

Performance analysis of solar milk refrigerator using energy efficient R290

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ABSTRACT

In this paper, an experimental investigation on the performance of vapor-compression based milk refrigerator using R290 as refrigerant is carried out. Milk refrigerator is driven by solar photovoltaic. R290 is considered to be the next generation refrigerant due to its excellent thermodynamic properties, cost, and environmental characteristics. The experimental set up consists of milk refrigerator that includes variable speed R290 DC compressor and solar PV modules along with batteries. Various performance parameters i.e. coefficient of performance, solar coefficient of performance, cooling capacity, and energy consumption are investigated for the different room temperature using variable speed mode. The results obtained from the tests are presented and discussed.

1. Introduction

Refrigerants are responsible for two major environmental concerns i.e. Ozone Depletion and Global Warming. Various international treaties like the Vienna Convention, Montreal Protocol, Kyoto Protocol, United Nations Framework Convention on Climate Change and the Kigali amendment took place for taking suitable actions to overcome these problems. The Vienna convention followed by the Montreal Protocol (1987) gave the phase-out schedule of ozone depletion substance. Most popular refrigerant R22 will be phase out by 2030. Kyoto Protocol came into existence in 1997 due to another environmental problem called Global warming. It sets the target for a reduction in Greenhouse gases i.e. CFC, HCFC, HFC, carbon dioxide, methane, and nitrous oxide. Table 1 shows the environmental effect of some refrigerants. R134a is being utilized for domestic refrigerators in India due to its excellent thermodynamic properties. R134a has a GWP of 1300. In order to solve the problem of global warming, a next-generation refrigerant is required which should have good thermal characteristics. R290 can be considered a possible substitute for R22 & R134a. A solar photovoltaic refrigerator is also one of the solutions to reduce global warming. Solar energy appears to be a good solution to this problem especially in countries where high solar irradiations are available. DC compressors are most suitable for renewable types of energy such as solar energy and provide energy-efficient solutions [1–3].

Su et al. [4] proposed the variable speed DC refrigerator driven by solar PV without the use of battery and inverter. The speed of the DC compressor changes with the solar intensity. DC compressor was based on R134a. They presented the dynamic model of the refrigerator to simulate the behavior and several experiments were conducted to validate the model. They reported that the cooling capacity of the variable speed compressor is increased by 32.76% and average PV utilization efficiency increases by 45.69% as

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compared to fixed mode. They concluded that the surrounding temperature has a great influence on the cooling capacity and less influence on the power consumption.

Ekren et al. [5] studied the variable speed refrigeration system using an AC compressor in a latent heat thermal energy storage system with the aim of increasing the efficiency of energy storage. They have compared the four different compressor speeds criteria to get the constant heat transfer fluid temperature at the inlet of the energy storage tank. These criteria were - control with evaporation temperature, control with ethylene glycol at the compressor outlet, control with compressor suction pressure, and On-Off control. They concluded that the control with ethylene glycol at the compressor outlet was the best strategy in terms of COP of the system and efficiency of the latent heat thermal energy storage system. Ekren et al. [6] in another study carried out the experimental performance analysis of 79 L refrigerator. It is fitted with a DC compressor compatible with R134a. They performed the experiments using four different fixed speeds and one operation with variable speed and recorded the power, pressure, and temperature in the interval of 30 s. They concluded that the variable speed operation is more efficient than the fixed speed operation, especially for high speed. Aprea et al. [7] studied the variable speed refrigeration system using AC scroll compressor for both water chiller and heat pump. They reported that the 20% energy saving is obtained while working with variable speed. In another study, Aprea et al. [8] identified the current frequency of variable speed compressors for optimizing the energy & exergy and economy aspects. They have carried out the tests for scroll and reciprocating compressors. They reported that 15% of energy-saving is obtained at 30 Hz for the reciprocating compressor as compared to basic frequency. Similarly, 25% of energy-saving is obtained for scroll compressors.

