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Design and Performance Assessment of a Solar-Biogas Hybrid Vapor Absorption Refrigeration System Using Heat from Solar and Biogas Sources

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Abstract
This research covers the design and performance assessment via experimental testing of a solar-biogas driven hybrid vapour absorption refrigeration system. The system is designed for a 40-liter capacity with a cooling capacity of 0.05 TR for ammonia-water mixes. This refrigeration system was designed to operate at 140°C for generators using thermal sources such as solar energy and methane flames. The biogas flame served as a heat source, generating temperatures above 140°C, with the system achieving a coefficient of performance (COP) of 0.134 individually. When the system operates continuously throughout the day using biogas combustion. sun energy was used for 4 to 5 hours everyday when sun radiation was accessible. In this instance, the solar thermal system generated a temperature of just 70°C, but the solar panel supplying direct current to the heater resulted in a temperature of nearly 150°C. In a hybrid system using biogas flames as a heat source for 18 hours and solar energy via solar panel DC supply for 4 to 6 hours, a coefficient of performance (COP) of 0.1 was attained.

Keywords: Biogas, VARS, COP, Temperature, Hybrid

1. Introduction

Refrigeration systems are essential components for dairy producers. Energy is a critical component for the production of refrigeration products. The refrigeration technique is often impacted in rural areas or abroad due to the inconsistent supply of energy. This article posits the utilisation of energy derived from stars, as well as organic waste available at dairy farm facilities (e.g., calf dung, food waste, agricultural refuse, etc.), in conjunction with solar energy from the sun. At the time of independence, India's total milk output was roughly 17 million tonnes annually. Over time, India has emerged as the second biggest milk producer, generating 127 million tonnes annually, of which just 20% is managed by organised sectors. The village-level cooperative groups gather milk from dairy producers, which is then delivered to cooling centres. These cooling facilities include refrigeration units functioning on standard electrical supply. In the event of an electric supply failure, diesel generator sets are used to operate the refrigeration systems. Conventional refrigeration systems using grid electricity execute milk processing, climate control for dairy products, packing, and cold storage of dairy items. Given that refrigeration is a process with significant energy consumption, the issue of peak load penalties may be mitigated by the implementation of a solar-biogas hybrid vapour absorption system, which can also accommodate part load demands. Renewable energy sources, such as solar and biogas, are often used in dairy applications for hot water supply from boilers, hot water generators for milk processing, or for CIP cleaning. The practical applications of solar-biogas refrigeration systems for milk preservation, as well as their commercial use in milk-related cooling operations and climate control for cold storage and packing facilities for dairy products, are notably limited. Consequently, there is a critical need for the development of a commercially viable solar-biogas refrigeration system to satisfy the refrigeration demands of the dairy product business. The current understanding of refrigeration and air conditioning systems, reliant on a constant power supply and diesel generators, will be used to design and build energy-efficient solar-biogas refrigeration systems for the chilling of milk and its products in rural areas. The use of solar energy and biogas, both sustainable resources, has significant potential for commercial application in dairy product processing, facilitating the design and development of solar-biogas refrigeration systems for dairy producers.

