

Model-Based Analysis of Recovered Heat Driven Vapor Absorption Refrigeration System Using the Waste Heat from a 5.2 kW Single Cylinder Diesel Engine

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ABSTRACT

The exhaust gases from an engine contain significant amount of heat energy that is wasted through the burnt gases. Part of this heat energy can be harnessed to achieve a specific purpose. This work therefore studied the feasibility of utilizing the recovered heat energy within the exhaust gases of a compression ignition engine for a vapor absorption refrigeration (VAR) system. This is as an alternative to vapor compression refrigeration widely used in the refrigeration system. The paper explained the possibility and advantages of waste heat application on VAR and also evaluated the heats gained and losses at the different components of the VAR system. The parameters for the study are coefficient of performance (COP); generator temperature (T_g); heat loads in generator (Q_g), evaporator (Q_e) and condenser (Q_c). The study was done by mathematically modeling and applying thermodynamics first law to the individual components of a lithium bromide-water (LiBr-H₂O) solution VAR system. With cooling capacity, $Q_e=3.8\text{KW}$; constant $T_e=4^\circ\text{C}$, $T_c=35^\circ\text{C}$, $T_a=30^\circ\text{C}$ and varying generator temperatures from 85°C to 135°C , the parameters for the study were computed using the results from the models for the generator, evaporator, absorber and condenser. This study elucidates the fact that with waste heat temperature of 85°C , the COP of VAR can be as much as 0.861 depending on refrigeration capacity.

Keywords: COP; Diesel Engine; Generator Load; Generator Temperature; Lithium Bromide Water; Refrigeration Effect; Waste Heat; Condenser Load; Absorber; VAR.

1.0. Introduction

Tropical climate like that of Nigeria, with temperatures within the range of 32°C - 38°C and relative humidity of more than 60% in the southern part, creates an environment that is uncomfortable for people. Therefore, comfort-improving technologies in this type of climate conditions is no longer a luxury but a necessity (Pathania and Mahto, 2012; Ajay et al., 2020). Cooling can be achieved by refrigeration, which is the process of extracting thermal energy from a substance, controlled or an enclosed space to lower its temperature (Maurya et al., 2014).

Conventionally, the refrigeration system requires a high-grade energy input to do some work. This leads to higher power and fuel consumption (Mehta et al., 2025). In addition, the working fluids used for their operation have been reported to cause the depletion of ozone layer (Kaynakli and Kilic, 2007) and account for more than 10% of the global greenhouse emissions (Itani et al., 2025; Dong et al., 2021).

For the conventional vapor compression refrigeration (VCR), a fan draws warm air across the evaporator and by reason of temperature difference, the low pressure; low temperature liquid (refrigerant) is transformed to vapor phase in the evaporator. By this means, the refrigerant absorbs heat from a space and keeps the space cool. From the evaporator, the refrigerant vapor is compressed to a high pressure and temperature region as it passed through a mechanical compressor and thereafter, it is converted to liquid in the condenser. Finally, the pressure and temperature of the liquid exiting the condenser are reduced by passing through a metering device (expansion valve) to the evaporator. In comparison to the VAR, the absorber, vapor generator and the solution pump together perform similar function as the compressor in VCR (Mathapati et al., 2014).

1.1. Aim and objectives of the study

The aim of this study is to carry out performance analysis of the effect of waste heat within the exhaust gases of a diesel engine on a VAR system. To achieve this, the objectives are to:

- 1) Study the potential of waste heat recovering system.
- 2) Evaluate the amount of heat available in a diesel engine exhaust and that required to evaporate the liquid refrigerant in LiBr-H₂O solution.
- 3) Analyze the effects of waste heat on the VAR system using mass and energy balance on each of the components.
- 4) Determine the COP of a VAR employing the recovered waste heat from a diesel engine.

