

## Research Article

# A Comprehensive Analysis of Organic Rankine Cycle Using Different Organic Working Fluids

Prince<sup>1</sup>, Ikroop Singh Grover<sup>2</sup> and Ashwni Goyal<sup>3,\*</sup><sup>1-3</sup>Student, Department of Mechanical Engineering, Maharaja Agrasen Institute of Technology, New Delhi-110086, India.\*Corresponding Author: Ashwni Goyal. Email: [ashwni@mait.ac.in](mailto:ashwni@mait.ac.in)

Received: 06/04/2025; Revised: 25/05/2025; Accepted: 15/06/2025; Published: 30/06/2025

DOI: <https://doi.org/10.69996/fmep.2025011>

**Abstract:** The research provides an in-depth analysis of the Rankine Cycle and Organic Working Fluids, with a focus on the Organic Rankine Cycle (ORC) as a type of thermodynamic cycle in thermal engineering. The research explores the use of organic, high-molecular-mass fluids, allowing heat recovery from lower-temperature sources for conversion into useful work and electricity. The research also provides detailed information on different types of organic working fluids and their COP under various working conditions, presented with the aid of charts, tables, and numeric data. The findings of this research provide valuable insights for future applications of ORC technology in the context of sustainable energy generation and heat recovery.

**Keywords:** Coefficient of Performance, Organic Rankine Cycle, Waste Heat Recovery, thermodynamic, steam Rankine cycle.

## 1. Introduction

The organic Rankine cycle is similar to the steam Rankine cycle but uses an organic fluid, such as refrigerants and hydrocarbons, instead of water as the working fluid. An ordinary Rankine cycle uses heat energy to turn water into steam, which expands through a turbine to generate electricity [1].

The Organic Rankine Cycle (ORC) is commonly accepted as a viable technology for converting low-temperature heat into electricity. In addition, ORCs are designed for unmanned operation with minimal maintenance. Thanks to these excellent properties, several ORC waste heat recovery plants are already in operation

## 2. Literature Survey

Before proceeding to take up the research topic, the authors carried out an extensive study on the ORC and formulated a detailed report to quantify the benefits of this research.

During the research, they carried out multiple experiments and developed various simulations in EES to simulate the working conditions of an ORC with various working fluids to derive the results.

## 3. System Working

The principle of operation of the organic Rankine cycle is the same as that of the Rankine cycle, that is, the working fluid is pumped into the boiler, where it is vaporized, passes through an expansion device (turbine, screw, spiral, or other expander), and then through a condenser heat exchanger, where it is finally recirculated and condenses.



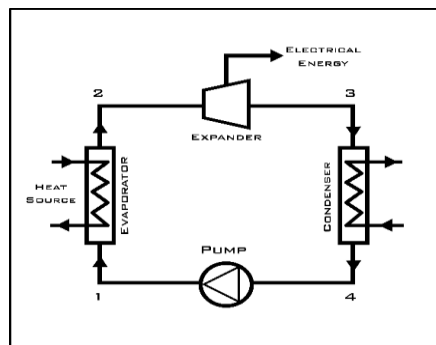


**Figure 1:** Schematic diagram of an Organic Rankine Cycle

From the above figure, we can categorize the four processes as follows:

- Process 1-2 is Isobaric heat absorption
- Process 2-3 is Isentropic Expansion
- Process 3-4 is Isobaric heat rejection
- Process 4-1 is Isentropic compression

### 3.1 Application of the ORC

The Waste Heat Recovery (WHR) market is segmented into small (< 1 MW) and large ORCs up to 20 MW, and includes industries such as: Cement plants, electric thermal plants, steel plants, etc., where exhaust energy is lost.

- Geothermal power plant: ORC can be used for exhaust from geothermal power plants with outlet temperatures from 100°C to 400°C. Below 100°C, the cycle efficiency is too low and therefore not usable.
- Biomass power plant: One of the advantages of ORC is the low operating pressure, which reduces the equipment costs compared to conventional ones and is also suitable for smaller power plants.
- Solar thermal power plant: In a trough collector solar power plant where the working fluid is oil, ORCs can be installed at the end of the plant to increase their efficiency by at least 15%.
- Apart from these industrial applications, ORC is successfully used in small units in the range of 1 to 10 KW in domestic applications, but with the disadvantage of low efficiency of 7-8%

### 3.2 Main components of the ORC

- 1) Turbine- It is a key component of the entire ORC power plant that determines the performance of the ORC system. It expands the working fluid producing mechanical energy, which is converted into electricity by a generator connected to the turbine shaft.
- 2) Evaporator- The working fluid flows through the evaporator and removes heat from the heat source. Shell and tube heat exchangers are commonly used, but may vary in geometry and layout depending on the power source and total heat input.
- 3) Condenser- With a direct air/liquid heat exchanger, the organic liquid is cooled and liquefied before entering the pump. The use of air eliminates the need for water for treatment and replenishment. It is also possible to use a water-cooled condenser.

