechanical energy, which is an additional source of energy; The amount of waste heat available can be calculated using the equation below.

$$Q = V \times \rho \times Cp \times deltaT \tag{13}$$

Where, Q (J) is the heat content, V is the material flow rate ($m^3/s$), ρ is the flue gas density ($kg/m^3$), Cp is the specific heat of the material (J/kg.K) and deltaT is the difference in material temperature (K) between the highest final temperature at the outlet (Tout) and the initial temperature at the system inlet (Tin) [23].

## II.3.1. Recuperators

A type of heat exchanger that has separate flow paths, most of these recuperators operate as counter-flow heat exchangers, in this technology hot exhaust gases or an organic fluid is passed inside the pipes and cold air is introduced that comes into contact with them from the outside, This results in the transfer of heat from the pipes to the cold air, which leads to heating the air before it enters the process, for example, heat is recovered from the organic working fluid exiting the pump before entering the condenser, and used to heat the fluid coming from the pump before entering the evaporator [24].

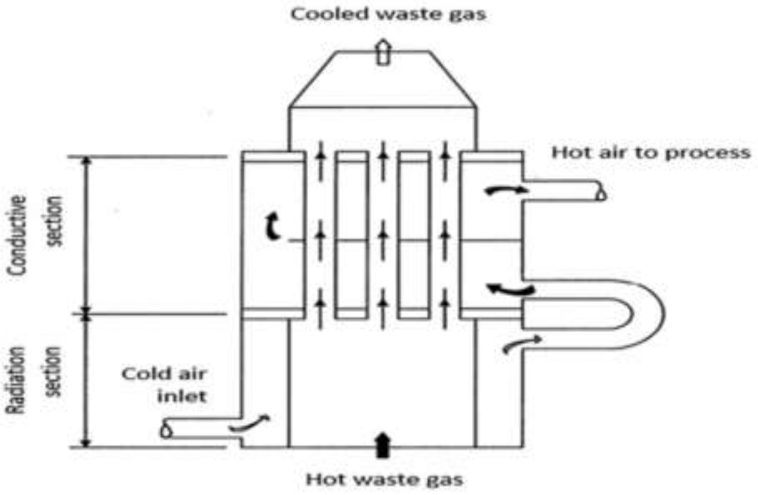


***Figure II.1.*** *Combined radiation and convective type recuperator [23].*

Recuperators are usually classified into radiation or convection types, and there is another type of recuperator that combines the advantages of both types, as it features a larger head with smaller tubes, allowing cold air to flow around the head, the material used in the manufacture of recuperators can be either ceramic or metal.

When temperatures are high, it is best to use metal recuperators, while ceramic ones are used at moderate temperatures, and their applications include blast furnaces, radiant tube burners, combustion furnaces and others [25].

## II.3.2. Regenerative/regenerative burners

Rotary regenerators regenerators use a rotating porous disk between two channels, one for hot source and the other for the cold one.

Whithin this system, heat wheels are typically limited to low to medium temperature applications due to the thermal stresses resulting from large temperature differentials, which can affect.

Same the integrity of the air seals, In some cases, ceramic wheels can be used for higher temperature applications; Heat wheels also face the challenge of preventing cross-contamination between gas streams due to the potential for pollutants to be transferred within the porous material of the wheel [26].

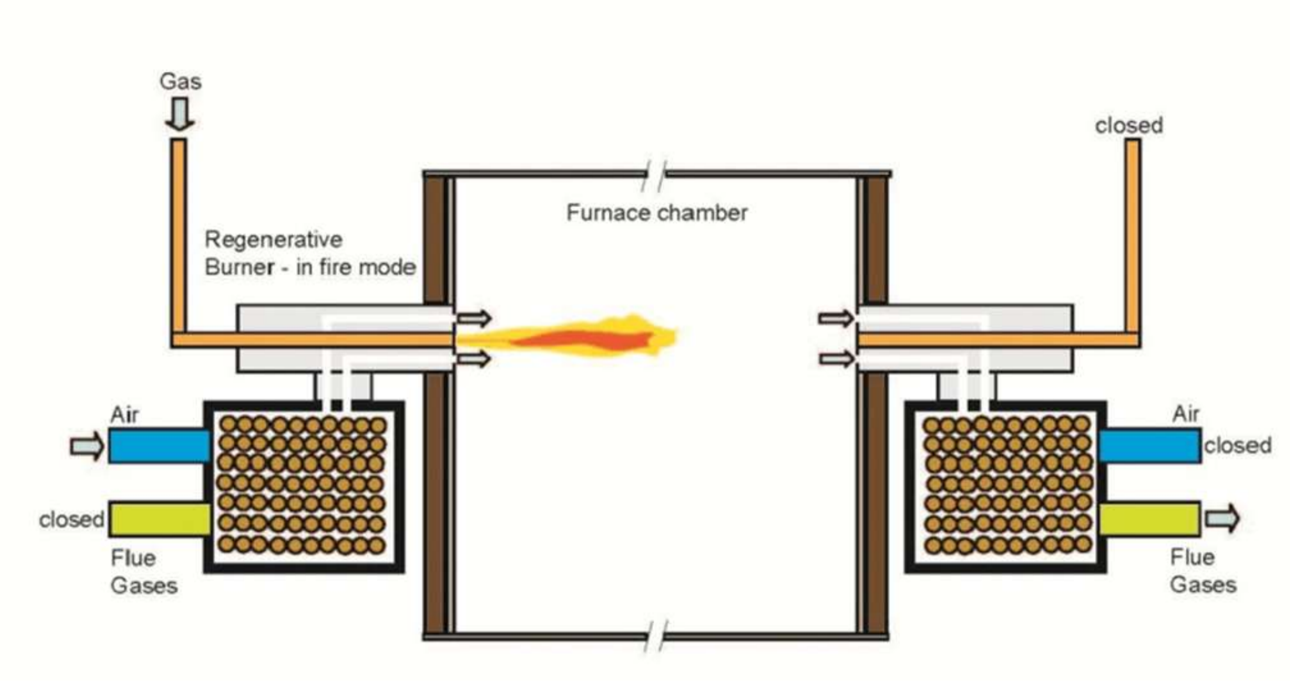


***Figure II.2.*** *Regenerative burner mechanism [27]*

### II.3.3. Organic Rankine Cycle

It is a closed system in which the working fluid moves periodically and repeatedly through four components to exploit and convert waste heat into mechanical or electrical energy, the working fluid under high pressure evaporates and then expands by passing through the turbine, where the energy generated through the expansion process drives a generator to produce electricity, this cycle is considered a typical example of a good power cycle and is used in many modern power plants [28].

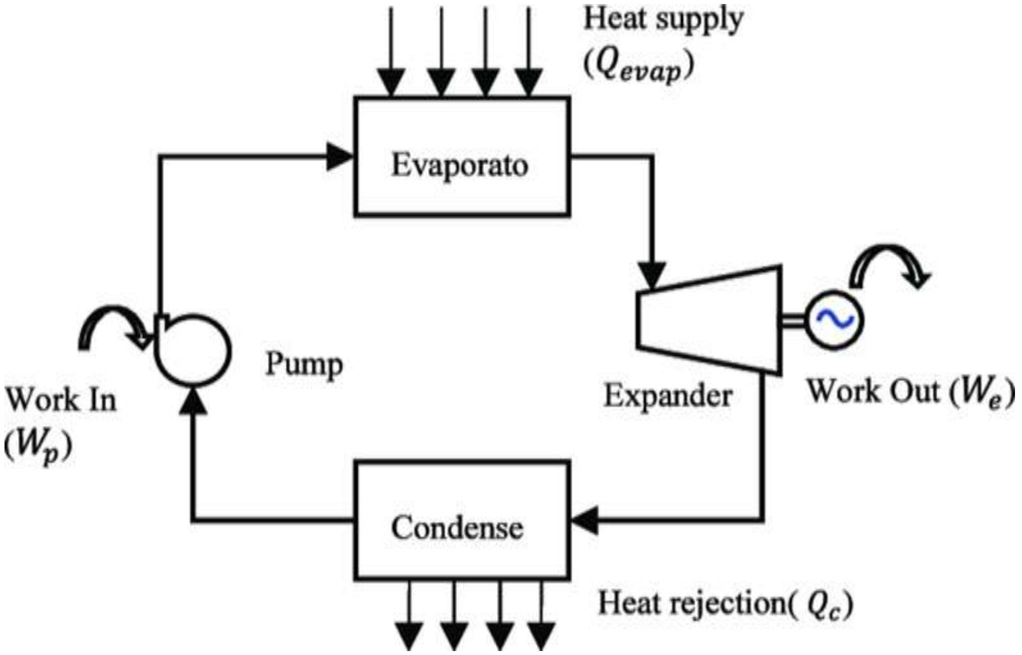


***Figure II.3.*** *Schematic of a Typical Organic Rankine cycle [29]*

### II.3.4. Waste heat boiler

A two-pass boiler used in medium to high temperature applications, consisting of water tubes arranged in parallel to recover heat from exhaust gases, the water tube boiler is used to produce steam by exchanging energy between the exhaust gases and cold water in parallel tubes [17 ].

### II.3.5. Economisers

It consists of a circular tube with fins to increase the surface area for heat transfer as it captures waste heat from the exhaust gases or the hot source and uses it to heat liquids, where the liquid that passes through the tubes is heated using the exhaust gases flowing through the finned tubes, and then the liquid is returned to the system, which increases and improves thermal efficiency.

We find this device in the production of hot water for domestic use as well as hot liquids for processes, heating and others [17].

### II.3.6. Heat Pumps

It is a thermodynamic device that takes heat and transfers it from a heat source to a heat sink using a small amount of heat, the heat pump uses a refrigeration cycle to produce hot air or water by extracting heat from a heat source and transferring it to the evaporator to heat the refrigerant at low pressure, then this refrigerant is sent to a compressor to produce a high pressure and high temperature gas that can be connected to a heat exchanger (condenser) [30].

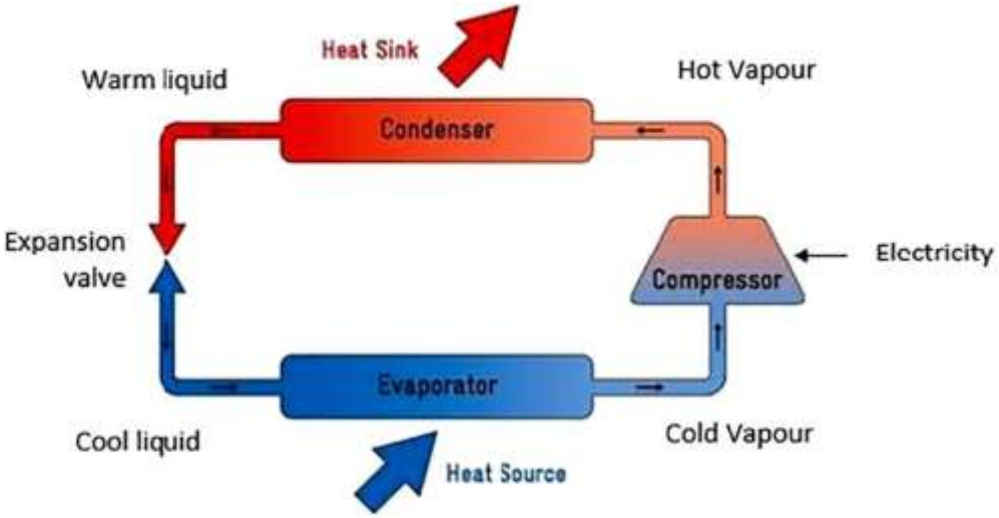


***Figure II.4.*** *Heat pump diagram in the context of WHR [23]*

### II.3.7. Waste heat boiler

A two-pass boiler used in medium to high temperature applications, consisting of water tubes arranged in parallel to recover heat from exhaust gases, the water tube boiler is used to produce steam by exchanging energy between the exhaust gases and cold water in the parallel tubes [17].

As industries are diverse and each item needs its own method of heat recovery, there are other methods as well:

- Thermoelectric generation
- Kalina cycle
- Air preheaters
- Rotary regenerators
- Heat Recovery Steam Generator (HRSG)

- Plate Heat Exchanger
- Heat Pipe Systems
- Piezoelectric Power Generation
- Direct Contact Condensation Recovery
- Inirect Contact Condensation Recovery
- Transport Membrane Condenser

### II.4. Practical applications of the ORC cycle to recover and use heat

The organic Rankine cycle is a key technology in the field of waste heat recovery in many industrial fields due to its simple configuration and acceptable efficiency, especially for low and medium grade temperatures, where the organic liquid is used as a medium to convert this waste heat that is discharged from the system into high quality energy to improve the overall energy use; A review the existing literature about the application of the organic Rankine cycle, its methodology of work and the different uses in waste heat recovery, the next points showed the various applications of this technology in at the industrial and energy sectors levels.

