ORGANIC RANKINE SYSTEM

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INTRODUCTION

Modern urban environments and industries produce large amounts of waste heat, a largely unused resource that contributes that contributes to environmental degradation and energy inefficiency. In commercial areas, such as shopping malls, heat energy is often released to the atmosphere without being used. This not only increases the reliance on traditional energy sources but also contributes to higher carbon emissions.

With the growing demand for sustainable solutions, its crucial to address this issue by finding ways to convert the waste heat into usable energy. Recovering this energy could decrease the demand for external power, lowering both operational costs and environmental impact.

Identifying practical technologies to achieve this goal is essential for improving energy efficiency in large-scale urban operations. By tackling the problem of waste heat, industries and commercial spaces can promote more sustainable energy practices, reduce carbon footprint, and create long term economic benefits.

WHY CHOOSE ORC SYSTEM?

The ORC is highly efficient in recovering low-grade heat, which is almost exactly the type of heat released by cars in parking lots. Traditional Rankine Systems that use water as liquid may require higher temperatures to operate efficiently. However, the ORC uses organic fluids with lower boiling points, making it well-suited for capturing and converting the low-temperature waste heat.

To achieve maximum efficiency for the Organic Rankine System, I used the following approach:

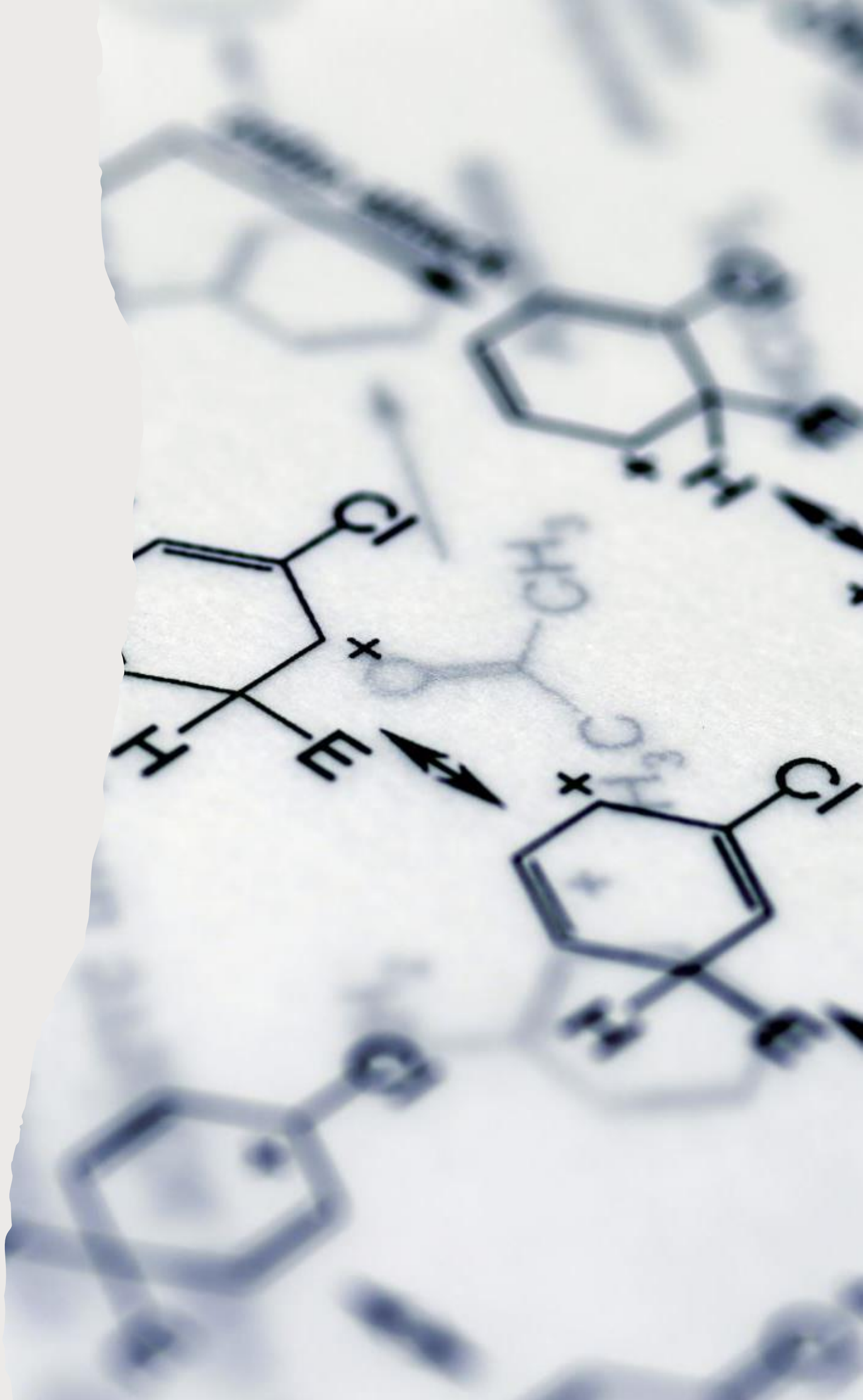
- Understand and research on the ORC Cycle and the key components needed for it.
- Research on the advantages and disadvantages of the method.
- Create a basic design of the ORC model.
- Derive a formula to calculate efficiency.
- Calculate whether the method is cost-effective.

