Analysis of the Organic Rankine Cycle

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CHE 0200

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Group Contribution Section:

Liam Cunningham: Liam's primary focus was the optimization and sensitivity analysis. Using the Aspen model, he worked on finding a parameter to evaluate the power output for the cycle. He looked at the pump pressures and created a graph in Aspen to evaluate the power output with changing pump pressures.

Aarya Dani: Aarya worked on the introduction, background, and methods and approach section. In addition, he worked on determining the best fluid to run through the ASPEN simulation, helping to select which fluid to use and confirming the range of values utilized for the heating and cooling of the system.

Andrew Davis: Andrew worked exclusively on the efficiency analysis section of the report. Using the Aspen model and efficiency data, he compared the efficiency of the group's model to the efficiency of an ideal Carnot cycle and gave reasons as to why this ORC did not perform as efficiently. In addition, he wrote about the selected heat source and heat sink temperatures in the Methods and Approach section.

Nathan Feichtel: Nathan worked on the Aspen model, running sensitivity analysis and adjusting the plot generated by the sensitivity analysis. He also calculated efficiency for each pressure and temperature increment of the sensitivity analysis. On the report, he wrote the section defending pentane as the working fluid.

Matvey Zoukovski: Matvey worked on the conclusion and recommendations section of the report. He worked on summarizing key findings from the rest of the report and discussing the validity and practicality of using the Organic Rankine Cycle in industry. He discussed what optimizations and conditions could be used by companies to maximize power output and maintain feasible operating conditions.

Table of Contents:

Introduction and Background:

There are several environmental factors, such as global warming, ozone depletion, and atmospheric pollution that are causing a lack of dependency on fossil fuels. Fossil fuels are still a primary source of energy, and as energy demands continue to rise, they will only be used throughout the coming decade. Because of this, there is a demand in utilizing low-grade waste heat to minimize energy losses. Current climate change trends indicate that it is all but imperative for optimization of power generation, and the organic Rankine Cycle (ORC) serves as an example of a cycle that can become optimized. According to Suresh Sivan, a mechanical engineer from the National Institute of Technology, the ORC claims to produce 15-50% more power output for the same heat, and it primarily serves as a low-temperature heat recovery [1]. The ORC uses organic fluids, such as toluene, cyclohexane, and acetone, because fluids are advantageous when the maximum temperature is low and/or the power plant is small [2]. At lower temperatures, which the organic Rankine Cycle operates at, organic fluids allow for higher efficiency than water. This is because water is better for higher efficiency plants at higher pressures, which are not economically feasible for smaller plants that the ORC would be used for. According to Dr. Atia, a researcher at Electronic Research Institute, the ORC plant is more economical for geothermal fluid temperature below 180˚C [3]. Geothermal resources are effective because these resources are in many areas and represent a high potential energy resource. For this project, the team is focusing on modeling and analyzing a Geothermal ORC using Aspen Plus. Additional goals include assessing the ORC's efficiency relative to the Carnot cycle, identifying real-world irreversibility, and exploring optimization strategies through sensitivity analysis.

A simple ORC system consists of four main components: a pump, an expander/turbine, an evaporator, and a condenser. The evaporator and the condenser perform as high-temperature and low-temperature heat reservoirs, respectively. At the same time, the pump circulates the working fluid across the system components, whereas the turbine generates a useful work out from the cycle.

Methods and Approach

For this report, our group utilized Aspen Plus to simulate an ORC. In this simulation, we modeled an expander, condenser, pump, and evaporator while utilizing a geothermal heat source and a heat sink. However, in Aspen, there are several assumptions made to simplify the model. Primarily, the system is assumed to be at a steady state, as our group did not utilize Aspen Dynamics. This means no mass or energy is accumulated. Additionally, the Peng-Robinson equation of state was utilized to make calculations, which has slight deviations as opposed to real world conditions. Furthermore, all pipes, reactors, and columns are adiabatic or isothermal. Figure 1 showcases the Aspen simulation.

