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Green Energy Solutions: Vapor Absorption Chiller for Harnessing Engine Jacket Water Waste Heat

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ABSTRACT

Vapor absorption chiller is a machine that works on a closed-loop system following vapour absorption cycle which can serve as an agent of utilizing the waste heat and is considered a highly economic industrial solution. In this paper, we have analyzed the thermodynamics of the system. We have performed a comprehensive analysis of a vapor absorption chiller using the industry-provided input parameters by utilizing the heat dissipated from the engine jacket water system. A single effect vapor absorption chiller is opted for this study as jacket water temperature falls within it's operating temperature range. A process flow diagram depicting the vapor absorption cycle for this scenario is made and all the design parameters are calculated accordingly with a software Engineering equation solver (EES). Computer aided graphs are produced in EES that portrays the trend of various important variables relevant to vapor absorption cycle. The co-efficient of performance (COP) of this system came out to be 0.629.

Keywords: Vapour Absorption Chiller (VAC), Gas Engine, Jenbacher, Lithium Bromide (LiBr), Engineering Equation Solver (EES), Jacket Water

Highlights

- Cooling capacity is calculated from waste heat of engine's Jacket Water
- Thermodynamics of Vapour Absorption system are considered for Mathematical Modelling
- Graphical models of important chiller parameters using EES have shown favourable trends

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Nomenclature

	Symbols
H	Enthalpy (kJ)
h	Specific enthalpy (kJ/kg)
LiBr	Lithium Bromide
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa)
$\dot{Q}$	Heat transfer rate (kW)
T	Temperature (°C)
$\dot{V}$	Volume flow rate (m^3/s)
x	Lithium Bromide in solution, % by mass
	Subscripts
abs	Absorber
cond	Condenser
cooling, capacity	Tons of refrigeration of Absorption cycle
cooling, tower	Cooling load on cooling tower
evap	Evaporator
engine, in	Jacket water at the inlet of Generator/De-absorber (°C)
engine, out	Jacket water at the outlet of Generator/De-absorber (°C)
gen	Generator or De-absorber
high	Higher pressure zone (including generator/de-absorber and condenser)
low	Lower pressure zone (including evaporator and absorber)
	Abbreviations
AHU	Air handling unit
COP	Co-efficient of performance
	Greek letters
ν	Specific volume (m^3/kg)
ρ	Density (kg/m^3)
	States of refrigeration cycle
1	Diluted solution leaving the absorber
2	Diluted solution after exchanging heat with the strong solution
3	Strong solution leaving the generator
4	Strong solution after exchanging heat with the diluted solution
5	Refrigerant water vapor leaving the generator
6	Condensed refrigerant water leaving the condenser
7	Refrigerant water vapor leaving the evaporator

1. Introduction

Refrigeration is a process of lowering the temperature of a space below the ambient temperature. The practical application of the refrigeration began since 1758 and since then the research in this field is still going on. The invention of the refrigeration machine has increased the production of farms, made it convenient to transport food from where it is grown to distant markets and also made it possible to live in very warm regions around the globe. A lot different industries depend on refrigeration like pharmaceutical, beverages, chemicals, petrochemicals and even electricity production. There are mainly two types of refrigeration system, one is vapour absorption system and the other is vapour compression system. In the early twentieth century vapour absorption systems were used but with they were replaced with vapour compression system because of there low COP. But still vapour absorption system are used because of their ability to reuse the waste heat. Vapour Absorption chiller produces cooling effect by utilizing heating agents such as warm water, steam, and gas. The working principle of vapor absorption chiller makes it economically attractive for large industrial units. The main leverage of the vapour absorption refrigeration system on vapour compression refrigeration system is that it requires no moving part like a compressor to function except for a small pump which is used to transport liquid solution and operates on either waste heat or renewable energy. In the vapour absorption cycle, lithium bromide solution is heated, the boiling point of LiBr is higher compared to water therefore when the solution is heated water vaporizes. In this absorption refrigeration cycle, the refrigerant is water, and lithium bromide is the transport medium [1]. This paper shows a comprehensive study of a vapour absorption chiller in which design parameters are calculated using the industry-provided data.

To design an absorption chiller there are three standards. And only one of them dealt with hot water-driven Absorption Chillers and it was AHRI Standards 560-2000 for Absorption Water Chilling and Water Heating Packages [2]. Commonly there are two kinds of absorption chillers used i.e. the single-effect and double-effect [3]. Labus et al. [4] stated that the designing of the high-pressure portion of the cycle and the advanced models of absorption refrigeration for instance double-effect and triple-effect are given. AHRI Standard 560-2000 and BS EN Standard 12309-2:2000 [2, 5] suggested that the COP will be in the range of 0.6 to 0.8. The maximum COP according to the literature [4, 5, 6, 7] can be around 0.73 to 0.79 in the best optimal condition. In Zheng et al. [8] the heat created by the solar collector was provided to the absorption chiller throughout its chilling period. Ammar and Seddiek [9] utilized the surplus heat from exhaust and jacket water of maritime engines. Franchini et al. [10] studied the performance of microscale absorption chiller under diverse working conditions. Mathapati et al. [11] studied automobile refrigeration system using waste heat of its exhaust and mathematically modeled it using EES.

Research work in the industrial sector is very rare whereas the improvement in performance and cost reduction is only possible through research. This study will help promote the trend of research in the industrial sector as research work contributes to the most efficient utilization of waste energy. This paper has been organized into the following major sections: Section 1 gives a brief overview of the vapour absorption chiller and its operation. Section 2 contains the methodology. Section 3 shows the results obtained from the analysis and Section 4 describes the conclusion of this study.

