Indian Institute of Technology Delhi

WINTER PROJECT REPORT

THERMAL ANALYSIS OF A SIMPLE ORGANIC RANKINE CYCLE FOR WASTE HEAT RECOVERY SYSTEM

SESSION - 2024-25

Guided By-
Dr. P.M.V Subbarao

Submitted By-
Shubham Kurre [2022ME11325]
Kartik Yadav [2022ME22093]

PROJECT OVERVIEW

TASKS COMPLETED IN WINTER PROJECT

1. Study of Organic Rankine Cycle (ORC) for Waste Heat Recovery System (WHRS):
    - Researched the fundamentals of ORC and its application in low-temperature waste heat recovery.
2. Analysis of ORC Components and Efficiency Enhancement:
    - Read about turbine efficiency improvement through design.
    - Investigated working fluid selection to optimize thermodynamic efficiency.
3. Potential for Waste Heat Recovery in Textile Industries:
    - Analyzed the exhaust heat characteristics from textile industry operations.
4. Development of a Simple ORC Model:
    - Created a basic ORC model to simulate system performance.
    - Implemented preliminary thermodynamic calculations to evaluate efficiency and output.

ORC TECHNOLOGY

ORGANIC RANKINE CYCLE

Organic Rankine cycle (ORC) is a technology that can convert thermal energy at relatively low temperatures in the range of 80˚C - 350˚C to electricity.

There are several cycle configurations for (ORC), they are

- sub-critical,
- transcritical or super-critical,
- basic or regenerative,
- single pressure or dual-pressure cycles

The basic and regenerative, sub-critical, and single pressure (ORC) systems have been intensively dealt with and are adopted in the practical field due to their allowable working pressure range and sizing.

SIMPLE ORGANIC RANKINE CYCLE

01

HEAT SOURCE (WASTE HEAT EXCHANGER / EVAPORATOR)

- Extracts waste heat from sources like industrial exhaust gases.
- Transfers heat to the organic working fluid, converting it into high-pressure vapor.

02

EXPANDER (TURBINE)

- Converts the high-pressure vapor’s thermal energy into mechanical work.
- Drives a generator to produce electricity.

03

CONDENSER

- Cools and condenses the low-pressure vapor back into liquid form.
- Uses cooling water or air to reject excess heat.

04

PUMP

- Pressurizes the condensed liquid and sends it back to the evaporator.
- Ensures continuous fluid circulation in the cycle.