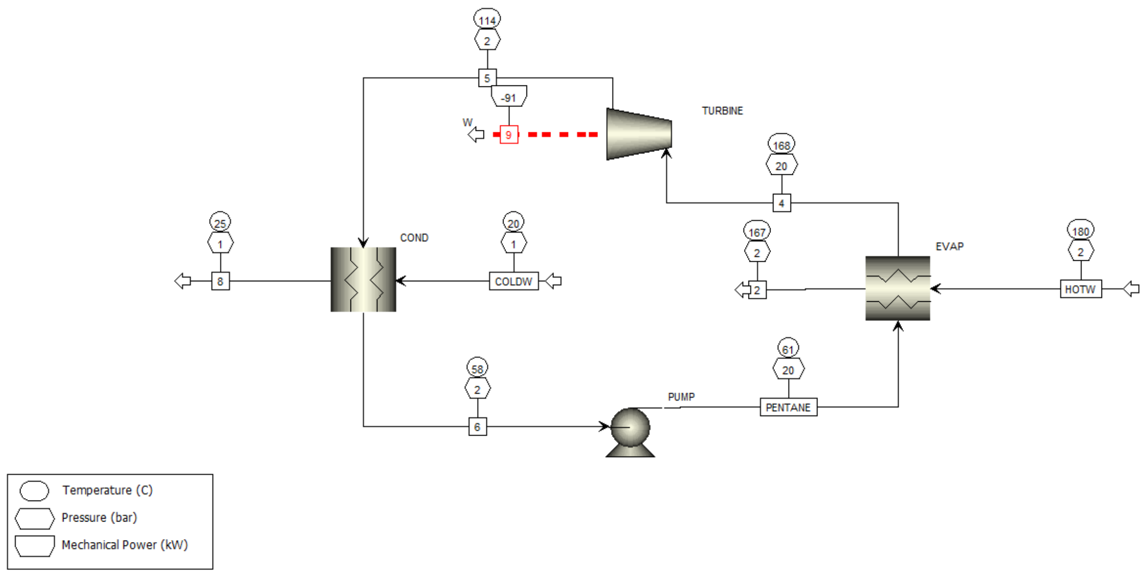

Figure 1: Aspen ORC Simulation

As previously mentioned, the ORC plant is more economical for geothermal fluid temperatures below 180°C. Because of this, it is best to optimize the geothermal heat source temperature based off the heat sink temperatures and the fluid conditions. According to researchers from the University of Moratuwa, "it can be observed that the specific mass flow rate increases when decreasing the efficiency of the ORC. The findings of the study show that the performance of Benzene is significantly higher, and efficiency lies in between 14%–19% at evaporator operating temperatures. Benzene as a working fluid provides significantly improved efficiencies for a range of operating conditions with comparative to other ORC fluids." [4]. From this article, it makes sense to utilize benzene. The findings of the study show that the performance of Benzene is significantly higher, and efficiency lies in between 14%–19% as opposed to toluene, pentane, and R245fa at evaporator operating temperatures of 100°C to 200°C.

However, what also needs to be considered for a process is how environmentally friendly it is. One such environmentally friendly working fluid is pentane. Findings have shown that pentane has one of the lowest environmental impacts over the lifespan of an ORC, as compared to other working fluids [6]. Pentane also has a high latent heat of vaporization, meaning that the use of this working fluid in the ORC can lead to a higher system efficiency, as compared to other low impact working fluids [7]. Pentane is also a better choice of working fluid due to its critical temperature. According to Koretsky, the critical point of pentane is 469.6 K or 196.45 °C, while the critical point of benzene is 562.1 K or 288.95 °C [8]. Since less energy needs to be transferred to the system to completely vaporize pentane, it is a better choice of working fluid in the ORC. Due to this factor, as well as the lower environmental impact and higher expected ORC efficiency, this ORC uses pentane as the working fluid. After considering this information and testing other working fluids (R-245fa, toluene, hexane, and butane), pentane allowed the ORC to achieve the highest work output under the specified conditions.

