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Article

Fabrication and analysis of solar operated vapour absorption refrigeration system using methanol water

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Abstract: This study investigates the performance assessment of methanol and water as working fluid in a solar-powered vapour absorption refrigeration system. This research clarifies the system's performance across a spectrum of operating conditions. Furthermore, the HAP software was utilized to determine and scrutinize the cooling load, facilitating a comparative analysis between software-based results and theoretical calculations. To empirically substantiate the findings, this research investigates methanol-water as a superior refrigerant compared to traditional ammonia- water and LiBr-water systems. Through experimental analysis and its comparison with previous research, the methanol-water refrigeration system demonstrated higher cooling efficiency and better environmental compatibility. The system's performance was evaluated under varying conditions, showing that methanol-water has a 1% higher coefficient of performance (COP) compared to ammonia-water systems, proving its superior effectiveness in solar-powered applications. This empirical model acts as a pivotal tool for understanding the dynamic relationship between methanol concentration (40%, 50%, 60%) and system performance. The results show that temperature of the evaporator (5–15 ℃), condenser (30 ℃–50 ℃), and absorber (25 ℃–50 ℃) are constant, the coefficient of performance (COP) increases with increase in generator temperature. Furthermore, increasing the evaporator temperature while keeping constant temperatures for the generator (70 ℃–100 ℃), condenser, and absorber improves the COP. The resulting data provides profound insights into optimizing refrigerant concentrations for improved efficiency.

Keywords: renewable energy; solar energy; environmental sustainability; methanol-water; VARs

1. Introduction

Worldwide, the vapour compression refrigeration process in the air-cooling system utilizes 70%–75% of domestic power, necessitating the use of more fossil fuels to generate the required electricity from fossil fuel power plants. The combustion of fuel in such structures leads to the disintegration of additional greenhouse gases (CO_2), negatively impacting the world's atmosphere. Therefore, it is imperative to establish a substitute refrigeration process that utilizes electricity from renewable energy sources in order to alleviate the detrimental effects of fossil fuel powerplants on the global environment [1,2].

The extensive use of sustainable energy resources for driving air conditioning cycles, especially solar energy, has been a current priority due to its readily available nature [3]. Solar-powered refrigeration systems are ideal for use in fields such as agriculture and medicine because they are not dependent on outside energy sources or the electric grid, and they are compatible with environmental conditions of Narowal, Pakistan.

When considering absorption refrigeration cycles, it is crucial to choose an appropriate absorbent-refrigerant combination based on scientific parameters. For a liquid to be an efficient refrigerant, it must possess the following properties: it must have a boiling temperature, a vaporization pressure that is lower than atmospheric pressure, a high heat of vaporization, non-flammable and non-explosive features, and be beneficial to the atmosphere and ozone [4]. A couple of literary masterpieces were offered. One of the suggested approaches was the transformation of refrigerant vapour to liquid phase using an adequate absorbent to absorb the refrigerant vapour. The mixing propensity between the components was enhanced by the close association between the absorbent and the refrigerant molecules. This was done using the same low-pressure method [5].

The scientists' primary goal was to improve the COP values of the absorption-refrigeration system. Multiple subjects were studied in the earlier research through the number of experiments. Sierra developed solar bonding to boost the discontinuous absorption of refrigeration using NH_3-H_2O solution. It has been demonstrated that a significant generation value of 73 ℃ while preserving a vaporization value of −2 °C can be attained. The variation of the calculated COP outcomes was from 0.24 to 0.28 [6]. Porumb examined the influence of operational factors like solar heated water, chilled water, and cold-water temperature on the coefficient of performance of the LiBr-H_2O absorption refrigerator, and the outcomes proved that the computational model is capable of estimating the suitable operational circumstances of the refrigeration system while assuming crystallization [7].