#### II.4.1. Geothermal energy

Geothermal energy is believed to be a viable solution to reduce and limit the effects of global warming and dependence on fossil fuels, so engineers sought to exploit low grade ground heat and convert it into electrical and mechanical energy, the organic Rankine cycle was considered a good technology to exploit geothermal sources, with low to medium temperatures as mentioned earlier, so that the organic Rankine cycle was characterised by its conversion of heat into electricity at a good rate, especially in areas with low and medium temperature, organic fluids with low boiling points are used here, making them suitable for these applications.

Worldwide, the global installed capacity of underground power plants using the organic Rankine cycle is estimated at about 3 GWe until the end of 2022, and is expected to reach 10 GWe by 2032, with an annual growth rate of approximately 12.8% during this period [17].

### II.4.2. Heavy industries

ORC systems are increasingly used in heavy industries such as cement, glass, steel, ceramics, etc.; to recover waste heat and convert it into electricity, This technology contributes to improve energy efficiency and reduce carbon emissions, for example: In the ceramics industry, a pilot study of the Organic Rankine Cycle (ORC) for low grade waste heat recovery in the ceramics industry, showed that by recovering heat from furnace gases at temperatures between 200 and 300 °C, the maximum efficiency of the cycle can reach 12.5% in terms of gross electrical efficiency and 11% in terms of net electrical efficiency.[23]

### II.4.3. The food industry

The food industry is characterised by the multiple evaporation and distillation processes it relies on, where mechanical vapour pressure heat pumps play an important role in increasing the temperature and pressure of the vapour produced by the evaporation units, the application of waste heat recovery technologies such as ORC in the food sector contributes to reducing energy and investment costs, and these technologies also have a positive impact on the environment by reducing the emission of greenhouse gases and improving the quality of the final products.

As mentioned before, the recovered heat can be used to heat water or generate electricity to power equipment. These applications are particularly useful in industries that require large amounts of heat, such as the dairy and canning industry [31].

## II.5. Conclusion:

Within the aim of this chapter, there is insightful conclusion that waste heat recovery is one of the most important modern strategies to improve the efficiency of thermal systems and reduce the environmental impact of industrial processes, it has become possible to generate additional energy in an effective and sustainable manner, and the ORC has emerged with its effective techniques, especially in environments that provide low to medium grade heat sources, and by relying on suitable working fluids, the ORC was able to find the issue of heat waste in various sectors, making it a promising option in the transition towards more sustainable energy systems.

# *Simulation Part*

# Chapter III

# Case Study

# III. Case Study

## III.1. Introduction

In industrial energy systems, especially in the petroleum sector, significant quantities of waste heat are produced and often underutilized. This chapter presents a selected case study of a petroleum processing plant located in southern Algeria, where high temperature flue gases are released as a by product of thermal processing units such as cracking furnaces, reforming reactors, and combustion chambers.

Due to the high operational demands and remote location of such facilities, there is a real need to optimize on site energy usage. Recovering this waste heat to generate electrical power through an Organic Rankine Cycle (ORC) system presents an efficient and cost-effective solution.

This case study is adopted as a means to perform a detailed thermodynamic assessment of ORC integration through the Algerian Petroleum Industries, focusing on the selection of suitable organic working fluids that could be adopted for ORC cycle and the development of a reliable thermodynamic model.

## III.2. Context and Industrial Relevance

The most of Algerian petroleum industries are located in southern Algeria, they play a central role in the national economy. However, these facilities typically operate with energy conversion efficiencies below 50%, meaning that more than half of the primary energy input is lost, mostly in the form of waste heat.

The selected facility in this study associated with hot flue gases through its production within its continuous process that operates 24 hours a day, making it an ideal candidate for such integration of technologies of thermal energy recovery. Currently, the plant employs limited recovery systems that preheat feed water or combustion air, but there are no advanced recovery systems such as that for power generation.

Therefore, this study focused on the integration of an ORC system that could:

- Reduce the plant’s reliance on external electricity,
- Improve overall efficiency and sustainability,

- Decrease fuel consumption and operating costs,
- Lower greenhouse gas emissions in compliance with environmental regulations.

## III.3. Characteristics of the Heat Source

The goal of this study is to recover exhaust gas that has been discharged to the atmosphere within this petroleum industry. This exhaust gas is characterized by the following properties:

***Table III.1.*** *Different parameters of Exhaust gas*

| Parameter | Value |
|---|---|
| Source | Flue gas from process heater/cracking unit |
| Location | Petroleum facility, southern Algeria |
| Average temperature | 1402.83 K |
| Mass flow rate | 56232 kg/h |
| Pressure | 1.5 bar |
| Estimated recoverable heat | ~15 MW (first-order estimate) |
| Expected electrical output | 2–3 MW (assuming 20% efficiency) |
| Thermal quality | High, requiring materials resistant to corrosion and thermal stress |

## III.4. Justification for ORC System Selection

Among waste heat recovery technologies, the Organic Rankine Cycle is particularly well-suited for low-to-medium grade thermal sources, but with appropriate working fluid selection, it can also be adapted for higher temperature ranges.

Benefits of integrating ORC cycle for the Selected Case:

- Closed loop system with minimal maintenance needs.
- Operates at lower pressures than traditional steam Rankine cycles, improving safety.
- Capable of employing a wide range of organic working fluids, each could be used for specific temperature ranges.
- Compact and modular easily integrated into existing installations.

Therefore, the ORC cycle could offer an efficient, scalable, and relatively low risk solution to recovery high grade waste heat and transform it into valuable electricity at petroleum industries.

## III.5. Selection and Evaluation of Working Fluids

The working fluid is a central component of any ORC system. It doesn't only affect the thermodynamic performance of the cycle, but also its safety, its environmental impact, its material compatibility, and its economic viability.

So, for this study, four different working fluids were selected to be screened, they are presented as follows:

- Benzene
- Toluene
- Acetone
- Cyclohexane

These selected working fluids were chosen based on their:

- Thermal stability limits suitable for high-temperature recovery,
- Availability and cost in the industrial market,
- Environmental and health risks,
- Established use or promising potential in high-temperature ORC research.

***Table III.2.*** *Different parameters of selected working fluids*

| **Property** | **Benzene [32]** | **Toluene [32]** | **Acetone [33]** | **Cyclohexane [33]** |
|---|---|---|---|---|
| Boiling Point (°C) | 80.1 | 110.6 | 56.05 | 80.7 |
| Critical Temperature (°C) | 288.9 | 318.6 | 235.0 | 280.5 |
| Thermal Stability (°C) | ~300 | ~350 | ~200 | ~300 |
| Environmental Risk | High (carcinogen) | Moderate | Moderate | Low |
| Availability | Industrial chemical | Widely available | Low-cost solvent | Commodity chemical |
| Application Type | High-temp ORC | High-temp ORC | High-temp ORC | High-temp ORC |
| Chemical formula | $C_6H_6$ | $C_7H_8$ | $C_3H_6O$ | $C_6H_{12}$ |
| Molecular weight (g/mol) | 78.11 | 92.14 | 58.08 | 84.16 |
| Critical temperature (Tc) C° | 288.9 | 318.6 | 235.0 | 280.5 |
| Critical pressure(pc) MPa | 4.89 | 4.11 | 4.70 | 4.07 |
| Global warming potential (GWP) | 4(For 100 years) | (~3) Estimated | 1(Low) | (~6) Estimated |
| Ozone depletion potential (ODP) | 0 | 0 | 0 | 0 |
| ASHRAE classification | A3 Highly flammable | A3 Highly flammable | A3 Highly flammable | A3 Highly flammable |

## III.6. Performance Expectations and Challenges

Each working fluid introduces specific challenges and opportunities:

**Benzene**

- Advantages: Excellent efficiency due to high latent heat and pressure ratios.
- Challenges: Highly toxic and carcinogenic; strict safety measures needed. Limited acceptability in commercial-scale ORC.

**Toluene**

- Advantages: High thermal stability and proven performance in ORC systems. Well-documented in the literature.
- Challenges: Still flammable and moderately toxic; must be handled according to safety protocols.

**Acetone**

- Advantages: Inexpensive and suitable for low-pressure systems. Useful for a dual-stage recovery system with high-temperature topping fluid and low-temp acetone bottoming.
- Challenges: Lower thermal stability and efficiency compared to the others.

**Cyclohexane**

- Advantages: Balanced option with lower toxicity. Can be an alternative to benzene with safer handling.
- Challenges: Less thermodynamic data available in high-temperature ORC applications; needs thorough modelling.

## III.7. Working Fluid Selection Methodology

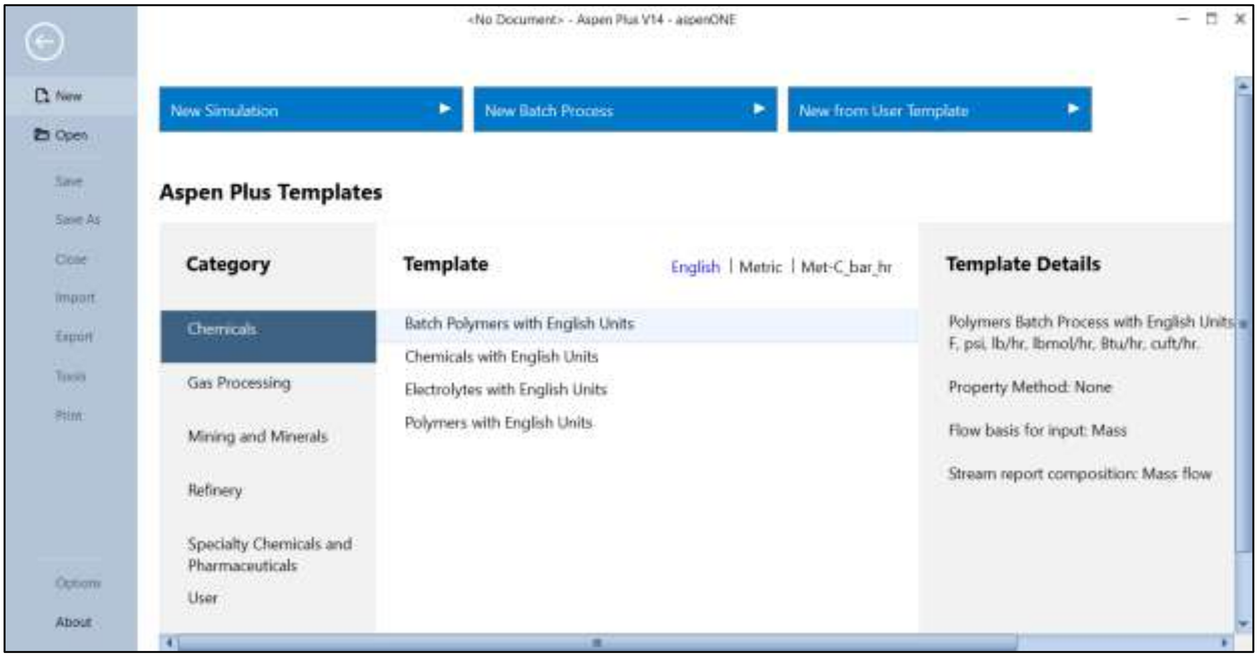
A multi-criteria decision-making approach is applied, combining thermodynamic performance in terms of net power output, efficiency, heat recovery

Simulation of each working fluid under identical heat source conditions will be conducted using Aspen Plus software. Results will be presented and compared in Chapter 4.

## III.8. Aspen Plus Software

### III.8.1. Definition of Aspen Plus

Aspen Plus is an advanced tool used for process modeling, simulation applications, design, performance analysis, optimization, and steady-state planning within industries such as chemicals, specialty chemicals, petrochemicals, and metallurgy. It is considered one of the most sophisticated process simulation tools in engineering, relying on precise mathematical models and comprehensive databases concerning the physical and chemical properties of materials [34].



Polymers Batch Process with English Units
F, psi, lb/hr, lbmol/hr, Btu/hr, cuft/hr.

Property Method: None

Flow basis for input: Mass

Stream report composition: Mass flow

***Figure III.1.*** *Aspen Plus window*

### III.8.2. Characteristics of Aspen Plus [34]

- The software relies on mathematical models to predict process performance.
- Engineers can use the program to simulate processes in order to optimize existing designs.