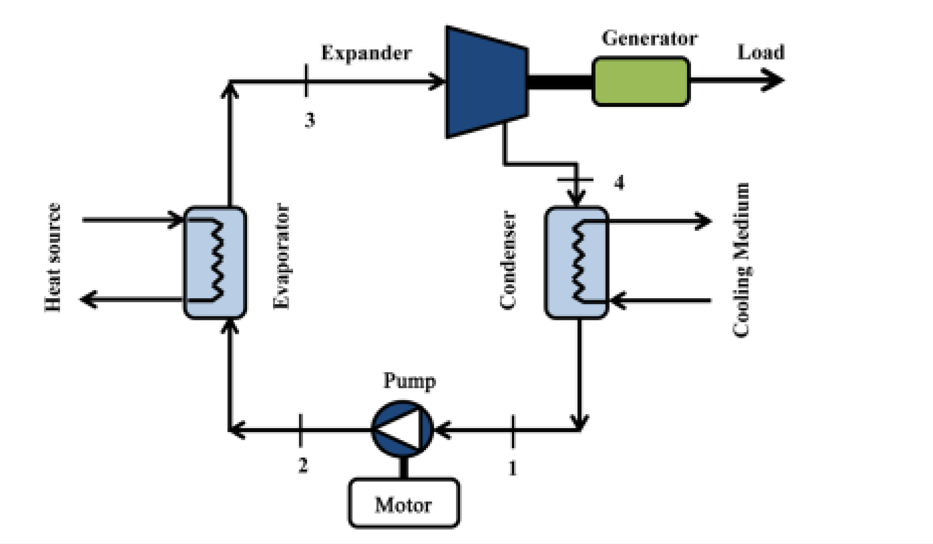


Fig:- Schematic diagram of SORC

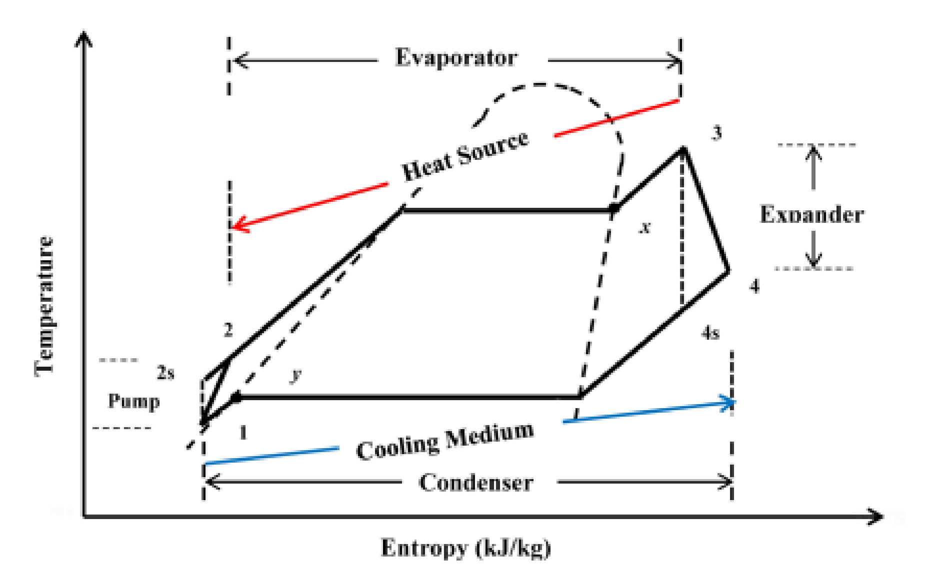


Fig:- T-s diagram for SORC

APPLICATIONS OF ORC IN LOW-TEMPERATURE WASTE HEAT RECOVERY

1. **Industrial Exhaust Heat Recovery:**
   - Captures waste heat from industries like textile, steel, cement, and glass manufacturing to generate electricity.
   - Improves overall plant efficiency by utilizing heat that would otherwise be lost.
2. **Geothermal Power Generation:**
   - Converts low-temperature geothermal energy (80–180°C) into electricity, making geothermal resources more viable.
3. **Biomass and Biogas Power Plants:**
   - Utilizes heat from biomass combustion or biogas engines to enhance power generation.
4. **Internal Combustion Engine (ICE) Waste Heat Recovery:**
   - Recovers heat from diesel generators, marine engines, and heavy-duty vehicle exhausts to increase fuel efficiency.
5. **Solar Thermal Power:**
   - Works with low-concentration solar collectors (CSP, parabolic troughs, etc.) to generate power even at moderate temperatures.
6. **District Heating & Cogeneration:**
   - Enhances combined heat and power (CHP) systems by converting excess thermal energy into electricity.

WASTE HEAT SOURCES

Heating energy losses represent 25% - 55% of the total energy use.

The waste heat sources categorize into three different zones depending on their temperature level.

In the industrial sector, there is a lot of waste heat available, often on low-temperature levels and on small to moderate thermal power scale.

Significant heat recovery opportunities are available from the waste heat sources in the temperature of 25˚C - 150˚C, representing more than 80% of the total estimated waste heat.

01

LOW TEMPERATURE

Twaste< 230˚C

02

MEDIUM

Twaste= 230 - 650˚C

03

HIGH TEMPERATURE

Twaste > 650˚C.