2. System Description

Karachi is the 12th largest city in the world and having a huge energy demand. All of its electricity needs are provided by a private company called "K-Electric". K-Electric's combined cycle power plant in Korangi (latitude 24° 50' 53.7", longitude 67° 8' 42.01") operates on gas engines combined with steam turbines. And for the gas engine to operate efficiently and to protect it against damage, the temperature of gas engines is maintained through a channel of water known as "Jacket water system". This jacket water performs cooling of gas engines by taking heat from it and then rejects this heat to the open atmosphere through a radiator. So, this radiated heat should be regarded as waste energy. But this heat energy could be used to operate an absorption chiller to produce cooling for the office or warehouse facility. The maximum cooling load that can be achieved with this system is to be calculated. This whole system is shown in Figure 1.

An absorption chiller has four basic portions namely evaporator, absorber, generator or de-absorber, and condenser [12]. This cycle has two pressure zones, evaporator and absorber stand at the P_{low}, whereas the generator and condenser stand at the P_{high} [13]. The absorption refrigeration cycle operates on the tendency of LiBr salt to absorb water vapours and to de-absorb it at high temperatures. Since the LiBr-H_2O solution is liquid, the need for a compressor is eliminated and instead, a pump is used to increases the pressure [14].

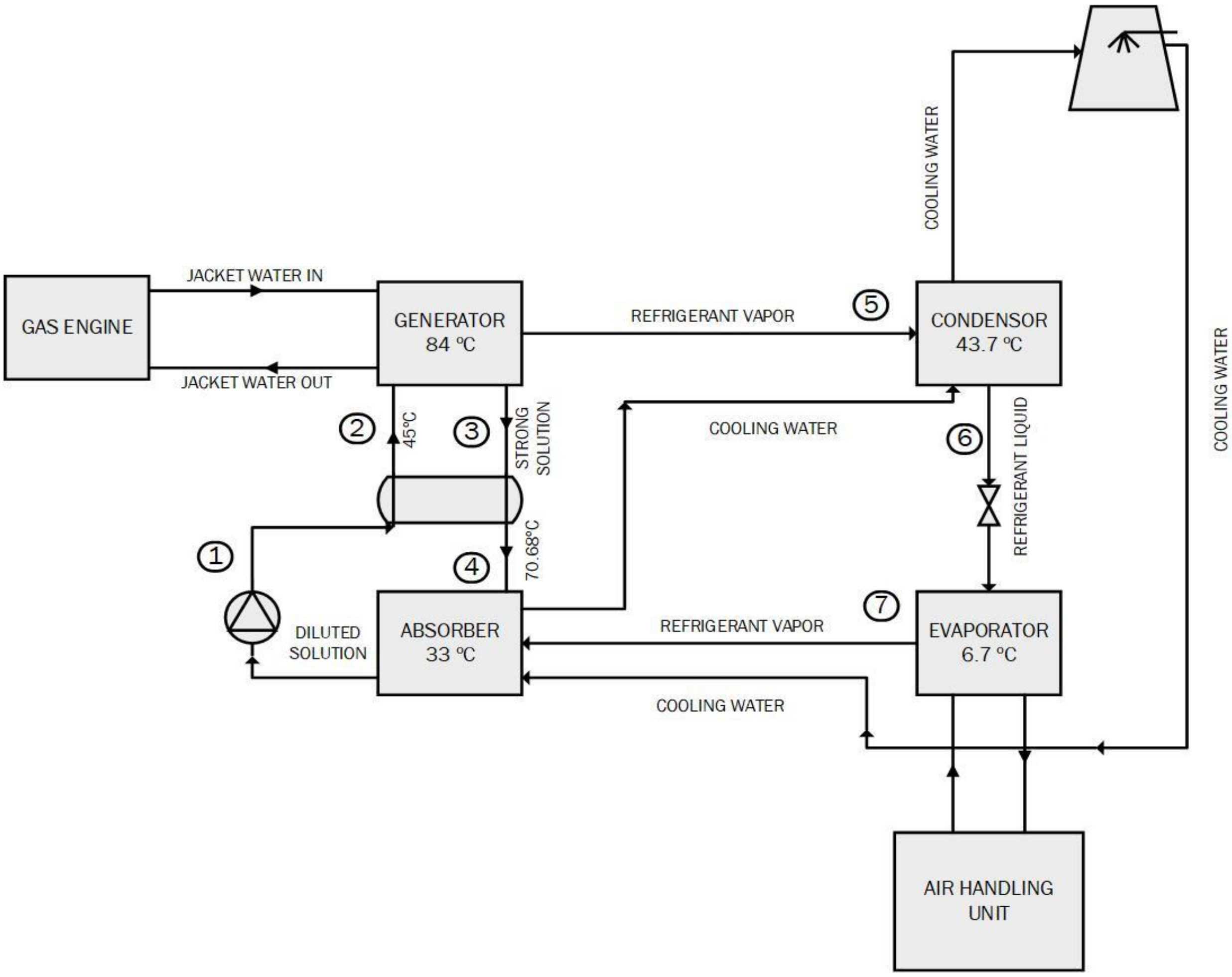

Figure 1: *Schematic of our single-effect hot water driven absorption chiller incorporating gas engine, air handling unit, and cooling tower*