Feed pump- Feeds the organic liquid from the condensing pressure to the maximum pressure of the organic Rankine cycle. The pump is usually driven by an electric motor with a

variable speed of rotation.

#### **4. Organic working fluids**

##### **4.1 Acetone**

Also known as propanone, it is a common organic working fluid used in small-scale ORC applications due to its low boiling point and high latent heat of vaporization. It has low toxicity but is flammable.

##### **4.2 Propane**

Also known as R290, it is a natural refrigerant that is widely used in ORC and other refrigeration systems. It has excellent thermodynamic properties, high energy efficiency, and is environmentally friendly.

##### **4.3 R40**

Also known as methyl chloride, it is a halocarbon refrigerant that has been largely phased out due to its ozone-depleting potential. It has high cooling capacity but is highly toxic and flammable.

##### **4.4 R12**

Also known as dichlorodifluoromethane, it was a popular refrigerant in the past, but is now largely phased out due to its ozone-depleting potential. It has high cooling capacity but is highly toxic and contributes to greenhouse gas emissions.

##### **4.5 R41**

Also known as chloroform, it is a halocarbon refrigerant that has been largely phased out due to its ozone-depleting potential and toxicity. It has a low boiling point and a high latent heat of vaporization.

##### **4.6 R600**

Also known as isobutane, it is a natural refrigerant that is environmentally friendly and energy-efficient. It has low toxicity but is highly flammable.

##### **4.7 Benzene**

It is a highly toxic and carcinogenic organic working fluid that is no longer used in ORC or other refrigeration systems due to health and safety concerns.

##### **4.8 Methanol**

Also known as methyl alcohol, it is a common organic working fluid that has low toxicity and is relatively easy to handle. It has a high latent heat of vaporization but a lower cooling capacity than other refrigerants.

##### **4.9 R123**

Also known as 1, 1, 1-trifluoroethane, is a non-ozone-depleting refrigerant that has been widely used as a replacement for R11 and R113. It has good thermodynamic properties and is relatively low in toxicity

##### **4.10 R131I**

Also known as difluoromethane, it is a halocarbon refrigerant that has low ozone-depleting potential and is being increasingly used as a replacement for other, more harmful refrigerants. It has a low boiling point and high energy efficiency.

##### **4.11 R32**

Also known as difluoromethane, it is a non-ozone-depleting refrigerant that has low global warming potential and is being used as a replacement for other, more harmful

refrigerants. It has good thermodynamic properties and high energy efficiency.

#### **4.12 R125**

Also known as pentafluoroethane, it is a non-ozone-depleting refrigerant that has low global warming potential and is being used as a replacement for other, more harmful refrigerants. It has good thermodynamic properties and high energy efficiency.

#### **4.13 R134a**

Also known as tetrafluoroethane, it is a non-ozone-depleting refrigerant that has been widely used as a replacement for R12. It has good thermodynamic properties and is relatively safe to handle, but has a high global warming potential.

#### **4.14 R141b**

Also known as dichloro fluoro ethane is a halocarbon refrigerant that has been largely phased out due to its ozone-depleting potential. It has good thermodynamic properties but is highly toxic and flammable.

#### **4.15 R142b**

Also known as chlorodifluoromethane, it is a halo carbon refrigerant that has been largely phased out due to its ozone-depleting potential. It has good thermodynamic properties but is highly toxic and flammable

#### **4.16 R143a**

Also known as 1, 1, 1-Trifluoroethane is an organic working fluid commonly used in refrigeration applications. R143a has a low ozone depletion potential (ODP) but a high global warming potential (GWP).

