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Organic Rankine Cycle (ORC) for a Compressed Air Engine

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ABSTRACT

The transportation sector in the Philippines is currently transitioning from oil-powered vehicles to zero carbon emission vehicles as a solution to the negative effects of internal combustion engines. This research paper focused on promoting the development of zero carbon emission vehicles in the country, by evaluating the thermodynamics of an air supply system that recovers and pressurizes exhaust air from an engine operating on compressed air or nitrogen. The system utilizes the Organic Rankine Cycle (ORC) to power the compressed air engine, wherein the thermal efficiency was found to be approximately 25% - 38% which makes it a viable alternative option to the internal combustion engine.

Keywords: Compressed Air Energy Storage, Compressed Air Engine, Liquid Air Energy Storage, Organic Rankine Cycle.

Introduction

An unexplored method of propulsion involves the use of compressed air engines, offering a potential solution for achieving zero carbon emissions in transportation (Mensah, 2013). Unlike traditional internal combustion engines and electric vehicles, compressed air engines do not produce excessive heat and do not rely on refrigerants other than air for air conditioning purposes (Rogers, Sr., 2020).

The objective of this research is to evaluate the possibility of utilizing self-generated compressed air in a compressed air engine, by means of computer simulation and analysis. Conversion of engines to operate without combustion is a viable solution to address the issues of incomplete combustion associated with internal combustion engines. This study further aims to enhance understanding of compressed air, air engines, compressed air power cycle, and air liquefaction, with potential for future research advancements.

The focus of this research paper is to simulate and analyze an engine as a thermal system that utilizes pressurized air or nitrogen, obtained from a low-temperature pressurization system, with minimal power consumption during the pressurization process. Numerical and graphical techniques were used to obtain the results which were verified using computer simulation software.

In the simulation and analysis, it was assumed that the air is dry. Hence, no consideration was made for the moisture content of ambient air entering the system. It was also assumed that air or nitrogen is an ideal gas therefore compressibility effects of real gases are excluded from this study. The negative enthalpy of liquid air or nitrogen was assumed to be zero (Shpilrain, 2011; Winterbone, 1997). Regarding percentage errors, this study assumed a maximum of 10% which is generally acceptable in scientific experiments (Helmenstine, 2016).

Theoretical Framework

In the present study, power generation in the engine for propulsion and air refrigeration was achieved through the use of the Organic Rankine Cycle (Ameel et al. 2011). Furthermore, the study employed an air liquefaction process to recover a portion of the exhaust air from the engine and convert into liquid form, which is then recompressed with minimal power consumption to match the engine's operating pressure (Ameel et al. 2011). This process allowed for the conversion of the liquid air back into compressed air, thus completing the cycle (Ameel et al. 2011).

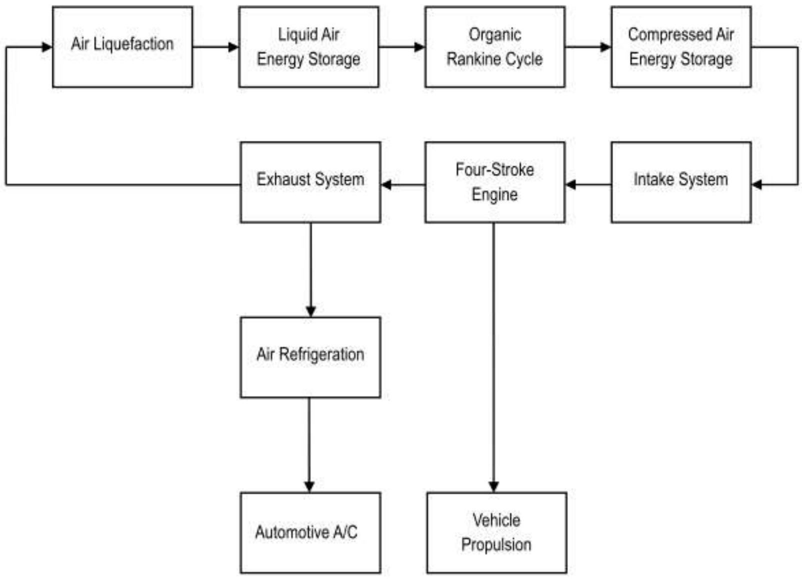

Figure 2-1. Conceptual Framework of the Study

According to Cassanova and Stephenson (1965), an ideal gas expanding through a nozzle undergoes a drop in pressure and temperature in accordance with $P/(T)^{\gamma/\gamma-1} = C$ (P is for pressure, T is for temperature, γ is for ratio of specific heats, and C is for constant), wherein the isentropic curve crosses the saturated pressure on a P-T plane resulting in the formation of liquid or solid droplets. A possible setup for this process, as part of the conceptual framework of the current study, is the proposed system shown in Figure 2-5.