Huang et al. [9] designed the stand-alone solar photovoltaic (PV) air conditioner. They designed the six air conditioners and connected with the solar PV through an inverter. They also installed the buffer batteries to balance the load power and solar PV power. They informed that air conditioners experienced the loss of power if the solar PV power generation is inadequate. They concluded that the solar photovoltaic modules should be designed for three times the power of the load. Kaplanis et al. [10] converted a conventional refrigerator into a solar-powered. In order to reduce the heat loss, they enhanced the refrigerator insulation of polyurethane by 25 mm and replaced the door's double glass by insulation. They installed the DC compressor in place of AC compressor. The speed of the DC compressor can vary between 2000 and 3500 rpm. These modifications reduced the useful volume capacity by 30% but reduced the heat losses and energy consumption fell down to 1.53 kW h/day. Modi et al. [11] carried out the performance analysis test of a 165-L domestic electric refrigerator which was powered by solar photovoltaic. Their results showed that 140 W solar PV capacity and 135 Ah batteries were the least possible configurable to work the system with satisfactory. They reported that the maximum COP was 2.012 at 7:00 AM and it was decreased from morning to afternoon. They further informed that the larger PV module and larger battery bank are required. Thomachan et al. [12] studied a small refrigerator powered by photovoltaic panels. It was backed up by a portable generator set. They reported that the main source of loss is an inverter. They concluded that the same kind of system can be successfully utilized for grid away areas after small modification in refrigeration electrical circuitry.

He et al. [13] did both the theoretical and experimental analysis using R290 and mixture of R290/R600a in 615-L chest freezer. The experimental data showed that the power consumption of the R290 system is lower by 26.7% as compare to R134a. Similarly, when the mixture of R290/R600a (93.75/6.25 wt %) is used, the power consumption is reduced by 27.5% as compared to R134a. Their theoretical data showed that R290 and the mixture of R290 & R600a are suitable for large capacity refrigeration and energy conservation as compared to R134a. Spatz et al. [14] carried out the experimental performance analysis of R290, R404A & R410A in replacement of R22 for medium temperature applications. The study included the thermodynamic analysis, comparison of heat transfer, and pressure drop characteristics. They informed that the fluid properties of R290 lead to slightly better efficiency than R22. Wu et al. [15] experimentally investigated the performance of the R22 window air-conditioner retrofitted with R290 & R1270. It has originally the cooling capacity of 2.4 kW and Energy Efficiency Ratio (EER) of 3.4. They retrofitted with the 20% larger displacement compressor for R290 which showed better performance. They further reported that the cooling capacity and EER were higher for both the refrigerants as compared to R22. Joudi et al. [16] experimentally investigated the comparative performance of R22 and its alternative R407C, R410A & R290 in split type air-conditioner. They have selected 1 TR and 2 TR capacity systems for the hot climate of Iraq. They proved that a R290 was better candidate to replace the R22 as compare to R407C and R410A in high ambient temperature. R290 air conditioner requires less refrigerant charge and lower power consumption. It is also suitable as a drop-in substitute. Devotta et al. [17] carried out the performance analysis of a 5.13 kW window type air conditioner using R290 as a drop-in substitute to

Table- 1
Environmental effect of refrigerant.

S. No	Group	Refrigerant	ODP	GWP (100 years)
1.	CFC	R11	1	3800
2.	CFC	R12	1	8100
3.	HCFC	R22	0.055	1500
4.	HCFC	R123	0.02	90
5.	HFC	R32	0	650
6.	HFC	R134a	0	1300
7.	HFC	R407C	0	1520
8.	HFC	R410A	0	1725
9.	Natural Refrigerants	R290	0	3
10.	Natural Refrigerants	R600a	0	3
11.	Natural Refrigerants	R717	0	0
12.	Natural Refrigerants	R718	0	0
13.	Natural Refrigerants	R744	0	1

R22. They reported that the COP of R290 air conditioner was greater by 7.9% and 2.8% for lower and higher temperatures respectively. Energy consumption of R290 system was lower in the range of 12.4–13.5% as compared to R22. Similarly, the discharge pressure of the R290 system was lower in the range of 13.7–18.2% as compared to R22 and pressure drop was also lower for both the heat exchanger. They further reported that the cooling capacity is reduced by 6.6% and 9.7% for lower and higher temperatures respectively as compared to R22. Devotta et al. [18] further carried out the performance analysis of R290, R407C, R134a and R410A as an alternative to R22 air-conditioner. After the experimentation, they reported that the R290 is the best candidate to replace the R22. Its characteristic is similar to R22 and the compressor required little modifications. While on the other hand, R407C was the best refrigerant for retrofitting. They reported that the R134a had the highest COP among all refrigerants but its capacity was lowest and required the largest compressor.