#### **4.17 R404a**

Also known as a blend of R125, R143a, and R134a, is an organic working fluid widely used as a refrigerant. R404a has a low ODP and a high GWP, making it a potential replacement for other refrigerants with higher environmental impacts. However, its high flammability and toxicity raises safety concerns

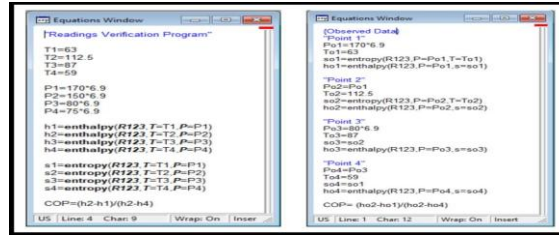
### **5. Methodology**

EES (**Engineering Equation Solver**), to test above listed organic working fluids in terms of their COP (**Coefficient of Performance**) value in different thermophysical conditions. This testing was done on the basis of a testing model built by us.

The model consists of 2 set of codes, one for the ideal case and one for verifying the experimental data that was collected from the ORC setup during the project. Enthalpy (h), Entropy (s), Temperature (T), Pressure (P) are the parameters which have been provided by the user as per the given conditions.

In order to find the COP of an organic working fluid in an Organic Rankine Cycle, one needs to:

- Determine the enthalpy values at the inlet and outlet of the evaporator and condenser for the working fluid. The inlet of the evaporator is where the working fluid enters the evaporator, and the outlet of the condenser is where the working fluid leaves the condenser.
- Calculate the heat absorbed by the working fluid in the evaporator, which is equal to the difference in enthalpy between the inlet and outlet of the evaporator.
- Calculate the work done by the working fluid in the turbine, which is equal to the difference in enthalpy between the inlet and outlet of the turbine.



- Calculate the heat rejected by the working fluid in the condenser, which is equal to the difference in enthalpy between the inlet and outlet of the condenser.

Calculate the COP, which is equal to the ratio of the heat absorbed by the working fluid in the evaporator to the work done by the working fluid in the turbine plus the heat rejected by the working fluid in the condenser

For working fluid, we can state that,

$$\text{COP} = \frac{\text{Heat absorbed in the evaporator}}{\text{Work done in the turbine} + \text{Heat rejected in the condenser}} \quad (1)$$

From Fig 1 we know about working fluid that,

$$\text{Heat absorbed in the evaporator} = h_2 - h_1 \quad (2)$$

$$\text{Work done in the turbine (expander)} = h_2 - h_3 \quad (3)$$

$$\text{Heat rejected in the condenser} = h_3 - h_4 \quad (4)$$

Hence, the COP formula now becomes:

$$\text{COP} = \frac{h_2 - h_1}{h_2 - h_3 + h_3 - h_4}$$

Or

$$\text{COP} = \frac{h_2 - h_1}{h_2 - h_4} \quad (5)$$

The formulae used for the calculation of enthalpy is a built-in formula in EES which is as follows:

$$h = (\text{<refrigerant name>}, T=\text{<temperature in Celsius>}, s=\text{<entropy in kJ/kg-K>}) \quad (6)$$

$$h = (\text{<refrigerant name>}, T=\text{<temperature in Celsius>}, P=\text{<pressure in kPa>}) \quad (7)$$

and for entropy the formula used is

$$s = (\text{<refrigerant name>}, T=\text{<temperature in Celsius>}, P=\text{<pressure in kPa>}) \quad (8)$$

Below are the code snippets from EES

**Figure2.**ReadingVerificationProgram(left),ORCmodel(right)

By running these programs, we calculated the ideal and actual values of COP for all the working fluids. The reading verification program was used to find out the actual value of COP using the readings. The ORC model code however, helped us calculate the value of COP in ideal working conditions i.e.,

- Process 1-2 is Isobaric heat absorption
- Process 2-3 is Isentropic Expansion
- Process 3-4 is Isobaric heat rejection
- Process 4-1 is Isentropic compression

In real world there are a number of variables which are beyond control and their effect cannot be measured. Hence, the error in the observed COP and theoretical COP values was also calculated and has been tabulated later in the results section.

Apart from this, the efficiency of ORC was calculated in a hypothetical scenario where the temperature at the evaporator outlet has been varied [4]. The obtained results have been plotted as a 2D graph between temperature at evaporator outlet and ORC efficiency. Detailed result is provided in the results section

## 6.Results and Discussion

### 6.1 Simulation result for R123

The readings for working fluid R123 were taken in different temperature and pressure conditions and then the COP was calculated. The data obtained was as follows:

**Table 1:** Temperature and pressure readings for R123 in an ORC

| S.N<br>o | Temperature(°C) |       |    |      | Pressure(kPa) |       |       |       |
|----------|-----------------|-------|----|------|---------------|-------|-------|-------|
|          | P1              | P2    | P3 | P4   | P1            | P 2   | P3    | P4    |
| 1        | 40              | 68    | 56 | 37   | 414           | 331.1 | 193.2 | 158.7 |
| 2        | 43              | 78    | 64 | 42   | 517.5         | 414   | 276   | 220.8 |
| 3        | 51              | 93    | 71 | 49   | 690           | 586.5 | 314   | 276   |
| 4        | 50              | 98.5  | 66 | 46   | 966           | 79    | 276   | 227.7 |
| 5        | 48              | 99    | 63 | 44   | 966           | 724.5 | 241.5 | 207   |
| 6        | 60.5            | 99    | 80 | 55   | 828           | 659   | 414   | 348.5 |
| 7        | 57.5            | 101.5 | 79 | 52.5 | 897           | 724.5 | 659   | 345   |
| 8        | 63              | 112.5 | 87 | 59   | 170           | 150   | 80    | 75    |

After calculating the COP for the given values following data is obtained

**Table 2:** COP values for R123 in different condition

| S.No | CalculatedC<br>OP | SimulatedC<br>OP | Error(<br>%) |
|------|-------------------|------------------|--------------|
| 1    | 0.9949            | 0.9826           | 1.236        |
| 2    | 0.9955            | 0.9939           | 0.161        |
| 3    | 0.9943            | 0.9881           | 0.624        |
| 4    | 0.9909            | 0.9769           | 1.413        |
| 5    | 0.9910            | 0.9773           | 1.382        |
| 6    | 0.9931            | 0.9674           | 2.588        |
| 7    | 0.9965            | 0.9737           | 2.288        |
| 8    | 0.9920            | 0.9264           | 6.613        |

From the above table we can see that the ideal COP value for any given temperature and pressure is higher than observed COP value. This variation in value is due to various reasons given below:

- The 4 were were i.e., isobaric. energy

thus,  
COP  
R123.

- There were limitations in measurement of pressure and temperature values or the measuring instrument might have had some very minute errors which were not possible to correct.

The working fluid change their properties in different environment conditions. We assumed the environment conditions to be constant but they can change with time and we can't do anything about it.

| Sno | Evaporator Temperature (°C) | Efficiency (%) |       |       |       |
|-----|-----------------------------|----------------|-------|-------|-------|
|     |                             | R141b          | R142b | R143a | R404a |

processes 1-2-3- not ideal as they supposed to be isentropic and This caused wastage and pressure loss reducing the calculated for

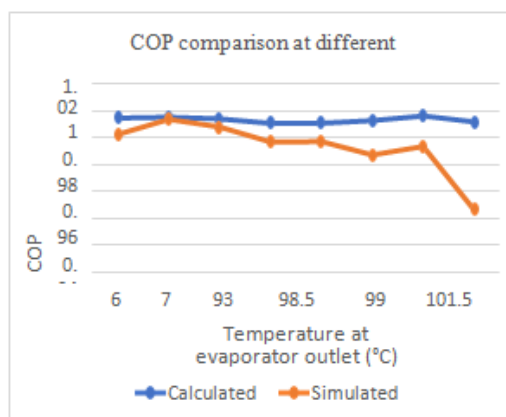


**Figure 3:** The data in tables 1 and 2 can be represented in the form of a line chart

### 6.2 Hypothetical evaluation of an ORC unit assuming ideal behaviour

We used our EES model to further get insights about the efficiency of a hypothetical ORC unit working on various different working fluids, in ideal working conditions and with a heat source having variable temperature range for the evaporator. The following results were obtained

**Table 3:** Variation of efficiency with evaporator temperature for different organic working fluids

|    |       |       |       |       |       |
|----|-------|-------|-------|-------|-------|
| 1  | 50    | 23.46 | 19.26 | 26.23 | 25.57 |
| 2  | 111.1 | 26.56 | 26.9  | 33.66 | 33    |
| 3  | 172.2 | 31.46 | 33.19 | 39.61 | 38.93 |
| 4  | 233.3 | 35.25 | 38.44 | 43.61 | 42.47 |
| 5  | 294.4 | 38.13 | 41.9  | 45.82 | 45.16 |
| 6  | 355.6 | 40.37 | 42.69 | 45.82 | 44.12 |
| 7  | 416.7 | 41.79 | 43.06 | 45.85 | 44.04 |
| 8  | 477.8 | 41.7  | 43.05 | 45.61 | 43.75 |
| 9  | 538.9 | 41.22 | 42.85 | 45.22 | 43.34 |
| 10 | 600   | 40.54 | 42.55 | 44.76 | 42.87 |