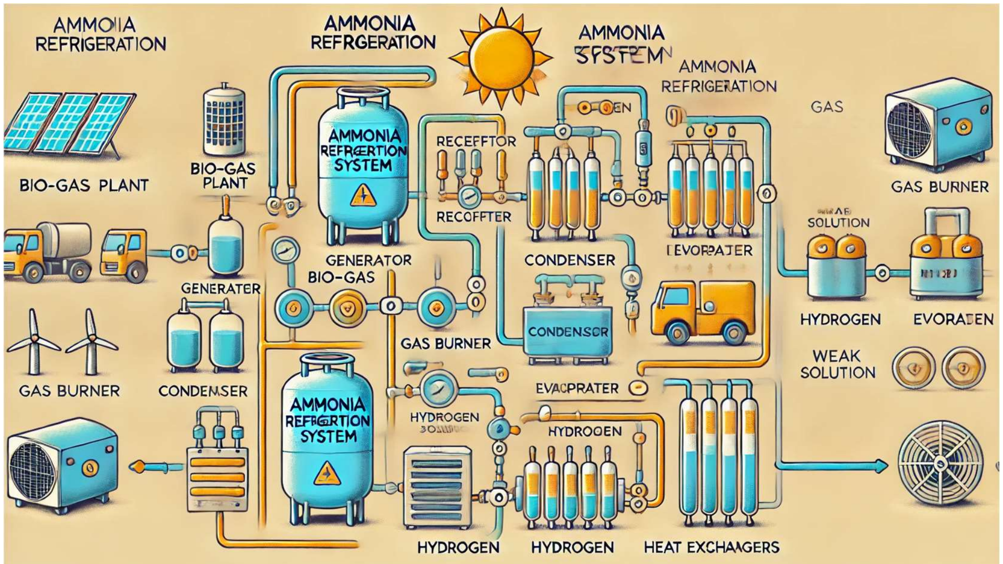

Fig. 1 Schematic of hybrid solar/biogas system

The dairy and food sectors are rapidly expanding, with new technology being launched daily to enhance food quality. The use of conventional energy is prevalent in the primary processing of milk. Currently, almost all dairy businesses rely on grid supplies, with diesel generators serving as backup. The milk procurement system in India has evolved, now including a cold chain to enhance its microbiological purity. The suggested solar-biogas refrigeration system would enable dairy producers to diminish their reliance on grid power, thus conserving a significant quantity of energy used for refrigeration in dairy farming.

2. Methodology

The methodology for the design of the VARS (vapour absorption refrigeration system) primarily includes the generator tube, absorber unit, and the evaporator and condenser units. The dimensions of each component of a 40 L capacity absorption refrigerator were developed and established. The following parameters were computed for the design of the VARS. The design of the Vapour Absorption Refrigeration System (VARS) primarily involves key components including the generator tube, absorber unit, evaporator, and condenser. In this study, a 40-liter capacity absorption refrigerator was designed with specific dimensions determined for each part. The following parameters were calculated to guide the design of the VARS:

Heat Absorbed by the Refrigerant in the Evaporator (QE):

$QE = mp \times Cp \times \Delta T$, where:

- mp: Mass of the product to be cooled (kg)
- Cp: Specific heat of the product (kJ/kg K)

Mass Flow Rate of Solution in the Evaporator:

The mass flow rate of liquid ammonia in the evaporator was calculated using the formula:

$m1 = QE / (h1 - h5)$, where:

- h1: Enthalpy of vapour ammonia leaving the evaporator
- h5: Enthalpy of liquid ammonia leaving the condenser
- QE: Heat absorbed by the refrigerant

Flow Balance for Aqua-Ammonia Solution:

The flow balance equation is given as:

$m3 = m1 + m2$, where:

- m1: Mass flow rate of solution in the evaporator
- m2: Mass flow rate of strong aqua-ammonia solution leaving the absorber
- m3: Mass flow rate of weak aqua-ammonia solution leaving the generator

Design of the Evaporator:

The heat absorbed by the refrigerant in the evaporator is given by:

$QE = U \times A \times LMTD$, where:

- U: Overall heat transfer coefficient
- A: Area of the evaporator coil
- LMTD: Logarithmic Mean Temperature Difference

Design of the Condenser:

The heat rejected from the condenser is determined by:

$QC = U \times A \times LMTD$, with the parameters defined similarly to the evaporator.

Design of Absorber Unit:

The volume of the absorber vessel was calculated as:

$VAV = \pi \times (DAV/2)^2 \times LAV$, where:

- DAV: Diameter of the absorber vessel
- LAV: Length of the absorber vessel

Design of Generator Tube:

The volume of the generator tube was computed using:

$VG = \pi \times (DG/2)^2 \times LG$, where:

- DG: Diameter of the generator tube
- LG: Length of the generator tube

Calculation of Coefficient of Performance (COP):

The COP of the system was calculated as the ratio of the refrigerant's cooling effect (QE) to the total energy supplied to the system, which includes work done by the pump (Wp) and the heat supplied (QG) to the generator.

Required Capacity of Biogas Plant:

The energy required from the biogas plant, QB, was calculated based on the generator's heat requirement (QG) and efficiencies of the biogas burner and generator.