LITERATURE REVIEW

01

AXIAL TURBINE FLOW PATH DESIGN FOR AN ORGANIC RANKINE CYCLE USING R-245FA
-LEONID MOROZ, CHI-RON KUO, OLEG GURIEV, YI-CHEN LI, BORIS FROLOV

02

THERMAL INTEGRATION OF REHEATED ORGANIC RANKINE CYCLE (RH-ORC) WITH GAS TURBINE EXHAUST FOR MAXIMUM POWER RECOVERY
-VINAYAK B. HEMADRI , P.M.V. SUBBARAO

03

WASTE HEAT RECOVERY IN TEXTILE INDUSTRY: A REVIEW
-V.J.SONAWANE, A.A.KESTE

04

A STEADY-STATE EVALUATION OF SIMPLE ORGANIC RANKINE CYCLE (SORC) WITH LOW-TEMPERATURE GRADE WASTE HEAT SOURCE
-ALI H. TARRAD

1. AXIAL TURBINE FLOW PATH DESIGN FOR AN ORGANIC RANKINE CYCLE USING R-245FA - LEONID MOROZ, CHI-RON KUO, OLEG GURIEV, YI-CHEN LI, BORIS FROLOV

1. **Turbine Configuration Optimization**
   - The study compared one-stage vs. two-stage axial turbines and found that a one-stage turbine with a constant mean diameter provided the highest efficiency.
   - Two-stage turbines exhibited higher leakage losses, reducing efficiency, making the one-stage design preferable.
   - The final turbine achieved 81.8% efficiency at the design point.
2. **Effect of Blade Design on Efficiency**
   - Twisted blades improved efficiency (~1-1.5%) by reducing incidence losses but increased manufacturing complexity and cost.
   - Cylindrical (untwisted) blades were chosen as they offered a good balance between performance and ease of production.
3. **Leakage Loss Minimization**
   - Tip clearance significantly affected performance (~1% efficiency loss per 0.1mm increase in clearance).
   - Shrouded blades improved efficiency by ~2.5% by reducing leakage but increased weight and cost.
   - The final design used unshrouded blades to balance performance and manufacturability.

4. **Axial Thrust Optimization for Performance and Durability**
   - The initial axial thrust of 13,079 N exceeded the 4700 N limit, necessitating modifications.
   - Two solutions were tested:
     a. Balance holes in the disk (but resulted in a 3.2% efficiency loss).
     b. Lower reaction turbine design (~28% mean reaction), which successfully reduced axial thrust without significant efficiency loss.
   - The final design utilized the lower reaction approach for optimal performance.
5. **Impact of Inlet and Outlet Flow Optimization**
   - Pressure losses at the turbine inlet (~2%) were mitigated through optimized inlet scroll duct design.
   - The exhaust diffuser provided a 3% efficiency boost by enhancing pressure recovery.
6. **Structural and Modal Analysis for Reliability**
   - The turbine underwent structural analysis using ANSYS FEA to ensure stress and vibrational safety.
   - The final integrally bladed disk (blisk) had a 6mm thickness, balancing structural integrity and weight reduction.

CONCLUSION

The selection of the working fluids has a vital role in system efficiency and environmental impacts. In the efficiency issue, the organic fluid should have favourable thermal properties and the capacity of absorbing the energy from the heat source with a low pinch temperature difference between a waste stream and the organic fluid. The critical point characteristics, pressure, and temperature also play a significant role in the working fluids’ selection philosophy.

2. THERMAL INTEGRATION OF REHEATED ORGANIC RANKINE CYCLE (RH-ORC) WITH GAS TURBINE EXHAUST FOR MAXIMUM POWER RECOVERY -VINAYAK B. HEMADRI , P.M.V. SUBBARAO

Reheating in Organic Rankine Cycle for Waste Heat Recovery

Organic Rankine Cycle (ORC) has gained significant attention for low-temperature waste heat recovery applications due to its flexibility in working fluid selection and compatibility with industrial exhaust heat sources. Traditional ORC systems use single-stage expansion, but recent studies have explored advanced cycle modifications, including regeneration, reheating, and dual-pressure cycles to improve performance.

This study by Hemadri and Subbarao (2021) introduced a Reheated Organic Rankine Cycle (RH-ORC) configuration designed to maximize power recovery from gas turbine exhaust. The study investigated the thermal integration of RH-ORC with recuperated gas turbines (Solar Mercury 50 and Rolls-Royce WR-21) and evaluated the impact of working fluid selection, reheat pressure ratio, and exergy efficiency on overall performance.