The absorber initially contains a high-concentrated solution of LiBr-H_2O and absorbs the vapor continuously creating a decrease in pressure. This decrease in pressure causes the water in the evaporator to vaporize and go towards the absorber (State 7), extracting heat from the incoming water from the AHU and is responsible for the cooling effect [15]. The high-concentrated solution keeps absorbing the vapor until its concentration becomes low, after which it is pumped (State 1) to the generator or de-absorber. The heat from the absorber is removed continuously to promote the absorption of vapor into the LiBr salt solution. The generator or de-absorber is where the source of heat is provided. The high temperature of generator causes the H_2O in low-concentrated solution to evaporate hence increasing its concentration [16]. This high-concentrated solution is then throttled back (State 3) to the absorber and the water vapour is tranfered to the condenser (State 5). The vapor loses heat in the condenser and liquid water is collected by condensation. Then this liquid water is throttled (State 6) towards the evaporator which has low pressure and the cycle repeats. The heat of the absorber and condenser is removed through water circulation passing through a cooling tower. The process is enhanced by using a heat exchanger amid the absorber and the generator, the low-concentrated solution from the absorber gains heat (state 2) from the high-concentrated solution coming from the generator (state 4).

3. Methodology

In this section of the paper a systematic strategy is adopted that begins with the methodology for the calculation of design variables of vapor absorption cycle followed by simulation and economic analysis.

3.1 Jacket Water System

The amount of heat that can be provided to the absorption chiller relys on the temperatures of jacket water system. The temperatures and flow rate of jacket water has been provided by the K-electric and the Jenbacher's catalog [17]:

- Temperature of Jacket water at the inlet of gas engine should be 62 °C.
- Temperature of Jacket water at the outlet of gas engine is in the range of 82-89 °C.
- The flow rate of Jacket water is in the range of 42.7-47 m^3/h.

So these are the parameters that need to be maintained for the proper functioning of the gas engine even if the jacket water is being used for the absorption chiller.

3.2 Absorption Chiller

In the view of the gas engine's parameters and available resources, the most suitable type of chiller would be selected for the current system. There are different kinds of absorption chillers depending on the generator effect, these are single-effect, double-effect, and triple-effect. The single-effect absorption chiller is the most uncomplicated absorption cycle configuration. There COP (coefficient of performance) is around 0.60-0.80 [4, 7]. According to research articles [3, 7, 8], the COP of single-effect absorption systems has the optimum range of 0.73–0.79 and the COP of double effect absorption systems stay within 1.22–1.42, which is almost twofolds of single-effect. But for double-effect, the source has to be at a higher temperature than that of a single-effect chiller. According to the articles by Kalogirou [6] and Mokhtar [18]:

Table 1: *Types of Absorption refrigeration cycle based on Source temperature*

	Heat source temperature [°C]		
Chiller type	Single-effect	Double-effect	Triple-effect
Mean Temperature	90	130	220
Temperature Range	(60-140)	(120-180)	(200-250)

From Table 1, the design of a single-effect absorption chiller is selected because the heat source has a temperature range of 82-89 °C.

If the source of heat is even lower than 82 °C then a half-effect absorption chiller would have been selected. The half-effect absorption chiller runs on lower than the least essential temperature required for a single-effect chiller [19].

3.3 Standards

The standards that deal with absorption systems are only a few. Among these only three, in particular, provide standards for absorption chillers. The standards that apply to water-cooled steam and hot-water operated water chilling units, are taken from AHRI [2]. The other two are CEN [5, 20] and JIS B 8622 [21]. But only AHRI standards provide a draft for hot-water operated absorption chillers.

The AHRI/ANSI Standard 560-2000 is used for water-cooled single-effect hot water chillers [2] and according to this, the standard rating conditions are:

- Absorber/Condenser water at the inlet of the absorber should have a temperature of 29.4 °C (26.7 to 32.2 °C) in increments of 3 °C or less.
- Water from the evaporator to the air handling unit should have a temperature of 6.7 °C (4.4 to 8.9 °C) in increments of 1 °C or less.

3.4 Designing a Single-Effect Absorption Chiller

To design a single-effect absorption chiller, the four portions of the absorption chiller are assigned certain input parameters. These four portions are “Evaporator”, “Absorber”, “Generator” and “Condenser”.

3.4.1 Design parameters of Evaporator

The evaporator is the portion of the cycle where the refrigeration takes place [22]. The water to be chilled comes here from the air-handling unit and losses all the unwanted heat from the cooled place and then is pumped to the air handling units (AHU) with decreased temperature. According to the AHRI standard [2] evaporator leaving water temperature (chilled water) should be between 4.4 to 8.9 °C in increments of 1 °C or less. A drawback of the LiBr/H_2O systems is their inability to run on a lower temperature than 5 °C because water vapour is the refrigerant [7]. The single-effect absorption chiller is usually utilized when the chilled water is required at 6–7 °C [7, 23].

The Temperature-pressure-concentration diagram of saturated LiBr-water solutions [1] shows that there is a dependency of the absorbers concentration and temperature on the evaporator temperature, so by keeping a constant absorber’s temperature, as the evaporator’s temperature reaches 4.4 °C the absorbers concentration increases which will cause less absorption of H_2O vapors). So 6.7 °C is nominated as the evaporator’s temperature because it delivers more absorption capacity for the Li-Br solution than 4.47 °C and pressure slightly less than saturation pressure to ensure complete evaporation.