Jasim designed a digital model to imitate three separate working fluids: ammonia-water, ammonia-lithium nitride, and ammonia-sodium thiocyanate. Equations based on polynomials were included in the simulation to compute the heating and cooling characteristics. The variance in temperatures among all three process and the generator, evaporator and condenser demonstrates that the ammonia-water process has worse efficiency than the remaining two cycles [8]. The inspection, design and manufacturing of a green, advantageous VARs for unit output was done by Bajpai, utilizing ammonia and water as the solution pair. The system was designed and evaluated under different operating situations utilizing hot water as a power source and a planar solar collector; the obtained COP for this arrangement was 0.58. Moreno utilized a CPC device in Mexico with a tripartite mixture (NH_3/$LiNO_3$/H_2O). The COP was 0.098, which reached an evaporator temperature of −11°C. He discovered that the time of cooling is 8 h, and the COP goes up by 24% greater than the binaries combination (NH_3/$LiNO_3$) in the CPC device [9]. Agrouaz conducted energy evaluations to determine the effectiveness of using solar refrigeration systems under Moroccan meteorological conditions. The findings indicated that variety of factors, such as the inclination of solar energy collector, collector surface field, and evaporator and generator circulation rates, play a vital role in boosting the overall functionality [10]. Applying a methanol-water combination a solar-powered absorption cooling system was built and tested Nabeel A. Ghyadh, having every single factor computed separately. The components of the parabolic trough collector are a 2.1 m^2 aperture stainless steel reflector and an illuminated evacuated tube containing a black-painted helical copper tube receiver (12.7 mm in diameter and 1 mm in thickness). Convection inefficiencies and radiation are reduced by the glass cover [11].

There are actually two proactive liquids utilized in VARs, which include water-LiBr and NH_3-water solutions because of their high coefficient of performance. Both substances have restrictions. The framework becomes more complicated due to necessity for an analyser and rectifier due to the difference in boiling temperatures between the two parts of NH_3-water system. Water-LiBr shows challenges with crystallization, and in both scenarios, the components electrolytic character could lead to corrosion occurrence. Consequently, there has been a significant amount of research into the recognition of different functioning fluid opportunities, such as deep eutectic solvents and organic and ionic liquids. Developments have been pointed out in working VARs, like the COP and percentage concentration [12].

The main objective of this research is to utilize a methanol-water combination to figure out the system's COP and to make a comparison study between refrigerants like ammonia-water. A VARs may allow us to achieve excellent energy efficiency, especially when surplus heat or low- quality sources of energy i.e., solar, are present. The solution of methanol and water meets all the specifications for an appropriate refrigerant; as it does not produce crystallization and does not need any additional components. The methanol-water combination has advantageous thermodynamic characteristics that allow it operate across a broad temperature spectrum. Its low price and accessibility make it an environment friendly for cooling needs.

2. Research methodology

The research methodology of this research is divided into three portions: mathematical modelling in which different governing equations are discussed to calculate COP and Cooling load, simulation analysis to validate theoretical cooling load and experimental setup and all these are explained below.

2.1. Mathematical modelling

There are two main parts of mathematical modelling in this research: first is for calculating the coefficient of performance of VARs and second is for calculating the cooling load of the system.

The coefficient of performance is a dimensionless ratio that evaluates the efficiency of heat pumps, refrigeration systems, and other heat-transfer apparatuses. It is defined as the ratio of the intended output to the necessary input energy. A higher COP implies a more effective system since it transmits more heat per unit of energy unit. The parameters required to calculate coefficient of performance is shown in **Table 1.**

Table 1. Parametric values to calculate COP.

Parameter	**Expression**	**Units**	**Value**
Generator temperature	T_g	℃	90
Condenser temperature	T_c	℃	30
Absorber temperature	T_a	℃	26

Table 1. (*Continued*).

Parameter	Expression	Units	Value
Evaporator temperature	T_e	℃	5
Heat input	Q_{in}	W	30
Concentration at Absorber exit	X_{abs}	-	0.35
Concentration at Generator exit	X_{gen}	-	0.45
Enthalpy at evaporator exit	h_{fge}	kJ/kg	2434.6
Enthalpy at condenser exit	h_{fgc}	kJ/kg	115.6
Enthalpy at generator exit	h_{sg}	kJ/kg	2401.3
Enthalpy at absorber exit	h_{sa}	kJ/kg	44.0

The volume of refrigerant that moves via a particular location in the system in unit time is called the mass flow rate (m_r) in arefrigeration system.

