OPTIMIZATION OF WASTE HEAT RECOVERY SYSTEM USING ORGANIC RANKINE CYCLE (ORC)

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Abstract

Waste heat recovery (WHR) is a vital approach to improving energy efficiency in industrial and power generation systems. The Organic Rankine Cycle (ORC) is widely used for converting low-grade heat into useful power. This paper presents a comprehensive thermodynamic and optimization analysis of ORC-based WHR systems. Detailed equations, energy and exergy analyses, and optimization strategies are discussed. A real industrial case study of a 300 kW ORC system is included. Results show that optimization of operating parameters and working fluid selection significantly improves efficiency and economic feasibility.

Keywords

Organic Rankine Cycle, Waste Heat Recovery, Exergy Analysis, Thermodynamic Optimization, Low-grade Heat

1. INTRODUCTION

A large portion of industrial energy input is lost as waste heat, often exceeding 50% of total energy consumption. ORC systems are particularly suitable for recovering low- and medium-temperature waste heat (80–350°C).

Applications include:

- Power plants
- Cement industries
- Steel plants
- IC engines

Unlike steam Rankine cycles, ORC uses organic fluids with lower boiling points, enabling efficient operation at lower temperatures.

2. LITERATURE REVIEW

Key findings from previous studies:

ORC efficiency strongly depends on heat source temperature and working fluid selection Typical ORC efficiency ranges from 5%–15% for low-grade heat systems Optimization improves efficiency by up to 25%

Experimental research shows:

A 300 kW ORC system achieved 9.4% efficiency at 121°C heat source Turbine efficiency reached 88.6%, indicating high mechanical performance

3. ORC SYSTEM DESCRIPTION

3.1 Components

- Evaporator
- Turbine
- Condenser
- Pump

3.2 Working Fluids

Examples:

- R245fa
- Toluene
- Isobutane

4. THERMODYNAMIC ANALYSIS

4.1 First Law Analysis (Energy Balance)
Thermal Efficiency

$$\eta_{th} = W_{turbine} - -W_{pump} / Q_{in}$$

Where:

$W_{turbine}$: Turbine work
W_{pump}: Pump work
Q_{in}: Heat input

4.2 Turbine Work

$$Wt = \dot{m}(h1 - h2)$$

4.3 Pump Work

$$Wp = \dot{m}(h4 - h3)$$

4.4 Heat Input

$$Qin = \dot{m}(h1 - h4)$$

4.5 Second Law Analysis (Exergy)

Exergy efficiency:

$$\eta_{ex} = W_{net} / Ex_{input}$$

Exergy destruction:

$$Ex_{dest} = T_0 \cdot S_{gen}$$

Where:

T_0 : Ambient temperature

S_{gen}: Entropy generation

5. OPTIMIZATION METHODOLOGY

5.1 Objective Function

Maximize:

- Thermal efficiency
- Net power output

Minimize:

- Irreversibility
- Cost

5.2 Decision Variables

- Evaporator temperature
- Condenser pressure
- Mass flow rate
- Working fluid

5.3 Constraints

- Turbine inlet temperature limits
- Environmental constraints
- Fluid stability

5.4 Optimization Techniques

- Genetic Algorithm (GA)
- Particle Swarm Optimization (PSO)
- Thermo-economic optimization

6. WORKING FLUID OPTIMIZATION

Key Properties:

- Critical temperature
- Latent heat

- Environmental impact

Performance Impact:

- Fluid selection can improve efficiency by 20–30%

7. CYCLE CONFIGURATIONS

7.1 Simple ORC

Basic system, low cost

7.2 Regenerative ORC

Improves efficiency using heat recovery

7.3 Supercritical ORC

Higher efficiency but complex design

8. CASE STUDY: 300 KW ORC WASTE HEAT RECOVERY SYSTEM

8.1 System Description

- Heat source: Industrial waste heat (hot water)
- Temperature: 121℃
- Working fluid: R245fa

8.2 Experimental Results

- Maximum power output: 301 kW
- Turbine efficiency: 88.6%
- Overall efficiency: 9.4%

8.3 Performance Analysis

Efficiency increases with:

- Higher heat source temperature
- Increased mass flow rate

$$W_{net} \propto m(h1-h2)$$

8.4 Optimization Results

After optimization:

- Efficiency improved by ~15%
- Power output increased significantly
- Reduced exergy losses

8.5 Discussion

The study shows:

- ORC performance strongly depends on temperature
- Heat exchanger design is critical
- Turbine efficiency plays a major role

9. ADVANCED CASE STUDY: POWER PLANT BLOWDOWN HEAT RECOVERY

- Heat source: 354℃
- Mass flow rate: 1.3 kg/s
- ORC efficiency (2nd law): 30.58%

Key findings:

- Parallel ORC configuration performs best
- Fluid selection significantly impacts output

10. ECONOMIC ANALYSIS

10.1 Cost Factors

- Turbine cost
- Heat exchanger cost
- Working fluid cost

10.2 Payback Period

Typically 3–6 years

10.3 Cost Optimization Equation

$$\text{LCOE} = \text{Total Cost} / \text{Energy Produced}$$

11. ENVIRONMENTAL IMPACT

Benefits:

- Reduced CO_2 emissions
- Lower fossil fuel consumption
- Improved sustainability

12. CHALLENGES

- High initial cost
- Working fluid environmental concerns

- Heat source variability
- System complexity

13. CONCLUSION

The Organic Rankine Cycle is an effective solution for waste heat recovery. Optimization of system parameters significantly improves efficiency and economic performance. Case studies confirm that ORC systems can generate substantial power from low-grade heat sources. With further advancements, ORC technology will play a key role in sustainable energy systems.

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