**Table 4:** Variation of efficiency with evaporator temperature for different organic working fluids

| Sno | Evaporator Temperature (°C) | Efficiency (%) |       |       |       |       |
|-----|-----------------------------|----------------|-------|-------|-------|-------|
|     |                             | R13I1          | R32   | R125  | R123  | R134a |
| 1   | 50                          | 22.14          | 26.36 | 26.04 | 13.25 | 21.68 |
| 2   | 111.1                       | 29.61          | 34.3  | 33.42 | 21.17 | 29.26 |
| 3   | 172.2                       | 35.68          | 40.73 | 39.06 | 27.69 | 35.56 |
| 4   | 233.3                       | 40.62          | 44.42 | 41.4  | 33.25 | 40.16 |
| 5   | 294.4                       | 44.44          | 47.28 | 42.08 | 36.69 | 42    |
| 6   | 355.6                       | 46.88          | 49.8  | 42.08 | 37.84 | 42.57 |
| 7   | 416.7                       | 48.31          | 52.06 | 41.8  | 37.98 | 42.54 |
| 8   | 477.8                       | 49.22          | 53.74 | 41.38 | 37.7  | 42.21 |
| 9   | 538.9                       | 49.85          | 54.92 | 40.9  | 37.2  | 41.69 |
| 10  | 600                         | 50.3           | 55.71 | 40.41 | 36.59 | 41.08 |

**Table 5:** Variation of efficiency with evaporator temperature for different organic working fluids

|    |       |       |       |       |       |
|----|-------|-------|-------|-------|-------|
| 1  | 50    | 8.457 | 25.81 | 21.08 | 30.02 |
| 2  | 111.1 | 16.57 | 33.37 | 28.54 | 37.9  |
| 3  | 172.2 | 23.26 | 39.61 | 35.29 | 39.03 |
| 4  | 233.3 | 28.95 | 44.33 | 41.34 | 43.19 |
| 5  | 294.4 | 33.95 | 46.23 | 44.8  | 46    |
| 6  | 355.6 | 38.29 | 46.59 | 47.39 | 47.35 |
| 7  | 416.7 | 40.47 | 46.27 | 49.65 | 48.06 |
| 8  | 477.8 | 41.22 | 45.61 | 51.71 | 48.43 |
| 9  | 538.9 | 41.36 | 44.8  | 53.44 | 48.59 |
| 10 | 600   | 41.21 | 43.92 | 54.73 | 48.62 |

**Table 6:** Variation of efficiency with evaporator temperature for different organic working fluids

| Sno | Evaporator Temperature (°C) | Efficiency (%) |       |         |          |
|-----|-----------------------------|----------------|-------|---------|----------|
|     |                             | R41            | R600  | Benzene | Methanol |
| 1   | 50                          | 32.29          | 18.22 | 5.366   | 6.121    |
| 2   | 111.1                       | 40.44          | 26.06 | 13.67   | 14.59    |
| 3   | 172.2                       | 45.1           | 32.53 | 20.53   | 21.82    |
| 4   | 233.3                       | 48.25          | 37.5  | 26.34   | 28.3     |
| 5   | 294.4                       | 50.94          | 39.25 | 31.37   | 35.53    |
| 6   | 355.6                       | 53.38          | 39.33 | 35.38   | 39.15    |
| 7   | 416.7                       | 55.63          | 38.77 | 36.97   | 41.24    |
| 8   | 477.8                       | 57.52          | 37.96 | 37.15   | 43.02    |
| 9   | 538.9                       | 58.95          | 37.07 | 36.79   | 44.61    |
| 10  | 600                         | 59.99          | 36.16 | 36.22   | 45.8     |

By observing tables 3, 4, 5, 6, we can definitely see a trend of increasing efficiency as the temperature increases up to a certain threshold value, after which the efficiency starts dropping again. We can sum up the maximum efficiencies of all the working fluids above in the form of a table as follows

**Table 7:** Variation of maximum efficiency with temperature for different working fluids

| Working fluid | Temperature at maximum efficiency(°C) | Maximum efficiency(%) |
|---------------|---------------------------------------|-----------------------|
| Acetone       | 538.9                                 | 41.36                 |

|          |       |       |
|----------|-------|-------|
| Propane  | 355.6 | 46.59 |
| R40      | 600   | 54.73 |
| R12      | 600   | 48.62 |
| R41      | 600   | 59.99 |
| R600     | 355.6 | 39.33 |
| Benzene  | 477.8 | 37.15 |
| Methanol | 600   | 45.8  |
| R13I1    | 600   | 50.3  |
| R32      | 600   | 55.71 |
| R125     | 294.4 | 42.08 |
| R123     | 416.7 | 37.98 |
| R134a    | 355.6 | 42.57 |
| R141b    | 416.7 | 41.79 |
| R142b    | 416.7 | 43.06 |
| R143a    | 416.7 | 45.85 |
| R404a    | 355.6 | 44.12 |