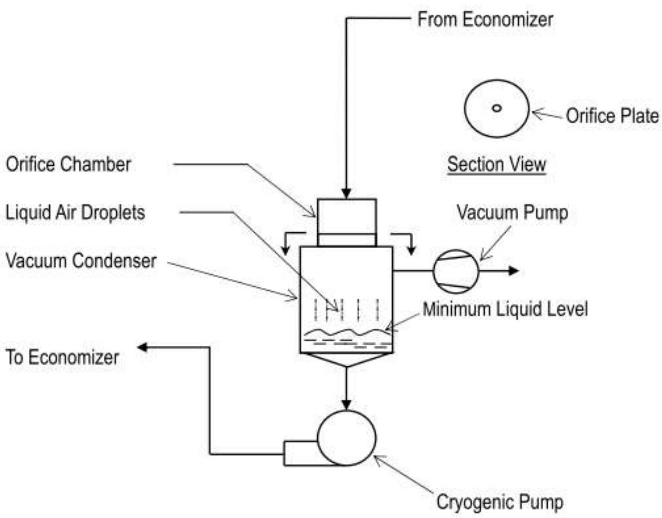

Figure 2-5. Air Passing through Nozzle (Orifice) and Expanding in a Vacuum Condenser to Form Liquid Air Droplets

When the Cryogenic Pump extracts fluid from the condenser, the space above the fluid level inside the condenser becomes a vacuum, which is further maintained by the vacuum pump. This in turn caused a drop in pressure and temperature of the air from the orifice chamber when the air passed through the orifice hole and expanded into the vacuum condenser. At this point the air condensed into liquid droplets which are collected in a pool at the bottom. The level of this pool of liquid at the bottom of the vacuum condenser is maintained above the pump inlet during operation, which kept the pump's suction head positive to minimize or prevent cavitations.

Organic Rankine Cycle (ORC) systems are commonly used in waste heat recovery and renewable energy technologies, wherein the working medium is an organic fluid other than steam (Jiménez-García et al., 2023). A proposed adaptation for the conceptual framework of the current study is shown in Figure 2-6.

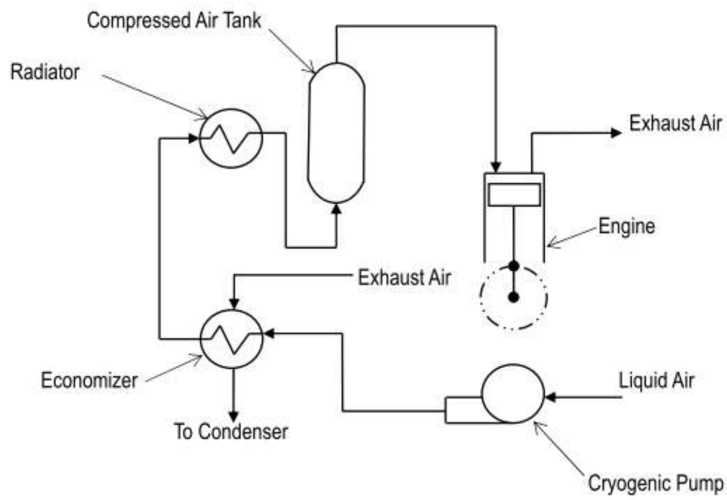

Figure 2-6. Organic Rankine System

The process cycle can be seen as beginning with the air tank, wherein compressed air is supplied to the engine. Once the air undergoes expansion work in the engine, the engine's exhaust air is cooled in the heat exchanger, after which the air is captured and liquefied in the condenser. This liquefied air is then pressurized by the cryogenic pump, after which the pressurized air is then reheated in the heat exchanger. The pressurized liquid air is then vaporized and superheated in the radiator before being returned to the air tank for subsequent repeat of the cycle.