2.0. Literature Review

Several studies have been carried out on VAR system using different heat energy sources and refrigerants. The VAR is a thermally driven refrigeration system that uses a low-grade energy (Patil et al., 2025) to effect change of refrigerant conditions to produce cooling effects (Sowjanya, 2013). Therefore, the energy required to power a VAR need not necessarily come from an electric power, but could be provided from any other less expensive heat source provided the temperature is sufficiently high (Micallef and Micallef, 2010; Qandil et al., 2025). This low-grade energy could come from exhaust waste heat (Igwe et al. 2024), or renewable energy such as solar energy (Chukwu et al., 2019), wind energy, biomass or geothermal energy (Kaynakli and Kilic, 2007, Tetemke et al., 2021; Mehyo et al., 2018).

The temperature of the waste gases immediately exiting the engine could be in the range of 450-600°C (Orido et al., 2017; Jadhao and Thombare, 2013; Maurya et al, 2014). The heat contained in the exhaust can be employed for VAR application and therefore, could be seen as a pathway toward reducing global carbon footprint. It has been reported that an internal combustion engine utilizes only about 35% of the energy in the fuel and the remaining energy is wasted through cooling and exhaust systems (Pathania and Mahto, 2012; Poku and Ogbonnaya, 2018). Furthermore, the air conditioning system further consumes about 5% of the total energy (Sandeep and Pravin, 2017), and 17% of the world electricity consumption has also been attributed to refrigeration and heat pump (Ahmad et al., 2022). Therefore, the VAR systems could be explored as a viable alternative to saving electricity and energy consumption.

Another unique feature of the VAR refrigeration is that the working fluids (refrigerants) work in refrigerant-absorbent pairs. The common working fluid pairs for VARs are: LiBr-H₂O, Lithium chloride-water (LiCl-H₂O) or ammonia-water (H₂O-NH₃). Amongst these pairs, the LiBr-H₂O pair has been reported for higher COP, low toxicity, non-flammability and zero potential to cause global warming (Mahendru et al., 2012; Mehta et al., 2026). LiBr-H₂O pair VAR system operates at a generator temperature in the range of 80–90°C (Itani et al., 2025). The COP is usually between 0.6 and 0.8 (Mittal et al., 2005). In addition, water is the cooling medium in the absorber and condenser.

The performance of a single stage LiBr-H₂O solution VAR cycles has been studied extensively in recent years. This work employs thermodynamic modeling to investigate the performance of VAR system. This was carried out by

applying the waste heat from an engine exhaust gas whilst LiBr-H₂O solution served as the absorber-refrigerant pairs.

3.0. Materials and methods

3.1. Engine specification

The heat energy supplied to the VAR system was obtained from the exhaust of a four stroke, single cylinder compression ignition engine with characteristics as shown in Table 1.

Table 1. Engine parameters and characteristics.

Parameter	Units	Characteristics
Engine	-	Single-cylinder, four-stroke
Power output	kW	5.2
Speed	Rpm	1500
Specific fuel consumption (SFC)	Kg/kWhr	0.22
Compression ratio	-	16:1
Density of air (ρ_a)	Kg/m ³	1.3
Specific heat capacity of gases (C_p)	kJ/kgK	1.1
Generator Temperature (T_g)	°C	85 - 135
Ambient Temperature (T_{amb})	°C	38
Heat exchanger effectiveness (η_{ex})	-	0.80

3.2. System Description

In an absorption system, heat is absorbed by the refrigerant from a space, thereby making the space to be cooler. The refrigerant after absorbing the heat evaporates and the vapor thereafter is absorbed by an absorbent in the absorber forming a refrigerant-absorbent (LiBr-H₂O) solution. The solution is sent by the pumped to the high-pressure vapor generator where it is heated directly by the waste heat from the exhaust of the compression ignition engine. The refrigerant vaporizes from the solution to a high temperature and pressure gas and leaving behind a weak mixture with very low content of the refrigerant which returns to the absorber through the solution pressure reducer. The refrigerant vapor moves the condenser where it releases some of its thermal energy and becomes high temperature and pressure liquid. The refrigerant liquid exiting from the condenser passes the expansion valve (or throttled) to the evaporator. The solution heat exchange was introduced in order to allow the heat contained in the strong solution from the generator to preheat weak solution entering the generator. This way enhances the COP of the system as it minimizes the heat requirement at the generator. Experimental studies have shown that COP can be increased up to 60% with the application of solution exchanger (Babu and Yadav, 2015).

