# Modelling and Simulation of Combined Vapor Compression System and Organic Rankine Cycle

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**Abstract**
Cogeneration systems refer to energy systems that have the ability to produce two useful commodities simultaneously. In practical terms, what cogeneration usually means is the use of what would otherwise be wasted heat (such as a manufacturing plant's exhaust) to produce additional energy benefit, such as to provide heat or electricity for the building in which it is operating. Cogeneration is great for the bottom line and also for the environment, as recycling the waste heat saves other fossil fuels from being burned.

For this project, we make use of the concept of cogeneration to recover heat liberated from the condenser of a vapour compression refrigeration cycle and transfer this heat to a boiler in an organic rankine cycle in order to produce steam which runs a turbine, thereby producing power.
To carry out this project we use a programming language such as python in order to generate the outputs such as COP, Power generated in the turbine, efficiencies, etc depending upon the user inputs.

**Keywords: :** organic rankine cycle;vapor compression cycle;python,modelling;simulation;cogeneration

## 1. Introduction

Energy requirement is a fundamental need for human development. Energy can be considered as a key-element for promoting or improving base services such as lightning, drinking water access, health services, education or communications.
Taking thermodynamic cycles in general there is a lot of heat rejection from the cycle. This heat instead of going waste can be utilized effectively. This heat can be utilized to generate electricity. As population increases, demand for electricity also increases. Heat which when converted into electricity can be used to satisfy this demand.
Polygeneration System is a hot topic which could provide solutions to the above energy needs. This Polygeneration system could be implemented in various ways like Cogeneration, Trigeneration, Multigeneration, etc...
In Vapour compression Refrigeration cycles, there is a lot of heat rejected by the refrigerant as it passes through the condenser. This heat is released as waste to the atmosphere. Using this heat it is utilized and power is generated.

### 1.1 THERMODYNAMIC CYCLES

A thermodynamic cycle consists of a linked sequence of thermodynamic processes that involve transfer of heat and work into and out of the system, while varying pressure, temperature, and other state variables within the system, and that eventually returns the system to its initial state. In the process of passing through a cycle, the working fluid may convert heat from a warm source into useful work, and dispose of the remaining heat to a cold sink, thereby acting as a heat engine.

Conversely, the cycle may be reversed and use work to move heat from a cold source and transfer it to a warm sink thereby acting as a heat pump.
The two thermodynamic cycles that we will be using in our mini project are
(i)Vapour Compression Refrigeration Cycle (VCR) and
(ii) Organic Rankine Cycle (ORC)

*1.1.1* Vapour Compression Refrigeration Cycle (VCR

This refrigeration cycle is approximately a Rankine cycle run in reverse. A working fluid (often called the refrigerant) is pushed through the system and undergoes state changes (from liquid to gas and back). The latent heat of vaporization of the refrigerant is used to transfer large amounts of heat energy, and changes in pressure are used to control when the refrigerant expels or absorbs heat energy.

Step 1: Compression
The refrigerant enters the compressor at low temperature and low pressure. It is in a gaseous state. Here, compression takes place to raise the temperature and refrigerant pressure. The refrigerant leaves the compressor and enters to the condenser.
Step 2: Condensation
The condenser is essentially a heat exchanger. Heat is transferred from the refrigerant to a flow of water. This water goes to a cooling tower for cooling in the case of water-cooled condensation.
Step 3: Throttling and Expansion
When the refrigerant enters the throttling valve, it expands and releases pressure. Consequently, the temperature drops at this stage. Throttling valves play two crucial roles in the vapor compression cycle. First, they maintain a pressure differential between low- and high-pressure sides. Second, they control the amount of liquid refrigerant entering the evaporator.
Step 4: Evaporation
At this stage of the Vapor Compression Refrigeration Cycle, the refrigerant is at a lower temperature than its surroundings. Therefore, it evaporates and absorbs latent heat of vaporization. Heat extraction from the refrigerant happens at low pressure and temperature. Compressor suction effect helps maintain the low pressure.