3. Results and discussion

Table 1 Dimensions of vapour absorption refrigeration system

Components	Volume (m^3)	Diameter (m)	Length (m)	Additional Info
Heat Exchanger Copper Coil	4.24×10^{-3}	0.006	1.5	No. of Turns = 28
Generator Tube	7.85×10^{-3}	0.02	0.25	
Absorber Vessel	3.30×10^{-4}	0.06	0.125	
Absorber Tube	2.5×10^{-3}	0.03	3.6	
Evaporator	4.6×10^{-5}	0.014	0.3	
Condenser Tube	4.9×10^{-5}	0.014	0.32	
Condenser Fins	3.5×10^{-6}			
Condenser Fins	Length (m)	Width (m)	Thickness (m)	No. of Fins
	0.07	0.05	0.001	35

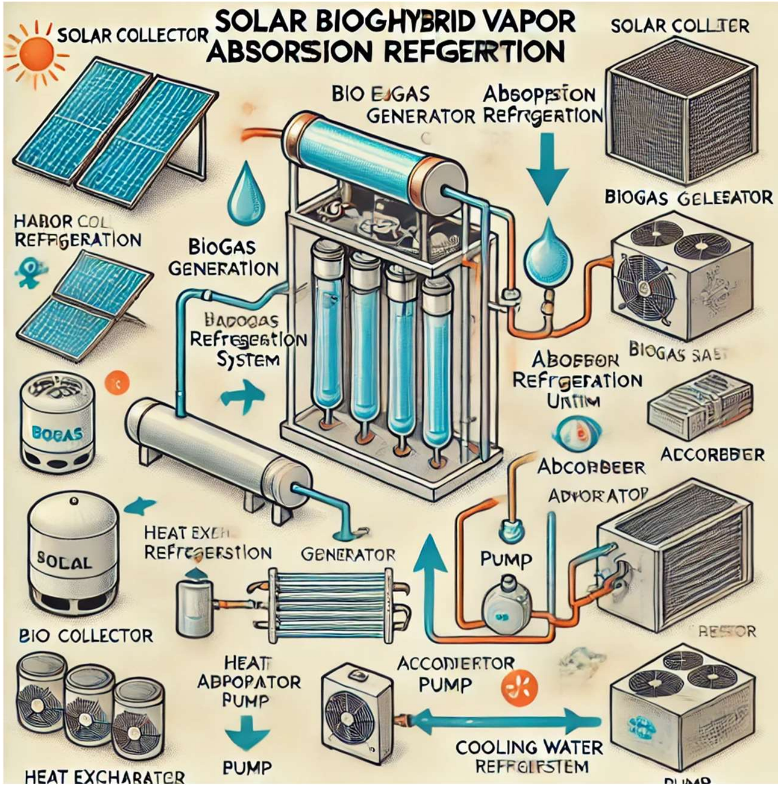

Fig. 2 Schematic of hybrid solar/biogas system VARS

Figure 3 illustrates the fluctuation of generator temperature and the variance of Coefficient of Performance (COP) during a 24-hour period under full load conditions.