3.3. Determination of Heat Supplied to Generator

Determination of the heat requirement in the generator was carried out a shown in equations 1 to 6.

$$\text{Mass flow rate of fuel } (\dot{m}_f) = \text{SFC} \times \text{Engine power output} \quad (1)$$

$$\text{Volumetric flow rate of air } (Q_a) = (\text{Swept volume} \times \text{Engine speed}) / 2 \quad (2)$$

$$\text{Mass flow rate of air } (\dot{m}_a) = \rho_a \times Q_a \quad (3)$$

$$\text{Mass flow rate of exhaust gas } (\dot{m}_{ex}) = \dot{m}_a \times \dot{m}_f \quad (4)$$

$$\text{Available heat in exhaust gases } (Q_{ex}) = \dot{m}_{ex} \times C_p \times (T_g - T_{amb}) \quad (5)$$

$$\text{Heat added to generator } (Q_g) = Q_{ex} \times \eta_{hex} \quad (6)$$

3.4. Vapor Absorption Refrigeration System Modeling

The schematic representation of the VAR set up is as shown in Figure 1. The system comprises the basic components like the generator, pump, absorber, evaporator, expansion valve and the condenser. The purpose of the solution heat exchanger is to improve the efficiency of the system. This study is limited to using the theoretical knowledge of thermodynamics to carry out a performance analysis of a single stage LiBr-H₂O VAR system. In this system, H₂O is the refrigerant whilst LiBr serves as the absorbent. Thermodynamics first law (law of conservation) was used to model the system. Enthalpy-concentration chart for LiBr solution as well as refrigeration tables were also used. Results were analyzed using Microsoft excel.

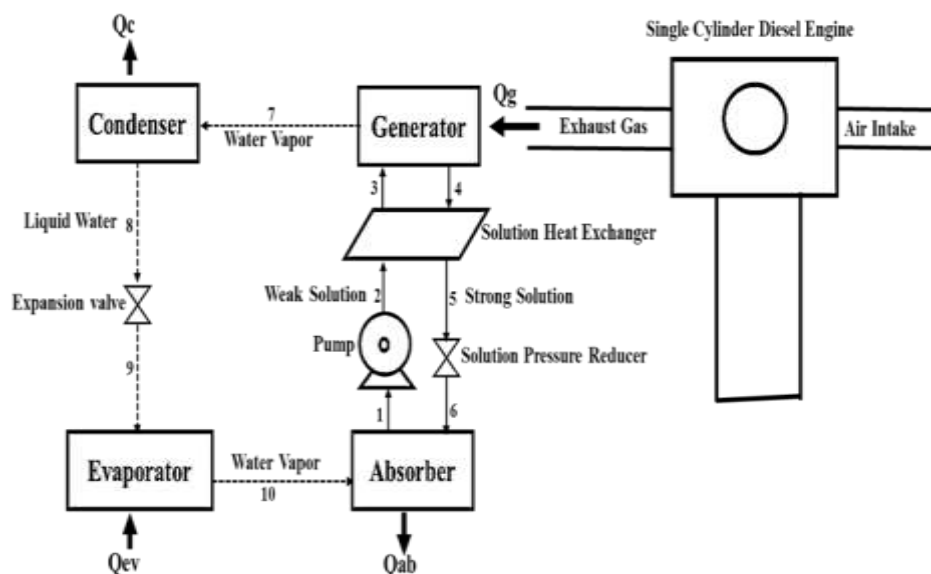


Figure 1. Schematic diagram of the VAR system with the single cylinder diesel engine. The engine supplied the heat required to evaporate the refrigerant from the LiBr-H₂O solution.