Operational Framework

Simulation & Analysis Procedure

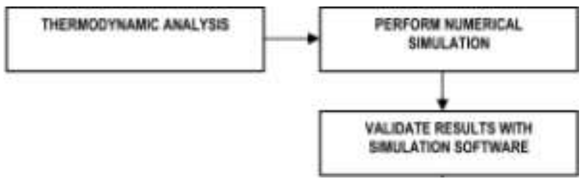

Figure 3-1. Simulation and Analysis Flow Chart

Mathematical Model

The mathematical equations used to model the equipment shown in figures 2-5 and 2-6 for the thermodynamic analysis in this research paper are presented below.

<u>Pump</u>

The pump is modeled by a constant volume work process:

$W_p = v_{17} (P_{17} - P_{16})$ (1)

Where,

W_p = Pump Work, kJ/kg

v_{17} = Specific Volume of Air or Nitrogen, m^3 /kg

P_{17} = Discharge Pressure, kPa (kN/m^2)

P_{16} = Suction Pressure, kPa (kN/m^2)

<u>Heat Exchanger (Heating)</u>

The heat exchanger (heating) is modeled by a constant pressure heating process:

$Q_{Aeco} = h_{18} - h_{17}$ (2)

Where,

Q_{Aeco} = Heat Added, kJ/kg

h_{17} = Inlet Specific Enthalpy of Air or Nitrogen, kJ/kg

h_{18} = Outlet Specific Enthalpy of Air or Nitrogen, kJ/kg

Radiator

The radiator is modeled by a constant pressure heating process:

$Q_{Arad} = h_{19} - h_{18}$ (3)

Where,

Q_{Arad} = Heat Added, kJ/kg

h_{18} = Inlet Specific Enthalpy of Air or Nitrogen, kJ/kg

h_{19} = Outlet Specific Enthalpy of Air or Nitrogen, kJ/kg

Engine

The engine is modeled by an isothermal expansion process:

$W_e = P_2 v_2 \ln(P_1/P_2)$ (4)

Where,

W_e = Isothermal Expansion Work, kJ/kg

P_1 = Compressed Air Supply Inlet Pressure, kPa

v_2 = Specific Volume of Exhaust Air or Nitrogen, m^3/kg

P_2 = Final Exhaust Pressure, kPa

Heat Exchanger (Cooling)

The heat exchanger (cooling) is modeled by a constant pressure cooling process:

$Q_{Reco} = h_{13} - h_{14}$, (5)

Where,

Q_{Reco} = Heat Rejected, kJ/kg

h_{13} = Inlet Specific Enthalpy of Air or Nitrogen, kJ/kg

h_{14} = Outlet Specific Enthalpy of Air or Nitrogen, kJ/kg

Nozzle

The nozzle is modeled by an isentropic expansion process:

$W_{noz} = h_2 - h_1$ (6)

Where,

W_{noz} = Isentropic Expansion Work, kJ/kg

h_1 = Inlet Specific Enthalpy of Air or Nitrogen, kJ/kg

h_2 = Outlet Specific Enthalpy of Air or Nitrogen, kJ/kg

Vacuum Condenser

The vacuum condenser is modeled by a constant pressure cooling process:

$Q_{Rvc} = h_{15} - h_{16}$, (7)

Where,

Q_{Rvc} = Heat Rejected, kJ/kg

h_{15} = Inlet Specific Enthalpy of Air or Nitrogen, kJ/kg

h_{16} = Outlet Specific Enthalpy of Air or Nitrogen, kJ/kg

Energy Balance

The energy balance of the system represented by figure 2-5 and figure 2-6 is modeled according to the first law of Thermodynamics, wherein the total energy entering the system is equal to the total energy leaving the system.

$\Sigma E_{in} = \Sigma E_{out}$ (8)

Where,

$\Sigma E_{in} = mQ_{Aeco} + mQ_{Arad} + mW_p$ (9)

$\Sigma E_{out} = mW_e + mQ_{Reco} + mW_{noz} + mQ_{Rvc}$ + Losses (10)Where,

ΣE_{in} = total energy entering the system, kJ/sec

ΣE_{out} = total energy leaving the system, kJ/sec

Q_{Aeco} = Heat added to the heat exchanger, kJ/kg

Q_{Arad} = Heat added to the radiator, kJ/kg

W_p = work input to the pump, kJ/kg

W_e = work output from the engine, kJ/kg

Q_{Reco} = Heat removed from the heat exchanger, kJ/kg

W_{noz} = apparent work output from the nozzle, kJ/kg

Q_{Rvc} = apparent heat removed from the vacuum condenser, kJ/kg

m = mass of motive fluid in the system, kg/sec

Losses = (friction losses, leakage, unaccounted), kJ/sec

Ideal Carnot Efficiency

The ideal Carnot Efficiency is modeled from the maximum temperature and minimum temperature of the system.

