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Exploring Waste Heat Utilization in Refineries for Power Generation: Case Study

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This study focuses on the utilization of low-grade waste heat for power generation in refineries. Refinery is an integral component of the petrochemical industry and is known for its significant waste heat discharge, offering an opportunity for energy recovery and efficiency improvement. Innovative strategies for harnessing waste heat for power generation within refinery operations are explored in this work. The application of Organic Rankine Cycle (ORC) technology with a recuperator significantly enhances waste heat recovery, leading to an increase in thermal efficiency from 7.20 % to 8.74 %. Additionally, this technology saves an overall cooling utility of 4.94 MW and enables the turbine to generate an extra 1.83 MW.

1. Introduction

In the realm of energy management within industrial settings, refineries are notable for their substantial energy consumption and significant potential for energy recovery. The refining process inherently generates large quantities of waste heat, particularly at low temperatures, which are traditionally discarded. This has sparked a growing interest in the field of low-temperature waste heat recovery, which will enhance both energy efficiency and environmental sustainability in refineries. A significant amount of the energy consumed in these processes is lost as waste heat through flue gases, cooling water, and equipment inefficiencies. In particular, the diesel hydrofining units in refineries often produce low-temperature waste heat around 160 °C that remains unutilized. The rising energy costs, combined with stringent environmental regulations aimed at reducing greenhouse gas emissions, have compelled refineries to adopt strategies that include the recovery of waste heat. The effective recovery and utilization of low-temperature waste heat hold significant potential for enhancing overall energy efficiency.

Research on recovery technologies for specific waste heat sources is also a focus in the literature. For instance, Valerievich et al. (2023) analyzed different schemes for refinery waste heat utilization, highlighting the importance of thermodynamic properties and material selection in waste heat recovery process. Organic Rankine Cycle (ORC) technology has shown significant potential in this field. According to Yu et al. (2016), the choice of working fluid is crucial for the performance of ORC systems, necessitating customization based on the characteristics of the waste heat source. The design and optimization of waste heat recovery systems are key to achieving efficient energy use. Wang et al. (2023) introduced a method using mathematical planning models that provide a multi-period design strategy for integrating solar thermal energy with waste heat based on ORC. Advances in ORC technology have expanded the range of temperatures at which waste heat can be converted into useful energy, making the recovery of low-grade thermal energy more attractive.

This paper explores the utilization of waste heat in refineries for power generation, with a specific focus on hydrofining units. Assessments were based on economic benefits of the proposed systems.

This paper explores the utilization of waste heat in refineries for power generation through a detailed case study, with a specific focus on the recovery of waste heat from refined diesel in hydrofining units, and assesses the economic and environmental benefits of implementing such systems.

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2. Case study: diesel hydrodesulfurization (HDT) unit

The process flow diagram of a diesel hydrodesulfurization (HDT) unit is illustrated in Figure 1. In the HDT unit, the crude oil undergoes a high-temperature and high-pressure hydrogenation reaction to eliminate impurities such as sulfur, nitrogen, and heavy metals present in the feed oil. This process enhances the molecular structure of hydrocarbons and supplies refined products or clean fuels for subsequent downstream production. In the last operation, i.e. distillation T2, the refined diesel from its bottom product stream may reach a temperature of nearly 300 °C. After preheating the feed stream, the temperature of the refined diesel may still remain at 150-170 °C, and it requires further cooling (with air cooler or cooling water) before it can be transferred to the storage tank. In other words, a significant amount of low-grade energy is wasted. Figure 2 shows the GCC of the case study, where column T2 rejects heat in the region below the Pinch.