A representative heat source temperature of 150°C (423.15 K) and a heat sink temperature of 30°C (303.15 K) were selected for comparison. These values were chosen based on several considerations. First, geothermal ORC systems typically operate with fluid temperatures below 180°C, as mentioned in the background section. Given that the working fluid in this study is pentane, which has a critical temperature of 196.45°C, an average heat source temperature of 150°C represents a reasonable midpoint within the expected operating range of the evaporator.

The heat sink temperature of 30°C reflects the practical conditions of water-cooled condensers, as described in the project prompt. Water cooling systems usually operate between 20°C and 40°C, making 30°C a suitable and conservative estimate for a real-world ORC setup. These assumptions allow for a good comparison between the real cycle's performance and its ideal thermodynamic limit.

Efficiency Analysis

The efficiency of the Organic Rankine Cycle (ORC) is inherently limited by the second law of thermodynamics. In theory, the upper bound for any heat engine is defined by Carnot efficiency, which is described by the equation:

$$\eta_{Carnot} = 1 - (T_{hot} / T_{cold}),$$

where T_{hot} and T_{cold} are the absolute temperatures (in Kelvin) of the heat source and heat sink, respectively. As previously mentioned, a heat source temperature of 150°C (423.15 K) and a heat sink temperature of 30°C (303.15 K) were selected for comparison.

Substituting the selected values into the Carnot equation gives

$$\eta_{Carnot} = 1 - (303.15/423.15) = 0.2835 \text{ or } 28.4\%.$$

Aspen Plus was used to simulate a wide range of operating pressures (5-20 bar) and degrees of superheating (5°C -20°C above saturation) to evaluate how real cycle efficiency compares to the theoretical Carnot limit. From the results, it is evident that the thermal efficiency of the ORC increases with both superheat temperature and operating pressure. This efficiency was calculated using the equation

$$\eta = |W_{Turbine} - W_{Pump}| / Q_{Evap}.$$

At 5 bar, efficiency ranged from 6.93% with 5°C superheat to 8.28% with 20°C superheat. At 10 bar, efficiency improved from 9.17% to 11.28%. The 15-bar condition yielded efficiencies between 10.15% and 12.34%, while the highest pressure, 20 bar, resulted in the best performance, ranging from 10.71% up to 13.17%. These trends confirm that increased superheating and higher boiler pressure allow for more energy to be extracted as work.

Despite this improvement, the simulated efficiencies remain well below the theoretical Carnot efficiency of 28.4%. This gap highlights the impact of real-world irreversibility. For instance, the expansion in the turbine is not isentropic due to frictional losses and mechanical inefficiencies, which reduce the net work output. Similarly, the heat addition in the boiler is not ideal as temperature gradients between the heat source and working fluid introduce entropy generation, and incomplete heat transfer further limits energy conversion. Even the pump, though it contributes a smaller energy input, introduces inefficiencies due to imperfect mechanical conversion and fluid viscosity. These losses altogether prevent the ORC from approaching the Carnot limit.

In comparison, a similar ORC using water achieved up to 65% of the Carnot efficiency [9]. The best-case scenario in this pentane-based cycle reached only about 48% (13.75/28.4%). This shortfall is likely due to the differences in pentane from water (i.e. thermal conductivity), as well as the specific conditions modeled. While pentane remains suitable for moderate temperature geothermal systems, this comparison highlights the potential for further optimization in ORC performance through fluid selection, system design, and refined operating parameters.

Sensitivity Analysis

To optimize the amount of power released in an Organic Rankine Cycle, one can manipulate the heat source temperature, heat sink temperature, turbine inlet pressure, or inlet pump pressure. The inlet pump is a key component to the cycle. The main goal of the pump is to send the working fluid, pentane, to the evaporator. While the pentane is in the pump, the pump is compressing the pentane to a higher pressure. To analyze how increasing the pump pressure alters the power produced, the team performed a sensitivity analysis on the inlet pump pressure in Aspen.