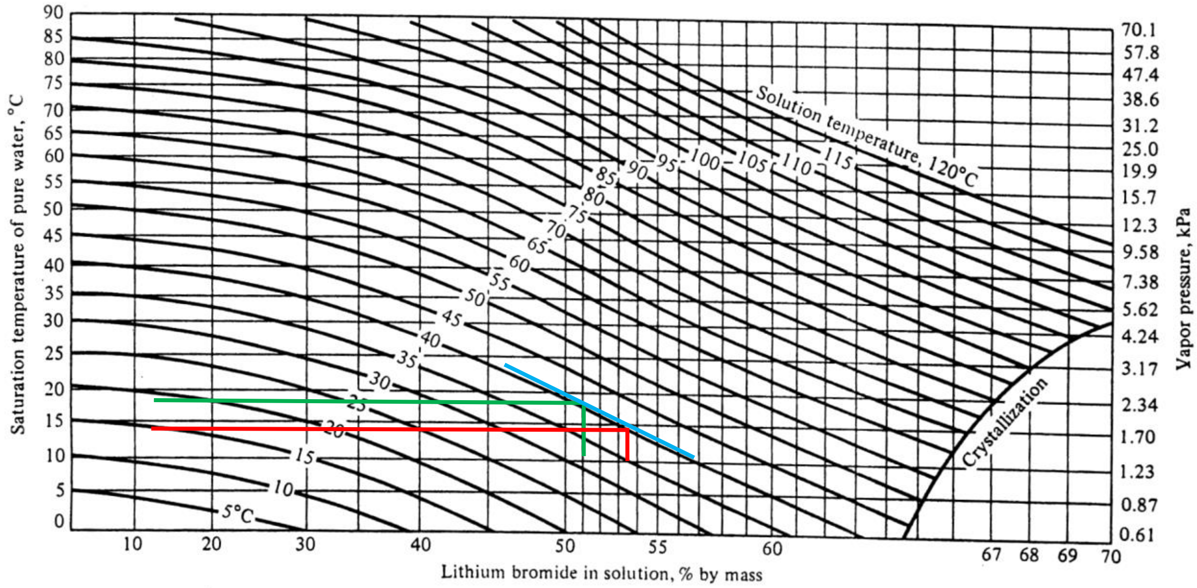

Figure 2: *Constant evaporator temperature lines on Temperature pressure concentration diagram of saturated LiBr-Water solutions [1]*

- Temperature of the evaporator (T_7) is selected to be 6.7 °C.
- Saturation pressure at T_7 is 0.993404 kPa. Therefore, selecting the pressure of evaporator (P_7) to be 0.98 kPa.
- Note that the evaporator is in the lower pressure zone, implying that P_7 is the same as P_{low}.

3.4.2 Design parameters of the Absorber

In the absorber, the pressure is the same as that of the evaporator (0.98 kPa) because they are both in the lower pressure zone of the absorption refrigeration cycle. The temperature of the absorber depends on several factors. The first thing to note is that the hot (84 °C) highly concentrated LiBr-H_2O solution is sent to the absorber, which takes all the heat with itself to the absorber and hence increasing its temperature. The increase in temperature decreases its solubility and hence decreasing the evaporation effect in the evaporator, which then decreases the refrigeration capacity of the absorption chiller and thus decreasing the COP. So the highly concentrated solution coming towards the absorber should be cooled down or the absorber temperature should be maintained to provide a suitable working condition. Both can be attained, by using a heat exchanger between the low concentrated solution going to the generator and the hot concentrated solution coming towards the absorber; and by removing heat continuously from the absorber through circulating water from a cooling tower.

According to the AHRI standard [2], the absorber/condenser water, from the cooling tower, entering the absorber should be 29.4 °C or in the range of 26.7 to 32.2 °C. Therefore, the absorber's temperature should be greater than the condenser water's temperature to make heat flow from it to the condenser water.

- Temperature of Absorber (T_1) is selected to be 33 °C.
- Pressure of the Absorber (P_1) is already defined as 0.98 kPa.

3.4.3 Design parameters of Generator

The generator or de-absorber is where the low concentrated solution after passing from the heat exchanger goes. The generator has the heat source in the form of hot water at 85.5 °C (for this scenario) and the high temperature decreases the solubility of the solution and hence the water gets separated in the form of vapor. Then the vapor drives towards the condenser.

The generator and condenser are at the high-pressure zone of the single-effect absorption refrigeration cycle. And, to permit the heat rejection of the refrigerant at generally accessible temperatures the pressure in the condenser should be relatively ten times above the evaporator's pressure [4]. So,

$$\mathbf{10 \times P_{low} = 10 \times 0.98\, kPa = 9.8\, kPa} \qquad \textbf{(1)}$$

But the Temperature-pressure-concentration diagram of saturated LiBr-water solutions [1] shows that if you follow the solution temperature line then reducing the pressure increases the concentration of the solution in the generator which would eventually increase the absorption capacity of the solution in the absorber, hence increasing the cooling capacity.

