Theoretical performance evaluation of R600a and R134a refrigerant based variable speed DC compressors for solar based cold storage applications

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ABSTRACT

The theoretical performance evaluation of R600a and R134a refrigerant based DC compressors are simulated for different compressor speeds (2000 rpm, 2500 rpm, 3000 rpm and 3500 rpm) using the data collected for Chennai, from NREL for a period of one year. The PV output is simulated based on the hourly average solar irradiance, ambient temperature and wind speed. Based on the simulation results it can be implied that during a cloudy day, R600a can produce cooling energy significantly greater than R134a, whereas for a sunny day, the average cooling energy for R134a is slightly greater than R600a. Considering the daily average of various parameters for a year, if the speed of the compressor is increased from 2000 to 3500 rpm, the operating time per day decreased from 8.45 to 6 hours for R600a and 7.88 to 5 hours for R134a. Consequently, the ice formation and system energy utilisation efficiency for R600a increased from 7.13 to 8.29 kg and 11.7% to 13.6% but for R134a it increased from 7.44 to 8.33 kg and 12.2% to 13.7% and decreased after 3000 rpm. At maximum speed of 3500 rpm, R600a compressor has more annual operating time of 2216 hours (20.4% more than that of R134a) and total cooling energy production of 1014 MJ (4.4% greater than R134a). Thus, for solar based cold storage applications R600a refrigerant based DC compressor is much suitable for Chennai climatic condition.

Keywords: cooling energy, ice formation, solar insolation, compressor running time, system energy utilisation efficiency.

Nomenclature

T_C– Cell Temperature (°C)	Q_h – Hourly cooling Energy (kJ)	$\dot{m}$ -Mass flow rate (g/s)	G – Solar Irradiation (W/m^2)
T_a– Ambient Temperature (°C)	Q_d – Daily cooling Energy (kJ)	h – Enthalpy (kJ/kg)	COP – Coefficient of Performance
Q_y – Total cooling energy (kJ)	rpm – revolution per minute	TCE – Total Cooling Energy (MJ)	
Q_{ma} – Monthly average cooling Energy per day (kJ/day)		η_{SEU} – System Energy Utilisation Efficiency (%)	
TCWT – Total Compressor Working Time (hour)		SEUE – System Energy Utilisation Energy Efficiency (%/day)	

1 INTRODUCTION

India's cooling energy demand will rise to 2.2 times the existing level by 2027 and interventions can reduce cooling-related carbon emission by 20 per cent in the next decade, a report by the Indo-German Energy Forum. India, which currently has one of the lowest accesses to cooling across the world, is poised for rapid and significant growth in cooling demand [1]. To reduce the carbon emissions and increase the access to cooling, solar energy can be widely used and it is considered to be the best alternate for coal-based power plant [2]. The solar energy has many applications and advantages [3]. The only drawback of solar energy is discontinuity [4] but storing the solar energy can solve the problem. Solar thermal energy storage can be categorised into two types, one is heat energy storage [5,6] and other is cold energy storage. Cold thermal energy storage plays a significant role in conserving the available energy by improving its utilization and reducing the mismatch between the supply and demand. The cold thermal storage can again be categorised into two types one is latent cold thermal storage and sensible cold thermal storage. The advantages of the latent cold thermal storage systems when compared with sensible cold storage are high cold storage density, reduced system size and a narrow temperature change during storage and recovery processes [7] so, the latent cold thermal is the best thermal energy storage. The applications based on the latent cold thermal storage improves the social and economic benefit in the remote areas were the preservation of agricultural products, food, medicines and vaccines are not possible [8]. At present, the most common technology to produce ice using solar energy is electrically driven ice maker where the electricity is produced by photovoltaic panels and stored in batteries. The new trend in solar operated thermal systems uses direct-current, variable speed compressor. This analysis aims to eliminate the use of battery and to operate the compressor efficiently directly taking power from solar PV array. As the solar PV array is a variable power source a different approach is required for the constant operation of the compressor. In many studies, most of the researchers use R134a refrigerant based variable speed DC compressor [9-12]. Considering the environmental impact, R134a is not suitable due to its high GWP of 1300. In addition, R134a refrigerant has a high-pressure drop-in both compressor and evaporator [13]. In this paper the performance at different speeds of the DC compressor are compared and the performance of R134a and R600a are analysed.