$$m_r = \frac{Q_{in}}{hfg_e} \tag{1}$$

An important parameter in VARs is mass flow rate of strong solution and is given by;

$$m_s = m_r \times \frac{X_{gen} - X_{abs}}{X_{abs} - X_{gen}} \tag{2}$$

The mass of a solute (weak solution) flowing through a specific site in a unit time is usually expressed as the mass flow rate of the weak solution.

$$m_w = m_s + m_r \tag{3}$$

First of all, we'll calculate heat transfer rate at evaporator i.e., Q_e

$$Q_e = m_r \times \mathrm{hfg}_e \tag{4}$$

Now, we'll calculate the heat transfer at condenser so the equation required to find the heat transfer rate at condenser Q_c is;

$$Q_c = m_r \times \mathrm{hfg}_c \tag{5}$$

Now, we'll calculate the heat transfer at absorber so the equation required to find the heat transfer rate at absorber Q_{abs} is;

$$Q_{\mathrm{abs}} = m_s \times (\mathrm{hs}_g - \mathrm{hs}_a) \tag{6}$$

Now, we'll calculate the heat transfer at generator so the equation required to find the heat transfer rate at generator Q_{gen} is;

$$Q_{\mathrm{gen}} = Q_e + Q_{\mathrm{abs}} + Q_c \tag{7}$$

Finally, now we'll calculate coefficient of performance COP for methanol-water solution so;

$$\mathrm{COP} = \frac{Q_e}{Q_{\mathrm{gen}}} \tag{8}$$

Finding the vapor absorption refrigeration system's theoretical cooling load is the main goal of the experiment's first phase. To determine the quantity of heat needs to be removed from the assigned space in order to maintain the required temperature, extensive calculations must be performed. Theoretical calculations consider various parameters, including ambient conditions, heat transfer characteristics, and refrigeration system specific requirements. Parameters to calculate cooling load and air properties of air at 20 °C is shown in **Tables 2** and **3** respectively.

Table 2. Parameters to calculate cooling load.

Parameter	Expression	Units	Value
Area	A	m^2	0.577
Material	-	-	Iron (darkgrey surface)
Sunlight	-	-	Very lessor none
Doors/Windows	-	-	None Extra
Extra Heat Devices	-	-	None
Ambient Temperature	TA	°C	30
Required Temperature	Td	°C	20
Iron emissivity	ε	-	0.31
Stefan-Boltzmann constant	σ	W/m^2K^4	5.67×10^{-8}

Table 3. Properties of air at 20 °C.

Property	Expression	Units	Value
Volumetric thermal expansion coefficient	β	1/K	3.43×10^{-3}
Kinematic viscosity	v	m^2/s	2.02×10^{-5}
Thermal diffusivity	α	m^2/s	2.17×10^{-5}
Thermal conductivity	k	W/mK	0.025

Natural convection can be useful in a number of system parts in a vapor absorption refrigeration system, especially the absorber and the generator.

$$Q_{\text{natural}} = (\mathrm{h})(\mathrm{A})(\mathrm{Tamb} - \mathrm{Tdesired}) \quad (10)$$

Now we will find out the forced convection and its value is 0 because no door and window are included.

Hence, total convection is the sum of natural convection and forced convection and is given as;

$$Q_{\text{convection}} = Q_{\text{natural}} + Q_{\text{forced}} \quad (11)$$

Now we will find out the cooling load

$$Q_{\text{total}} = Q_{\text{radiation}} + Q_{\text{convection}} \quad (12)$$

2.2. Simulation analysis

HAP 4.9 software is employed to estimate the cooling load of a chamber having dimensions 3 by 3ft. HAP has given us the different graphical on the basis of parameters given to it according the Narowal's geographical considerations. **Figure 1** is a bar graph of yearly cooling load that illustrates the cumulative cooling for each day of the year. As heating load is not required and our main focus is cooling load so the graph shows the cooling load The U-value taken for the system is 0.397(BTU/(hr-ft^2-°F)). The value for zone flow is fixed 4.4 but the value of sensible load from hour to hour and has a minimum value 41.0 BTU/hr. and maximum value 61.8 BTU/hr. and these values are set according to condition of Narowal, Pakistan.