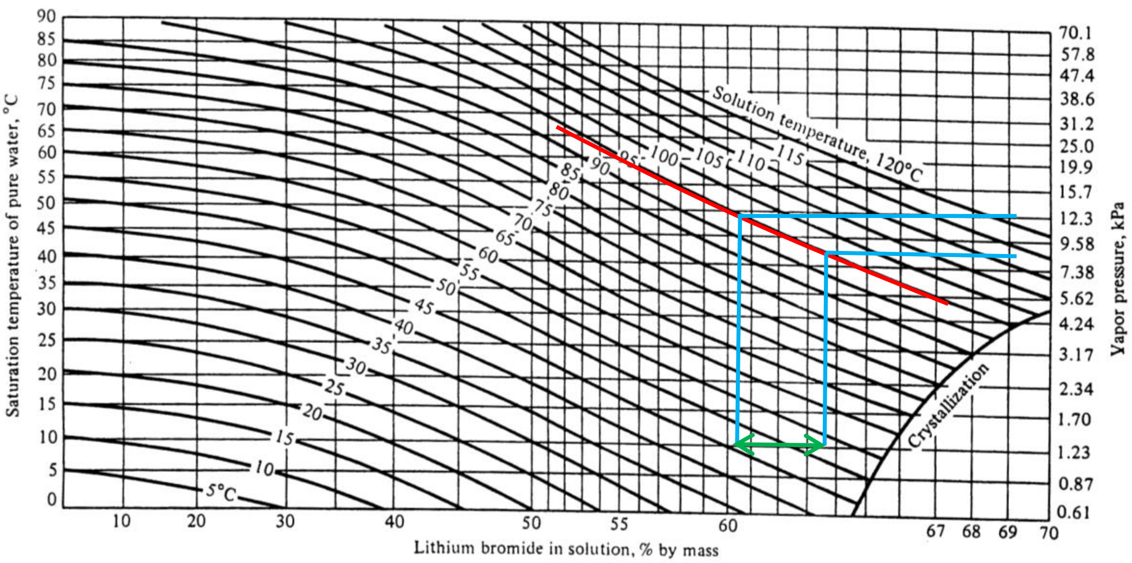

Figure 3: *Constant generator's pressure lines on Temperature pressure concentration diagram of saturated LiBr-Water solutions [1]*

- Since the average source temperature is 85.5 °C, assuming the temperature of the generator (T_3) to be 84 °C.
- The high-pressure zone (P_{high}) is selected to be 9.0 kPa.

3.4.4 Design parameters of the Condenser

The refrigerant vapors (H_2O) goes to the condenser from the generator, where it loses its latent heat to the condenser water and condenses into saturated liquid. Since the pressure inside the condenser is the same as that of the generator (i.e. 9 kPa), therefore the condenser temperature is correspondent to the saturation temperature of water at P_{high}. The saturation temperature of water at 9 kPa is 43.77 °C

- Temperature of the condenser (T_6) is selected to be 43.77 °C.

3.4.5 Design parameters of the Heat exchanger

As discussed earlier in the design of the absorber, the high concentrated solution from the generator coming towards the absorber is very high in temperature which will decrease the solubility of the solution in the absorber and thus reducing the refrigeration capacity of the chiller. One way to cool it is to pass it through a heat exchanger giving its heat to the low concentration solution travelling towards the generator since the low concentrated solution is already going to be heated in the generator. So the heat exchanger is estimated such that the low concentrated solution's temperature reaches from 33 °C to 45 °C.

- The temperature of the low concentrated solution at state 2 is assumed to be 45 °C.

3.5 Mathematical Model

The mathematical modeling has been done from the process cycle shown in figure 1, single-effect hot water driven absorption chiller [9, 10, 11]. It will be solved in EES (engineering equation solver).

The surplus heat from the Jacket water to the atmosphere through radiation can be found using the following equations,

$$\dot{Q}_{waste\ heat\ from\ the\ engine} = \dot{m}(h_{out} - h_{in}) \quad (2)$$

The above equation in terms of volume flow rate is,

$$\dot{Q}_{waste\ heat\ from\ the\ engine} = \dot{V}(\rho_{out}h_{out} - \rho_{in}h_{in}) \quad (3)$$

Mass balance equations are given by,

$$\dot{m}_1 = \dot{m}_2 \quad (4)$$

$$\dot{m}_3 = \dot{m}_4 \quad (5)$$

$$\dot{m}_5 = \dot{m}_6 = \dot{m}_7 \quad (6)$$

$$\dot{m}_2 = \dot{m}_3 + \dot{m}_5 \quad (7)$$

$$\dot{m}_1 \times x_1 = \dot{m}_3 \times x_3 \quad (8)$$

Energy balance across the heat exchanger,

$$\dot{m}_1(h_2 - h_1) = \dot{m}_3(h_3 - h_4) \quad (9)$$

Energy balance across generator,

$$\dot{m}_2h_2 + \dot{Q}_{gen} = \dot{m}_3h_3 + \dot{m}_5h_5 \quad (10)$$

Energy balance across condenser,

$$\dot{Q}_{cond} = \dot{m}_5(h_5 - h_6) \quad (11)$$

Energy balance across absorber,

$$\dot{m}_1h_1 + \dot{Q}_{abs} = \dot{m}_4h_4 + \dot{m}_7h_7 \quad (12)$$

Energy balance across evaporator,

$$\dot{Q}_{evap} = \dot{m}_5(h_7 - h_6) \quad (13)$$

Load on the cooling water of cooling tower,

$$\dot{Q}_{cooling\ tower} = \dot{Q}_{abs} + \dot{Q}_{cond} \tag{14}$$

The COP of this Single-effect Hot water-driven Absorption Chiller will be

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{gen}} \tag{15}$$

4. Results

The calculation based on the specified parameters (normal condition) of the absorption cycle gives following results,

Table 2: *Heat transfer Results from different portion of the Chiller and COP at normal condition*

Parameters	Values
Heat loss from Absorber ($\dot{Q}_{abs}$)	1101 kW
Heat supplied to Generator ($\dot{Q}_{gen}$)	1143 kW
Heat loss from Condenser ($\dot{Q}_{cond}$)	761.6 kW
Heat gained in Evaporator ($\dot{Q}_{evap}$)	719.3 kW
Cooling capacity ($\dot{Q}_{cooling\ capacity}$)	204.5 tons
Load on cooling tower ($\dot{Q}_{cooling\ tower}$)	1863 kW
COP	0.6291

Therefore the normal design conditions suggest a cooling load capacity of 204.5 tons and the COP of this system is 0.6291 which is within the range as specified earlier [4, 7].