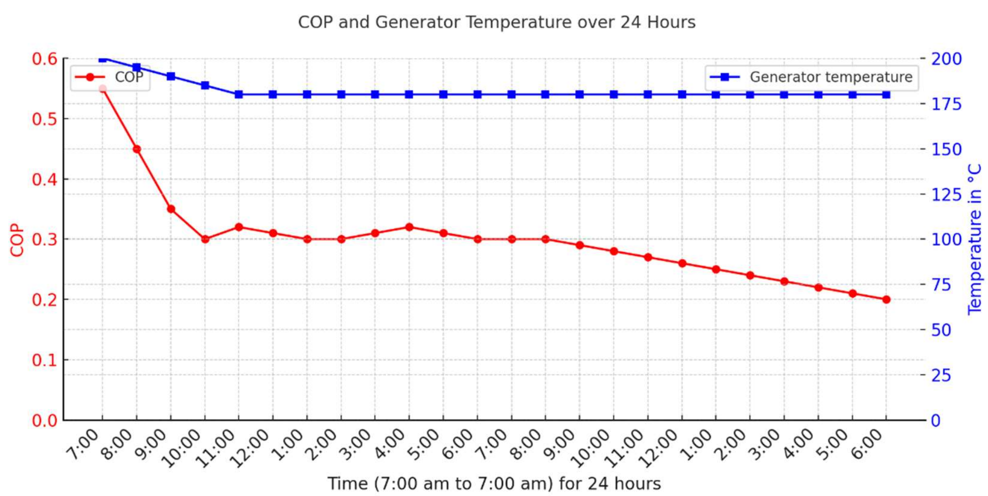

Fig. 3 Generator temperature and COP variations with time

During this period, the refrigerator operates on biogas for the first four hours and thereafter transitions to a DC power source supplied by solar photovoltaic for the next six hours. During the last hour of operation, the refrigerator is once again fuelled by biogas and continues to operate on biogas for the remainder of the duration. The following observations were recorded: The generator's startup temperature is recorded at 140°C, which decreases little throughout the first hour of operation. During the second hour of operation, the generator's temperature stays stable at 140°C, with a minor rise occurring after the fourth hour when refrigeration is powered by a solar panel producing DC electricity. When solar panels provide DC electricity, the generator's temperature stays almost constant during the whole operational duration. A dramatic decline in generator temperature is seen during the 12th hour of operation. The generator temperature thereafter rises quickly and reaches 140°C once again when the refrigerator operates on biogas. The temperature of 140°C is maintained consistently throughout the duration of operation. The generator temperature is determined to be between 135°C and 140°C. The fluctuations in COP are examined as follows: The initial COP is measured at 0.45, which declines swiftly during the first four hours of operation. Throughout this timeframe, the refrigerator operates on biogas at full load conditions. At the conclusion of the fourth hour, the COP reaches a value of 0.23, thereafter seeing a rapid escalation upon transitioning the refrigerator to a DC power supply. The coefficient of performance (COP) recorded during the 12th hour of operation under full load conditions is 0.16. As previously mentioned, the greatest achievable temperature in solar thermal power yields a coefficient of performance (COP) of 0.12. At the 13th hour of operation, the refrigerator is once again fuelled by biogas, which serves as the heat source for the generator for the remainder of the operational period. Figure 4.38 illustrates a progressive decline in the coefficient of performance (COP), followed by a gradual rise during the 15th hour of operation. This is accompanied by modest variations, with the refrigerator maintaining an approximate COP of 0.104. Figure 4 illustrates the fluctuation of evaporator temperature and the change of the coefficient of performance (COP) during a 24-hour period under full load conditions.