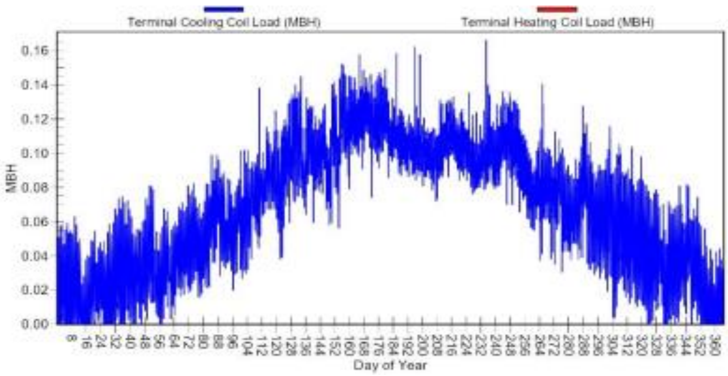

Figure 1. Yearly cooling load.

2.3. Experimental setup

To complete the experimental setup, the following key components were used;

- Evacuated Tube Solar Collector
- Absorber
- Condenser
- Evaporator
- Generator

2.3.1. Solar collector

Solar Collectors are heat exchangers that collect solar radiation and transform it into thermal energy. In VARs, thermal energy s utilized to fuel the generation process, which entails boiling a methanol and water solution. The reinsulating methanol vapour travels to a condenser, where it discharges heat before condensing back into a liquid. The liquid methanol is then sent to absorber, where it combines with water vapour from the evaporator. This absorption process releases heat, which is absorbed by the chilling water. Solar collector is shown in **Figure 2**.

Figure 2. Solar collector.

2.3.2. Absorber

In a vapour absorption refrigeration system, the absorber performs an important function. Imagine a sponge absorbing water—that's what the absorber does, but rather than water, it absorbs refrigerant vapour. This refrigerant vapour comes from the evaporator, where it's been transformed from liquid due to low pressure and is ready to be absorbed. The absorber contains a liquid absorbent, often water in methanol-water system. As the refrigerant vapour gets absorbed by the absorbent, it produces a richer solution. This absorption process is exothermic, mean it releases heat. The enriched solution is then circulated to another part of the system for regeneration. The absorber is shown is **Figure 3**.

Figure 3. Absorber.

2.3.3. Condenser

The condenser is a heat transfer mechanism, usually a tube-and-fin design. Hot, high-pressure refrigerant vapour goes into the condenser. This vapour emanates from the generator, where it was distilled out of a mild methanol-water solution. Outside the condenser tubes, chilling water or air circulates. As the heated methanol vapour encounters the colder walls of the condenser, it condenses back into the liquid. This process releases the heat accumulated in the generator, and that's what ultimately provides the chilling effect. Now liquid methanol, at a lower temperature, then departs the condenser, heading to the expansion valve for the next stage of the cycle. The colder liquid conveying the relinquished heat is then drawn away from the condenser.

The condenser functions as a radiator, dispersing the heat extracted from the space to be chilled to the surrounding environment through the chilling water or air. This enables the low-pressure methanol to return to the evaporator, ready to absorb heat and repeat the cycle. It also functions like a heat disposal mechanism, removing the energy accumulated by the coolant and dispersing it to the surroundings. This enables the system to operate on a consistent refrigeration cycle. The condenser is shown in **Figure 4**.

Figure 4. Condenser.

2.3.4. Evaporator

The evaporator functions as a heat absorber in a refrigerator that absorbs methanol and water vapour. The refrigerant's vaporization point is substantially reduced as a result of the low pressure. The heat is readily transferred from the heated object to the refrigerant when it comes into contact with these channels. The refrigerant undergoes a phase change, transitioning from a liquid to a low-pressure vapour as it absorbs this heat. This phase transition is essential. The refrigerant achieves the desired chilling effect by absorbing heat and vaporizing, thereby removing thermal energy from its surrounding and resulting in a decrease in temperature. This low-pressure methanol absorbs heat from the object that needs to be cool, such as air or water. The methanol becomes vapour as it heats up, leaving the water solution behind to absorb additional heat and maintain a mild temperature. In a vapour absorption refrigeration system, the evaporator functions as a heat sink, absorbing heat from its surrounding through the process of refrigerant evaporation, which creates a revitalizing and cold atmosphere. The evaporator is shown in **Figure 5**.