Sánchez et al. [19] carried out the performance analysis of R600a, R290, R1234yf, R1234ze (E) and R152a as a direct drop-in substitute for R134a. All these refrigerants are tested without a change in the refrigerating facility. It is fitted with R134a hermetic compressor. Experiments are carried out for 0 °C & –10 °C as evaporating level and 25 °C, 35 °C and 45 °C as condenser level. They reported that the R290 had the best results among all the refrigerants for cooling capacity and COP. It increased between 40.5%–67.4% and 22.4%–2.8% respectively. However, power consumption was increased up to 44.8% which showed that R290 required a larger compressor than R134a. They concluded that the R290, R1234ze(E), and R600a are not appropriate drop-ins for R134a as it required different displacement while R1234yf and R152a can be considered as potential drop-ins for R134a.

Colbourne and Espersen [20] carried out the Quantitative risk assessment of R290 in horizontal type ice cream cabinets in order to know the consequences of leaked refrigerant. The positioning of an ice cream cabinet, effect of room size, airflow of compressor compartment, and ignition source distribution were evaluated. They reported that maximum overpressure was 3 kPa and 6.5 kPa within the room and compressor compartment respectively. Similarly, thermal intensity for room and compressor compartment was 200 s (kWm⁻²)^{4/3} and 20 s (kWm⁻²)^{4/3}. They reported that negligible leakage risk is associated with the use of R290 refrigerant.

Mastrullo et al. [21] carried out the experimental investigation of the R290 vertical freezer and compare it with the R404A system. They considered the two design options of R290 freezer for an experiment in the Psychrometric chamber (a) directly purchased heat exchanger with standard volume (b) reduced volume heat exchanger. They reported that the performance of the system i.e. power consumption, a duty cycle of the compressor can be enhanced by selecting the right combination of refrigerant charge and regenerative capillary length. They further reported that the refrigerant charge can be reduced up to 30% by reducing the refrigerant side volume up to 50% in the heat exchangers. They concluded that the R404A can be successfully replaced by R290 with a reduction in energy consumption up to 34%.

There are several studies on solar air conditioner and refrigerator using conventional refrigerant and ac compressor but still there is a gap in performance of milk refrigerator using natural refrigerant or R290. In this study, a novel variable speed solar DC milk refrigerator using R290 is proposed which is designed for both cooling and heating purpose and performance parameters are calculated.

2. System description

Refrigeration facility is designed and fabricated for the refrigerant R290. Properties of R290 are given in Table 2. It is a hydrocarbon and environment-friendly refrigerant. It consists of excellent thermodynamic properties. It is a non-toxic but flammable refrigerant. Therefore, it is more suitable for a new HVAC system. It is compatible with POE.

The experimental test rig consists of a vapor compression refrigeration system and solar photovoltaic module as shown in Fig. 1. Vapor compression test rig includes variable speed DC compressor, condenser, capillary tube, and evaporator. Both condenser and evaporator is 15-L milk tank which are circular in shape. Coils are wrapped around the evaporator and condenser tank. Insulations are provided around the circumference of the tank for avoiding thermal losses. DC compressor is compatible with R290. It has a brushless electric motor that requires 12–24 V direct current supply. This compressor can be easily powered by solar PV through the battery. Specifications of compressor are given in Table 3.

In this test rig, seven PT-100 - platinum resistance thermometers are installed in order to measure the temperature. Similarly, two dial pressure gauges are installed to measure the suction and discharge pressure. The wattmeter displays the power consumption of the DC compressor. Another beauty of the test rig is to one can reduce the speed of the compressor with the help of resistance. It has five different speed modes i.e. 4400 RPM, 3800 RPM, 3100 RPM, 2500 RPM, and variable speed. Variable speed adjusts the speed as per the

Table 2
Properties of R290.