**1.2 Organic Rankine Cycle**

Organic Rankine Cycle (ORC) systems are used for power production from low to medium temperature heat sources in the range of 80 to 350 °C and for small-medium applications at any temperature level. This technology allows for exploitation of low-grade heat that otherwise would be wasted. The main components of an Organic Rankine Cycle power plant design are:

1. THE TURBINE

it's the key component of the entire ORC power plant, which determines the ORC system performance. It expands the working fluid producing mechanical energy that is converted into electricity by a generator coupled with the turbine shaft.

2. THE HEAT EXCHANGERS

The working fluid flows through the heat exchangers, extracting the heat from the heat source.

3. THE CONDENSER

With the direct air to fluid heat exchanger, the organic fluid is cooled and liquefied before entering the pump. The use of air eliminates the requirement for water to treatment and make up. It is possible to use also a water-cooled condenser.

4. THE FEED PUMP

Brings the organic fluid from the condensation pressure to the maximum pressure of the Organic Rankine Cycle. The pump is usually driven by an electric motor at variable rotating speed.

## 2. Cogeneration system

The Cogeneration system that we use here in our project consist of both the Vapour Compression Refrigeration cycle and Organic Rankine cycle being used so that the waste heat liberated by the condenser of the VCR is absorbed by the ORC and used to run the turbine by employing a heat exchanger between the two cycles.

### 2.1 Proposed Cogeneration System

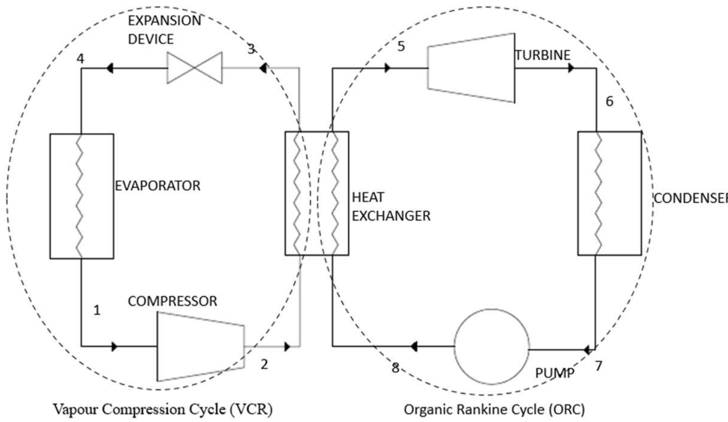



*Fig 3: Schematic Representation of the proposed cogeneration of system*

In this proposed cogeneration system, it consists of two cycles namely:

- Vapour Compression Refrigeration Cycle (VCR)
- Organic Rankine Cycle (ORC)

The Proposed Cogeneration system consists of a heat exchanger which acts as a medium for heat transfer between the two thermodynamic cycles. Here, in the VCR the condenser rejects waste heat which when captured by the heat exchanger transfers this heat to the boiler in the ORC. The heat is used to evaporate the working fluid in the ORC and used to run the turbine.