Figure 5. Evaporator.

3. Complete experimental setup

In this research, a solar powered VARs was fabricated and tested. Methanol-water was used as solution pair in which methanol worked as refrigerant and water as absorbent. The design, working and testing of the system was carried out at University of Engineering and Technology Lahore, Narowal Campus, Narowal city, Punjab province, Pakistan, under the outdoor conditions of Narowal. The complete experimental setup of solar powered VARs is shown in **Figure 6**.

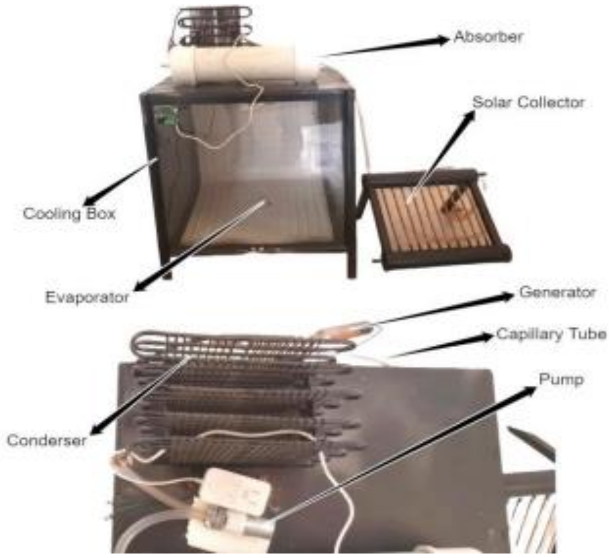

Figure 6. Complete experimental setup.

In vapour absorption refrigeration system low pressure methanol vapors enters the absorber from the evaporator. The methanol vapour dissolve within the absorber into cold water, forming a concentrated methanol solution. The energy discharged during methanol ingestion is dispersed by flowing chilly water through tubes within the absorber. The extremely strong methanol solution is delivered to the generator via a heating element. In the heating element, the highly concentrated methanol solution is warmed due to the blisteringly weak solution coming from the generator to the absorber. The tepid solution is heated more inside the generator, enabling methanol vapors to emerge from the solution. Methanol's boiling temperature is lower than that of water. The excess feeble solution from the generator flows back to the absorber. The precisely purified methanol vapour then moves forward towards the condenser. In the condenser, the unused energy of methanol vapour is given off to the chilled water, resulting in methanol vapour condensing into liquid state. The elevated pressure of methanol causes a decrease in temperature, resulting in incomplete vaporization. This slightly vaporized liquid travels to the evaporator. Inside the evaporator, the liquid methanol thoroughly vaporizes. The unused energy of evaporation is taken in from additional substances being chilled, like air or water. The low-temperature methanol vapour departing the evaporator comes back to the absorber, completing the cycle. **Figure 7** represents the process diagram of proposed system.

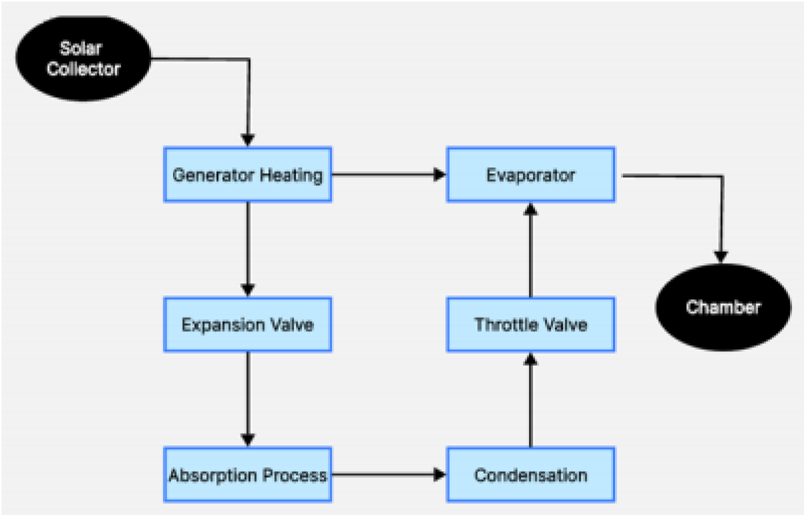

Figure 7. Schematic diagram of the system.