Key Findings

1. Reheating in ORC improves power recovery potential by expanding the working fluid in two stages (high-pressure and low-pressure turbines).
2. Working fluid selection plays a crucial role—Benzene, Cyclopentane, and Hexane were identified as optimal candidates for RH-ORC, with benzene showing the highest power output.

3. The maximum power output was achieved at a reheat temperature of 557.15 K:
   - 1292.033 kW (SM-50 Gas Turbine)
   - 4772.631 kW (RR WR-21 Gas Turbine)
4. Exergy efficiency was significantly improved, reaching 67.03% for RR WR-21, making RH-ORC more effective than conventional ORC.
5. Lower reheat pressure ratios (Prh = 0.435 for benzene) resulted in enhanced net specific work output, demonstrating the benefits of multi-stage expansion in ORC.

COMPARISON WITH EXISTING STUDIES

- Previous studies focused on basic ORC configurations for waste heat recovery, showing lower efficiency (~40–50%) compared to the 67% exergy efficiency achieved in this study.
- Traditional ORC systems prioritize thermal efficiency, whereas this study emphasizes power recovery, which is crucial for industrial waste heat utilization.
- Other works have investigated dual-loop ORC (DORC) and regenerative ORC, but RH-ORC proves to be a simple and effective cycle modification for increasing power output.

RELEVANCE TO THIS PROJECT

This research is highly relevant to the current project on ORC for low-temperature waste heat recovery (140–180°C). The insights from this study will be applied in:

- Working fluid selection to optimize power recovery and system efficiency.
- Reheat pressure optimization to enhance turbine performance.
- Exergy efficiency analysis for determining the best cycle configuration.
- Integration of ORC with industrial exhaust systems (e.g., textile industry, manufacturing plants).

3. WASTE HEAT RECOVERY IN TEXTILE INDUSTRY: A REVIEW -V.J.SONAWANE, A.A.KESTE

WASTE HEAT RECOVERY IN THE TEXTILE INDUSTRY

The textile industry is one of the most energy-intensive sectors, with a significant portion of energy used in steam-based processes such as dyeing, drying, and hot rinsing. Studies have shown that a large fraction of this energy is lost as waste heat, making heat recovery systems an attractive solution for improving efficiency and reducing fuel costs.

Sonawane and Keste (2016) reviewed various waste heat recovery (WHR) techniques in the textile industry and identified key heat loss sources, including boiler blowdown, condensate return, exhaust air, cooling water, and wastewater discharge. The study emphasizes that recovering waste heat can improve thermal efficiency, reduce operational costs, and lower environmental impact.

KEY FINDINGS

1. **Major Waste Heat Sources in Textile Industry**

- Boiler blowdown flash steam contains significant thermal energy that can be recovered.
- Hot condensate retains 16% of the total steam energy, which can be reused in boilers.
- Exhaust air from drying operations (140–180°C) offers high recovery potential.
- Processed wastewater can preheat fresh water, reducing fuel consumption by 15–20%.
- Cooling water can be reused, with a payback period of ~12 months.

2. **Economic Viability of Waste Heat Recovery**
   - Heat recovery reduces fuel costs, leading to a payback period of just 1–2 years for most systems.
   - Case studies show substantial savings:
     - Bursa, Turkey textile plants saved $423,837 per year with heat exchangers.
     - Surat, India textile cluster saved ₹7,66,000 annually by using drain water heat recovery.
   - Waste heat recovery can also help meet environmental regulations by lowering CO_2 emissions.

3. **Integration of Waste Heat Recovery with ORC**
   - Textile mills generate waste heat in the 140-180°C range, which is ideal for low-temperature ORC applications.
   - Using an ORC system to convert this waste heat into electricity enhances overall energy efficiency and reduces dependence on fossil fuels.
   - Plate heat exchangers are recommended for heat recovery before integration with ORC systems.

RELEVANCE TO THIS PROJECT

This study provides a strong foundation for applying ORC technology to waste heat recovery in textile industries. The findings will be used in this project to:

- Identify optimal waste heat sources for ORC integration.
- Analyze working fluid selection for low-temperature ORC (140-180°C).
- Evaluate the feasibility of using heat exchangers to recover and transfer waste heat efficiently.
- Develop an ORC-based waste heat recovery model for industrial applications.