2. Simulation Procedure

2.1 PV Panel

Considering the hourly average solar irradiance, ambient temperature and wind speed data collected for Chennai (latitude 13°05' longitude 80°25'), from NREL for a period of one year the PV output is calculated using equation 1 and the PV cell temperature is calculated by using equation 2 [14].

$$PV_{Output} = G * 0.15 * \left(1 - 0.003859\ (T_C - T_a)\right) \quad (1)$$

$$\text{Where,}\quad T_C = T_a + \frac{0.32\ G}{8.91 + 2V_W} \quad (V_w > 0) \quad (2)$$

2.2 Refrigeration System

The figure 1 shows that the processes flow diagram of the vapour compression refrigeration system and the cycle. For analysis it is assumed the VCR system has no sub cooling during condensation and super heating during evaporation. There is no heat transfer between evaporator and atmosphere. The properties of the refrigerant are taken from Refprop software. From the figure 1.b point 1 represents the saturated vapour property of refrigerant corresponding to evaporation temperature. Point 2 represents the superheated property of refrigerant corresponding to the discharge

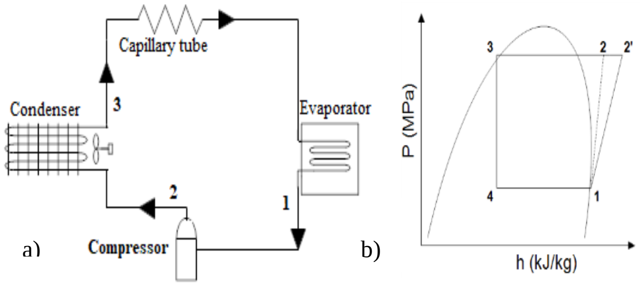


Figure.1 (a) Vapour compression refrigeration system and (b) pressure-enthalpy diagram

temperature of compressor and the condenser pressure with 100% isentropic efficiency, point 2' represents the superheated property of refrigerant corresponding to the discharge temperature of compressor and the condenser pressure with actual isentropic efficiency. Point 3 represents the sub cooled liquid property of refrigerant corresponding to condenser temperature and point 4 represents the refrigerant property corresponding to the liquid enthalpy of refrigerant at point 3. Evaporator temperature and temperature difference between condenser and ambient are taken as −5°C and 22.4°C. The compressor specifications are referred from Danfoss specification sheet shown in table 1. The isentropic efficiency of compressor is calculated based on the values shown in table 1 and the variation of the COP and isentropic efficiency with respect to speed is shown in Fig 2. The output of PV power is greater than compressor working power so, the mass flow rate of refrigerant is calculated as follows else taken as zero. $\dot{m} = \frac{P_{comp}}{h_{2'} - h_1}$ (3)

Table.1 Compressor Specification

Speed (rpm)	Power (W)	Cooling Energy (W) at −5°C	Power (W)	Cooling Energy (W) at −5°C
2000	36.5	88.6	43	78.4
2500	43.6	111	56.2	94.3
3000	56.5	130	66.8	113
3500	67.1	150	78.5	129

Hourly Cooling Energy: $Q_h = \dot{m} * (h_1 - h_4) * 3.6$ (4)

The analysis is done for the period of 12 hours with time interval of one hour (6 am to 6pm) in a day.

Cooling Energy per day: $Q_d = \sum_{i=1}^{12} Q_{h_i}$ (5)

Monthly average cooling energy per day: $Q_{ma} = \frac{\sum_{i=1}^{n} Q_{d_i}}{n}$ (6)

Total cooling energy for one year: $Q_y = \sum_{i=1}^{N} Q_{d_i}$ (7)

System Energy Utilisation Efficiency

$$\eta_{SEU} = \frac{\text{Cooling Energy per day}}{\text{Solar Energy per day}} \quad (8)$$

3. Results and Discussions

3.1 Day wise analysis

Figure 3 shows the variation of solar insolation and cooling energy per day for one year (January 1st to December 31st 2014) for the compressor speed at 3500 rpm. On the 80th day (March 21st summer season) the cooling energy produced by R134a is 14.3% higher when compared to R600a and it is the maximum energy produced by R134a in the year when compared to R600a. On the 159th day (June 8th, monsoon season) the cooling energy produced by R600a is 247.3% higher than R134a and it is the maximum energy produced by R600a in the year when compared to R134a. During the period of one-year R600a has produced more cooling energy for 225 days when compared to R134a. R134a refrigerant based system has not produced cooling energy for 22 days whereas the R600a has not produced cooling energy for 15 days in the year because low solar irradiation.