- It provides accurate modeling of thermodynamic properties.
- Aspen Plus includes a built-in database of pure and binary component parameters that have been re-evaluated.
- The program is capable of handling highly complex processes.
- Aspen Plus enables comprehensive process simulation and performance evaluation under various operating conditions.
- The software helps reduce operational risks associated with industrial processes.
- Aspen Plus enhances both the economic and technical efficiency of industrial facilities.
- The program is considered a fundamental tool in the fields of chemical engineering and energy.

### III.8.3. Thermodynamic Models [35]

Models based on equations of state, such as Redlich-Kwong (RK), Soave-Redlich-Kwong (SRK), and Peng-Robinson (PR), are among the most commonly used tools for analyzing hydrocarbon systems and systems that approach ideal behavior. Their ability to accurately represent interactions between components using binary interaction coefficients makes them highly valuable. These equations provide a mathematical framework that allows for the calculation of all physical and chemical properties of the components, such as pressure, temperature, volume, and density, based on molar composition and operating conditions.

Among these equations, the Peng-Robinson equation is distinguished by its higher accuracy in estimating liquid phase properties compared to the Soave equation. The attraction term in the Peng-Robinson equation has been modified to enhance the accuracy of density calculations and liquid phase properties without the need to introduce new parameters. This makes it suitable for many industrial applications, especially in simulating separation processes and complex liquid mixtures.

The mathematical expression for the Peng-Robinson equation is as follows:

$$\boldsymbol{p} = \frac{\boldsymbol{RT}}{\boldsymbol{V-b}} - \frac{\boldsymbol{a(T)}}{\boldsymbol{V(V+b)+(V-b)}} \tag{14}$$

Where (p) represents pressure, (T) is temperature, (V) is volume, and (a(T)) and (b) are parameters that depend on the material properties and temperature. This allows the model to adapt to different operating conditions and achieve accurate predictions of the behavior of multi-component systems.

The parameters (a ($T_R$)) and (b) are defined as follows:

$$a = 0.45724\frac{R^2T_C^2}{P_C}a(T_R) \quad (15)$$

The term (a ($T_R$)) has the same general form as in the case of the Soave equation:

$$a(T_R) = \left[1 + m(1 - \sqrt{T_R})\right]^2 \quad (16)$$

However, the function relating the parameter (m) to the acentric factor (omega) is different:

$$m = 0,37464\,\omega + 1,54226 - 0,26992\omega^2 \quad (17)$$

These equations are widely used in simulation models for gas production and processing. The most recommended equation for hydrocarbon systems is the Pang-Robinson equation, as it aligns more closely with actual values compared to other equations.

Moreover, regarding the temperature and pressure where Peng Robinson could be adopted, the following table lists the limitation of this model [36]

***Table III.3.*** *Range of Temperature and Pressure for Peng Robinson Model*

| Parameter | Typical Range |
|---|---|
| Temperature (T) | ~0.5 to 2.0 × Tc (critical temperature) |
| Pressure (P) | up to about 200 bar (20 MPa) |

## III.9. Conclusion

In conclusion, Aspen Plus is an advanced and effective tool for simulating industrial processes, and it serves as an essential element in the field of chemical engineering, This software provides engineers with the ability to analyze, design, and optimize complex systems with precision and efficiency, helping to increase productivity, reduce costs, and improve safety levels within industrial facilities, With the rapid advancement of modern technologies, it has become essential for engineers today to master the use of tools like Aspen Plus to ensure they maintain their competitiveness and meet the demands of the job market.

# *Chapter IV*

# *Results and Discussion*

# IV. Results and Discussion

## IV.1. Introduction

Sensitivity analysis is an essential step for understanding and enhancing the performance and efficiency of the Organic Rankine Cycle (ORC), guaranteeing optimal results in energy recovery and economic viability. The ORC system, intended to capture low and medium grade waste heat and transform it into usable energy, necessitates careful calibration for best performance. Enhancing characteristics such as working fluid selection, operating conditions (pressure, temperature), and system architecture can substantially elevate the total energy efficiency of the cycle. This technique improves thermal and electrical production while reducing operational expenses and environmental effect.

Implementing an improved ORC system in an industrial environment can yield significant advantages. Industries frequently produce significant quantities of waste heat via exhaust gases, heated water streams, or various thermal processes. In the absence of recovery methods, this energy is generally dissipated into the environment, signifying a squandered potential for energy conservation. An optimally designed ORC may harness this otherwise squandered heat and transform it into electricity, diminishing dependence on external power sources and decreasing energy expenses. Furthermore, the incorporation of an ORC system is consistent with global sustainability objectives by reducing carbon emissions and enhancing the overall energy efficiency of industrial processes.

Within the selected case study, a sensitivity analysis has been conducted on the basic configuration of ORC cycle, where the variation of various parameters took place as a means to fully understand the direct influence of them on the performance of the cycle, these parameters represented in the evaporation pressure, the condensation pressure, and the efficiencies of the Turbine and Pump.

## IV.2. Simulation of ORC cycle using Aspen Plus

The simulation of the ORC cycle took place through the use of Aspen Plus software, within the goal of evaluation of the thermodynamic behaviour of the system under various operating conditions. As defined in Chapter III, the Peng-Robinson fluid package was adopted for modelling the thermophysical properties of the working fluids, due to its reliability in handling non-ideal behaviour of organic compounds at elevated pressures and temperatures. The ORC cycle in its architecture includes four principal components: the evaporator, turbine, condenser, and pump, all connected in a closed-loop configuration (see Figure IV-1). Each unit operation was built using standard Aspen Plus blocks, with inputs defined for mass flow rates, inlet temperatures, and pressures, simulating the recovery of waste heat of the selected case study. Recovered heat was applied at the evaporator to vaporize the working fluid, which then expands through the turbine to generate mechanical power. The vapour is subsequently condensed within the condenser device and pumped back by the pump to complete the cycle. After achieving steady-state convergence, the model was validated to serve as a baseline for the upcoming sensitivity analysis, which explores the effect of varying key cycle parameters on system efficiency and output performance.

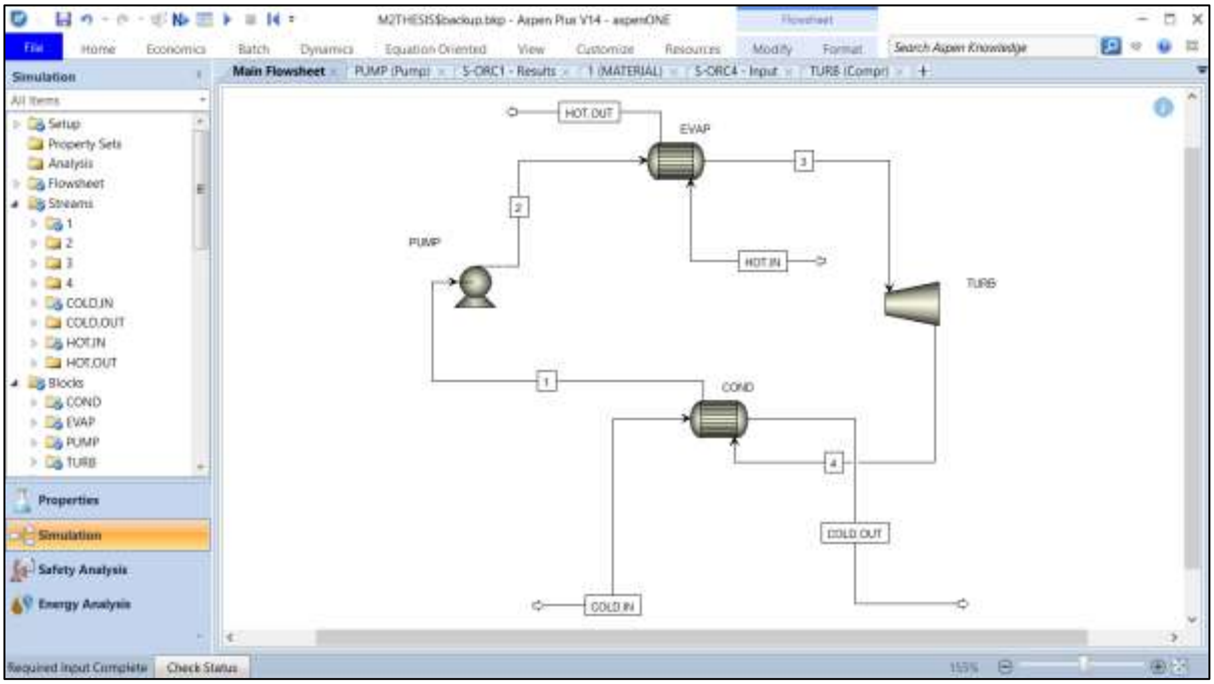


*Figure IV.1.* *ORC cycle scheme in Aspen Plus software*

## IV.3. Influence of different parameters on net power output of the cycle

### IV.3.1- Influence of $p_{evap}$ on Net Power Output

***Table IV.1.*** *$W_{net}$ of selected fluids vs $p_{evap}$*

| $p_{evap}$ | $W_{net\text{-}Benzene}$ | $W_{net\text{-}Toluene}$ | $W_{net\text{-}Acetone}$ | $W_{net\text{-}Cyclohexane}$ |
|---|---|---|---|---|
| 5 | 1029 | 956 | 731 | 968 |
| 10 | 1518 | 1413 | 1294 | 1436 |
| 15 | 1811 | 1687 | 1618 | 1720 |
| 20 | 2017 | 1878 | 1836 | 1920 |
| 25 | 2173 | 2020 | 1992 | 2072 |
| 30 | 2294 | 2129 | 2107 | 2189 |

The results outlined in Table IV-1 illustrate the variation of net power output of the cycle ($W_{net}$) as a function of evaporation pressure ($p_{evap}$) for the selected working fluids; Benzene, Toluene, Acetone, and Cyclohexane.

It is clear that for all screened fluids, increasing $p_{evap}$ leads to a significant increase in net power output of the cycle, highlighting a direct relationship between the evaporating pressure and the energy recovery potential of the cycle. Among the analysed fluids, Benzene exhibits the highest net power output across all pressure levels, reaching a maximum of 2294 kW at 30 bar. This is followed closely by Cyclohexane (2189 kW), which also demonstrates good performance due to its favourable thermodynamic properties under elevated pressure conditions. Acetone shows the lowest values of $W_{net}$ throughout the range, although it still benefits from the pressure increase, improving from 731 kW at 5 bar to 2107 kW at 30 bar. Toluene's performance lies intermediate between Benzene and Acetone, suggesting a balance between volatility and thermal stability. These results emphasize the importance of selecting an optimal working fluid in conjunction with an appropriate evaporator pressure to maximize cycle efficiency and power output.

### IV.3.2. Influence of $p_{cond}$ on Net Power Output

**Table IV.2.** *$W_{net}$ of selected fluids vs $p_{cond}$*

| $p_{cond}$ | $W_{net\text{-}Benzene}$ | $W_{net\text{-}Toluene}$ | $W_{net\text{-}Acetone}$ | $W_{net\text{-}Cyclohexane}$ |
|---|---|---|---|---|
| 1 | 2294 | 2129 | n.a | 2189 |
| 2 | 1811 | 1661 | 2107 | 1707 |
| 4 | 1316 | 1189 | 1545 | 1221 |
| 6 | 1026 | 916 | 1212 | 940 |
| 8 | 822 | 727 | 977 | 745 |
| 10 | 667 | 583 | 796 | 597 |

Table IV.2 shows the change in net power output ($W_{net}$) of the ORC cycle for various working fluids—benzene, toluene, acetone, and cyclohexane—relative to condenser pressure ($p_{evap}$). The results clearly illustrate an inverse correlation between condenser pressure and net power production, wherein $W_{net}$ substantially lowers as $p_{evap}$ increases.

At all condenser pressures, benzene always gives off the most power, reaching a peak of 2294 kW at 1 bar and then dropping to 667 kW at 10 bar. This better performance is due to its good thermodynamic qualities, which make energy extraction efficient even when pressures change. Toluene follows a similar pattern, but its $W_{net}$ values are lower, running from 2129 kW at 1 bar to 583 kW at 10 bar. This means that it is more sensitive to rising condenser pressure than benzene. Acetone doesn't work well at low condenser pressures (we don't have data at 1 bar), but it can hit 2107 kW at 2 bar and then drop sharply to 796 kW at 10 bar. This shows that acetone is very sensitive to changes in pressure and may need precise pressure optimization to work well. The efficiency of cyclohexane is average. It starts at 2189 kW at 1 bar and drops to 597 kW at 10 bar, keeping a balance between power output and thermal stability.