4. Results and discussions

Figure 8 elaborates the comparison of cooling load using mathematical model and simulation result. The comparison has been made for the month of June. Mathematical model shows a maximum value of 42.7 W and simulation result has shown 41.03 W cooling load in the month of June. The graph shows that value of cooling load is maximum in day time 12 pm–17 pm, after that graph start decreasing again.

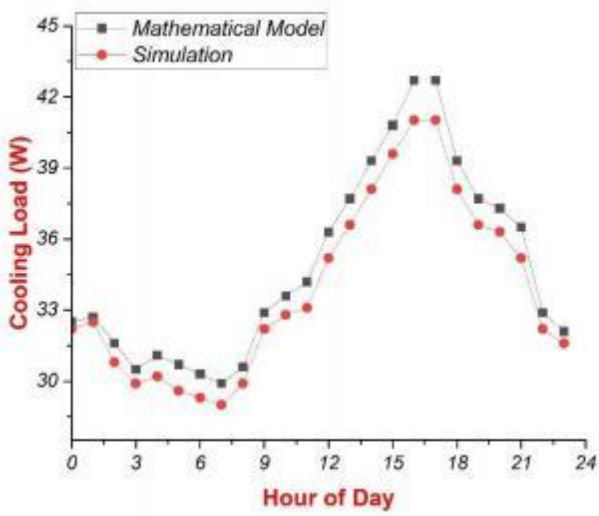

Figure 8. Comparison of mathematical model and HAP simulation for cooling load.

The comparative analysis of coefficient of performance (COP) from both the current research and existing literature is shown in **Figure 9**. The graph clearly illustrates that the COP of the methanol-water system exceeds that of the ammonia-water solution pair. In particular, the maximum COP for the methanol-water solution pair at the condenser temperature (T_c) of 30 ℃ and an evaporator temperature (T_e) of 5 ℃ is 0.42. Conversely, the ammonia-water solution pair attains a maximum COP of 0.41 under identical conditions. It has also been noted that the coefficient of performance in both systems increases as the generator temperature increases.

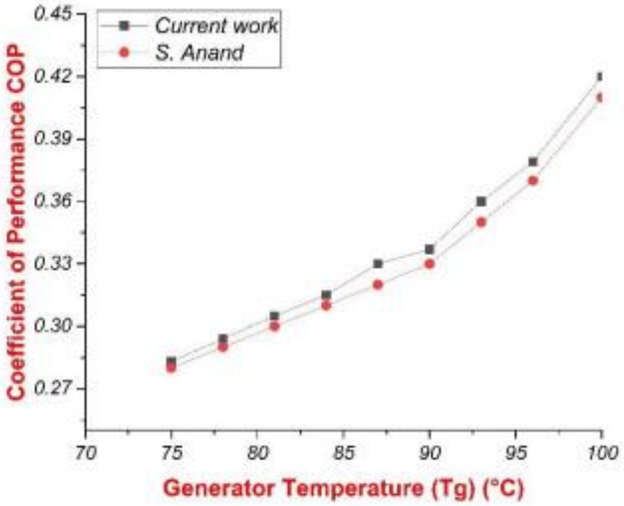

Figure 9. Comparison of COP of current work with the work of Anand [13].

The coefficient of performance (COP) of the refrigeration system is illustrated in **Figure 10**, which highlights the impact of varying evaporator and generator temperatures (T_e = 5 °C, 10 °C, and 15 °C). It is evident from the graph that the highest COP is attained at the maximum evaporator temperature, T_e = 15 °C, as the generator temperature increases. This discovery underscores the significance of refining evaporator temperatures to enhance the efficiency of refrigeration system, particularly when the generator temperatures fluctuate significantly. The advantage of operating at high evaporator temperature is illustrated by the relationship between higher generator temperatures and enhanced COP at higher evaporator temperature.