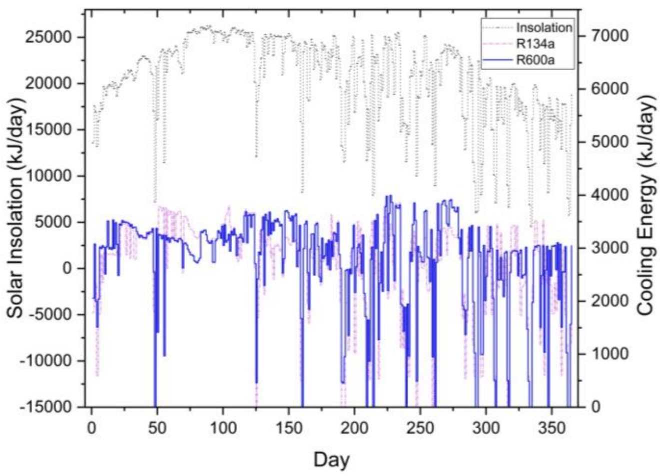


Figure.3 Variation of Solar insolation and cooling energy

3.2 Month wise analysis

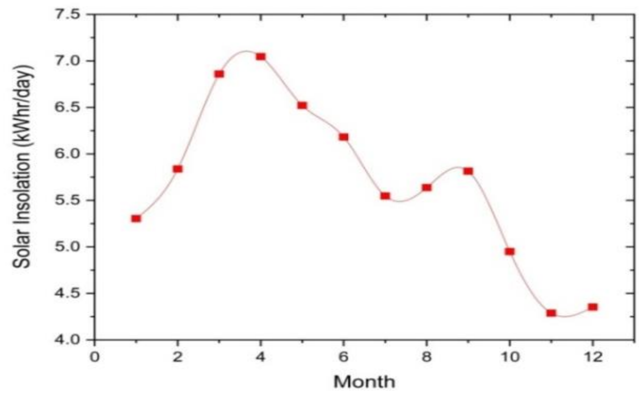
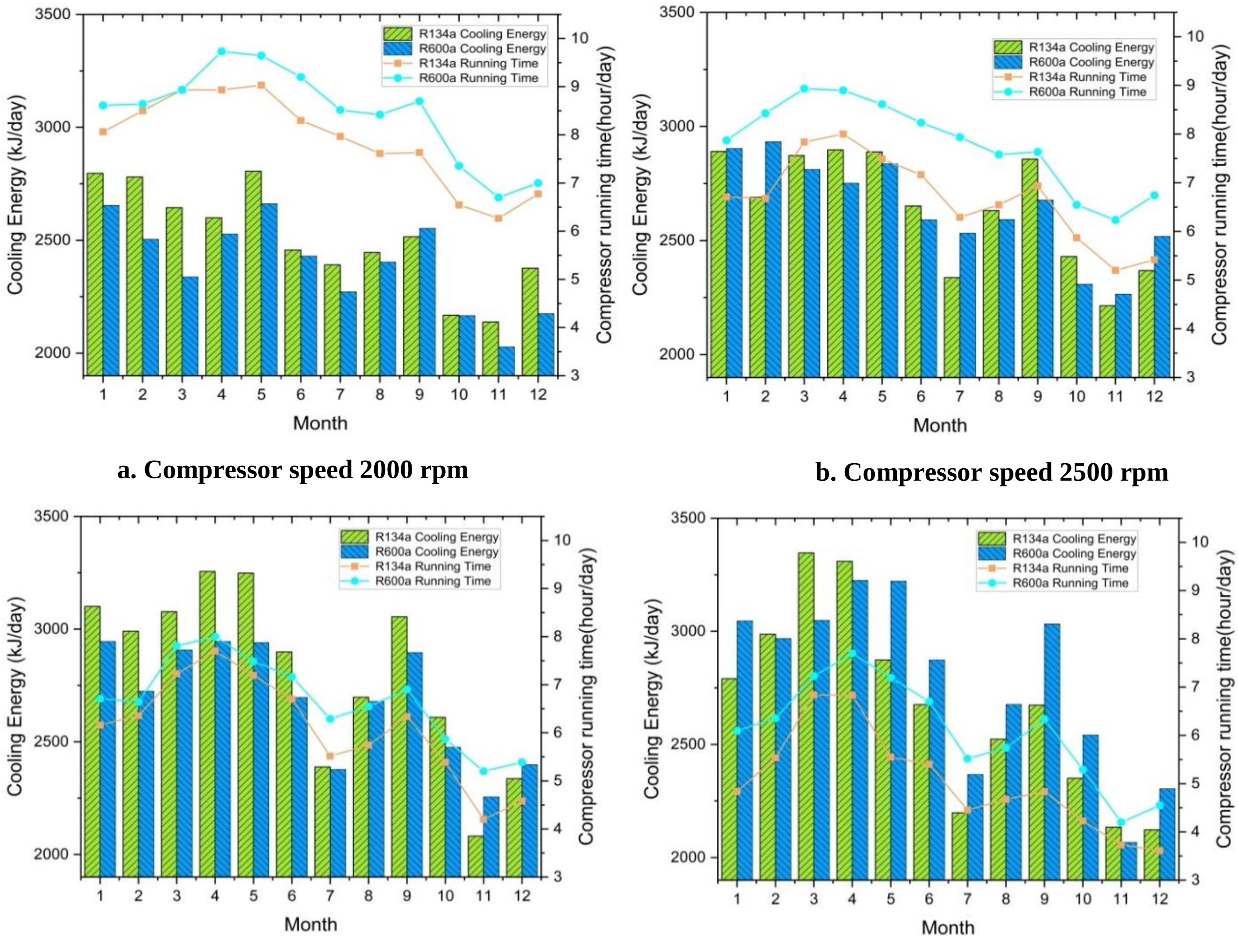