$\eta_{Carnot} = [1 - (T_2 / T_1)] \times 100\%$ (11)

Where,

η_{Carnot} = The ideal Carnot Efficiency, %

T_1 = The maximum temperature of the system, °K

T_2 = The minimum temperature of the system, °K

System Thermal Efficiency

The system thermal efficiency is modeled from the net work and total heat of the system.

$\eta_{Sys} = [W_{net} / Q_{in})] \times 100\%$ (12)

Where,

η_{Sys} = The system thermal efficiency, %

W_{net} = The net work of system, kJ/sec

Q_{in} = The total heat of the system, kJ/sec

Simulation Software

Numerical simulation and graphical techniques were utilized in performing analysis on the thermodynamic aspects of this study. Microsoft® Excel® spreadsheet software was employed for these tasks. The iterative process in numerical simulation is simplified in Microsoft® Excel® by using the Goal Seek function. Goal Seek will determine the required input value to achieve a known target value (Microsoft, 2024).

The thermodynamic calculations were verified using DWSIM chemical process simulation software. DWSIM is free and comparable in accuracy to the commercial brand ASPEN HYSYS (Acosta, 2024).

All simulation and analysis were done on a standard computing devise (Desktop PC).

Results and Discussion

The simulation of an Organic Rankine Cycle (ORC) using Nitrogen properties was performed with the pump operating at 1,379 kpa pressure and the engine discharging to approximately 101.325 kpa pressure. The system vacuum was approximately 12.5 kpa pressure. The engine and pump work were assumed to be isothermal and isochoric respectively. The heat exchanger efficiency was assumed to be 100% while the engine and pump mechanical efficiency was assumed to be 75%. This resulted in the T-S diagram shown in figure k-1.

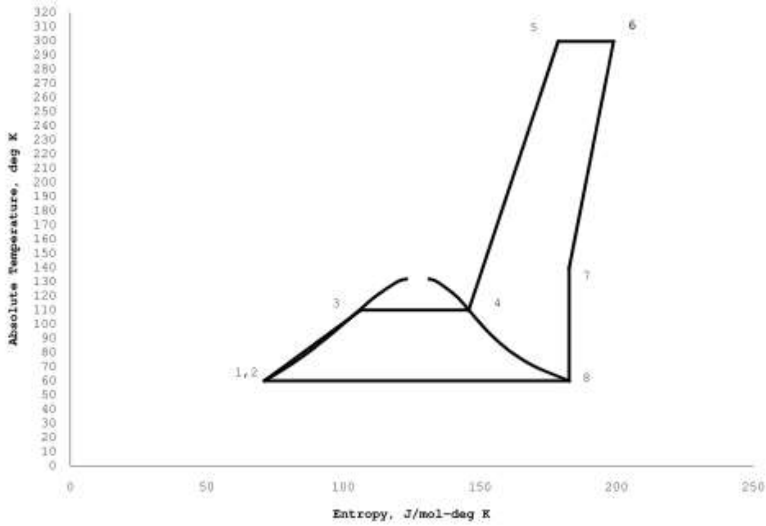

Figure K-1. T-S Diagram of Organic Rankine Cycle

With an engine speed of 1,500 rpm, the mass flow rate of the motive fluid in the system was approximately 0.30 kg/sec. This resulted in the energy balance shown in table n-1.

Table N-1. Energy Balance of Organic Rankine Cycle

Process	Energy In	Energy Out	Unit
Pump Work		-0.49	kJ/sec
HEX Heating	58.09		kJ/sec
Radiator Heating	86.69		kJ/sec
Engine Work		39.55	kJ/sec
HEX Cooling		58.09	kJ/sec
Nozzle Work		15.97	kJ/sec
Condenser Cooling		19.51	kJ/sec
Unaccounted		12.15	kJ/sec
Total	144.78	144.78	kJ/sec

The maximum temperature of the system was 300 °K at the engine's compressed air supply inlet while the minimum temperature was 63.151 °K at the vacuum condenser. This resulted in the Ideal Carnot Efficiency of η_{Carnot} = 78.95%.

The net work of the system was approximately 55.03 kJ/sec while the total heat of the system was approximately 144.78 kJ/sec. This resulted in the system thermal efficiency of η_{Sys} = 38 %.