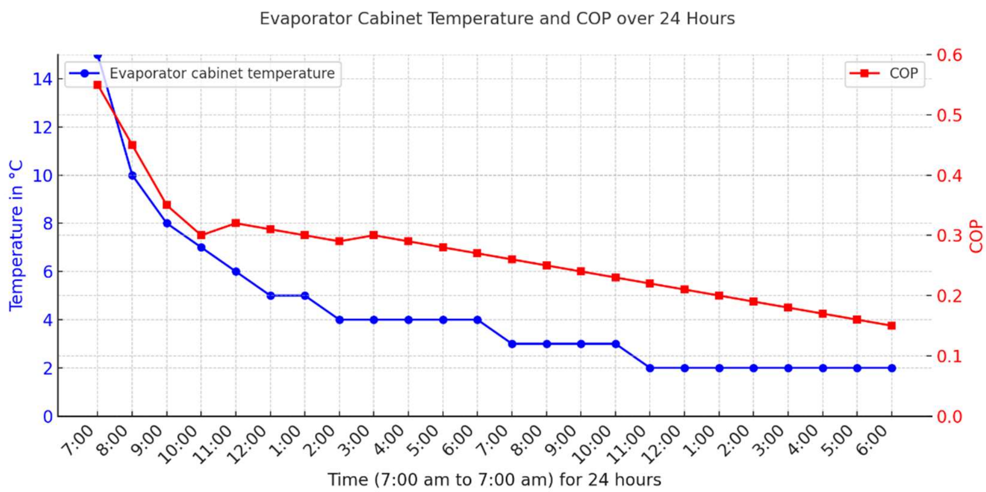

Fig. 4 Cabinet temperature of evaporator and COP variations with time

During this period, the refrigerator operates on biogas for the first four hours and thereafter transitions to a DC power source supplied by solar photovoltaic for the next six hours. In the last hour of operation, the refrigerator is once again fueled by biogas and continues to operate on biogas for the remainder of the duration. The following observations were recorded: The starting temperature of the evaporator (cabinet) is recorded at 16°C, which experiences a little reduction throughout the first hour of operation. During the second hour of operation, the evaporator (cabinet) temperature stays stable at 2°C, with a little rise occurring after the fourth hour when the refrigerator is powered by a solar panel. The evaporator temperature thereafter declines quickly, reaching a value of 2°C once again while the refrigerator operates on biogas. The temperature of 2°C is maintained consistently over the subsequent hour of operation. The discussion indicates that the evaporator temperature ranges from 2°C to 4°C. The fluctuation of COP is as follows: The initial coefficient of performance (COP) is measured at 0.45, which declines swiftly within the first four hours of operation. During this period, the refrigerator operates under full load conditions fuelled by biogas. At the conclusion of the fourth hour, the coefficient of performance (COP) reaches 0.23, subsequently followed by a rapid escalation upon transitioning the refrigerator to a direct current (DC) power source. The coefficient of performance (COP) recorded during the 12th hour of operation under full load conditions is 0.16. As previously mentioned, the maximum achievable temperature in solar thermal power results in a coefficient of performance (COP) of 0.12. During the 13th hour of operation, the refrigerator is once again powered by biogas, which serves as the heat source for the refrigerator's generator for the remainder of the operational period. Figure 4.38 illustrates a progressive decline in the coefficient of performance (COP), followed by a modest rise after the 15th hour of operation. This decline is accompanied by minor oscillations, with the refrigerator maintaining an approximate COP of 0.104. Illustration 4: During a 24-hour period, the observations recorded are as follows: The graph forecasts that the refrigerator cabinet temperature remains constant at 2°C during the first four hours of operation, after which the system transitions to solar panel power for the subsequent five hours. The system was then transitioned on biogas for the remaining operational hours. Currently, heat extraction via water has attained its peak value of 3660 KJ through a biogas-powered system for the initial four hours. Subsequently, the system transitioned to solar power for the next five hours before reverting to biogas for the remaining hours. Throughout this period, heat extraction remained consistent around this value for 24 hours, accounting for fluctuations in room and cabinet temperatures, resulting in an average heat extraction value of 2000 KJ over the 24-hour period. To sustain a cabinet temperature of 2°C to 4°C and extract 2000 KJ of heat, a constant source of heat in KJ is necessary. Biogas usage is 130 litres per hour. It generates 2600 KJ of energy every hour. The graph indicates that around 2600 KJ of heat energy is necessary per hour to sustain temperature and for heat extraction, while the solar panel generates 1442 KJ of energy per hour. The total biogas needed after a 24-hour test is around 2000 litres. It generates around 55,000 KJ of energy, which is the necessary amount for a biogas-operated refrigeration system. The graph indicates that the system's coefficient of performance (COP) originally peaked at 0.45, after which it consistently declined due to an increase in heat provided per hour, but heat extraction remained constant relative to cabinet and room temperatures. The coefficient of performance (COP) rapidly decreases during a 24-hour period. Following the comprehensive 24-hour operation, we noted that the average coefficient of performance (COP) of the system is 0.106.

4. Conclusion

A partial load of 3 cubic meters for the biogas plant and 0.8 kW for the solar panel, with a coefficient of performance (COP) value of 0.10, was achieved while operating the solar-biogas powered vapour absorption refrigeration system at generator temperatures of 140°C, despite the design operating generator temperature being 120°C with a design capacity of 0.05 kW. The system was operated at a heat source temperature of around 120°C rather than 140°C. The heat necessary for these circumstances may be generated by methane combustion and direct current from solar panels. The air-cooled absorption system functioned at ambient temperatures above 25°C. At an ambient temperature of 28°C, a cooling capacity of 0.05 kW was attained, with an ammonia mass flow of 0 kg/min and a water flow rate of 15 kg/min. The temperature of the diluted solution was 140°C, resulting in a coefficient of performance (COP) ranging from 0.1 to 0.13 under these circumstances.

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