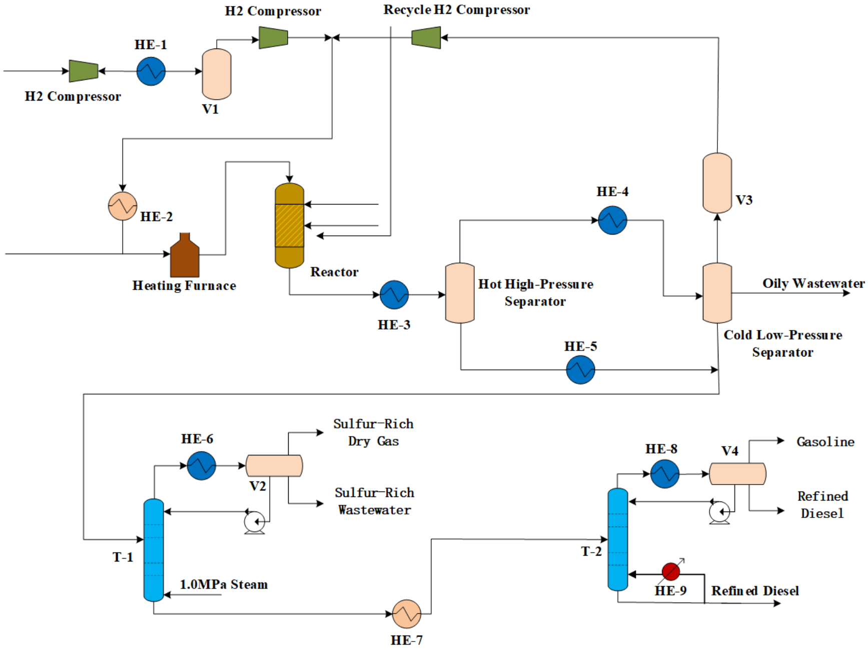

Figure 1: Diesel Hydrodesulfurization Process Flow Diagram

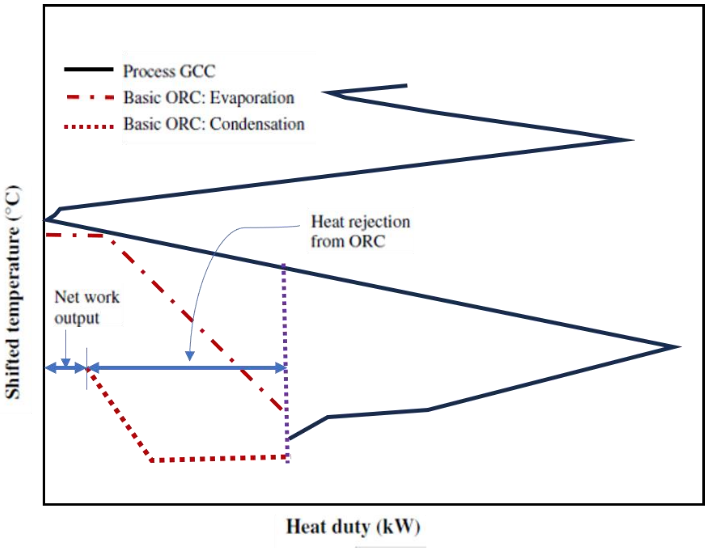

Figure 2: A GCC showing the integration of ORC with the background process in the region below the Pinch, along with its heat addition and rejection profiles. (Desai et al.,2009)

3. Base case scenario with ORC

A potential way of utilizing the low-grade energy is by introducing the ORC system. The latter can effectively utilize waste heat of low-to-medium temperature, allowing reduction of downstream cooling with air coolers and/or cooling water systems. A basic ORC process consists of four major components, i.e. evaporator, expander, condenser, and working fluid pump, as illustrated in Figure 3. In practical applications, additional components such as a liquid storage tank, cooling tower, and various pipes and valves may be required.