Particulars	Details
Chemical Formula	C ₃ H ₈
Normal Boiling Point	–42.11
Critical Pressure	4.251 MPa
Critical temperature	96.74
Molecular Weight	44.1 kg kmol ⁻¹
Heat of Combustion	50.4 MJ. kg ⁻¹
ODP	Zero
GWP (100 years)	3
Safety Group	A3

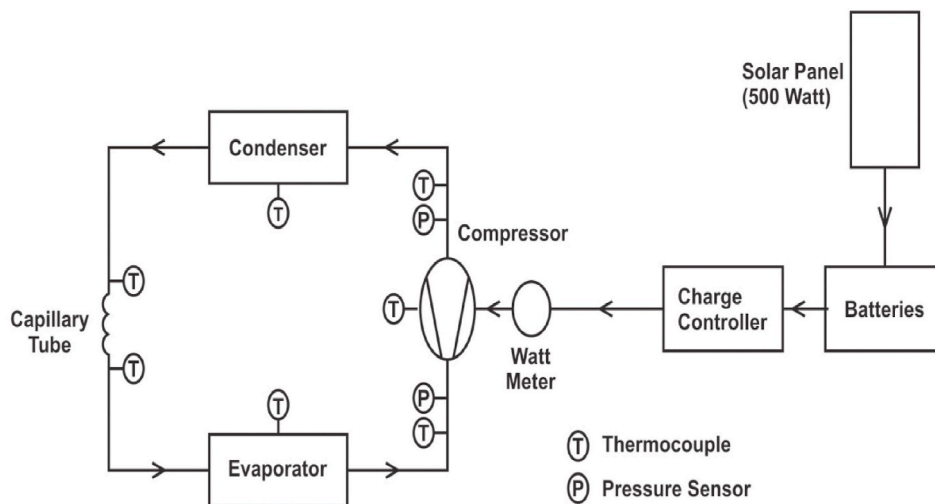


Fig. 1. Schematic of testing facility.

Table- 3
Specifications of compressor.

Particulars	Specification
Manufacturer	SECOP
Model	BD100CN
Refrigerant	R290
Application	LBP
Motor type	Variable speed
Displacement	2 cm ³
Oil quantity (type)	150 cm ³ (POE)
Maximum refrigerant charge	120 g
Voltage	24 V
Power consumption	125 W

cooling requirements.

In order to measure the various parameters of solar milk refrigerator i.e., Pt100 and Wattmeter are connected to Refrigeration test rig through data logger. Specifications of other equipment's are given in Table 4. The data logger is further connected to a computer. This set up provides temperature and compressor power every 20 s.

Table- 4
Specifications of other equipment's.

Pt100	Type: Stainless Steel Sensor Range (−243 °C–600 °C). Output: 4–20 mA Accuracy: ±0.15 °C
DC Wattmeter	Working voltage: DC 6.5–100V Measuring Accuracy: ±10 W currents shunt: 20A/75 mV
Data acquisition	16 Channel digital universal data logger
Solar Radiation Sensors	Solar Radiation Sensor PYRA-300V measuring Range: 0–1800 W/m ² Output: 0–5V, 4–20 mA Accuracy: ±5W/m ² Operating Temperature: −40° to +65 °C
Solar Photovoltaic	Transducer: Silicon photodiode Material type: Crystalline silicon Peak power: 120 V Rated working voltage: 17.5 Rated working current: 6.86 Open circuit voltage: 21.5 Short circuit current: 7.5
Battery	Tubular Lead acid battery Rated voltage: 12 V Rated capacity: 150 AH No of connection in series: 2

500 Watt capacity solar photovoltaic is installed at the roof to power the variable speed DC compressor. It is further connected to two 150 AH batteries through the charge controller. Batteries are connected in series in order to get 24 V. Solar radiation sensor is installed nearby solar panels to record solar irradiation which is further connected to the data logger. All the measured parameters are being monitored through a PC. Fig2.