4. A STEADY-STATE EVALUATION OF SIMPLE ORGANIC RANKINE CYCLE (SORC) WITH LOW-TEMPERATURE GRADE WASTE HEAT SOURCE -ALI H. TARRAD

PERFORMANCE ANALYSIS OF SIMPLE ORGANIC RANKINE CYCLE (SORC) FOR LOW-TEMPERATURE WASTE HEAT RECOVERY

Low-temperature waste heat recovery is a promising method for improving energy efficiency in industrial applications. The Organic Rankine Cycle (ORC) is widely used for converting low-grade heat (80–350°C) into electricity, with working fluid selection playing a crucial role in optimizing performance.

A study by Tarrad (2020) evaluated the thermal performance of a Simple Organic Rankine Cycle (SORC) using six different working fluids: R-123, R-134a, R-290, R-245fa, R-1233zd-E, and R-1234ze-E. The study considered a waste heat source >110°C with an evaporator temperature of 90°C and condenser temperature of 45°C in a 10 kW ORC system.

KEY FINDINGS

1. Working Fluid Selection and Performance

- R-134a had the highest thermal efficiency (7.7%) and net power output (~0.91 kW at 15°C superheat).
- R-245fa, R-123, and R-1233zd-E showed close efficiencies (7.5%–7.7%).
- R-290 extracted the most heat but had lower efficiency (6.7%).
- R-1233zd-E and R-1234ze-E were found to be viable low-GWP alternatives to conventional fluids.

2. Effect of Superheat on ORC Performance

- Increasing superheat from 5°C to 15°C improved thermal efficiency and power output:
  - +7.5% efficiency (R-134a)
  - +6% efficiency (R-245fa)
  - +1.5% efficiency (R-1233zd-E)
- Higher superheat increased net power output by up to 16% for R-134a.

3. Impact of Expander Efficiency

- A 10% increase in expander volumetric efficiency resulted in a 10%–12% gain in cycle efficiency, highlighting the importance of expander optimization in ORC systems.

4. Heat Absorption and Energy Extraction

- R-290 absorbed the most heat but required higher pumping power, reducing overall efficiency.
- Fluids with higher critical temperatures extracted more heat from the waste source.

RELEVANCE TO THIS PROJECT

This study provides a strong technical foundation for designing an ORC system for waste heat recovery (140–180°C). The findings will be applied in this project to:

- Select the most suitable working fluid for maximizing efficiency and net power output.
- Determine optimal superheat conditions (10–15°C) for performance enhancement.
- Optimize expander efficiency to improve thermal performance.
- Develop an ORC model that integrates waste heat recovery in industrial applications.