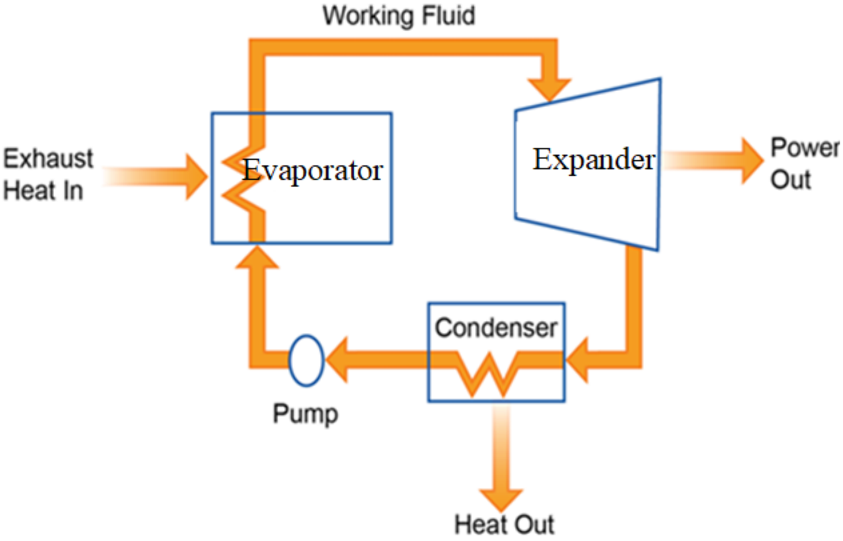

Figure 3: Basic configuration of an Organic Rankine Cycle

To make use of ORC in utilizing waste heat from the T2 bottom stream, the process configuration is shown in Figure 4. As shown, the liquid organic working fluid exchanges heat with the refined diesel in the preheater, evaporator, and superheater. Doing these evaporate the high-pressure working fluid into high-temperature vapor. The latter then flows into the turbine, where it expands and drives a coaxial generator to produce electricity. After exiting the turbine, the temperature and pressure of the working fluid decrease, turning it into low-temperature and low-pressure vapor. The working fluid next enters a cooler, where it releases heat (to cooling water) and condenses into liquid. Finally, the working fluid pump delivers the working fluid to the preheater and completes the entire cycle.

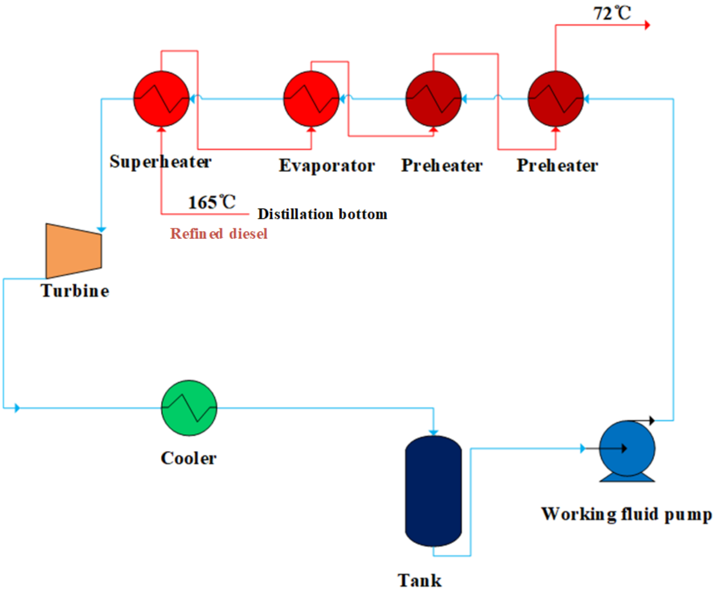

Figure 4: Process Flow of ORC for Recovering Waste Heat from Refined Diesel

The ORC uses organic substances with low boiling points and high vapor pressures as the working fluid for power generation. The use of organic fluid as working fluid allows the system to utilize low-grade waste heat for power generation. In this case study, the organic fluid of R245fa is selected as the working fluid. The specific data of refined diesel is shown in Table 1.

Table 1: Refined Diesel Composition Data

Item	Refined Diesel
Density (20°C) (kg/m³)	844.9
Initial Boiling Point (°C)*	218
10 %	242.5
30 %	264
50 %	288
70 %	303.5
90 %	333
95 %	343
100 %	354.5

*The initial boiling point refers to the temperature at which the first drop of liquid diesel vaporizes into a gas.

Thermal efficiency is the practical working efficiency of a heat engine operating between mechanical work (W) and waste heat (Qin). It is given by:

$$\eta = \frac{W}{Q_{in}} \tag{1}$$

The objective function is to maximize the overall thermal efficiency of the system. Manipulated variables include the working fluid flow rate, where adjustments to the mass flow rate can regulate the system's thermal load and power output, and the pressures of the evaporator and condenser, aimed at optimizing the working fluid's thermal performance and cycle efficiency. Control variables include the outlet temperatures of the heat exchangers at the evaporator and condenser, which directly impact the cycle's thermal efficiency. Constraints involve the temperatures of the heat and cooling sources, typically fixed by external processes, along with the equipment's minimum and maximum operating pressures.