The unaccounted losses, which total 12.15 kJ/sec, are approximately 8.36% of the overall Energy in the System. These losses are regarded as the percentage error in the numerical simulation.

Continuing with the analysis, the same parameters in the numerical simulation was used in the simulation with DWSIM chemical process simulation software. This resulted in the software's output data shown in figure r-1.

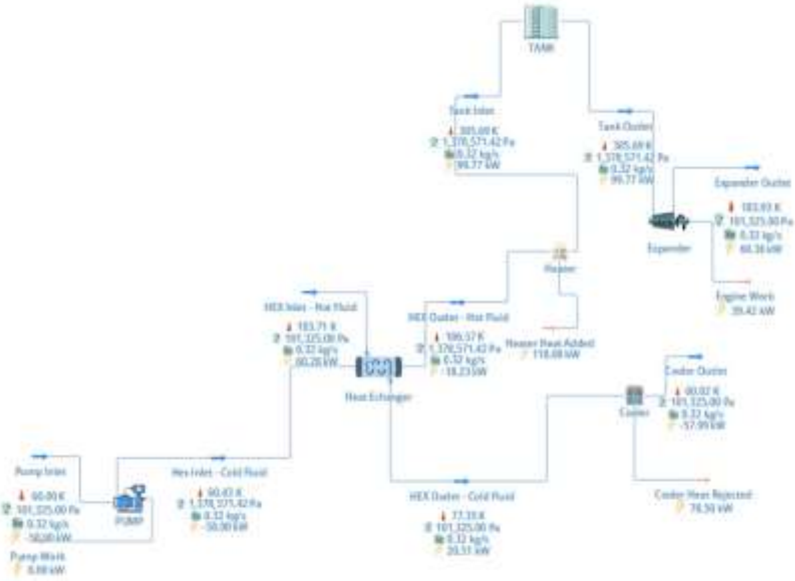

Fig. R1. Organic Rankine System Using Nitrogen (Air)

The corresponding heat balance is shown in table r-1.

Table R-1. Energy Balance of DWSIM Simulation

Process	Energy In	Energy Out	Unit
Pump Work		0.00	kJ/sec
HEX Heating	39.77		kJ/sec
Radiator Heating	118.00		kJ/sec
Engine Work		39.42	kJ/sec
HEX Cooling		39.77	kJ/sec
Nozzle Work		0.00	kJ/sec
Condenser Cooling		78.50	kJ/sec
Unaccounted		0.08	kJ/sec
Total	157.77	157.77	kJ/sec

The maximum temperature of the system was 300 ˚K at the engine’s compressed air supply inlet while the minimum temperature was 63.151 ˚K at the vacuum condenser. This resulted in the Ideal Carnot Efficiency of η_{Carnot} = 78.95%.

The net work of the system was approximately 39.42 kJ/sec while the total heat of the system was approximately 157.77 kJ/sec. This resulted in the system thermal efficiency of η_{Sys} = 25 %.

The unaccounted losses, which total 0.08 kJ/sec, are approximately 8.36% of the overall Energy in the System. These losses are regarded as the percentage error in the DWSIM simulation.

A comparison of selected data from the numerical simulation results vs the DWSIM simulation results is presented in table r-2.

Table R-2. Numerical Simulation vs DWSIM Simulation

Process	Numerical Simulation	DWSIM Simulation	% Diff.
Net Work	55.03 kJ/sec	39.42 kJ/sec	28.37%
Total Heat	144.78 kJ/sec	157.77 kJ/s	8.97%
Thermal Eff.	38.00 %	25.00 %	34.00 %

Average	23.78 %

The large percentages difference shown in Table R-2 can be attributed mostly to the process model in the DWSIM simulation being oversimplified for the sake of convenience.

Conclusion and Recommendations

The percentage error in either numerical simulation or the DWSIM simulation is below 10%. This therefore means that calculated error in each simulation is considered acceptable.

The thermal efficiency obtained in either numerical simulation or the DWSIM simulation is below the ideal Carnot efficiency. This therefore means that each cycle simulation is within the laws of Thermodynamics.

The average percentage difference between numerical simulation results and the DWSIM simulation results indicates some disagreement between the two simulation methods. By refining the process model in DWSIM, the percentage difference is expected to fall within acceptable range.

The system described above, which is applicable to compressed air engines used in motor vehicles, can also be adapted for potential applications in stationary units for electricity generation. Further research and simulation is therefore recommended.

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