### IV.3.3. Influence of $\eta_{is,turb}$ on Net Power Output

***Table IV.3.*** *$W_{net}$ of selected fluids vs $\eta_{is,turb}$*

| $\eta_{is,turb}$ | $W_{net\text{-}Benzene}$ | $W_{net\text{-}Toluene}$ | $W_{net\text{-}Acetone}$ | $W_{net\text{-}Cyclohexane}$ |
|---|---|---|---|---|
| 0.6 | 1698 | 1574 | 1556 | 1617 |
| 0.65 | 1847 | 1712 | 1694 | 1760 |
| 0.7 | 1996 | 1851 | 1831 | 1903 |
| 0.75 | 2145 | 1990 | 1969 | 2046 |
| 0.8 | 2294 | 2129 | 2107 | 2189 |
| 0.85 | 2443 | 2268 | 2244 | 2332 |

Table IV.3 presents a comprehensive analysis of the performance of four working fluids (Benzene, Toluene, Acetone, Cyclohexane) in an ORC cycle as the isentropic turbine efficiency ($\eta_{is,turb}$) varies from 0.6 to 0.85. The results clearly demonstrate a direct proportional relationship between improved turbine efficiency and increased net power output.

Benzene provides exceptional performance at all efficiency levels, $W_{net}$ values span from 1698 kW (at $\eta_{is,turb}$=0.6) to 2443 kW (at $\eta_{is,turb}$=0.85), shows the highest absolute performance increase (745 kW) across the studied efficiency range. Cyclohexane ranks second, sustaining its robust performance with values between (1617-2332 kW), reflecting an increase of 715 kW as efficiency enhances. Toluene exhibits an average performance ranging from 1574 to 2268 kW. Acetone exhibits the lowest values among the analyzed fluids, ranging from 1556 kW to 2244 kW.

### IV.3.4. Influence of $\eta_{pump}$ on Net Power Output

***Table IV.4.*** *$W_{net}$ of selected fluids vs $\eta_{pump}$*

| $\eta_{is,turb}$ | $W_{net\text{-}Benzene}$ | $W_{net\text{-}Toluene}$ | $W_{net\text{-}Acetone}$ | $W_{net\text{-}Cyclohexane}$ |
|---|---|---|---|---|
| 0.6 | 2265 | 2099 | 2075 | 2156 |
| 0.65 | 2274 | 2108 | 2085 | 2166 |
| 0.7 | 2282 | 2116 | 2093 | 2175 |
| 0.75 | 2288 | 2123 | 2100 | 2182 |
| 0.8 | 2294 | 2129 | 2107 | 2189 |
| 0.85 | 2299 | 2135 | 2112 | 2195 |

Table IV.4 illustrates the correlation between pump efficiency and net power output for four principal working fluids in ORC cycle.

The highest-performing benzene (2299-2265 kW) consistently outperforms at all efficiency levels, followed by cyclohexane (2156-2195 kW), which has a comparable response to benzene. Toluene has average performance (2099-2135 kW), whilst acetone demonstrates the lowest performance (2075-2112 kW).

## IV.4. Obtained results through sensitivity analysis

### IV.4.1. Benzene

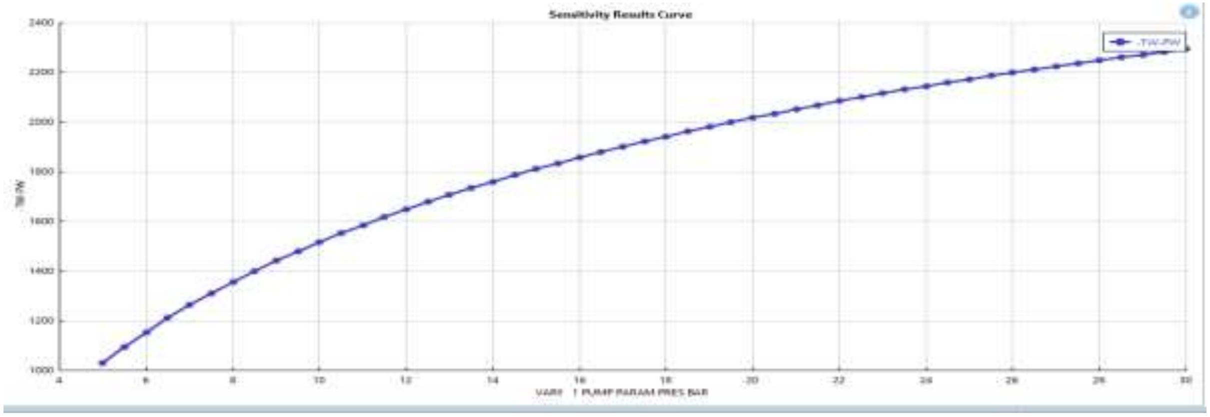


**Figure IV.2.** *$W_{net}$ vs $p_{evap}$ employing Benzene as a work fluid*

Figure IV.2 displays the sensitivity analysis results for the net power output ($W_{net}$) of the ORC cycle using benzene as the working fluid, as simulated in Aspen Plus. The curve demonstrates a clear and continuous increase in net power output with rising evaporator pressure ($p_{evap}$), ranging from 5 to 30 bar. This behaviour highlights the enhancement of cycle performance under higher pressure conditions, where the working fluid expands through the turbine with a greater enthalpy difference, resulting in higher mechanical work output. The rate of increase is more pronounced at lower pressures, while it gradually flattens as pressure approaches 30 bar, indicating diminishing performance gains beyond a certain threshold. This suggests that although higher evaporator pressures improve power generation, the benefits taper off due to increasing thermal and mechanical constraints within the cycle. The simulation confirms the effectiveness of benzene under varying pressure conditions and demonstrates the usefulness of Aspen Plus in conducting parametric studies for ORC optimization.

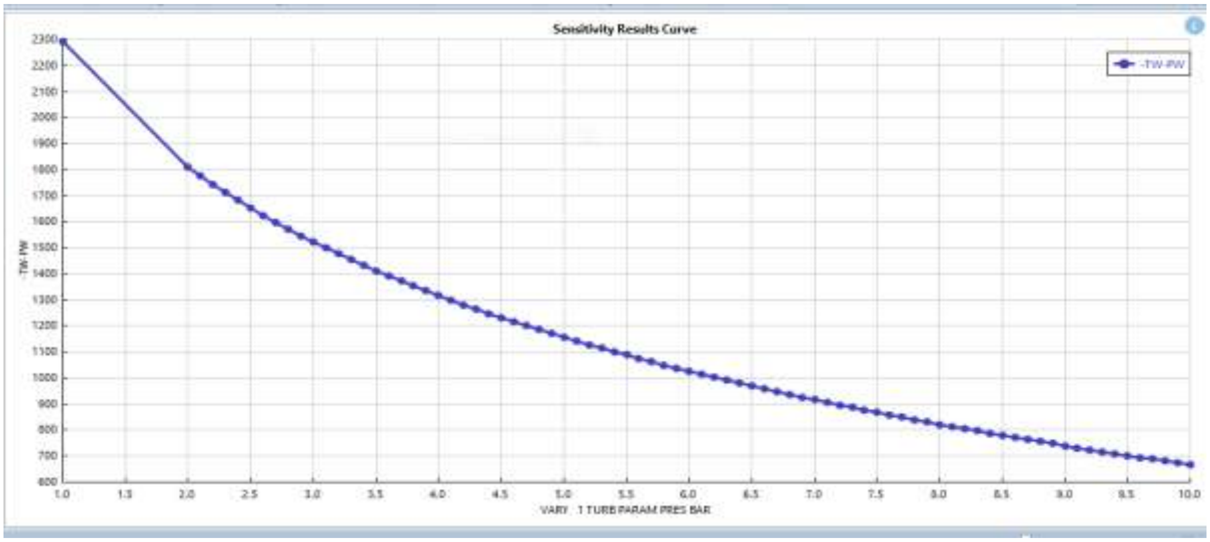


**Figure IV.3.** *$W_{net}$ vs $p_{cond}$ employing Benzene as a work fluid*

Figure IV.3 shows the results of the sensitivity analysis concerning the power differential between the turbine and the pump in the ORC cycle, as simulated in Aspen Plus. The graph illustrates a distinct increase in power differential as turbine pressure escalates from 1 to 10 bar, signifying that elevated pressure decreases the system's net power output. The decrease is significant at lower pressures and rapidly lessens at higher pressures, indicating a nonlinear reducing curve. It may be explained to higher internal losses or diminished enthalpy differential throughout the turbine. The results underscore the significance of choosing an adequate turbine pressure for best performance and illustrate the efficacy of Aspen Plus in evaluating system behavior across various operating situations.

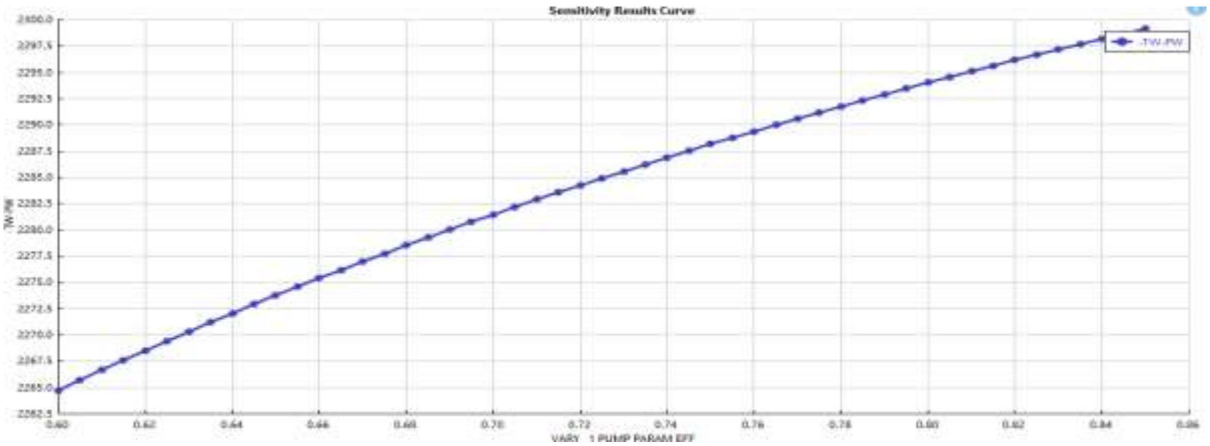


**Figure IV.4.** *$W_{net}$ vs $\eta_{is, pump}$ using Benzene as a working fluid*

Figure IV.4 illustrates the outcomes of the sensitivity analysis regarding the turbine-pump power differential ($W_{net}$) within the ORC cycle, utilizing Aspen Plus software. This figure examines the impact of Pump Efficiency, which varies from 0.60 to 0.85. The graph indicates that enhancing pump efficiency results in a progressive increase in the ($W_{net}$) power differential. Increased efficiency results in reduced energy consumption by the pump, hence enhancing the net power output of the cycle.

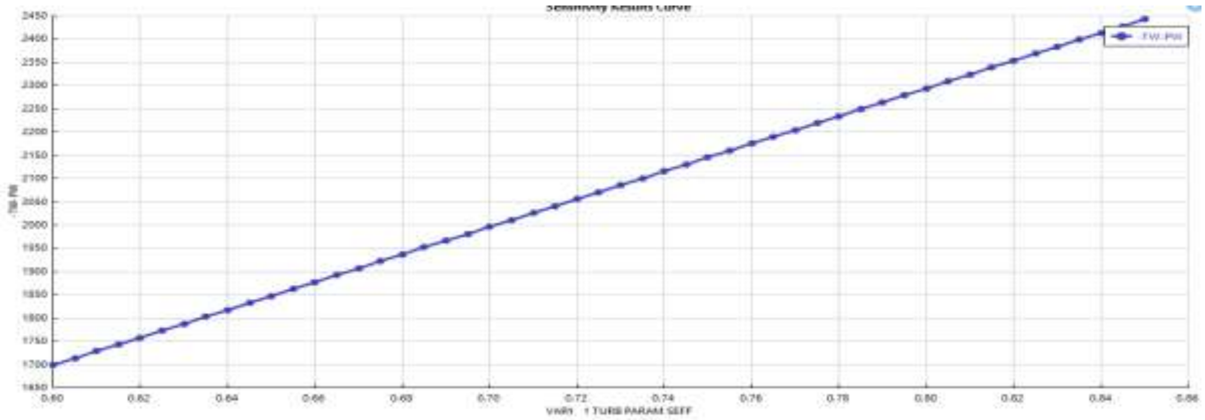


***Figure IV.5.*** *$W_{net}$ vs $\eta_{is,turb}$ using Benzene as a working fluid*

Figure IV.5 displays the outcomes of a sensitivity analysis about the turbine-pump power differential ($W_{net}$) in the ORC cycle, as depicted by Aspen Plus software. This review examined the impact of Turbine Efficiency, which varied from 0.60 to 0.85. The graph illustrates a distinct linear development in power differential corresponding to the rise in turbine efficiency. This signifies that enhancing turbine efficiency results in a direct augmentation of energy recovered from the cycle, as mechanical losses diminish and the available thermal energy is more effectively utilized. Any minimal enhancement in turbine efficiency results in a substantial advancement in total performance, illustrating the necessity of having high-efficiency turbines in the design of ORC systems.

