# Chapter 6: Conclusions and Future Study

## 6.1. Conclusions

This study focusses the low-medium waste heat recovery through thermodynamic power cycle. Various thermodynamic power cycles are compared using thermo-techno-economic prospectives. Then, novel ejector-enhanced ORCs are comprehensively analyzed for efficient waste heat recovery. Lab-scale ORC system is developed and experimented using electrical heater input. Finally, a feasibility study is conducted to implement the ORC system to recover waste heat from nuclear power plant based on the data provided by BRNS, Mumbai. Key findings can be summarized as follows:

- ✓ The selection of an appropriate thermodynamic cycle for waste heat recovery depends significantly on the heat source and sink temperature ranges and the priorities regarding performance, cost, environmental impact, and operational feasibility.
- ✓ $CO_2$ Rankine cycle excels at low heat source temperatures and TFC outperforms at medium-grade heat source temperatures. ORCs (both dry and wet) emerge as versatile and reliable options, particularly for large-scale and distributed power generation, due to their balanced performance, economic viability, and technological maturity.
- ✓ EEORC-1 with R123 achieves the highest net work output (122.2 kW). The basic ORC with R123, however, delivers the highest thermal efficiency (3.8%), exergy efficiency (40%), and yearly profit ($73,143) at 70°C waste heat temperature (WHT). EEORC-1 excels in work output across 60–150°C (R123) and 155–180°C (R1233zd(E)). Thermal and exergy efficiencies improve with WHT, with the basic ORC consistently leading.
- ✓ Economically, the basic ORC (R123) excels under the M1 model, while M2 boosts EEORC-1 profits by 7.32% at 90°C WHT, especially with subsidies or reduced power costs. So, EEORC-1 delivers superior power output, while the M2 model ensures economic viability for advanced cycles, supporting wider adoption.
- ✓ Increasing heat input (5–11.5 kW) experimentally boosts net power (up to 0.939 kW) and cycle efficiency (2.34% to 8.08%) of ORC, with optimal efficiency at high heat input and moderate flow rates. Excessive flow rate reduces the cycle efficiency. The evaporator's effectiveness improves with heat input and flow rates (0.78–0.84), while the expander reaches peak efficiency at higher thermal loads and flow rates.

- ✓ Experimental findings highlight the importance of balancing input parameters to optimize ORC performance and demonstrate its potential for electricity generation from waste heat. Optimization and prediction using RSM-ANOVA were experimentally validated, confirming its suitability for future predictions.
- ✓ Nine potential waste heat sources in nuclear power plants (NPPs) were identified, and two feasible bottoming ORC cases were proposed for waste heat recovery based on condenser temperature, optimizing heat extraction and evaluating system costs, environmental, and economic benefits using BRNS data.
- ✓ R245fa is optimal for case-1, while R236ea delivers higher annual profits in case-2, which is recommended for condenser temperatures below 41°C. Case-2 offers the best thermal and economic performance, with faster capital returns. Both cases generate 499.3 kW and yield a 204.62 thousand USD annual profit from a 764.96 thousand USD investment. Over 40 years, the total investment of 1.392 million USD ensures consistent profitability, making the upgrade viable for NPPs.

The proposed EEORC-1 emerges as the optimal ORC, combining high power output and economic feasibility. Experimental validation reinforces the potential of ORCs in waste heat recovery, and their successful application in NPPs demonstrates their scalability and versatility. By adopting tailored ORC configurations and economic models, industries can achieve substantial energy recovery, cost savings, and environmental benefits, aligning with global sustainability goals.

## 6.2. Future Study

The following are the future recommendations that need to be incorporated to enhance the system's performance further.

1) More net power generation is possible at the same input parameter condition by using a mixture of working fluids. The azeotropic mixture offers better temperature glide between two sides of the heat exchanger fluid (i.e., hot side and cold side) so that higher turbine inlet temperature can be achieved to generate more power and thus cycle efficiency. Another benefit of using an azeotropic mixture is that power can be generated from lower evaporator outlet temperature conditions, making ORC available to harness power from ultra-low-grade waste energy sources.

2) Use of nanoparticles in base working fluid enhances the heat transfer coefficient of heat exchangers. By the use of nanofluid, the heat exchanger's size decreases for the same parameter condition and thus, production cost per unit of power decreases. Apart from nanofluid, other base working fluids should be explored that offer higher thermal stability, low environmental impact, and better adaptability to varying heat sources, such as ultra-low-grade waste heat or solar-thermal sources.
3) A trilateral flash cycle can also replace ORC for waste heat recovery, as it gives more power output, exergy efficiency and annual profit at medium-grade waste heat (Source). Two-phase flash expansion is the only challenge in complex turbine or expander design to incorporate the experimental setup of the trilateral flash cycle. However, this challenge was solved completely by the advanced coating technique on the turbine blade to avoid erosion and corrosion. Other turbine expansion alternatives are available, like screw turbines, radial-inflow turbines and modified impulse turbines.
4) Introducing an internal heat exchanger or a regenerator in the cycle can improve thermal efficiency by recovering heat from the working fluid before it enters the condenser. This reduces the amount of heat that needs to be extracted from the heat source, improving net power output.
5) Combining multiple ORC stages (Cascaded ORC) can increase overall system efficiency. The first stage utilizes high-temperature heat, while the second stage uses the waste heat from the first cycle.