A process simulation model was constructed using Aspen Plus V14 for the system, as shown in Figure 5. The temperature and flowrate of refined diesel are 165 °C and 29 kg/s. The simulation studies indicate that the thermal efficiency of the ORC is significantly influenced by the temperature and flow rate of the refined diesel. When the waste heat temperature is high, the heat source temperature of the x-axis in Fig 6a increases, resulting in a higher thermal efficiency. High-temperature waste heat provides a larger temperature difference, enabling the ORC system to convert thermal energy into mechanical work or electricity more efficiently. The thermal efficiency of the ORC system increases as the waste heat temperature rises, as shown in Figure 6(a).

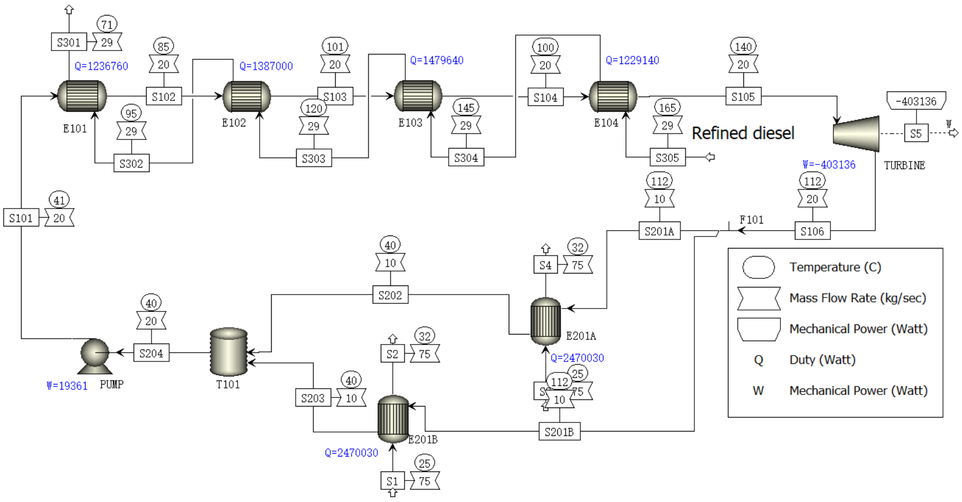

Figure 5: Simulation Flowsheet of traditional ORC without Recuperator

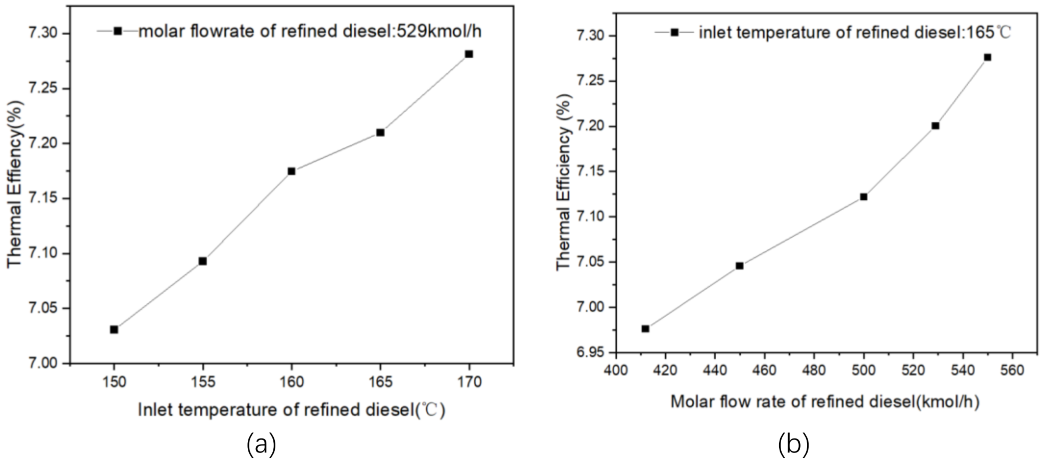

Figure 6: Relationship between ORC Efficiency and Refined Diesel Flowrate/Temperature

When the temperature of refined diesel remains constant, increasing the diesel flow rate also increases heat transfer to the working fluid. This leads to higher thermal energy and enhances the cycle's thermal efficiency. This increase in energy input allows the cycle to convert thermal energy into mechanical or electrical energy more effectively, as shown in Figure 6(b).