SELECTION OF WORKING FLUID

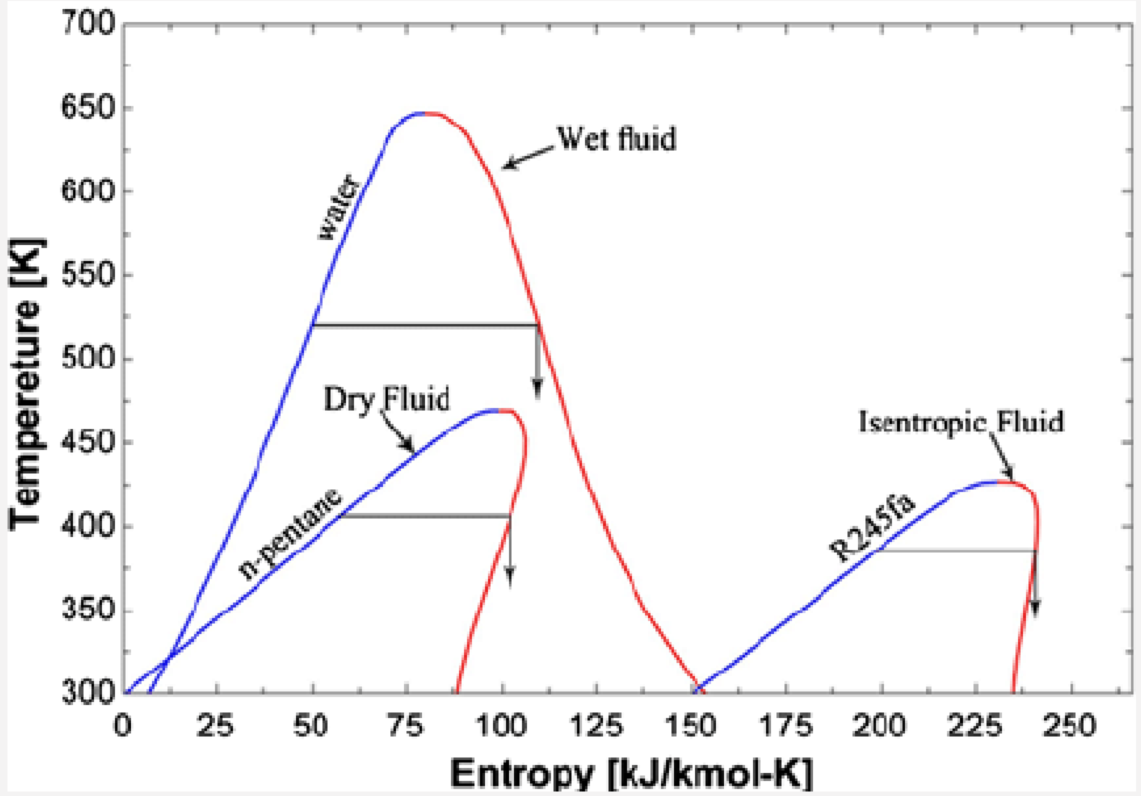
SYSTEM EFFICIENCY

The selection of the working fluids has a vital role in system efficiency and environmental impacts. In the efficiency issue, the organic fluid should have favourable thermal properties and the capacity of absorbing the energy from the heat source with a low pinch temperature difference between a waste stream and the organic fluid. The critical point characteristics, pressure, and temperature also play a significant role in the working fluids' selection philosophy.

ENVIRONMENTAL IMPACT

The fluid has to possess attractive global warming potential (GWP) and Ozone depletion potential (ODP). R-134a used in geothermal power plants or very low-temperature waste heat recovery and R-245fa is a low temperature working fluid, mainly used in waste heat recovery.

SELECTED WORKING FLUID



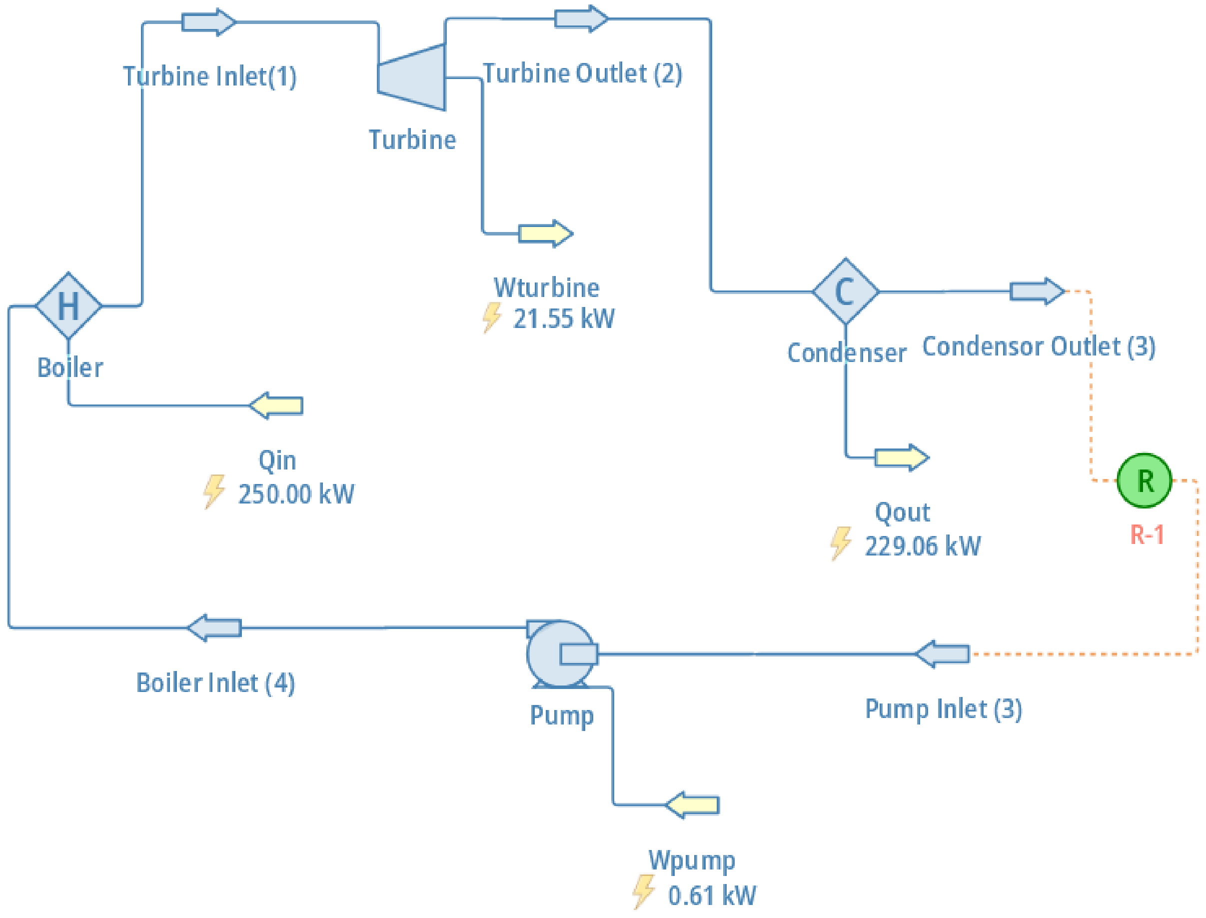
SELECTED WORKING FLUIDS AND THERE PROPERTIES