The constant temperature is maintained with the help of Environment Chamber. It is well known that performance parameters will change as per the change in temperature. COP will reduce on higher temperature. In order to conduct the experiments under different temperatures insulated room of 3×2.2 m along with circuit of heater and air conditioner are made. Both heater and air conditioner are connected to 4-channel uno type Arduino with the help of relay, which is further, connected to computer. It is also shown in Fig. 3.

3. Test procedure

The performance parameters of solar milk refrigerator are calculated for 25 °C, 30 °C, 35 °C, and 40 °C. These temperatures were achieved in environment chamber. The variable speed of the DC compressor was chosen for experimentation work. In this experimentation work, 14 kg of milk was tested. The evaporator and condenser tanks were filled with 14 kg and 15 kg of milk respectively with initial temperature of 22 °C and allow the temperature of evaporator to be reduced up to 4 °C at a particular room temperature. The temperatures, compression power consumption, solar irradiation were recording using data logger through PC.

4. Results and discussion

Table 5 shows the summary of the performance test.

4.1. Compressor power consumption

Fig. 4 Shows the compressor power consumption for different operating conditions 25 °C–40 °C in the interval of 5 °C. It is recorded with the help of DC wattmeter. It is found in the range of 282.53 W–158.55 W. Power consumption is 158.55 W which is lowest for 25 °C and highest 282.53 W for 40 °C. It increases with the increasing room temperature. At higher temperatures, the cooling requirement is high thence higher power consumption. Another reason for higher power consumption at higher temperatures is the increasing condenser temperature. If the temperature at which heat is rejected increases, compressor power consumption increases.

Fig. 5 Shows the compressor power consumption for different room temperatures over the time. It is showing that the power consumption is increasing with increase of temperature for all room temperatures. The graph of power consumption is gradually increasing for all temperatures due to increase of cooling requirement.



Fig. 2. Photograph of the testing facility.

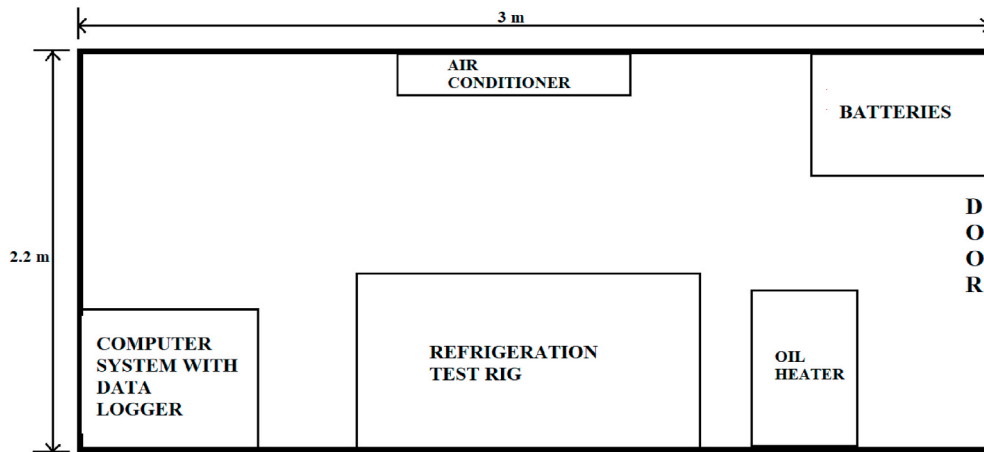


Fig. 3. Schematic of environment chamber.

Table- 5

Summary of performance test for different temperature.