## 3.State Points Of VCR

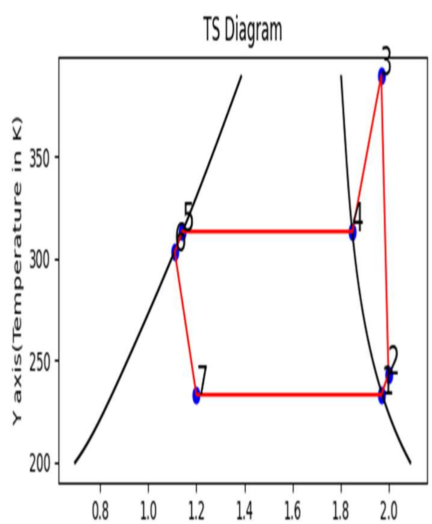


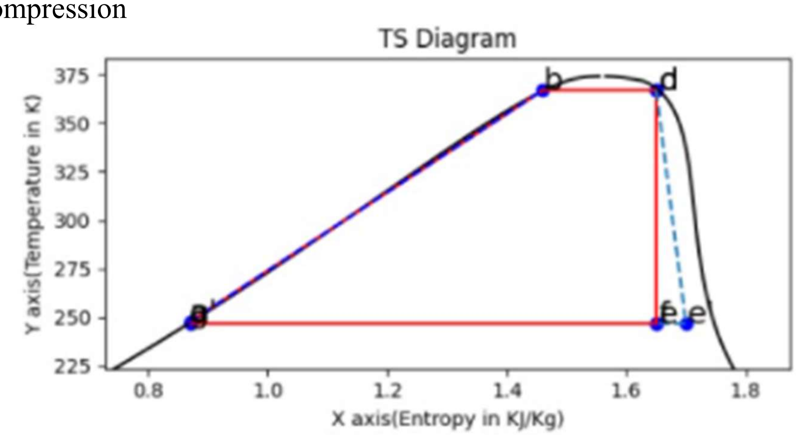

*Fig 4: T-S of VCR*

1-2: Superheating before inlet to compressor

2-3: Isentropic Compression
3-4-5: Constant pressure heat rejection
    3-4: De-superheating in condenser
    4-5: Phase change at constant temperature in condenser
5-6: Subcooling in Condenser
6-7: Expansion
7-1: Constant pressure heat addition

**4.State Points Of ORC**

a-b-c-d: Constant pressure heat addition in boiler
c-d: Superheating in boiler
d-e: Adiabatic expansion in turbine
d-e’: Actual expansion in turbine
e-f: Constant pressure heat rejection
f-a: Adiabatic compression
f-a’: Actual compression




**5.WORKING FLUIDS**

A working fluid is a gas or liquid that primarily transfers force, motion, or mechanical energy. In this project we use two working fluids in the co-generation system, one in each cycle. Few of the working fluids used in VCR and ORC cycles are:
R124, R125, R134a, R141b, R142b, R143a, R152a, R161, R21, R218, R22, R227ea, R12, R404a, R123, R11, CO2, NH3, R113, R114, R115, R116, R40, R407c, R41, R410a, and a few others.

For the working fluid in ORC, as the working temperature of the cycle is relatively lower compared to normal rankine cycles we use organic fluids which have lower boiling temperatures than water.

**5.1 Selection Criteria**

- For Organic Rankine Cycle, working Fluid Selection is based on Critical Pressure of Fluids.
- For Vapour Compression Cycle, working Fluid Selection is based on Critical Temperature of Fluids.
- Maximum Operating Pressure of Refrigerants is less than/equal to Critical Pressure of Refrigerant used.
- It is planned to use the working fluid to be free from Chlorine and Florine i.e. HFC and HC.

Hence, due to the above-mentioned criteria, we use only the following working fluids:
R22, R134a, R404a, R143a, R245FA, R21, Propane, Butane.

## 7. Formulae Used

### 7.1 General Formulae Used for Vapor Compression Cycle:

- S1+Cp1*ln(T2/T1)=S4+Cp4*ln(T3/T4)
- $H=H_f+(x*H_{fg})$
- $H=H_g+Cp(T2-T1)$
- $COP_{ideal}=T1/(T4-T1)$
- $COP_{actual}= (H2-H7)/(H3-H2)$
- Refrigerating Effect (RE)= $((H2-H7)*(m_{vcr}))/(3500)$
- Heat lost from Condenser $=m_{vcr}*(H3-H6)$
- Power input to Compressor$=m_{vcr}*(H3-H2)$

### 7.2 General Formulae Used for Organic Rankine Cycle:

- Work Input to Pump $(Wp)=V_f(P_a-P_f)$
- Work Input to Pump $(Wp)=H_a-H_f$
- Heat Supplied in Boiler $(Qin)=H_d-H_a$
- $Tsup=((H_d-H_c)/C_c)+T_c$
- $S_e=S_f+(x*S_{fg})$
- $H_e=H_f+(x*H_{fg})$
- $W_p=H_d-H_e$
- $ORC_{Ideal\ Efficiency}=W_t-W_p/Q_{in}$
- $Wp_{\ Actual}=W_p$/Pump Efficiency
- $Wt_{\ Actual}=W_t$*Turbine Eficiency
- $ORC_{\ ActualEfficiency} = (Wt_{\ Actual}-Wp_{\ Actual})/Q_{in}$
- Specific Fluid Consumption(SFC)$=3600/Q_{in}$