Fluid	Critical Temp (°C)	Critical Pressure (bar)	Fluid Type
p-Xylene	343.02	35.31	Dry
Toluene	318.6	41.26	Dry
Benzene	288.87	48.94	Dry
Ethanol	241.56	62.68	Dry
Methanol	239.35	82.16	Dry
Cyclopentane	238.57	45.71	Dry
n-Pentane	196.55	33.68	Dry
Isopentane	187.2	33.78	Dry
R245ca	174.42	39.41	Dry
R245fa	153.86	36.51	Dry
n-Butane	151.98	37.96	Dry

SORC MODEL

1.DWSIM MODEL FOR R245FA

Master Property Table					
Object	Wturbine	Wpump	Qout	Qin	
Energy Flow	21.5457	0.608085	229.062	250	kW



WORKING PARAMETERS AND SIMULATION SETUP

For the simulation of the Organic Rankine Cycle (ORC) using DWSIM, the following working parameters were considered:

- Pump Efficiency (η_p) = 0.75
- Turbine Efficiency (η_t) = 0.75
- Condenser Pressure (P3) = 2 bar
- Pressure Increase by Pump (ΔP_p) = 6 bar
- Heat Input ($\dot{Q}in$) = 250 kW

The above parameters were used to analyze the thermodynamic performance of the ORC system, including energy conversion efficiency, specific work output, and system feasibility for low-temperature waste heat recovery.