Table 3: *State parameters at specified parameters*

State point	Mass flow rate (kg/s)	Specific Enthalpy (kJ/kg)	Concentration (LiBr in solution)	Pressure kPa	Temperature °C
1	4.141	74.39	0.5317	0.98	33
2	4.141	99.33	-	-	45
3	3.832	192.2	0.5746	9	84
4	3.832	165.3	-	-	70.68
5	0.3088	2650	-	9	84
6	0.3088	183.3	-	-	43.77
7	0.3088	2513	-	0.98	6.7

4.1 Relation of various important parameters with respect to each other

The following Figure 4 shows the linear variation of $\dot{Q}_{gen}$ with jacket water temperature at the inlet of generator.

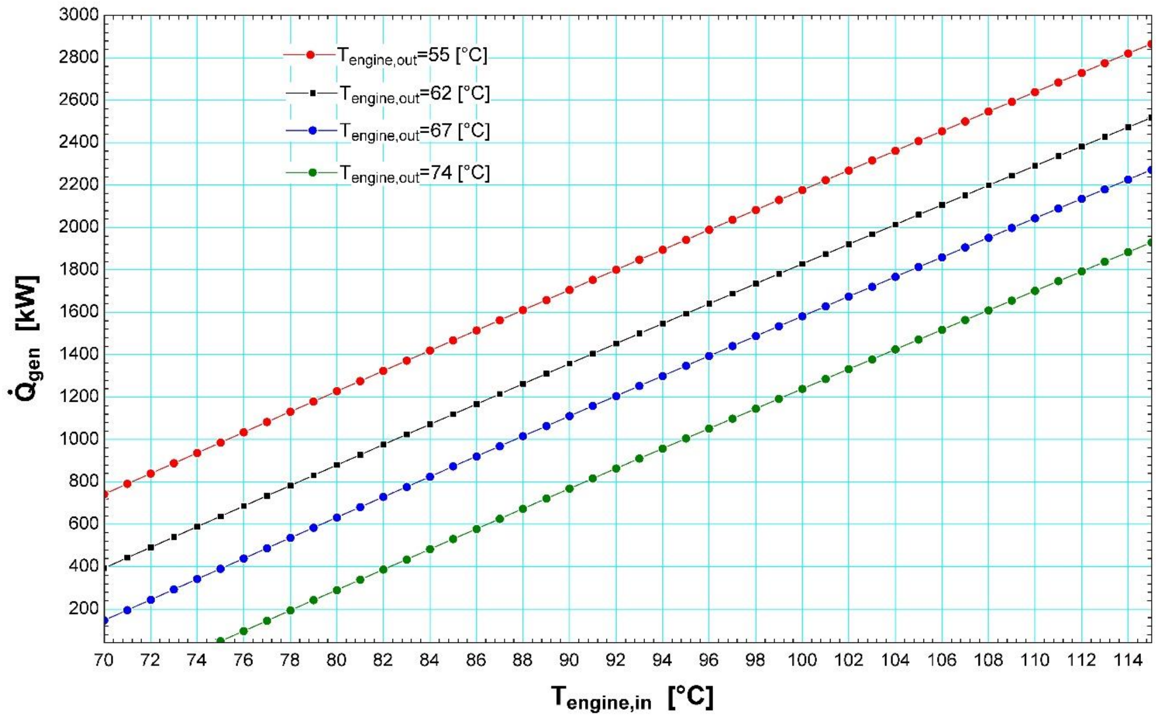

Figure 4: *Heat Supplied to Generator vs. Inlet Jacket Water Temperature at the constant values of Jacket Water Temperature at the outlet of generator*

From Figure 4, it shows that the $\dot{Q}_{gen}$ indirectly proportional with the jacket water temperature at the outlet of generator at a specified inlet temperature.