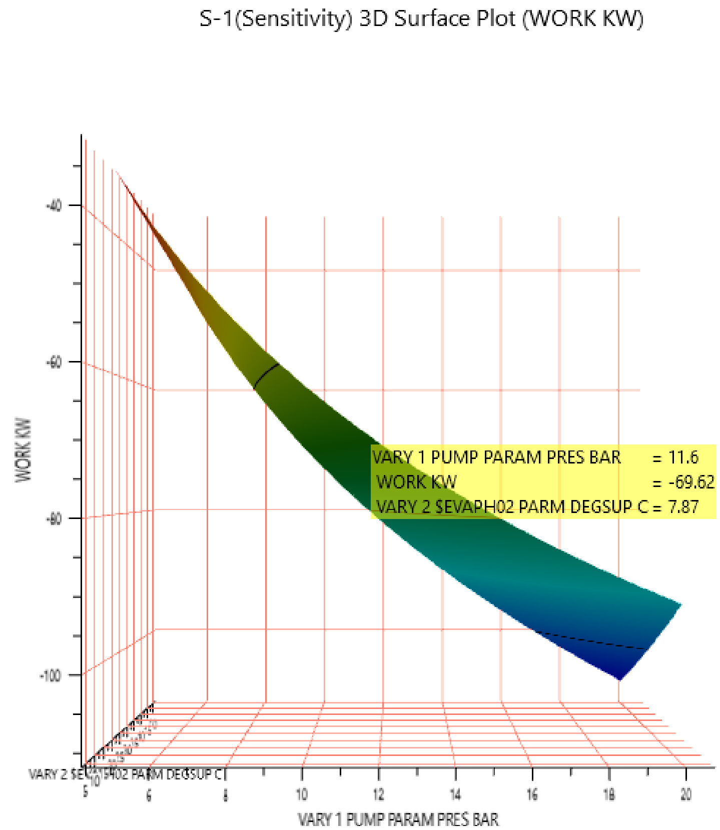

Figure 2: Sensitivity Analysis Plot

From the sensitivity analysis, the amount of power produced increases, as the inlet pump pressure increases. As the pressure increases from 5 bar to 20 bar, the power output increases. Increasing the pump pressure allows the pentane to increase its boiling point. Increasing the boiling point allows the pentane to absorb more heat before it becomes vapor. Thus, the enthalpy of the pentane is greater.

The equation for power in the turbine is defined by the equation

$$P_{turbine} = m * (H_{inlet} - H_{outlet}).$$

As the enthalpy of the inlet is greater, and the enthalpy outlet remains the same for the various pressures. The power produced is greater when the pump pressure is increased. To optimize power output, it is important to increase the pump pressure. Increasing pump pressure increases the boiling point, so then the pentane can absorb more heat.

Conclusions and Recommendation

The Organic Rankine Cycle has validity in producing energy through low temperature requirements. However, the cycle needs extensive optimization in order to achieve maximum power generation. Pentane is the best option when it comes to the choice of organic fluid in the cycle, as it yields competitive efficiency compared to other organic fluids such as toluene, cyclohexane, and acetone, while minimizing negative environmental impact. As for the process itself, it is quite inefficient in practice when comparing it to the ideal process due to irreversibility such as non-isentropic turbine expansion and heat transfer losses in the evaporator/condenser.

In order to minimize these and get closer to the ideal efficiency, there are many things that could be done. Increasing inlet pump pressure elevates the boiling point of pentane and thus increases enthalpy, which as a result increases power output. Boiler pressure and superheating are also key to maximizing efficiency, as efficiency is shown to rise as boiler pressure and/or superheating increase through the modeled processes. An increase in efficiency yields more work. Water is shown to be a better working fluid than pentane efficiency wise, but it's an impractical choice to use in industry due to the challenges that come with maintaining process conditions such as needing larger pressure ratios, expanders, and lower expander exhaust quality [9]. Given that water performs better than pentane, optimizing a mixture of water and pentane could increase efficiency and bring higher energy yields from the ORC while also allowing for practical maintenance conditions.

In summary, using a mixture of pentane and water with high inlet pressure, boiler pressure, and superheat would allow for the Organic Rankine Cycle to maximize process efficiency and power while minimizing environmental effects and operating conditions.

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