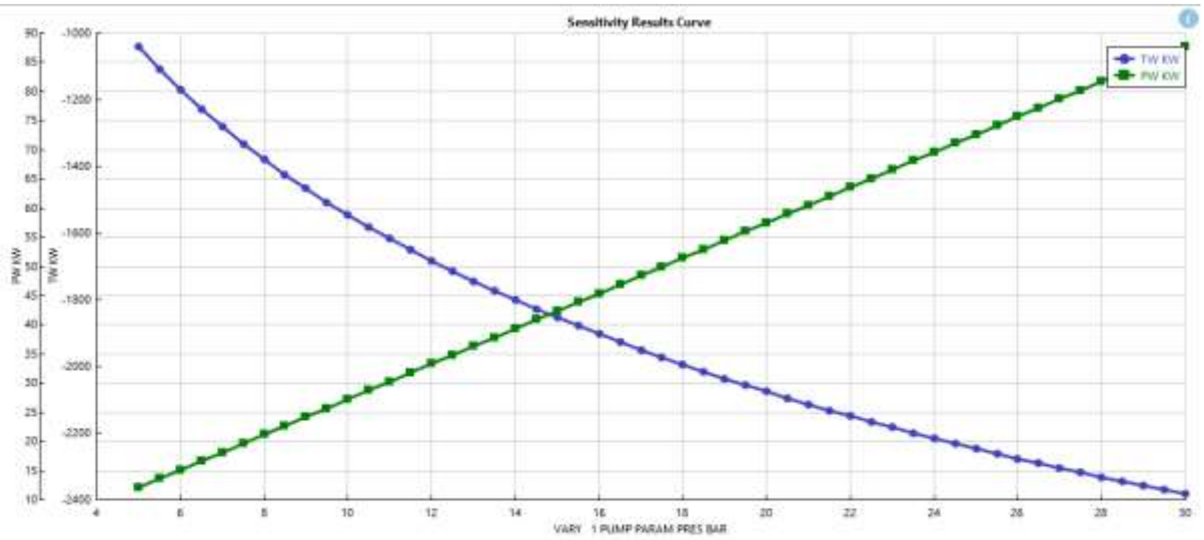


***Figure IV.6.*** *$W_{turb}$ and $W_{pump}$ vs $p_{evap}$ using Benzene as a working fluid*

Figure IV.6 presents the outcomes of the sensitivity analysis for turbine ($W_{tur}$b) and pump ($W_{pump}$) power within the ORC cycle, derived from Aspen Plus simulations, with evaporator pressure varying from 5 to 30 bars. The blue curve ($W_{tur}$b) illustrates an increasing expansion in turbine power related to a change in evaporator pressure. This results from the increased enthalpy differential across the turbine, which optimizes the expansion process and elevates power output. Conversely, the green curve ($W_{pump}$) shows an almost linear increase in pump power with rising pressure, as more work is needed to achieve higher evaporation pressures.

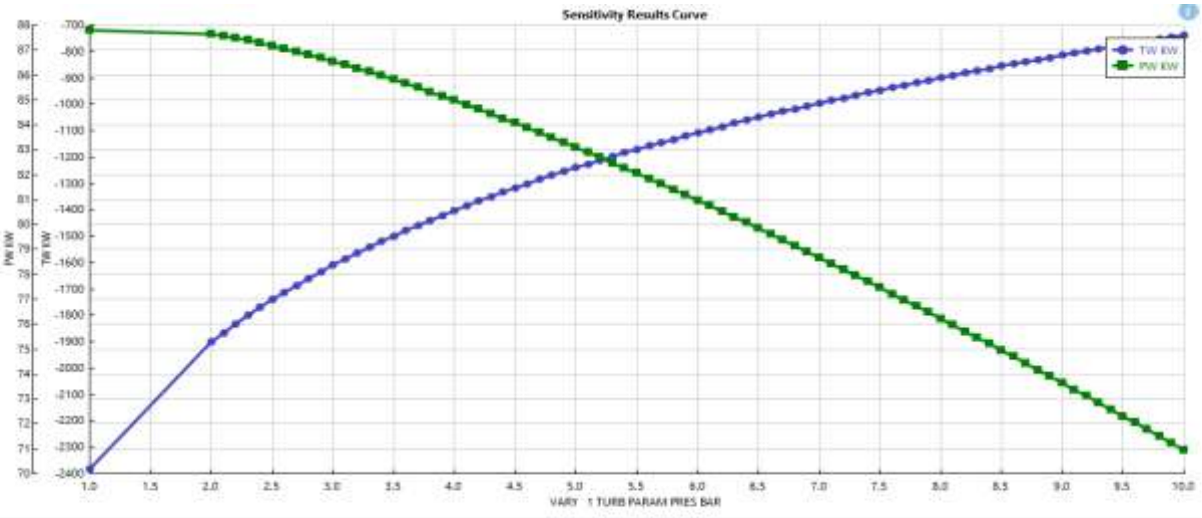


***Figure IV.7.*** *$W_{turb}$ and $W_{pump}$ vs $p_{cond}$ using Benzene as a working fluid*

Figure IV.7 shows the outcomes of the sensitivity analysis for turbine power output ($W_{tur}$b) and pump power consumption ($W_{pump}$) in the ORC cycle about condenser pressure, varying from 1 to 10 bars. The analysis relies on simulations performed with Aspen Plus. The blue curve ($W_{tur}$b) illustrates a distinct decrease in turbine power output with an increase in condenser pressure. This reduction results from the reduced enthalpy difference across the turbine, which constrains the quantity of mechanical work that can be extracted. The effect is more significant at reduced pressures, where the enthalpy decrease is greater. As the pressure nears 6 bar, performance stabilizes, signifying that the system is approaching a steady functioning condition. Meanwhile, the green curve ($W_{pump}$) illustrates a progressive reduction in pump power usage with the rise in condenser pressure. This is probably attributable to a diminished pressure differential across the pump, necessitating less energy for operation.

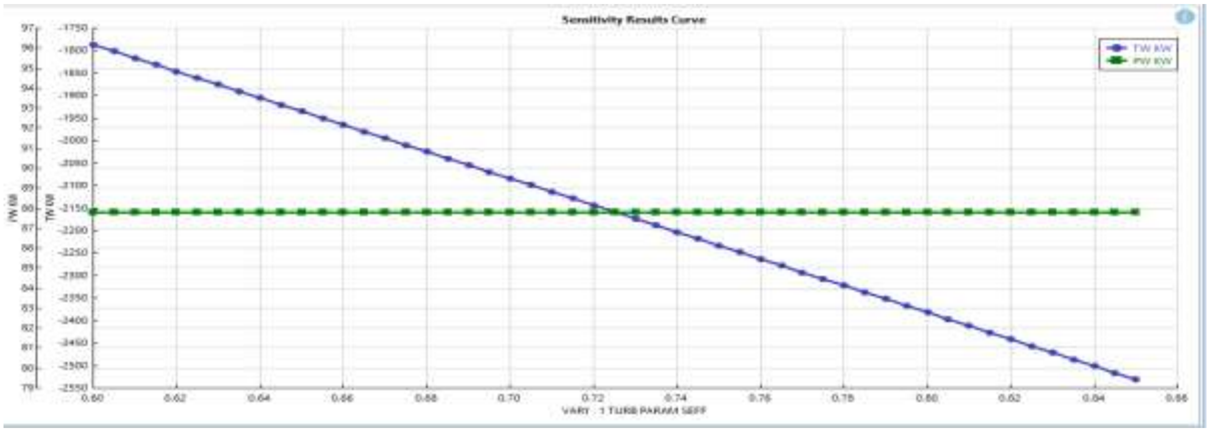


***Figure IV.8.*** *$W_{turb}$ and $W_{pump}$ vs $\eta_{is,turb}$ using Benzene as a working fluid*

Figure IV.8 displays the findings of the sensitivity analysis for turbine power output ($W_{tur}$b) and pump power consumption ($W_{pump}$) within the ORC cycle, utilizing benzene as the working fluid. The analysis utilized Aspen Plus simulations, with turbine isentropic efficiency ($\eta_{is,tu}{}^{t}$b) ranging from 0.60 to 0.85. The blue curve ($W_{tur}$b) demonstrates a distinct rise in turbine power output corresponding to enhancements in turbine efficiency. This tendency is attributed to the increased turbine efficiency, which enables greater mechanical work extraction from an equivalent thermal energy input, thereby improving the system's overall performance. Conversely, the green curve ($W_{pump}$) remains very stable, suggesting that turbine efficiency exerts minimal to no immediate effect on pump power. This is anticipated, as the pump functions in a distinct portion of the cycle, independent of the turbine's efficacy.

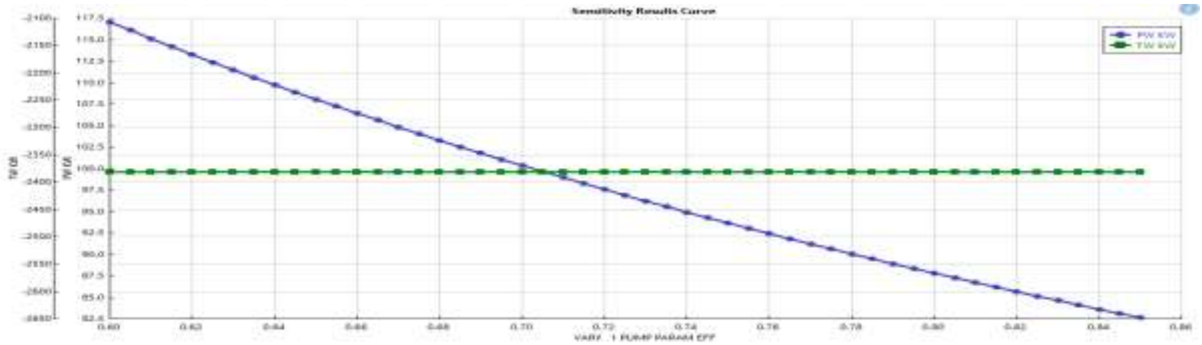


***Figure IV.9.*** *$W_{turb}$ and $W_{pump}$ vs $\eta_{is,\ pump}$ using Benzene as a working fluid*

Figure IV.9 illustrates the results of a sensitivity analysis about pump isentropic efficiency in the Organic Rankine Cycle (ORC), performed utilizing Aspen Plus with benzene as the working fluid. The pump efficiency ranges from 0.60 to 0.85. The green curve ($W_{pump}$) illustrates a distinct reduction in pump power consumption as efficiency enhances, as a more efficient pump necessitates less input energy to attain the equivalent pressure increase. The blue curve ($W_{tur}$b) remains rather stable, signifying that pump efficiency does not directly influence turbine power output.