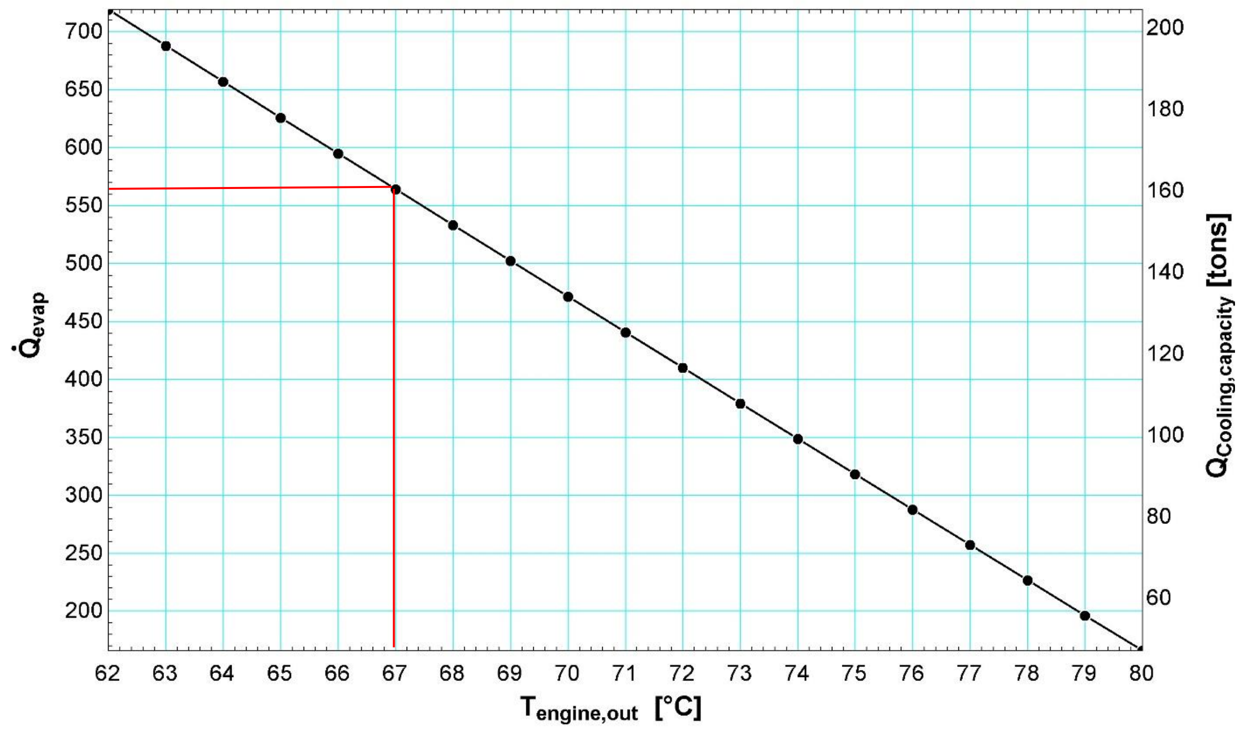

Figure 5: *Cooling capacity vs. Jacket water temperature at the outlet of generator*

From Figure 5, it is obvious that the cooling capacity of the cycle will increase with a decrease in jacket water temperature at the outlet of the generator because the decrease in $T_{engine,out}$ will increase the $\dot{Q}_{gen}$.

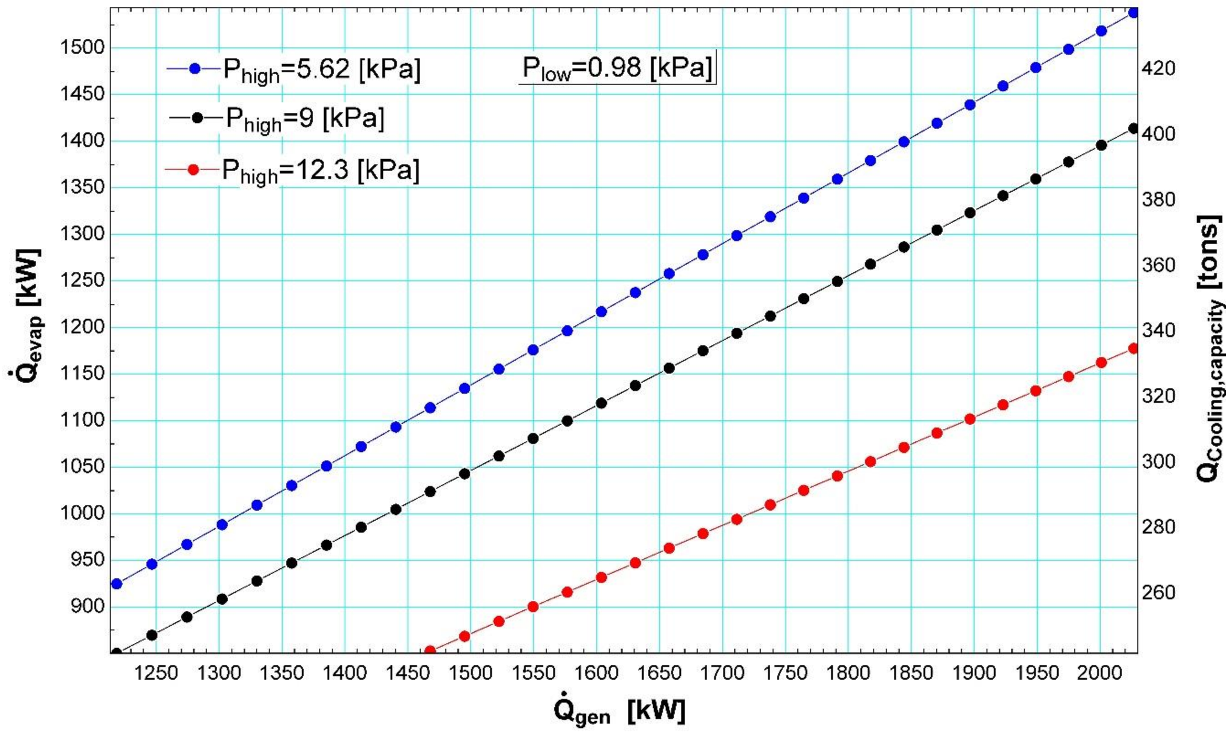

Figure 6: *Heat Transfer at Evaporator vs. Heat supplied to Generator at the constant values of Higher Pressure*

Now Figure 6 shows an increase in the cooling capacity with increasing $\dot{Q}_{gen}$. At a given value of $\dot{Q}_{gen}$ the cooling capacity is higher for lower P_{high}. At 9 kPa, the operating range is greater for $\dot{Q}_{gen}$. Therefore a lower P_{high} could be incorporated to increase the cooling effect if a lower heat energy source is available for the absorption cycle.

Now let's see the effect of temperature of $LiBr/H_2O$ solution at the outlet of the generator or de-absorber on the COP.