Figure.4 Variation of Solar insolation

Figure 4 shows that the variation of solar insolation for every month. April (Summer) month has more solar insolation (7 kW-hr/day) and November month (winter) has lowest solar insolation (4.3 kW-hr/day).

Based on the analysis, the maximum amount of ice formation occurred during summer 10kg by R134a and 9.6 kg by R600a.



a. Compressor speed 2000 rpm

b. Compressor speed 2500 rpm

c. Compressor speed at 3000 rpm

d. Compressor speed 3500 rpm

Figure.5 Variation of cooling Energy and compressor running time

Figure 5 shows the running time and cooling energy produced by R134a and R600a for every month. From the figure 5, if the speed of the compressor increases the operating hours of the compressors are decreased irrespective of the refrigerant used. When the speed of the compressor is increased from 2000 rpm to 3500 rpm the cooling energy produced by R600a increases to the maximum of 30.47% for all climatic conditions whereas the cooling energy produced by R134a increases to the maximum of 27.3% for summer seasons and decreases to the minimum of 10.6% for other seasons.

Figure 6 shows the ice formed and the system energy utilization efficiency (SEUE) for the monthly average. When the speed of the compressor is increased from 2000 rpm to 3500 rpm the ice formed by R600a increases to the maximum of 30.47% and the SEUE also increases to 30.53% for all climatic conditions. The ice formed by R134a increases to the maximum of 27.3% for summer seasons and decreases to the minimum of 10.6% for other seasons. The SEUE for R134a increases to 27.18% for summer season and decreases to 17.89% for other seasons.