The mass and energy balance equations were applied to each of the components in the VAR system. Standard set of condition for LiBr-H₂O system was referred as well as the followings were assumed:

1. Except through the flow restrictors, pressures changes were not considered.
2. Liquid through points 8 and 9 is saturated.
3. Vapor at point10 is saturated.
4. Pumping is isentropic.

The mathematical relationships employed for the heat, Q and mass, m balance for each component are stated in the given equations. The circulation ratio, λ is defined as the ratio of the flow rates of the strong solution to that of the refrigerant as stated in equations 7:

$$\text{Circulation Ratio, } \lambda = \frac{m_{ss}}{m} \quad (7)$$

$$m + m_{ss} = m_{ws} \quad (8)$$

Where:

m = mass flow rate of refrigerant (kg/s)

m_{ss} = mass flow rate of strong solution (kg/s)

m_{ws} = mass flow rate of weak solution (kg/s)

Condenser: $m_7 = m_8 = m$

$$Q_c = m(h_7 - h_8) \quad (9)$$

$$P_c = P_{sat}(T_c)$$

$$\text{Also, } h_7 = 2501 + 1.87(T_g - T_{ref})$$

Where T_{ref} (reference temperature) = 0

Expansion Valve:

$$m_8 = m_9 = m$$

$$h_8 = h_9$$

Throttling process, enthalpy of saturated water liquid at condenser temperature as presented in equation 10.

Refrigeration Capacity (cooling effect):

$$m_9 = m_{10} = m$$

$$Q_e = m(h_{10} - h_9) \quad (10)$$

$$P_e = P_{sat}(T_e)$$

Absorber:

$$\text{Equations 1 and 2: } m_{ws} = (1 + \lambda)m$$

Applying the mass balance of pure water as shown in equation 11:

$$m + (1 - \xi_{ss})m_{ss} = (1 - \xi_{ws})m_{ws} \quad (11)$$

$$\text{Hence, } \lambda = \frac{\xi_{ws}}{\xi_{ss} - \xi_{ws}}$$

$$Q_a = mh_{10} + m\lambda h_6 - (1 + \lambda)mh_1 \quad (12)$$

Solution pump for incompressible solution as shown in equation 13:

$$m_1 = m_2 = m_{ws}$$

$$W_p = (1 + \lambda)mV_g(P_2 - P_1) = (1 + \lambda)mV_g(P_c - P_e) \quad (13)$$

Where V_g is the solution specific volume.

Solution heat exchanger is as presented as shown in equations 14:

$$m_2 = m_3 = m_{ws}$$

$$m_4 = m_5 = m_{ss}$$

$$Q_{hex} = m_{ws}(h_3 - h_2) = m(1 + \lambda)(h_3 - h_2) = \lambda m(h_4 - h_5) \quad (14)$$

$$\text{From equation 8, } h_4 = \frac{m_{ws}}{m_{ss}} \times (h_3 - h_2) + h_5 \quad (15)$$

The COP was determined from equation 16 (Mathapati et al., 2014):

$$COP = \frac{\text{Refrigeration Effect}}{\text{Energy Consumed}} = \frac{Q_e}{Q_g + W_p} \quad (16)$$

Assumptions and calculated values

Temperature of evaporator, $T_e = 4^\circ\text{C}$

Temperature at condenser, $T_c = 35^\circ\text{C}$

Temperature at absorber, $T_a = 30^\circ\text{C}$

Varying generator temperature T_g from 85 to 135°C and also, from refrigeration tables at saturated T_e and T_c , the corresponding P_e and P_c are 0.008129 bar and 0.05629 bar, respectively. From enthalpy concentration chart, h_6 = point of intersection of evaporator pressure and absorber temperature and h_{10} = Enthalpy of saturated water vapor at 4°C .