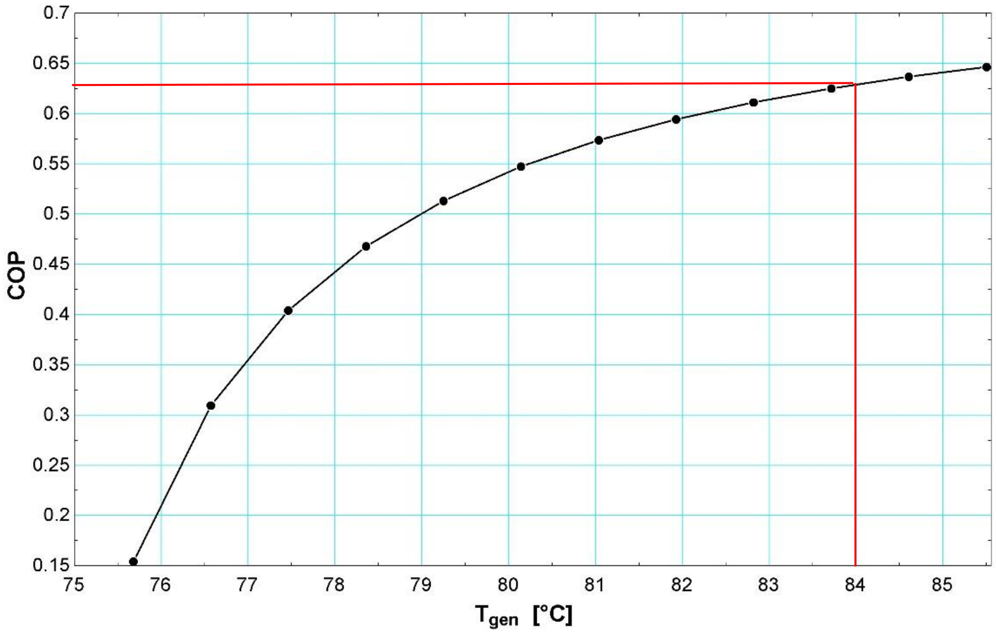

Figure 7: *Effect of Temperature at state 3 on COP*

From Figure 7, the increase in T_{gen} increases the COP but the slope decreases as T_{gen} approaches 86 °C. Note that the maximum value of T_{gen} is limited by the Jacket water temperature at the inlet to the generator.

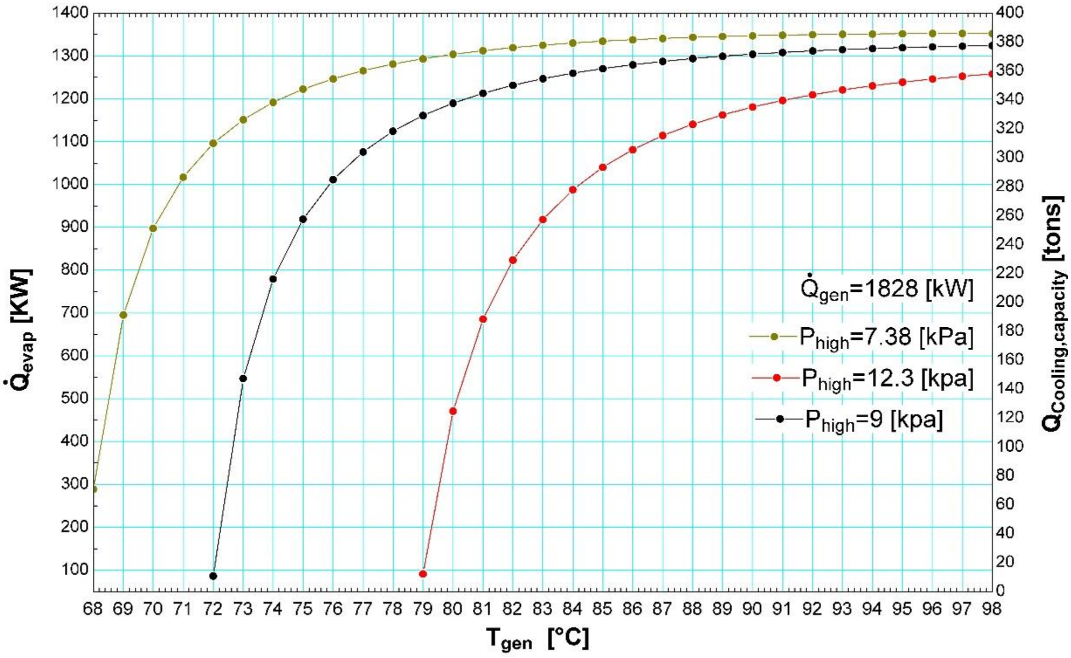

Figure 8: *Cooling capacity vs. State 3 Temperature at the constant values of Higher Pressure*

From Figure 8, the increase in T_{gen} also increases the cooling capacity of the absorption cycle. Note that Figure 8 is plotted at a constant value of $\dot{Q}_{gen}$ i.e. 1828 kW. But the slope becomes almost zero at T_{gen} greater than 98 °C. It is essential to note that lower values of P_{high} provide more cooling capacity and can operate on a greater range of T_{gen} or source temperature.

5. Conclusion

In this study, a detailed thermodynamic analysis of a single effect vapour absorption chiller was performed. Incorporating the temperature requirements of K-Electric in which the jacket water outlet temperature was desired to be 62 °C, an ideal vapour absorption cycle was mathematically modeled using AHRI standards [2], and the ideal cooling load and COP was found to be 204.5 tons and 0.6291 respectively, the ideal cycle was also validated from the analysis of vapour absorption cycle in Stoecker and Jones [1]. Moreover, the phenomenon was further studied in depth using computer-aided graphs produced by EES.

This paper throughout shows the significance of vapor absorption chiller in recovering the energy that is wasted in the industry everyday. The information in our work will serve as a lead for future researchers in improving the overall efficacy of vapor absorption technology.

6. Declarations

6.1 Competing Interests

The authors declare no conflict of interest.

6.2 Publisher's Note

AIJR remains neutral with regard to jurisdictional claims in institutional affiliations.

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