I believe these approaches will help me achieve the aims I have set for this project. The ORC is a well-established and widely researched technology in recent years. This means there is a wealth of existing knowledge and resources to support my project.

METHOD

Organic Rankine Cycle (ORC): The ORC systems will have to use fluids such as hydrocarbons. In this case, I chose pentane as it has a melting point of -130 degrees Celsius and boiling point of 36 degrees Celsius. This allows the perfect heat range for liquid evaporation.

First, the heat waste from the cars will be used as a source to heat the pentane, turning it in to vapor. The high-pressure pentane vapor expands through a turbine, converting the thermal energy to mechanical energy. The expanded vapor will then be turned back to a liquid by the process of condensation with the help of a condenser. A pump will then circulate the condensed liquid back into the heat source, completing the Rankine Cycle.



THE FLOW OF LIQUID DESIGN

Before embarking on the ORC design, I researched through various components essential for the project. During this process, I came across several, basic designs of the ORC system. Drawing inspiration from them, I added a few modifications of my own to develop a more tailored version of it.

Additionally, I drew parallels between the structure of the ORC system and the architecture of a Control Processing Unit (CPU) in computers, as using a similar design seemed more applicable and efficient for this project.

The Key Components I used in this design were: Heater, Turbine, Condenser, Pump, Working Fluid Storage Tank, Pipes and Valves, Extra Instruments (Pressure and Temperature Sensors)