4.0. Results and discussion

4.1. Effects of Generator Temperature on COP

Shown in Figure 2 is the change in generator temperature of VAR with respect to COP. It can be observed from the Figure 2 that increasing the generator temperature beyond 85°C results to decrease in the COP of the system. In this study, 85°C was the maximum temperature required to raise the vapor pressure and boils of the water from the LiBr- H_2O solution and allow the LiBr salt to flow back to the absorber. Therefore, it is believed that higher temperature could cause hardening of the LiBr and therefore slow the flow process to the absorber (Siddiqui and Alsulami, 2025). Furthermore, the refrigeration capacity (Q_e) was observed to be constant with the increase in generator temperature, suggesting the adverse effect of excess heat on the LiBr salt. Similar study has been carried out by Thakre et al (2014), who reported that the COP of a VAR system decreases as the increases generator temperature for constant Q_e . The reason is that as the generator temperature increases, the heat load of the generator also increases and therefore, the net effect is seen as decrease in value of COP. Furthermore, as the COP is defined

as the ratio of the heat removed from the cold space to the heat taken from the exhaust gas to drive the system. Therefore, the increase in heat taken against the constant heat removed leads to decrease in COP.

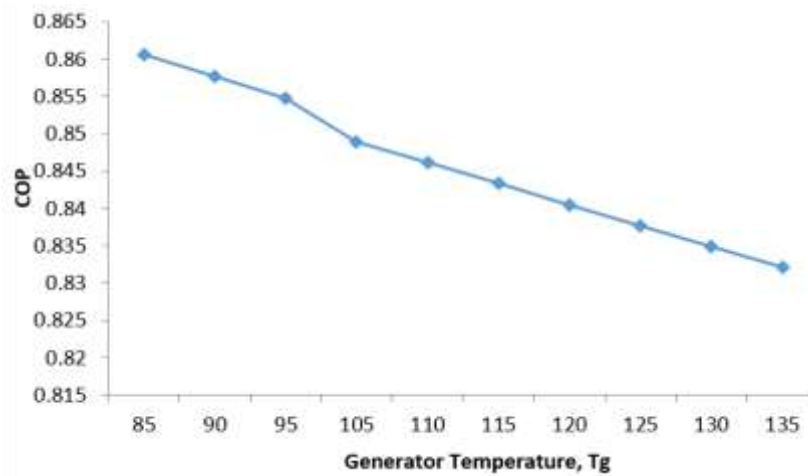


Figure 2. Effects of varying generator temperatures (T_g) on the COP of the VAR system.

4.2. Effects of Variation in Generator Temperatures on Generator and Condenser Loads

Figure 3 clearly shows the results of generator and condenser heat loads as the generator temperature changes. It can be seen in the Figure that the increase in the generator temperature gives rise to a corresponding increase in both generator and condenser loads, respectively. Generator load is the thermal energy input that would be required to convert the refrigerant from the liquid to vapor state. The effect of the rise in generator temperature is such that with 5°C increase in heat input to the generator, there is a corresponding increase in condenser and generator heat load by 0.015kJ/kg. This can be explained by the increase in the mass flow rate of refrigerant resulting from increasing the heat input to the generator.

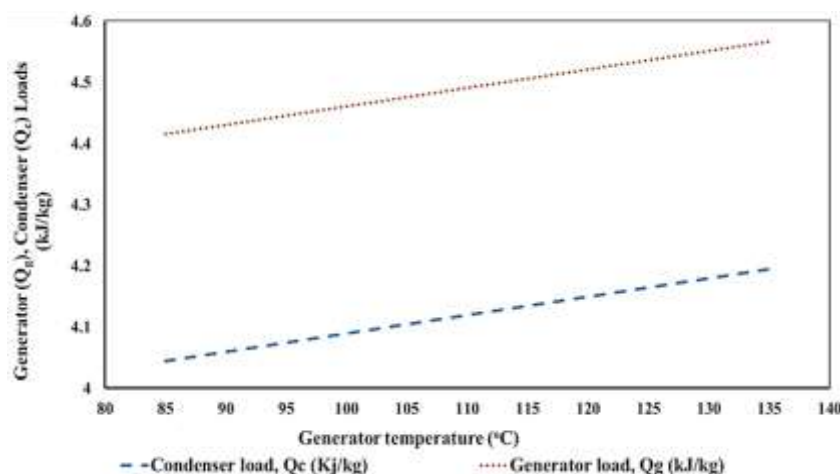


Figure 3. Effects of changes in generator temperature (°C) on performance of the condenser and generator loads (kJ/kg).