Based on the above table we can plot a line chart for a better understanding of variation of maximum efficiency with temperature

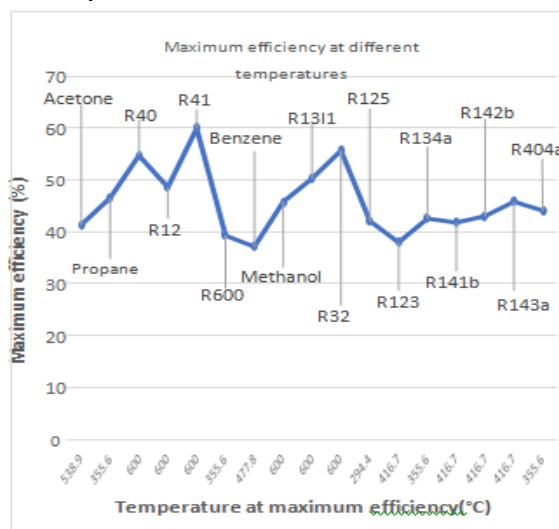


**Figure 4:** Temperature at maximum efficiency v/s Maximum efficiency for various working fluid chart

## 7.Conclusion

The present research provides a detailed analysis of the Organic Rankine Cycle (ORC) as a type of thermodynamic cycle in thermal engineering for sustainable energy generation and waste heat recovery. The ORC uses organic, high-molecular-mass fluids instead of water as the working fluid, allowing heat recovery from lower-temperature sources for conversion into useful work and electricity [5][6]. The study describes the system working and the main components of the ORC power plant. The ORC is a viable technology for converting low-temperature heat into electricity and is designed for unmanned operation with minimal maintenance. The research also

explains the different types of organic working fluids used in the ORC [7], such as Acetone, Propane, R40, R12, and R41, and their properties.

The findings of the study suggest that the ORC is a promising technology for waste heat recovery in different industries such as cement plants, electric thermal plants, and steel plants, among others [8]. The ORC can also be used for exhaust from geothermal power plants, biomass power plants, and solar thermal power plants. ORC technology is already in operation and has proven to be successful in small units in the range of 1 to 10 KW in domestic applications.

The research findings also reveal that the turbine is a key component of the ORC power plant that determines the performance of the system [9]. It expands the working fluid, producing mechanical energy, which is converted into electricity by a generator connected to the turbine shaft. The evaporator removes heat from the heat source, and the condenser cools and liquefies the organic liquid before entering the pump. The feed pump feeds the organic liquid from the condensing pressure to the maximum pressure of the organic Rankine cycle. The study provides detailed information on the working of each component.

The study provides valuable insights into the use of organic working fluids in the ORC and their coefficient of performance (COP) under various working conditions, presented with the aid of charts, tables, and numeric data [10]. The different types of organic working fluids and their properties are described in detail. The findings of the study can be used to improve the performance and efficiency of the ORC system by selecting the appropriate organic working fluid for specific applications [11]. The ORC technology has great potential to contribute to sustainable energy generation and waste heat recovery, thereby reducing greenhouse gas emissions and mitigating climate change.

In conclusion, the present research highlights the importance of the Organic Rankine Cycle (ORC) as a promising technology for sustainable energy generation and waste heat recovery [12][13]. The study provides a comprehensive understanding of the ORC system working, main components, organic working fluids, and their properties. The findings of the study can be used to improve the performance and efficiency of the ORC system [14] and to select the appropriate organic working fluid for specific applications. The ORC technology has the potential to contribute to reducing greenhouse gas emissions and mitigating climate change by converting low-temperature heat into electricity. Further research is required to address the challenges and improve the efficiency of the ORC system for widespread commercial applications [15]

**Acknowledgments:** The Authors are really thankful to the department of engineering Maharaja Agrasen Institute of Technology for providing all the required resources to carry out this research.

**Funding Statement:** The author(s) received no specific funding for this study.

**Conflicts of Interest:** The authors declare no conflicts of interest to report regarding the present study.

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