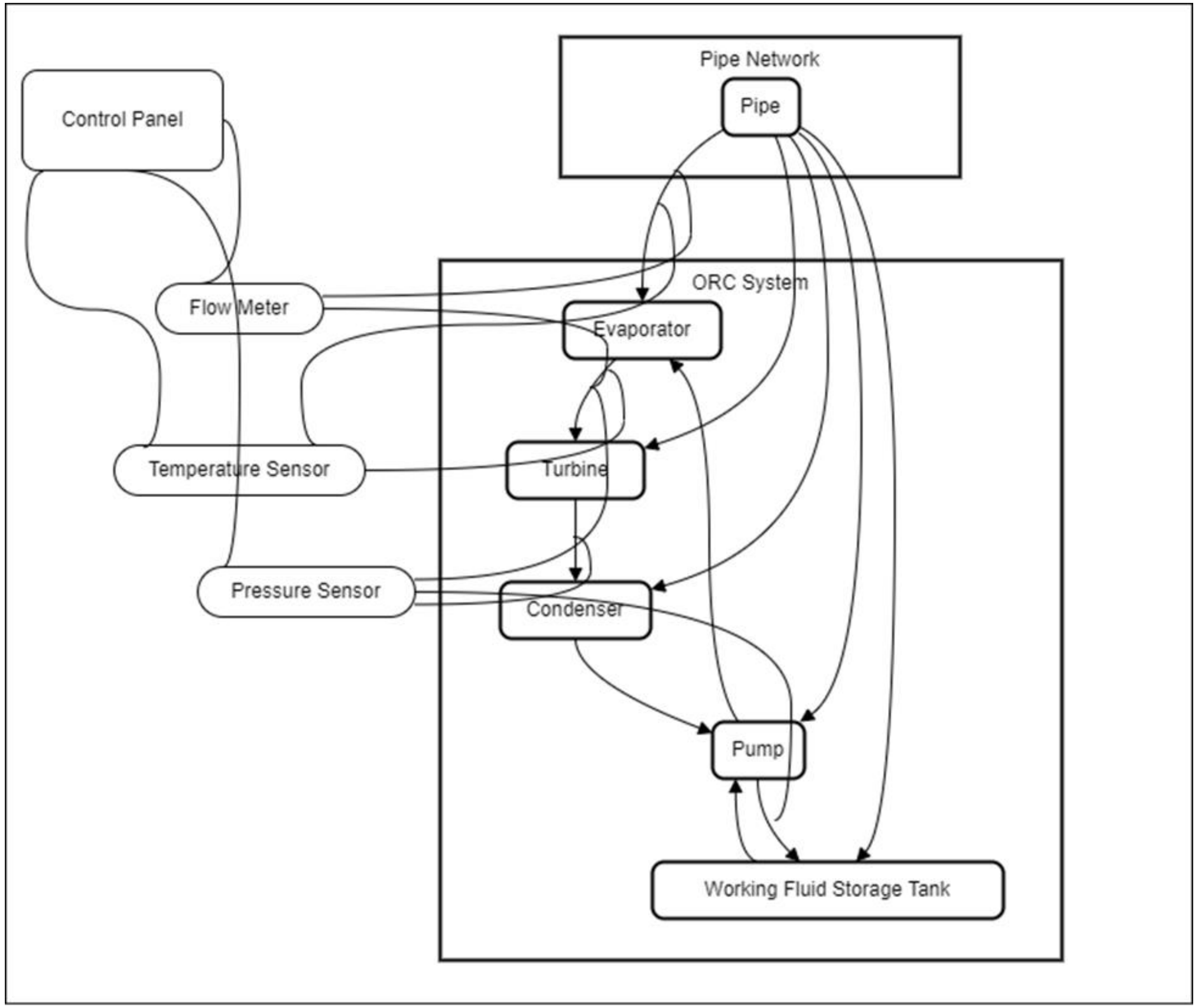
The flow of the liquid is depicted by arrows, representing the movement through the pipes. The process begins when the liquid is drawn from the Working Fluid Storage Tank and into the pump. The pump then propels the liquid towards the evaporator, which is heated and converted to vapor. The vapor then drives the turbine, creating a turning effect. The turbine is coupled with a generator, which converts the mechanical energy to electrical (further details on this process is provided later).

FLOW OF LIQUID DESIGN (CONTINUED)

After passing through the turbine, the vapor is then directed to the condenser, where it is cooled and condensed back to liquid. The liquid then either returned to the Working Fluid Storage Tank or will move back to the Evaporator to continue the cycle with the help of the pump.

To ensure the safety and efficiency of the system, I also incorporated extra instruments such as pressure and temperature sensors. Pressure sensors are added before and after the turbine, as well as after the pump, to monitor and maintain steady pressure, preventing potential damage to the pipes. Temperature sensors are also added before and after the evaporator to ensure the fluid temperature remains above the boiling point. Flow meters are also added to the pipes leading to and from the heat exchanger to monitor the flow rate of the liquid. To monitor and adjust the cycle of the liquid, a control panel is connected to the sensors, representing the systems control unit. Additionally, I also added an external pipeline system for maintenance purposes or in case of safety hazards detected by the sensors.