4.3. Effects of Heat Loads of Absorber and Evaporator on COP

The effects of heat loads of the absorber and evaporator on the COP is shown in Figure 4. As it can be seen, with the slight variations in COP, the absorber and evaporator heat loads remain unchanged. As the LiBr solution present in

the absorber needs to absorb sufficient water to form strong solution, the capacity of the absorber strongly depends on the heat expelled from the absorber by using cooling coil and chilled water arrangement. In this system, it is believed that the level of increase in the COP was due to the low heat supplied to the generator and the cooling effect on the absorber provided by the chilled water. Although, the performance of the cooling coil was not considered in this study, it is believed that a well-designed VAR system could operate at higher temperature to enhance the COP of the system.

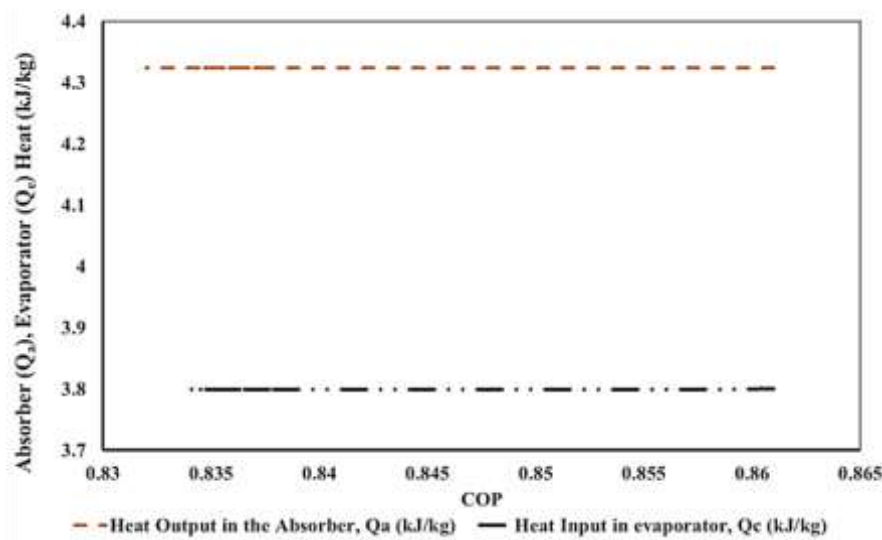


Figure 4. Effects of Absorber and Evaporator Heat Loads on COP.

5.0. Conclusion and Recommendations

5.1. Conclusion

Thermodynamic first law was employed to analyze the performance of a LiBr-H₂O VAR system. The analysis of each component was done by modeling the energy balance of each of the component of the system and the followings conclusions were derived:

1. When the generator temperature was increased beyond 85°C, the COP of the system decreases, suggesting that the performance of the system strongly depends on the generator temperature.
2. As the COP increases, the refrigerating effect increases slightly. Hence, the COP of the system should be high for better cooling effect.
3. It can therefore be concluded that waste heat driven VAR system, can be a dependable alternative to VCR system in ships' cabins and commercial cars.

5.2. Recommendations

The following are the recommendations in this course of this research:

1. This LiBr-H₂O VAR system can be effectively used to replace the conventional VCR system used widely in vehicle cooling. Hence, further study should be done on this. This can reduce the extra work on the vehicle engine and improve the performance of the vehicles.

2. A study should be conducted on the VAR system to determine the ideal temperature that would prevent crystallization of the working fluid.
3. Research should be conducted to reduce the weight and size of the VAR system to be more compact but effective.

Declarations

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Competing Interests Statement

The authors have not declared any conflict of interest.

Consent for Publication

The authors declare that they consented to the publication of this study.

Authors' Contributions

All the authors took part in literature review, analysis and manuscript writing equally.

Informed Consent

Not applicable for this study.

Availability of Data and Material

Supplementary information is available from the authors upon request.

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