### IV.4.2. Toluene

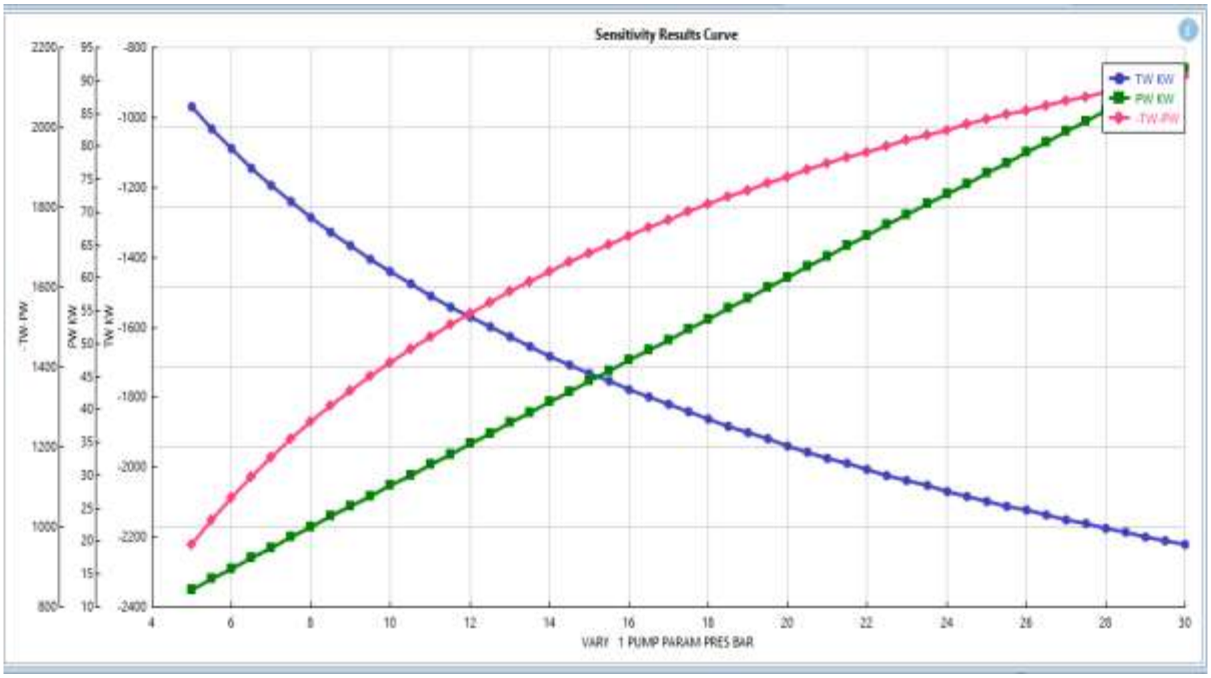


***Figure IV.10.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $p_{evap}$ using Toluene as a working fluid*

Figure IV.10 illustrates the outcomes of a sensitivity research regarding turbine power ($W_{tur}$b), pump power ($W_{pump}$), and net power production ($W_{net}$) within the Organic Rankine Cycle (ORC), executed utilizing Aspen Plus with toluene being the working fluid. The analysis encompasses evaporator pressures between 4 and 30 bars. The blue curve ($W_{tur}$b) illustrates an improving enhancement in turbine power related to the increase in evaporator pressure, because to the increasing enthalpy differential across the turbine. The green curve ($W_{pump}$) exhibits a nearly linear ascent with pressure, as elevated pressure necessitates increased energy for pump operation. The red curve ($W_{net}$) illustrates a progressive augmentation in net power output with increasing pressure, as the disparity between turbine output and pump demand expands, hence improving cycle performance.

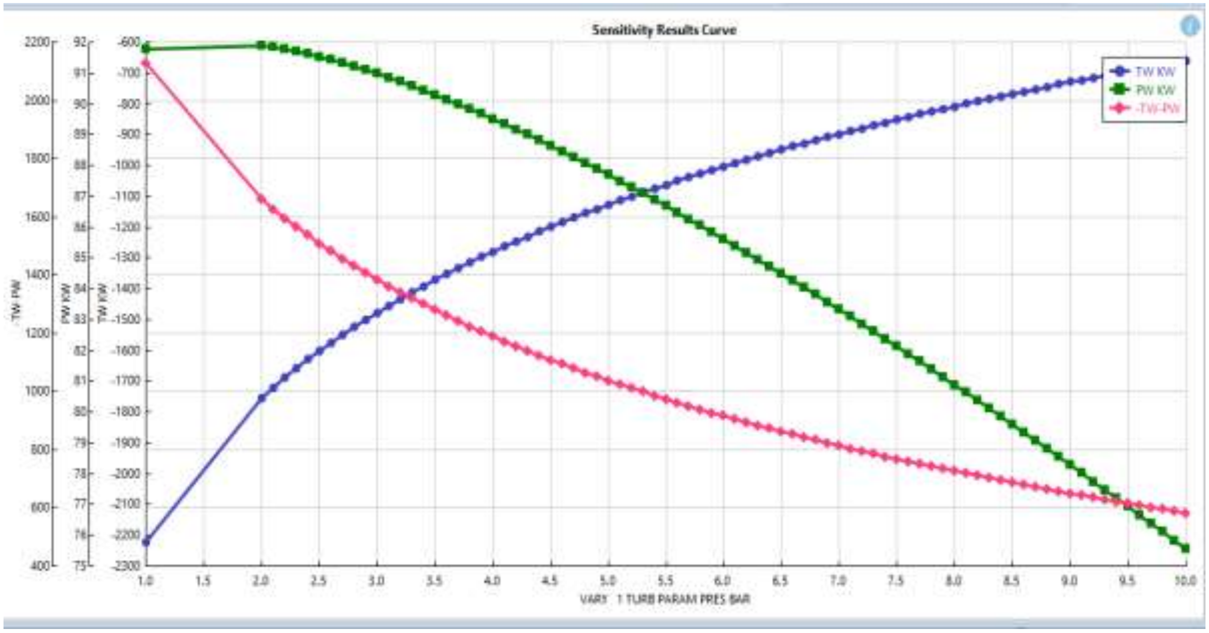


***Figure IV.11.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $p_{cond}$ using Toluene as a working fluid*

Figure IV.11 illustrates the results of a sensitivity analysis for turbine power ($W_{tur}$b), pump power ($W_{pump}$), and net power output ($W_{net}$) in the ORC cycle, utilizing Aspen Plus simulations with toluene as the working fluid. The analysis examines condenser pressure (turbine outlet pressure) within the range of 1 to 10 bars. The blue curve ($W_{tur}$b) illustrates that turbine power output diminishes as condenser pressure rises, attributable to a decreased enthalpy drop across the turbine.
The green curve ($W_{pump}$) illustrates a notable reduction in pump power consumption as condenser pressure rises, due to the pump operating against a decreased pressure differential. The red curve

($W_{net}$) shows that net power output is maximum at a condenser pressure of 1 bar and then decreases as pressure rises, proving that optimal system performance is achieved at lower pressures.

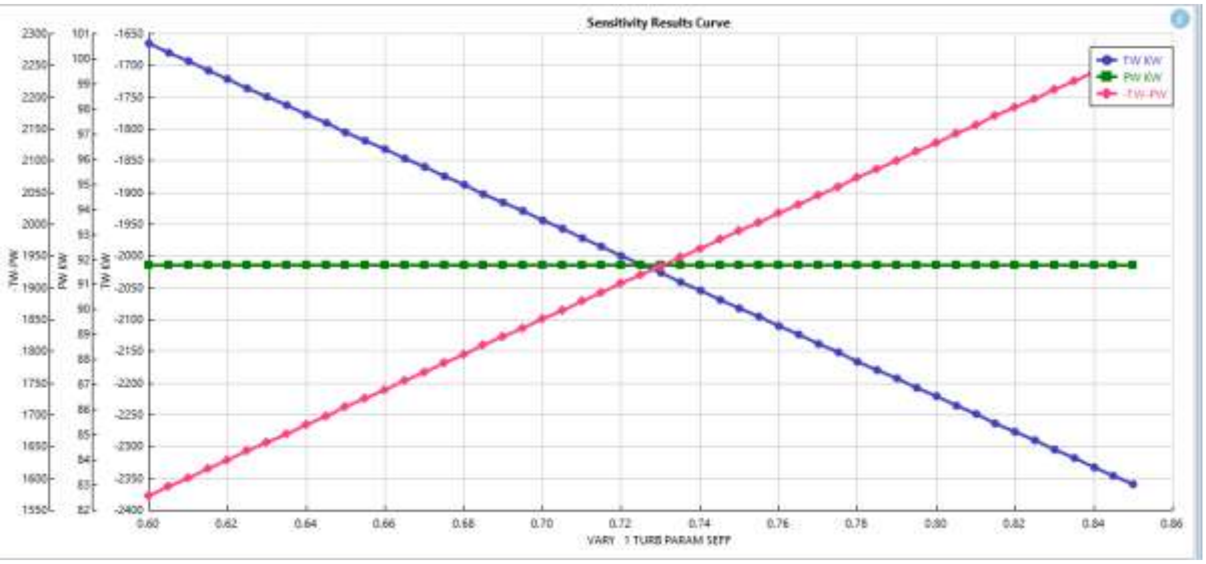


**Figure IV.12.** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $\eta_{is,turb}$ using Toluene as a working fluid*

Figure IV.12 illustrates the outcomes of a sensitivity analysis concerning turbine isentropic efficiency in an Organic Rankine Cycle, utilizing Aspen Plus simulations with toluene as the working fluid. The turbine efficiency ranges from 0.60 to 0.85. The green curve ($W_{pump}$) remains very stable over the efficiency range, suggesting that variations in turbine efficiency have minimal impact on pump power usage. The blue curve ($W_{tur}$b) rises gradually as turbine efficiency enhances, as a more efficient turbine derives greater work from the same thermal energy input. The red curve ($W_{net}$) displays a consistent ascent with enhanced turbine efficiency, indicating an improvement in overall system performance as net power output grows.

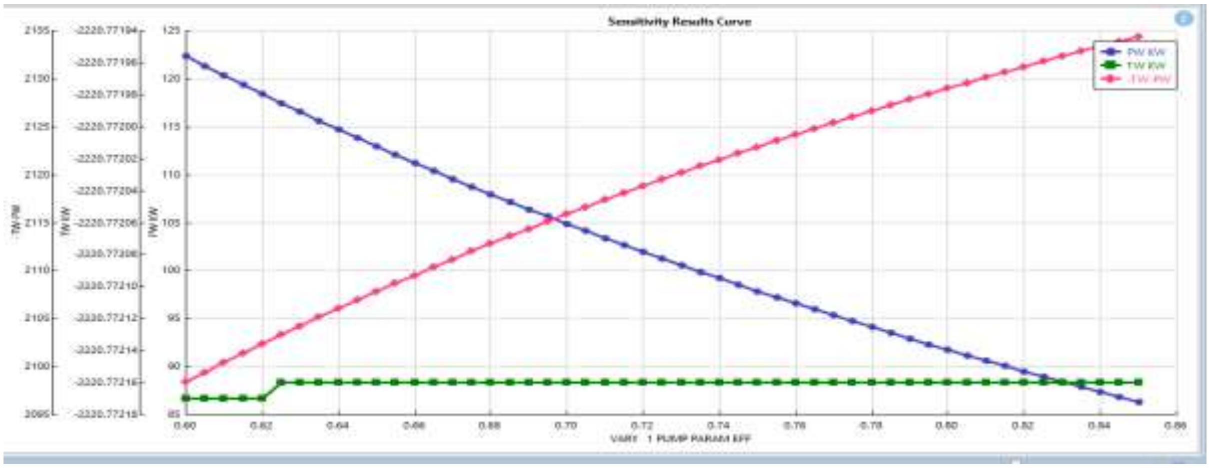


**Figure IV.13.** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $\eta_{is, pump}$ using Toluene as a working fluid*

Figure IV.13 illustrates the outcomes of a sensitivity study regarding pump isentropic efficiency in the Organic Rankine Cycle, with efficiency values varying from 0.60 to 0.85, derived from Aspen Plus simulations utilizing toluene as the working fluid. The green curve ($W_{tur}$b) remains rather stable, signifying that turbine power output is unaffected by variations in pump efficiency. The blue curve ($W_{pump}$) exhibits a progressive decline as pump efficiency enhances, as a more efficient pump requires less power to attain the equivalent pressure increase. The red curve ($W_{net}$) shows a distinct rise in net power production as pump efficiency improves, indicating superior overall system performance related to less internal energy losses.