THE DESIGN


Pipe Network
Pipe
Control Panel
ORC System
Flow Meter
Evaporator
Temperature Sensor
Turbine
Pressure Sensor
Condenser
Pump
Working Fluid Storage Tank

DERIVATION OF EFFICIENCY

The network output of the ORC is given by:

$$W_{net} = W_{turbine} - W_{pump}$$

Substituting $W_{turbine}$ and W_{pump}:

$$W_{net} = \; m \cdot [(h_1 - h_2) - (h_5 - h_6)]$$

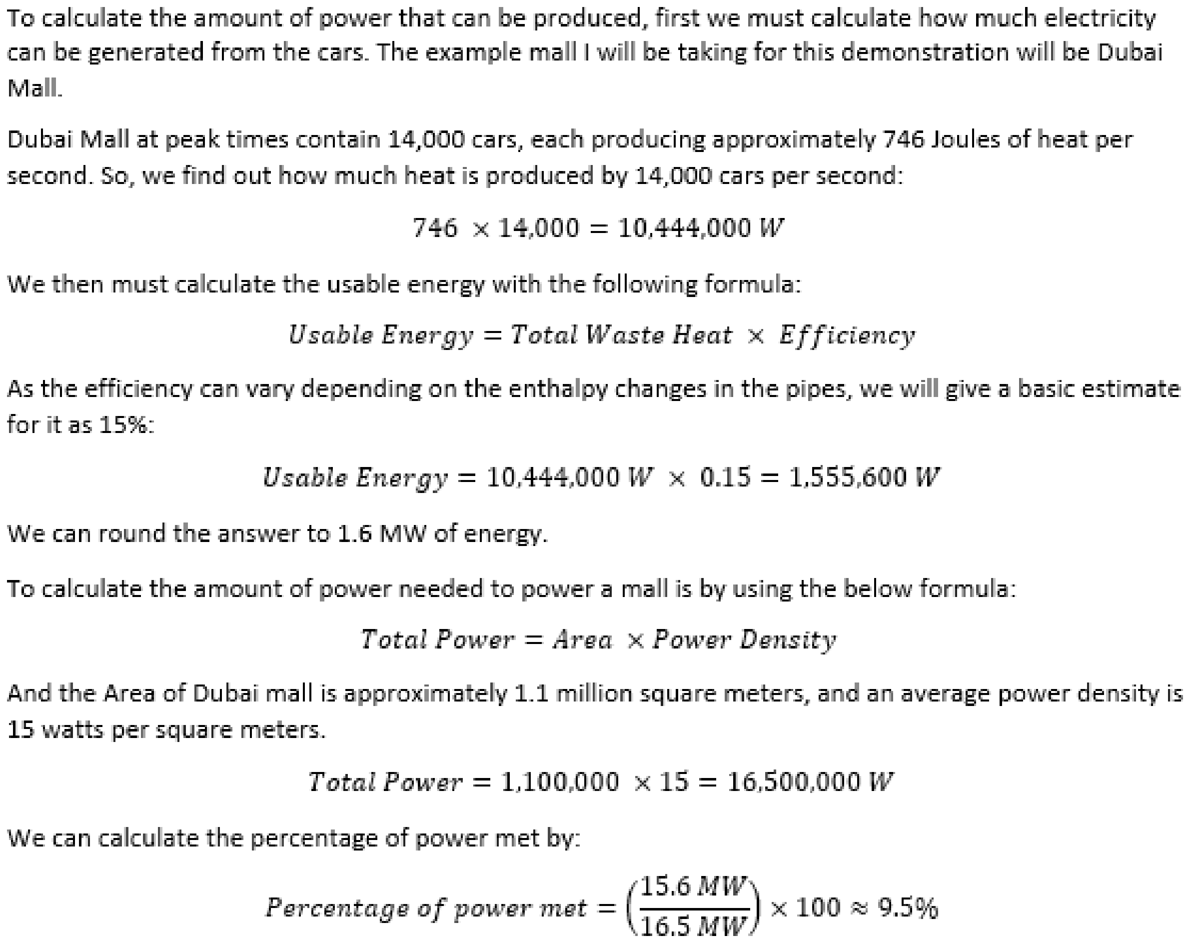
Finally, the efficiency of the ORC system, including the pump and turbine is:

$$n_{ORC} = \frac{W_{net}}{Q_{in}} = \frac{m \cdot [(h_1 - h_2) - (h_5 - h_6)]}{m \cdot (h_4 - h_3)}$$

The formula simplifies to:

$$n_{ORC} = \frac{(h_1 - h_2) - (h_5 - h_6)}{(h_4 - h_3)}$$

ESTIMATE OF POWER GENERATED



To calculate the amount of power that can be produced, first we must calculate how much electricity can be generated from the cars. The example mall I will be taking for this demonstration will be Dubai Mall.