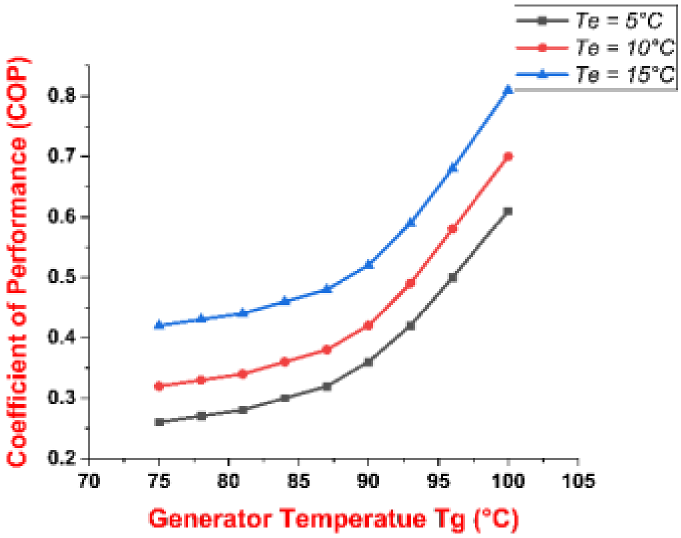

Figure 10. Variation of COP with generator temperature at different evaporator temperatures (T_c = 30 °C).

Impact of variations in the generator temperature on the coefficient of performance (COP), including the influence of varying condenser temperature is shown in **Figure 11**. It is evident that the COP reaches its maximum at a reduced condenser temperature, T_c = 10 °C, as the generator temperature increases. This underscores a critical insight: in order to achieve maximum system efficiency, the generator temperature should be maximized while simultaneously maintaining the condenser temperature at the lowest feasible level. The significance of precision control of temperatures in order to optimize the cycle's performance in underscore by the intricate interplay between these temperature variables.

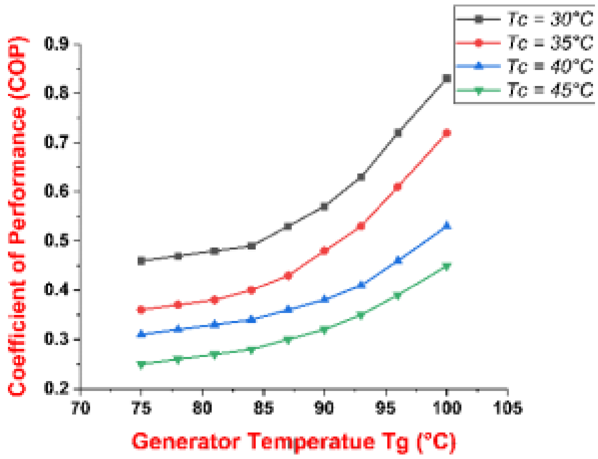

Figure 11. Variation of COP with generator temperature at different condenser temperatures (T_e = 5 °C).

The temperature drop fluctuation in the evaporator at 40%, 50%, and 60% solution concentrations is depicted in **Figure 12**. It has been noted that the largest concentration of methanol vapor produced in the evaporator results in the maximum temperature reduction. The evaporator has a temperature drop range of 7.8 °C–16.3 °C. High concentration was employed, resulting in increased methanol vapor emission and a significant variation in pressure across the evaporator and condenser.