### IV.4.3. Acetone

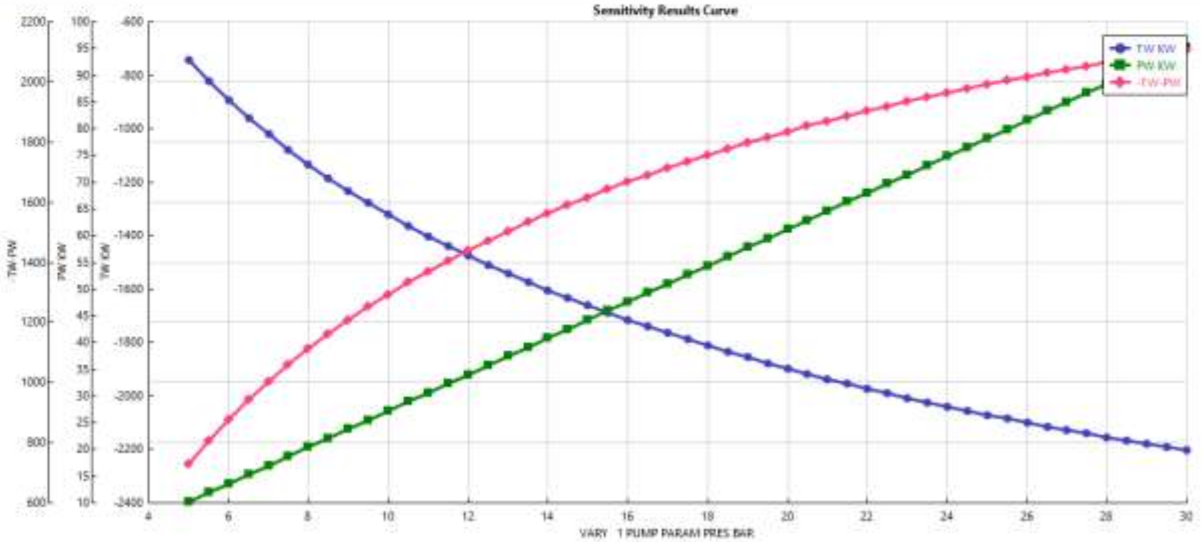


*Figure IV.14.* *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $p_{evap}$ using Acetone as a working fluid*

Figure IV.14 illustrates the outcomes of a sensitivity analysis concerning turbine power ($W_{tur}$b), pump power ($W_{pump}$), and net power output ($W_{net}$) inside the ORC cycle, utilizing Aspen Plus with acetone as the working fluid. The analysis examines pump (evaporator) pressures between 4 and 30 bar. The blue curve ($W_{tur}$b) demonstrates that an increase in pump pressure results in an elevation in turbine power output, attributable to a more significant enthalpy drop over the turbine. The green curve ($W_{pump}$) illustrates a nearly linear increase in power consumption with rising pump pressure, since greater energy is necessitated to achieve elevated evaporation pressures. The red curve ($W_{net}$) exhibits a progressive increase, signifying that the optimization of pump pressure augments the disparity between turbine output and pump usage, thus enhancing overall cycle efficiency.

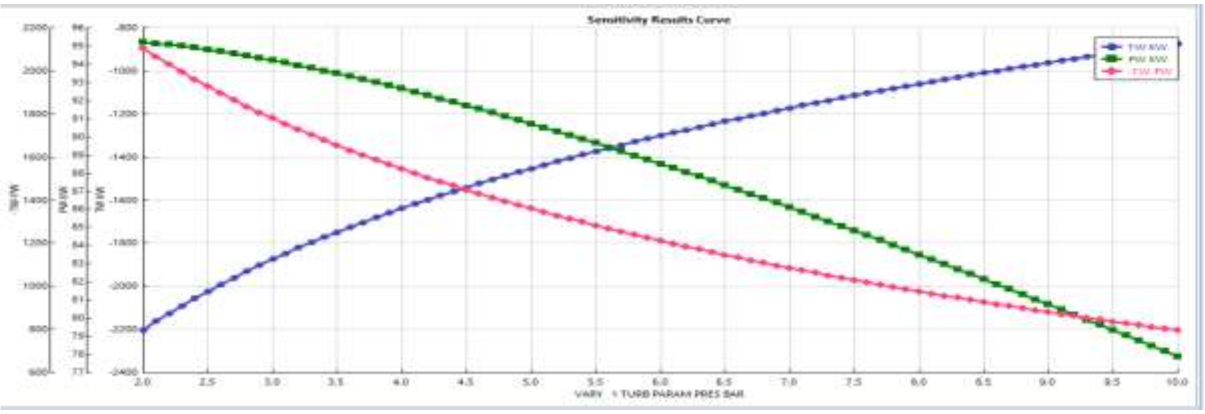


***Figure IV.15.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $p_{cond}$ using Acetone as a working fluid*

Figure IV.15 illustrates the results of a sensitivity analysis concerning turbine power ($W_{tu}^{\beta}$b), pump power ($W_{pump}$), and net power output ($W_{net}$) inside the Organic Rankine Cycle (ORC), derived from Aspen Plus simulations with acetone as the working fluid. The investigation investigates the impact of condenser pressure (turbine outlet pressure) within a range of 1 to 10 bars. The blue curve ($W_{tur}$b) shows a distinct decrease in turbine power output as condenser pressure rises, attributable to a diminished enthalpy drop over the turbine. The green curve ($W_{pump}$) exhibits a progressive reduction in pump power usage as condenser pressure rises, due to the less pressure lift required by the pump. The red graph ($W_{net}$) displays a declining trend in net power output as condenser pressure rises, signifying that the cycle attains enhanced efficiency at reduced pressures.

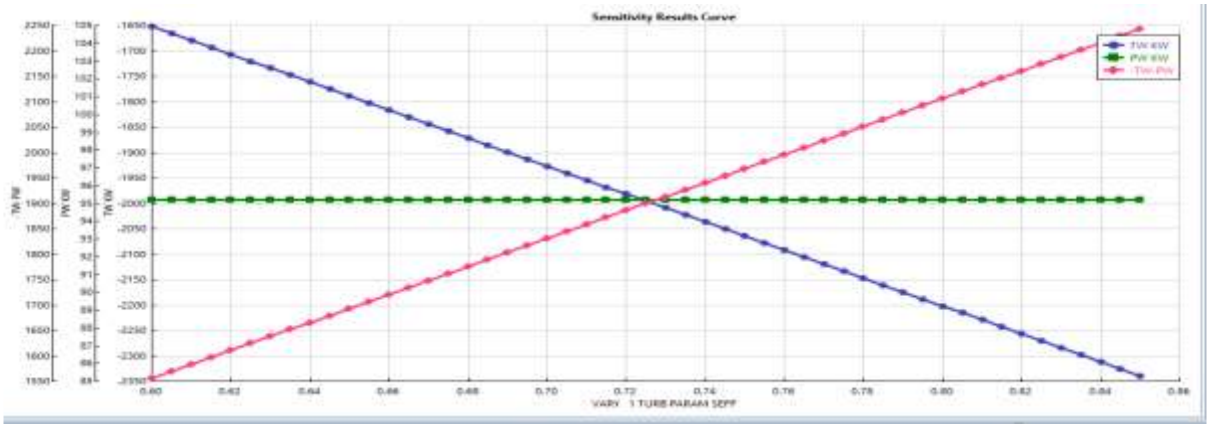


***Figure IV.16.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $\eta_{is,turb}$ using Acetone as a working fluid*

Figure IV.16 illustrates the outcomes of a sensitivity analysis on turbine isentropic efficiency within the Organic Rankine Cycle, with efficiency values varying from 0.60 to 0.85, derived from Aspen Plus simulations utilizing acetone as the working fluid. The green curve ($W_{pump}$) remains very stable over the efficiency spectrum, suggesting that variations in turbine efficiency have minimal impact on pump power usage. The blue curve ($W_{tur}$b) illustrates a progressive enhancement in turbine power output corresponding to improved efficiency, as a more efficient turbine can derive greater mechanical work from an equivalent quantity of thermal energy. The red curve ($W_{net}$) exhibits a consistent increase, indicating enhanced net power output and overall system performance as turbine efficiency improves.

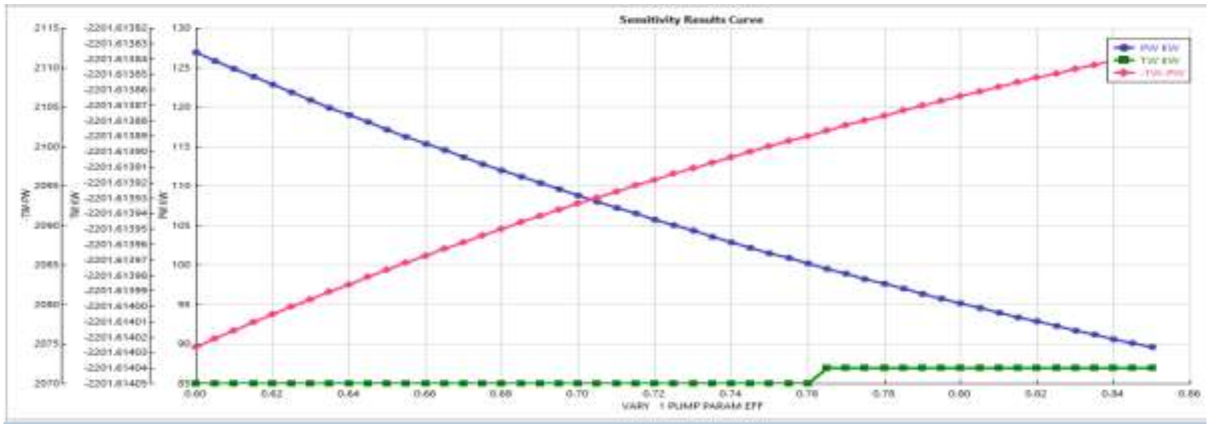


***Figure IV.17.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $\eta_{is,\ pump}$ using Acetone as a working fluid*

Figure IV.17 illustrates the outcomes of a sensitivity study regarding pump isentropic efficiency in the Organic Rankine Cycle, employing Aspen Plus simulations with acetone as the working fluid. The efficiency values span from 0.60 to 0.85. The green curve ($W_{tur}$b) remains rather stable over the efficiency range, signifying that turbine power output is not influenced by variations in pump efficiency. The blue curve ($W_{pump}$) illustrates a progressive decline, indicating a decrease in pump energy usage as efficiency enhances. The red curve ($W_{net}$) illustrates a consistent rise, indicating that increased pump efficiency amplifies the disparity between turbine output and pump demand, hence enhancing total cycle performance.

### IV.4.4. Cyclohexane

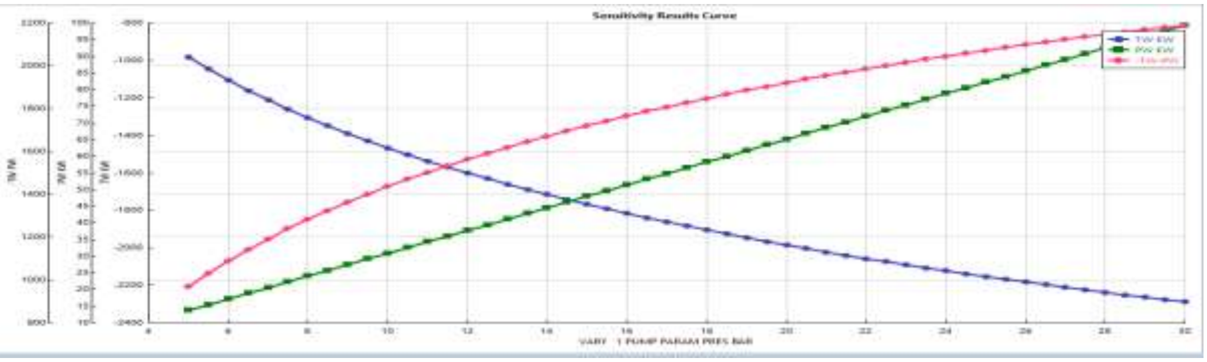


***Figure IV.18.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $p_{evap}$ using Cyclohexane as a working fluid*

Figure IV.18 illustrates the results of a sensitivity analysis for turbine power ($W_{tur}$b), pump power ($W_{pump}$), and net power production ($W_{net}$) inside the Organic Rankine Cycle (ORC), derived from Aspen Plus simulations with cyclohexane as the working fluid. The analysis examines pump (evaporator) pressures between 4 and 30 bar. The blue curve ($W_{tur}$b) indicates that turbine power output escalates with elevated pump pressure, attributed to the increased enthalpy loss across the turbine. The green curve ($W_{pump}$) exhibits a nearly linear increase as pump pressure escalates, since greater energy is necessitated to attain elevated evaporation pressures. The red curve ($W_{net}$) demonstrates a progressive ascent, signifying that the optimization of pump pressure amplifies the disparity between turbine production and pump usage, hence enhancing total cycle efficiency.