Dubai Mall at peak times contain 14,000 cars, each producing approximately 746 Joules of heat per second. So, we find out how much heat is produced by 14,000 cars per second:

$$746 \times 14{,}000 = 10{,}444{,}000\ W$$

We then must calculate the usable energy with the following formula:

$$Usable\ Energy = Total\ Waste\ Heat \times Efficiency$$

As the efficiency can vary depending on the enthalpy changes in the pipes, we will give a basic estimate for it as 15%:

$$Usable\ Energy = 10{,}444{,}000\ W \times 0.15 = 1{,}555{,}600\ W$$

We can round the answer to 1.6 MW of energy.

To calculate the amount of power needed to power a mall is by using the below formula:

$$Total\ Power = Area \times Power\ Density$$

And the Area of Dubai mall is approximately 1.1 million square meters, and an average power density is 15 watts per square meters.

$$Total\ Power = 1{,}100{,}000 \times 15 = 16{,}500{,}000\ W$$

We can calculate the percentage of power met by:

$$Percentage\ of\ power\ met = \left(\frac{15.6\ MW}{16.5\ MW}\right) \times 100 \approx 9.5\%$$

COST EFFECTIVENESS

To calculate the cost of powering 16.5 MW of power every second, you need to first need to know the cost of electricity per unit of energy, which is in Kilowatt-hour.

We first convert Megawatts to Kilowatt-hours:

$$1\ MW = 1000\ kW$$

$$16.5\ MW = 16{,}500\ kW$$

We now convert the Kilowatts to Kilowatt-hours:

$$16{,}500\ kW \times \left(\frac{1}{3600}\right) \approx 4.583\ kWh$$

Now to calculate the cost of electricity:

$$Cost\ per\ second = 4.583kWh \times 0.10\frac{USD}{kWh} \approx 0.4583\ USD$$

We then convert the money for 1 second to a whole year:

$$Cost\ per\ day = 0.4583\ USD \times 31{,}536{,}000\ s \approx 14{,}482{,}032\ USD$$

COST EFFECTIVENESS (CONTINUED)

If we do the same calculations for the power generated by the ORC, we will get:

$$1.56\ MW = 1{,}560\ kW$$

$$1560\ \times \left(\frac{1}{3600}\right) = 0.4333\ kWh$$

$$0.4333\ kWh\ \times 0.10\ \frac{USD}{kWh} \approx 0.04333$$

$$0.04333\ USD\ \times 31{,}536{,}000\ s \approx 1{,}366{,}000\ USD$$

The cost of the ORC system is approximately 4.8 million USD, and the annual cost can be calculated by the below equation:

$$\text{Annual Maintenance Cost} = 4{,}800{,}000\ \text{USD}\ \times 0.02 = 96{,}000\ \text{USD}$$

This means the Net Annual Savings for the ORC is:

$$Net\ Annual\ Savings = 1{,}366{,}000\ USD - 96{,}000\ USD = 1{,}270{,}000\ USD$$

To calculate how long the mall will take to recoup the initial savings through the annual savings is by:

$$Payback\ Period\ (Break\ Even\ Point) = \frac{4800000}{1270000} \approx 3.78\ years$$

ADVANTAGES AND DISADVANTAGES

- **Advantages:**
- Efficiency at low temperatures: The ORC can efficiently convert the low-temperature heat sources, such as heat waste, into electricity, making it ideal for waste heat recovery.
- Relatively higher efficiency: ORC systems generally have a higher efficiency (12% - 25%) compared to TEG systems, making them more suitable for maximizing output from waste heat.
- Established Technology: ORC systems are widely used in industries like geothermal energy and biomass power generation, meaning there is a lot of existing research and data that can be supportive for this project.
- **Disadvantages:**
- Complexity in the Design: The selection of the appropriate fluid for the optimization of the cycle can be complex, taking into consideration of the thermodynamic properties, environmental impact, and safety of that liquid.
- High initial cost: The cost of ORC can be high due to the specialized equipment and working fluids required. This makes the initial investment to be higher, making it substantial for this smaller-scale application.

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