	25 C	30 C	35 C	40°C
Initial Temperature (°C)	22	22	22	22
Final Temperature (°C)	4	4	4	4
Time (min.)	179	204	210	275
Compressor power consumption (W)	158.55	165.14	255.49	282.53
Cooling Capacity (W)	96.40	91.65	83.14	64.55
Coefficient of Performance	0.60	0.55	0.32	0.22
Solar Coefficient of Performance	0.052	0.050	0.045	0.035
Max Condenser milk temperature (°C)	44	49.38	49.56	52.86

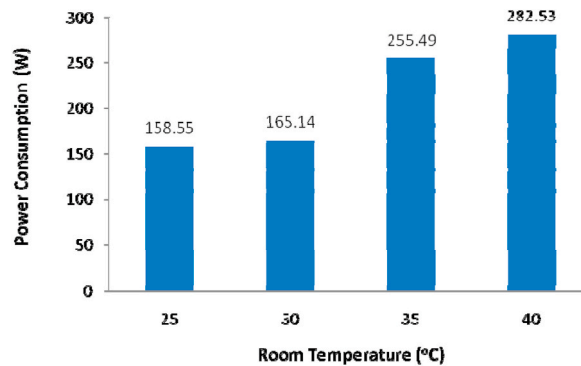


Fig. 4. Compressor power consumption for different room temperature.

4.2. Cooling capacity

Fig. 6 Shows the cooling capacity for different operating conditions. It is calculated with the help of Eq (1).

$$Q = mC_p (T_2 - T_1)/t \quad (1)$$

Where m is mass of milk in kg, C is specific heat of milk (4 kJ/kg K), T_2 is initial temperature of milk, T_1 is final temperature of milk and ' t ' is time required to change the milk temperature.

The cooling capacity is observed in the range of 96.41 W–64.56 W. It is highest for 25 °C which has a value of 96.40 W. It decreases continuously as the room temperature increases. The lowest value is 64.55 W for 40 °C. At higher temperature, the milk refrigerator took additional time to bring the final temperature 4 °C.

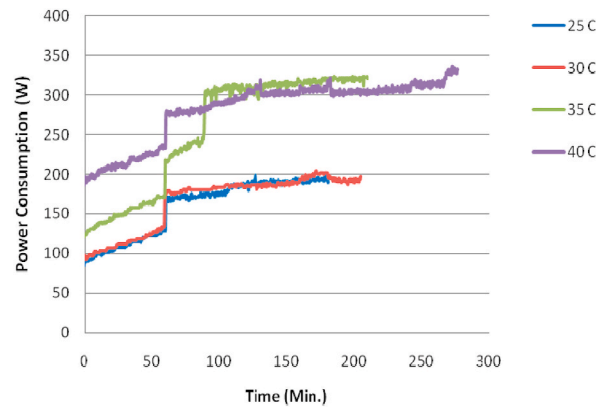


Fig. 5. Compressor power consumption for different room temperatures over the time.

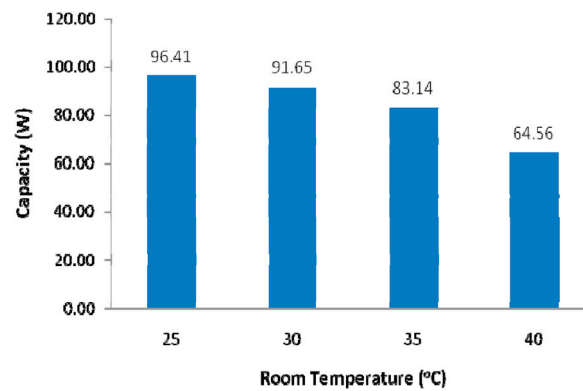


Fig. 6. Cooling capacity for different room temperature.

4.3. Coefficient of performance

Fig. 7 Shows the COP of the milk refrigerator for different room temperatures. It is the ratio of cooling capacity to the compression power consumption. It is 0.60 & 0.55 at 25 °C & 30 °C respectively. After 30 °C, it falls rapidly and reached up to 0.32 for 35 °C. The lowest value of COP is 0.22 for 40 °C. The performance of the refrigerator deteriorates as room temperature increases. At higher temperatures, compressor power consumption increases and cooling capacity decreases. This is the reason behind the low value of COP at higher temperatures. The system is worst performing for 40 °C and best for 25 °C as expected. COP is also dependent upon the condenser milk temperature. Fig. 8 Shows the condenser milk temperature for different operating conditions. It has a higher value for higher temperature and hence low value of COP. Milk refrigerator is designed for both cold and hot milk. It is obtained from evaporator and condenser respectively.