4. Extended scenario of ORC with Recuperator

The case study is extended by incorporating a recuperator to the base case ORC process in order to improve its power generation efficiency. Specifically, a new heat exchanger (recuperator) is added so that the heat flow from the turbine outlet may be utilized to preheat the cold flow from the pump outlet (see simulation flowsheet in Figure 7 under the temperature of 165℃ and flowrate of 29 kg/s). The power generation efficiencies of the extended scenario are compared under the same conditions as the base case in Figure 5. This temperature and flowrate are based on actual production data from a diesel hydrogenation unit at a petrochemical plant in China.

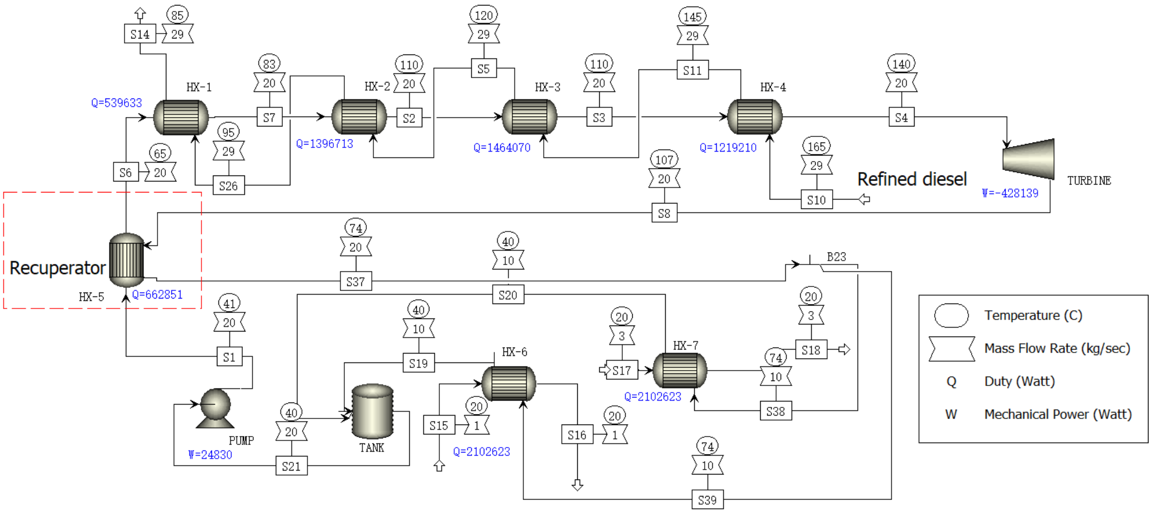

Figure 7: Simulation Flowsheet of Improved ORC with Recuperator

The addition of a recuperator has several potential benefits:

- Improved heat recovery: The additional heat exchanger recovers more heat from the turbine exhaust, which would otherwise be wasted.

- Enhanced efficiency: By preheating the pump outlet fluid, the evaporator requires less heat input to achieve the desired working fluid temperature, effectively increasing the system's overall thermal efficiency.
- Reduced temperature difference: The preheating reduces the temperature difference between the working fluid entering the evaporator and the waste heat source, improving its heat transfer efficiency.
- Reduced cooling load: The enhanced heat recovery and preheating of the pump outlet fluid not only boost the overall thermal efficiency but also decrease the load on the cooling system.

The simulation results show notable improvements in the following system performance:

- Thermal efficiency increases from 7.20 % to 8.74 %, reflecting a relative gain of approximately 1.54 % points.
- The substantial reduction in HX-6 and HX-7 load indicates effective utilization of the recuperator, which saves overall cooling utility of 4.94 MW
- The turbine generates extra power of 1.83 MW, contributing to higher efficiency and better energy utilization.

5. Conclusions

Utilizing waste heat for power generation through the ORC is an effective strategy for reducing energy consumption and improving efficiency. The introduction of a recuperator further enhances thermal efficiency and power generation. Overall, the application of ORC technology, especially with a recuperator, significantly improves waste heat recovery, leading to increased energy savings and reduced operational costs, making it a valuable advancement in refinery operations.

Acknowledgments

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