GOVERNING EQUATIONS FOR SORC MODELING

1. Expander

$$\eta_{is,exp} = \frac{h_3 - h_4}{h_3 - h_{4,is}}$$

$$\dot{W}_{exp} = \eta_{vol,exp}\,\dot{m}\left(h_3 - h_4\right)$$

3. Pump

$$\eta_{is,pump} = \frac{h_{2,is} - h_1}{h_2 - h_1}$$

$$\dot{W}_{pump} = \dot{m}\left(h_1 - h_2\right)$$

The cycle net thermal efficiency

$$\eta_{net} = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{Q}_{evap}}$$

2. Condenser

$$\dot{Q}_{cond} = \dot{m}\left(h_4 - h_1\right)$$

4. Evaporator

$$\dot{Q}_{evap} = \dot{m}\left(h_3 - h_2\right)$$

SORC MODEL

2. MATHEMATICAL MODEL

```
!pip install CoolProp

# Import CoolProp
import CoolProp.CoolProp as CP

# Turbine Inlet Conditions
T_1 = 433 # Boiler exit Temp (Kelvin)
P_1 = 200000 # Pressure (Pa)
M_ORC = 1 # Mass flow rate (kg/s)
Turb_eff = 0.8 # Turbine efficiency

# Thermodynamic Properties at point 1 (Boiler Outlet)
H_1 = CP.PropsSI('H', 'T', T_1, 'P', P_1, 'R245fa') # Enthalpy (J/kg)
S_1 = CP.PropsSI('S', 'T', T_1, 'P', P_1, 'R245fa') # Entropy (J/kg-K)

# Thermodynamic Properties at point 2 (Turbine Exit)
T_2 = 298 # Condenser Temperature (Kelvin)
S_2 = S_1 # Assuming isentropic expansion
H_2_isentropic = CP.PropsSI('H', 'T', T_2, 'S', S_2, 'R245fa') # Isentropic enthalpy
H_2 = H_1 - Turb_eff * (H_1 - H_2_isentropic) # Actual enthalpy after turbine

# Thermodynamic Properties at point 3 (Condensed Liquid Exit)
T_3 = 298 # Kelvin
Pump_eff = 0.8 # Pump efficiency
H_3 = CP.PropsSI('H', 'T', T_3, 'Q', 0, 'R245fa') # Enthalpy of saturated liquid
P_3 = CP.PropsSI('P', 'T', T_3, 'Q', 0, 'R245fa') # Condenser pressure
D_3 = CP.PropsSI('D', 'T', T_3, 'Q', 0, 'R245fa') # Density (kg/m³)
SV_3 = 1 / D_3 # Specific Volume (m³/kg)

# Thermodynamic Properties at point 4 (Pump Exit / Boiler Inlet)
P_4 = P_1 # Pump raises the pressure to boiler pressure
PW = SV_3 * (P_4 - P_3) / Pump_eff # Pump work
H_4 = H_3 + PW # Enthalpy after pump

# Performance Calculations
HI = M_ORC * (H_1 - H_4) # Heat input from boiler (J)
TW = M_ORC * (H_1 - H_2) * Turb_eff # Turbine work output (J)
SOP = TW - PW # Net work output (J)
Cycle_eff = SOP / HI # Cycle Efficiency

# Print Important Details
print("====== Organic Rankine Cycle (ORC) Analysis ======")
print(f"Turbine Inlet: T1 = {T_1} K, P1 = {P_1 / 1000} kPa, H1 = {H_1:.2f} J/kg, S1 = {S_1:.2f} J/kg-K")
print(f"Turbine Exit: T2 = {T_2} K, H2 = {H_2:.2f} J/kg, S2 = {S_2:.2f} J/kg-K")
print(f"Pump Inlet:  T3 = {T_3} K, P3 = {P_3 / 1000} kPa, H3 = {H_3:.2f} J/kg, Density = {D_3:.2f} kg/m³")
print(f"Pump Exit:  P4 = {P_4 / 1000} kPa, H4 = {H_4:.2f} J/kg, Pump Work = {PW:.2f} J/kg")
print(f"Cycle Work Output: {SOP:.2f} J/kg")
print(f"Cycle Efficiency: {Cycle_eff * 100:.2f} %")
```

RESULT

- Turbine Inlet: T_1 = 433 K, P_1 = 200.0 kPa, H_1 = 558,393.60 J/kg, S_1 = 2,107.96 J/kg-K
- Turbine Exit: T_2 = 298 K, H_2 = 454,088.70 J/kg, S_2 = 2,107.96 J/kg-K
- Pump Inlet: T_3 = 298 K, P_3 = 147.76 kPa, H_3 = 232,784.88 J/kg, Density = 1,338.87 kg/m^3
- Pump Exit: P_4 = 200.0 kPa, H_4 = 232,833.65 J/kg, Pump Work = 48.77 J/kg
- Cycle Work Output: 83,395.15 J/kg
- Cycle Efficiency: 25.62 %

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THANK YOU