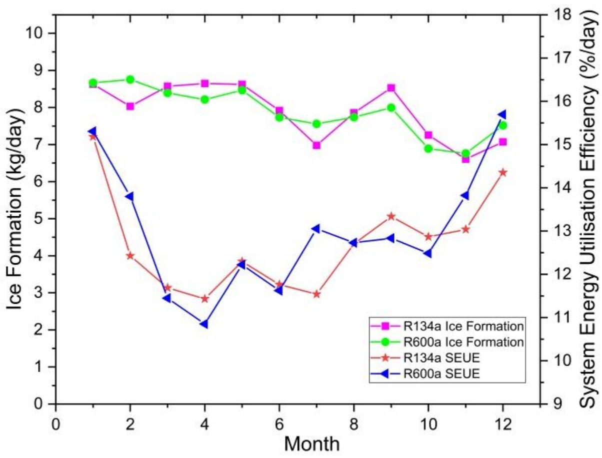
The maximum system energy utilisation efficiency occurred during winter 14.4% for R134a and 15.9 % for R600a. The maximum values were achieved only when the compressor operated at 3500rpm.

3.3 Analysis for One year

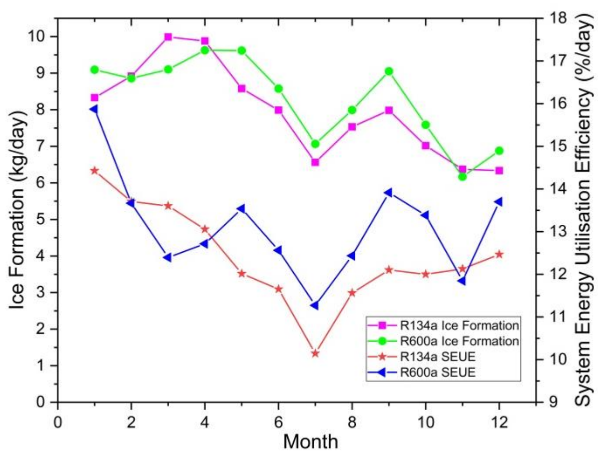
Figure 7 shows the total operating time of the compressor and the total cooling energy obtained for various speeds of the compressor for the period of one year. The speed of the compressor increased then the operating time of the compressor decreased significantly. When comparing R600a with R134a, the system energy utilisation efficiency and cooling energy increased with rpm for both refrigerant until 3000 rpm but dropped significantly for R134a beyond 3000rpm, while it continued to increase for R600a because the difference between the operating hours of R600a and R134a is very more.

4. **Conclusion**

The maximum cooling energy and system energy utilisation efficiency occurred only when the compressor is operated at 3500rpm. When the speed of the compressor is increased



a. Compressor speed 2000rpm



b. Compressor speed 3500 rpm

Figure.6 Variation of ice formation and system energy utilisation efficiency

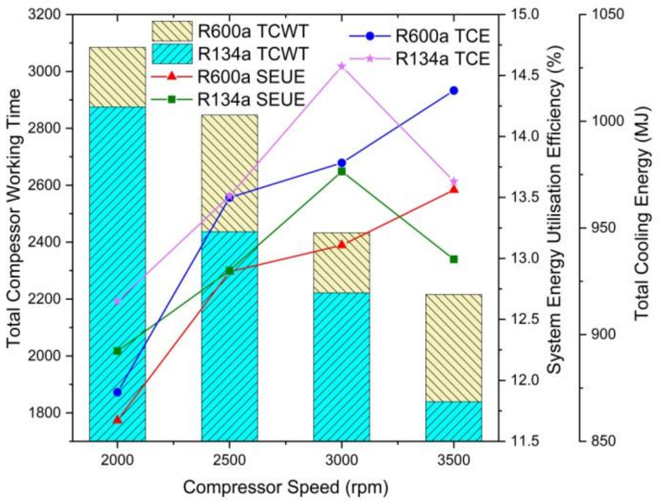


Figure.7 Variation of TCWT, SEUE and TCE

the operating time of the compressor is reduced significantly thus, increases the life of the compressor and it can be advantageous for the overall system. R600a based compressor produced total cooling energy for one year 1014.4 MJ which is 4.4% higher than R134a. When the speed increased from 2000 to 3500 rpm the total cooling energy produced by R600a increased from 873 to 1014.4 MJ. Based on the analysis, R600a based compressor is much suitable for the climatic conditions of Chennai.

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