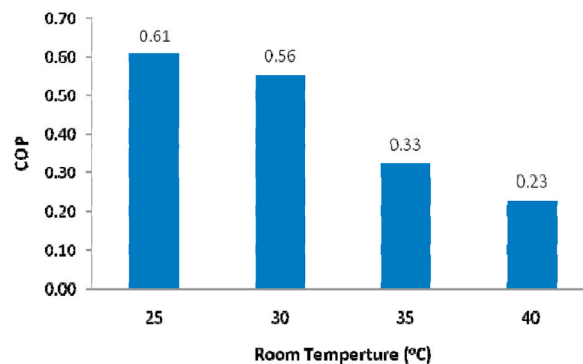


Fig. 7. COP for different room temperatures.

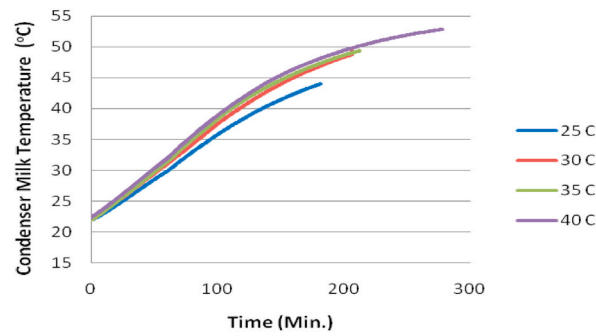


Fig. 8. Condenser milk temperature for different operating condition.

4.4. Condenser milk temperature

Fig. 8 Shows the condenser milk temperature for different operating conditions. In this test rig, the vapor compression refrigeration cycle rejects the heat into the condenser that is 15 L tank. The graph shows that milk temperature is growing with increase of temperature. It has reached up to 52.86 °C for 40 °C room temperature.

4.5. Solar coefficient of performance

Fig. 9 Shows the solar coefficient of performance for milk refrigerator. It is found in the range of 0.052 to 0.035. It is the ratio of cooling capacity to the solar irradiance. The value of solar irradiance is taken 441 W/m² for all speeds as constant for comparison purpose. It is the average value of all solar irradiance when experiments were conducted. The value of solar COP is also decreasing with increase in temperature due to dependency upon the cooling capacity.

4.6. Compressor body temperature

Fig. 10 Shows the compressor body temperature for different room temperatures. It is recorded for all temperatures during the experimentation work in order to check the possibility of overheating. The largest value of temperature is 60.61 °C which is recorded for 40 °C which is still a safe value. Lowest value of temperature is observed for lowest temperatures i.e. 25 °C as expected. The entire experiment was performed without any cooling fan.

4.7. Evaporator milk temperature

Fig. 11 Shows the milk cooling curve or decrease of evaporator milk temperature for different room temperatures. At 40 °C, milk refrigerator took 275 min to reach 4 °C and least time for 25 °C. It is obvious from the figure that time taken to chill the milk is continuously increasing as room temperature is increasing.

4.8. Discharge temperature

Fig. 12 Show the variation of discharge temperature with different operating conditions. 57.7 °C is the lowest temperature for 25 °C and 68.76 °C is highest for 40 °C. Discharge temperature is continuously increasing with increasing surrounding temperature. 68.76 °C is still considered as safe value of discharge temperature. It shows that there is no requirement of cooling at compressor outlet. At

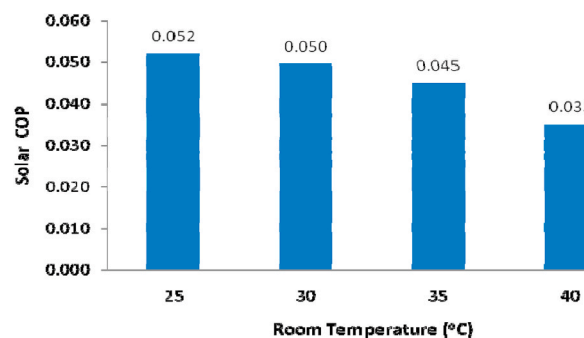


Fig. 9. Solar COP for different room temperatures.