### 7.3 Nomenclature

| SYMBOLS | ABBREVIATIONS |
|---|---|
| $\mathbf{M_f}$ | Mass flow rate |
| $\mathbf{V_f}$ | Volume flow rate |
| **P** | Pressure |

| | |
|---|---|
| **RE** | Refrigeration Effect |
| **$COP_{ideal}$** | Ideal Coefficient of Performance |
| **$COP_{actual}$** | Actual coefficient of performance |
| **$H_{fg1}$** | Latent heat of vaporization at evaporator pressure |
| **$H_{fg2}$** | Latent heat of vaporization at condenser pressure |
| **H2** | Enthalpy at the inlet of compressor |
| **H3** | Enthalpy at the outlet of compressor |
| **H4** | Enthalpy after De-superheating in condenser |
| **H5** | Enthalpy at the outlet of condenser |
| **H6** | Enthalpy at the inlet of expansion device |
| **H7** | Enthalpy at the inlet of evaporator |
| **S2** | Entropy at the inlet of compressor |
| **S3** | Entropy at the outlet of compressor |
| **S4** | Entropy after De-superheating in condenser |
| **S5** | Entropy at the outlet of condenser |
| **S6** | Entropy at the inlet of expansion device |
| **S7** | Entropy at the inlet of evaporator |
| **$T_{sub}$** | Temperature of subcooling |
| **$T_{sup}$** | Temperature of superheating |
| **X** | Dryness fraction |
| **$W_p$** | Work input to pump |
| **$W_t$** | Work done by |
| **$W_c$** | Work input to compressor |
| **$ORC_{Ideal\ Eff}$** | Ideal efficiency of ORC |
| **$ORC_{actual\ eff}$** | Actual efficiency of ORC |
| **SFC** | Specific fluid consumption |
| **$Q_{in}$** | Heat supplied to boiler |
| **$W_{p\ actual}$** | Actual work done by pump |
| **$W_{t\ Actual}$** | Actual work done by turbine |
| **$H_a$** | Enthalpy at the inlet of boiler |
| **$H_c$** | Enthalpy at the inlet of superheater |
| **$H_d$** | Enthalpy at the outlet of boiler |
| **$H_e$** | Enthalpy at the outlet of turbine |
| **$H_f$** | Enthalpy at the outlet of condenser |
| **$H_g$** | Enthalpy at the outlet of compressor |
| **RC** | Refrigeration capacity |

## Applications Of This Project

- Milk chilling plants
- Production of hydrogen and oxygen plants

- Petrochemical industries
- Pharma industries
- Food processing industries

## Conclusions

**Best VCR Working Fluid**

It is evident that from the graph of Various Working Fluids of VCR vs COP Actual that COP is very high for R21 as working fluid in VCR but since its GWP is very high it is best preferred to use R245fa since it is HFC and has low GWP and High COP for given working conditions.
In the graph of Various Working Fluids of VCR vs Compressor Power (KW) we can conclude that R404a is best working fluid in VCR since power consumed by compressor is low but it also has very low COP hence R245fa is preferred.
Hence overall in VCR it is best to use R245fa as working fluid.

**Best ORC Working Fluid**

By considering the ORC working Fluid based on Efficiency of ORC it is observed that not much difference in efficiency is observed. There exits the difference of maximum 2% with Propane being highest and R245fa being lowest.
By considering the mass flow rate of Working Fluid, it is evident that mass flow rate has to minimum as it reduces the complexity and overall cost of plant. Therefore, Propane or Butane is the best suited regarding the mass flow rate.
And Power Out of the Turbine is high for Propane and Butane with very minued difference.
Hence overall in ORC it is best to use Propane/Butane as working fluid.
Finally, we can say that for the given operating conditions the Working Fluid for VCR is R245fa and for ORC is Propane.

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