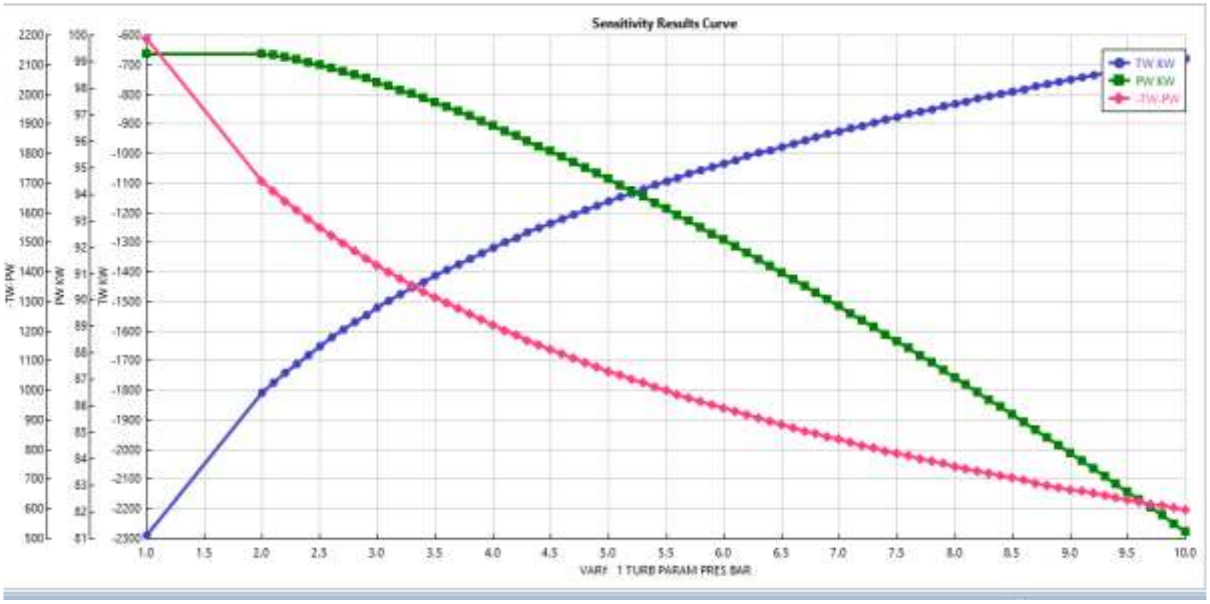


***Figure IV.19.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $p_{cond}$ using Cyclohexane as a working fluid*

Figure IV.19 presents the outcomes of a sensitivity study concerning turbine power ($W_{tur}b$), pump power ($W_{pump}$), and net power production ($W_{net}$) within the Organic Rankine Cycle (ORC), derived from Aspen Plus simulations utilizing cyclohexane as the working fluid. The analysis studies condenser pressures (turbine outlet pressures) between 1 and 10 bar. The blue curve ($W_{tur}b$) illustrates a distinct decrease in turbine power output as condenser pressure rises, attributable to a diminished enthalpy drop over the turbine. The green curve ($W_{pump}$) illustrates a minimal reduction in pump power usage as condenser pressure rises, due to the pump operating against a diminished pressure differential. The red curve ($W_{net}$) illustrates a declining trend in net power output as condenser pressure rises, signifying that cycle efficiency is superior at reduced condenser pressures.

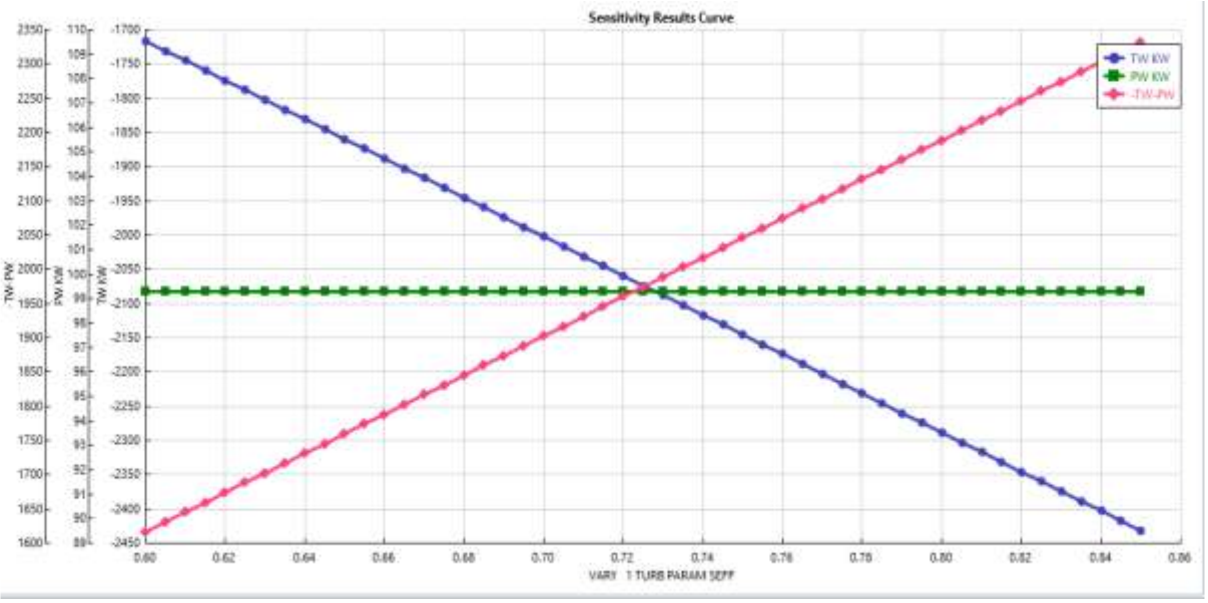


***Figure IV.20.*** *$W_{net}$, $W_{pump}$ and $W_{turb}$ vs $\eta_{is,turb}$ using Cyclohexane as a working fluid*

Figure IV.20 depicts the outcomes of a sensitivity analysis on turbine isentropic efficiency in the Organic Rankine Cycle (ORC), with efficiency values spanning from 0.60 to 0.85, utilizing Aspen Plus simulations and cyclohexane as the working fluid. The green curve ($W_{pump}$) remains nearly constant across the whole range, signifying that pump power usage is not impacted by changes in turbine efficiency. The blue curve ($W_{tur}b$) exhibits a progressive rise as turbine efficiency enhances, as a more efficient turbine generates greater power from identical thermal energy input. The red curve ($W_{net}$) demonstrates a consistent increase in turbine efficiency, indicating enhancements in net power generation and overall system efficacy.

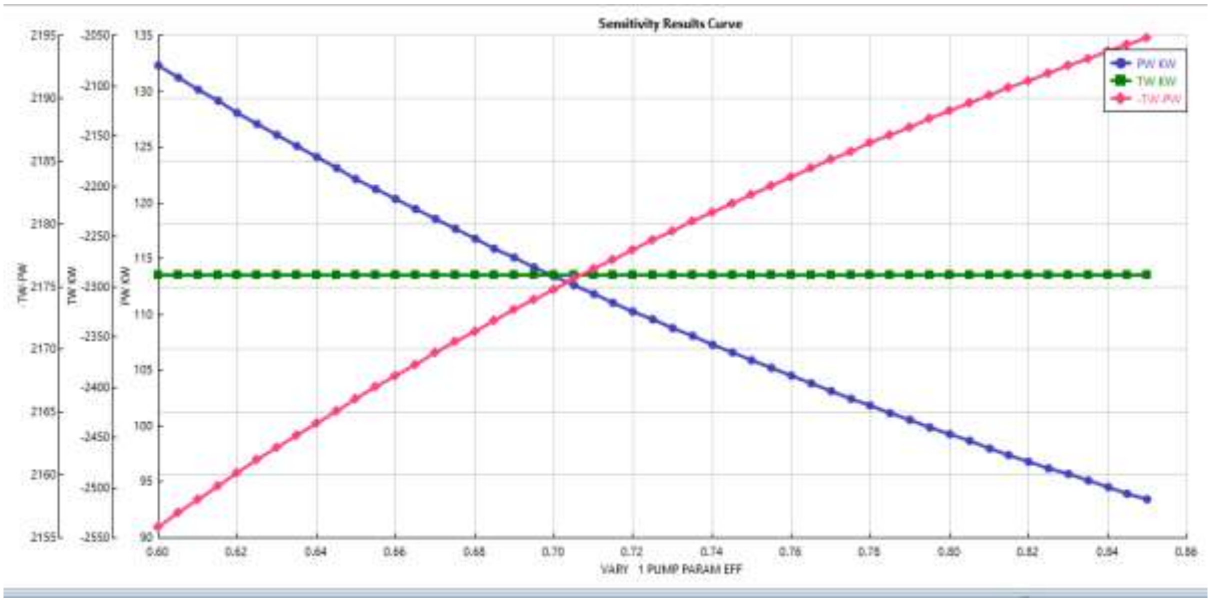


***Figure IV.21.*** *$W_{net}$, $W_{pump}$ and $W_{tur}$ vs $\eta_{is,\,pump}$ using Cyclohexane as a working fluid*

Figure IV.21 illustrates the outcomes of a sensitivity study regarding pump isentropic efficiency in the Organic Rankine Cycle (ORC), employing Aspen Plus simulations with cyclohexane as the working fluid. The pump efficiency ranges from 0.60 to 0.85. The green curve ($W_{tur}$b) remains rather stable across the efficiency spectrum, suggesting that turbine output is not substantially influenced by variations in pump efficiency. The blue curve ($W_{pump}$) progressively declines with enhanced pump efficiency, as a more efficient pump utilizes less energy to get the necessary pressure increase. The red curve ($W_{net}$) ascends consistently with improvements in pump efficiency, indicating increased net power production and overall system performance resulting from diminished internal energy use.

## IV.5. Conclusion

This study aims to analyze the impact of critical operational factors on the efficacy of the Organic Rankine Cycle (ORC) utilizing four distinct working fluids: benzene, toluene, acetone, and cyclohexane. Simulations were performed utilizing Aspen Plus to examine the correlation among evaporation pressure, condenser pressure, isentropic turbine efficiency, and pump effectiveness on the net power output ($\boldsymbol{W}_{net}$) of the cycle.

The results definitely indicated that benzene surpasses the other fluids for thermal performance, consistently producing the maximum net power production across all working conditions. In particular:

- Elevating the evaporation pressure markedly enhances power output, with the ideal value recorded at 30 bars.
- Minimizing the condenser pressure significantly improves cycle performance, achieving optimal results at 1 bar.
- Enhancing turbine isentropic efficiency significantly benefits $\boldsymbol{W}_{\text{net}}$, with an optimal value of 0.85.
- The efficiency of the pump also has a beneficial impact, albeit to a lesser extent, reaching a maximum of 0.85.

These findings show the need of choosing a suitable working fluid with optimal conditions for operations to enhance net power generation and attain superior thermal efficiency. The analysis indicates that benzene is the most appropriate working fluid for ORC systems, particularly at optimal pressure and efficiency settings, rendering it an attractive option for low- and medium-grade waste heat recovery applications.

# *General Conclusion*

# General Conclusion

In conclusion, this study involved the evaluation and enhancement of the Organic Rankine Cycle (ORC) performance using Aspen Plus simulation software, Four organic working fluids were used: benzene, toluene, acetone, and cyclohexane. The main objective was to analyze the influence of key operating parameters—evaporation pressure, condensation pressure, turbine efficiency, and pump efficiency on the net power output ($\boldsymbol{W}_{\text{net}}$) of the cycle. The results showed that benzene was the most effective working fluid, achieving a maximum net power output of 2443 kW at turbine efficiency of 0.85, with an optimal evaporation pressure of 30 bars and a low condensation pressure of 1 bar. Improving the pump efficiency from 0.60 to 0.85 increased the net power output from 2265 kW to 2299 kW, while the effect of turbine efficiency was more significant, with an increase of 745 kW within the same efficiency range. These results emphasize the importance of selecting the appropriate working fluid and performing sensitivity analysis to determine the optimal operating conditions that allow for maximizing the efficiency of the ORC cycle.

This study contributes to the field of thermal energy recovery by enhancing the understanding of the behavior of the Organic Rankine Cycle (ORC) system under different dynamic and thermal characteristics. This technology shows its potential to convert waste heat, especially in energy-intensive sectors and heat treatment, into useful electrical energy. The environmental importance of this system lies in its ability to reduce dependence on conventional energy sources and reduce greenhouse gas emissions, making it a strategic choice in the transition towards more sustainable and efficient energy solutions.

Future study should include a thorough economic analysis to evaluate the viability of implementing ORC systems on an industrial scale. Additionally, a life cycle assessment (LCA) may be performed to determine the environmental ramifications of utilizing different organic fluids. Conducting semi-industrial tests would be advantageous for validating the simulation results in real-world situations. Ultimately, the integration of the ORC with renewable energy sources, such as solar thermal or geothermal energy, may result in the creation of more efficient and hybrid sustainable systems.

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