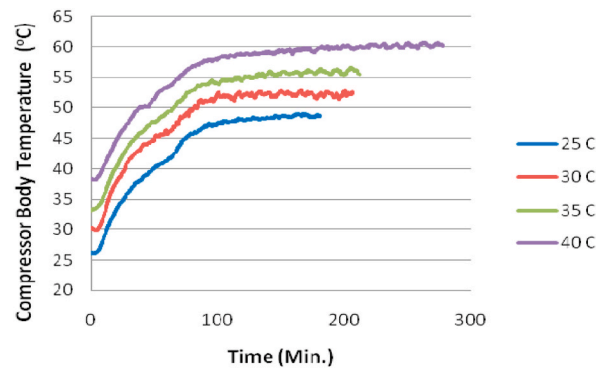


Fig. 10. Compressor body temperature for different surrounding temperatures.

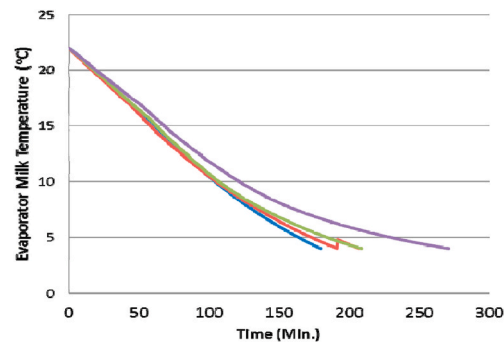


Fig. 11. Evaporator milk temperature for different room temperatures.

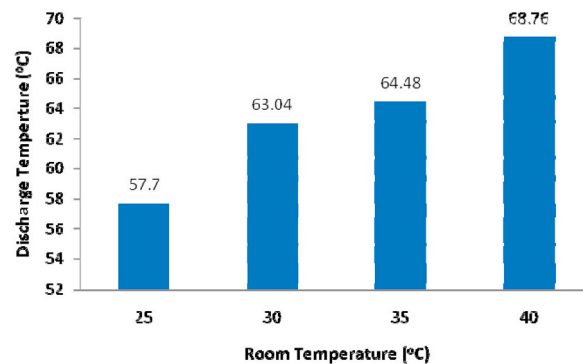


Fig. 12. Variation of discharge temperature with different room temperatures.

higher temperatures, lubricating oil loses its property resulting in more wear and tear of compressor.

Fig. 13 Show the variation of discharge temperature with different operating conditions over the time. It shows that curves are shifting in upward direction when room temperatures are increasing.

5. Conclusion

In this study, the performance analysis of a solar DC milk refrigerator using R290 is carried out. Performance parameters i.e. Cooling Capacity, Coefficient of Performance and Solar Coefficient of Performance were calculated for 14 kg of milk. It is observed that the cooling capacity decreases as temperature increases and power consumption increases as temperature increases. COP of the system decreases with increasing temperature as expected. COP is found in the range of 0.61 to 0.23. Milk refrigerator is designed for both cooling and heating purpose. The higher temperature of condenser milk is also a reason for low COP at high room temperature. 60.61 °C and 68.76 °C are the highest compressor body temperature and discharge temperature. It can be concluded that such type of system can be successfully applied for remote areas where electricity is not available and suitable speed can be applied as per the power

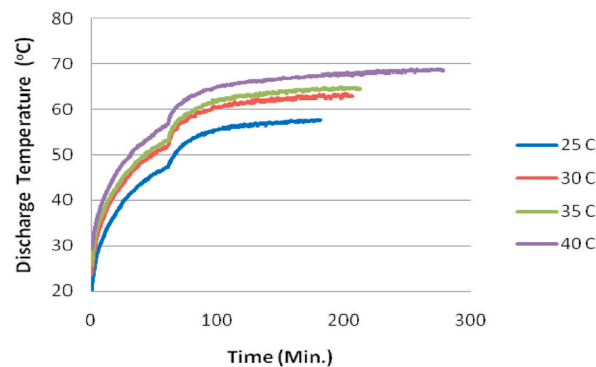


Fig. 13. Discharge temperature for different room temperatures over the time.

requirement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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