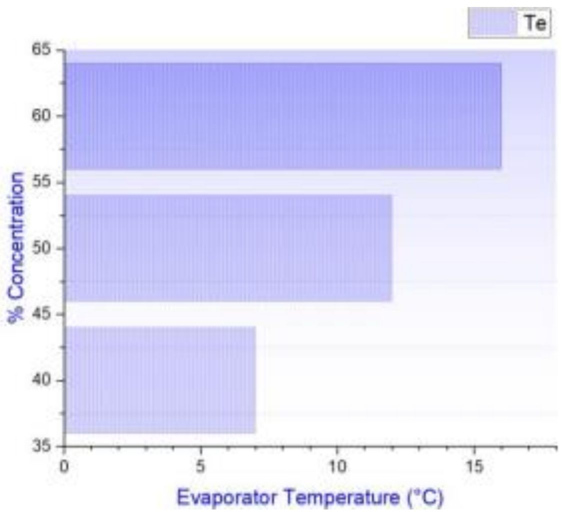

Figure 12. Variation of maximum temperature drop of evaporator.

The impact of solution concentration on the system's COP is displayed in **Figure 13**. This graph demonstrates how raising the concentrations raises the COP. It has been shown that high concentrations yield great performance since they produce a lot of methanol vapor. COP ranges from 0.35 to 0.62. Since the refrigeration system's coefficient of performance rises with increasing pressure variation between the condenser and evaporator (or generator), the high concentration results in both more released methanol and a greater pressure fluctuation between the two components.

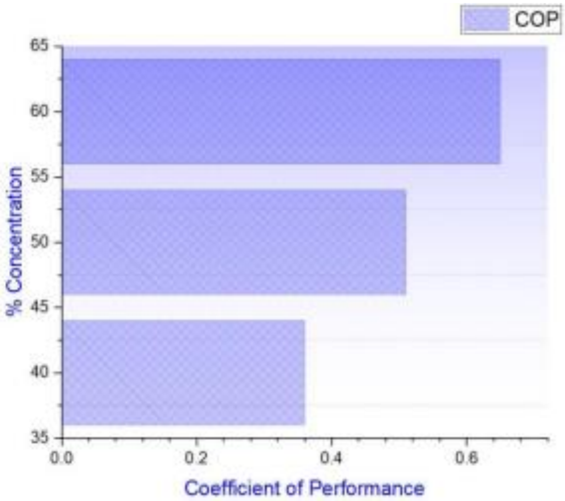

Figure 13. Maximum variable COP with variable concentration.

5. Conclusion

An experimental investigation was conducted in the present work using methanol as a refrigerant in an absorption-refrigeration cooling system at University of Engineering and Technology Lahore, Narowal Campus. It can be concluded that the investigated system is viable practically and ecologically, where the approach is more effective as an outcome of using a renewable energy source and does not harm the ozone layer, resulting in a smaller adverse effect on global warming. Physically, a higher temperature drop could be attained by the studied system at higher concentrations as an outcome of generating a higher amount of refrigerator vapor, where the drop ranged from 7.8 ℃ to 16.3 ℃, concluding that the system is more efficient thermally. Additionally, as generator temperature increases, COP increases as a consequence when the maximal generator temperature reaches 100 ℃. The COP of Methanol- Water solution is 6% higher than the COP of Ammonia-Water solution in the refrigeration system (VARS), i.e., 0.42, for Methanol-Water and 0.41, for Ammonia-Water. The theoretical cooling load is 42.7 watts, and by conducting analysis, the value of the cooling load is 0.14 MBU, i.e., 41.03 watts. The principal implementation of this undertaking is its use at the domestic level. Cost effectiveness and improved efficiency by using methanol as a refrigerant are the potential uses of a solar-operated refrigeration system. Non-renewable energy sources are scarce and could cease to be available to us by the next century, which makes it more crucial than ever for us to make use of all forms of renewable energy, such as solar. Despite challenges and limitations, solar-operated vapor absorption refrigeration systems using methanol water offer a promising and sustainable option for domestic cooling.

Author contributions: Conceptualization, FA and SA; methodology, FA, TE and ZA; software, FA; validation, SA, MR and FA; formal analysis, FA and ZH. All the authors agreed to the published version of the manuscript.

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Nomenclature

COP	Co-efficient of performance
mr	mass flow rate
Qin	heat input
mw	mass flow rate of weak solution
Xabs	Concentration at Absorber exit
ms	mass flow rate of strong solution
Qgen	heat transfer rate at generator
A	area
Tamb	Ambient Temperature
Xgen	Concentration at Generator exit

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