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Simulation and Performance Evaluation of CO_2 Booster System Integrated with Modified Evaporative Cooling for Supermarket Application in India

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Abstract

CO_2 is one of the rediscovered, ecologically safe refrigerants with very low global warming potential which has favorable thermo-physical properties. The CO_2 booster refrigeration system has already been identified as a suitable choice for the supermarket application to replace the conventional R404A (high GWP) system. However, the performance of the CO_2 booster system is still comparatively lower than the conventional R404A system, especially when operated at high ambient temperature, which compels to improve the performance of the CO_2 system with suitable modification. In the present work, an attempt has been made to examine the year-round performance of the basic booster system and basic booster system with the integrated modified evaporative cooling system for Ahmedabad city weather conditions (Hot and Dry climate region). The experimentally investigated and validated data are used for the modified evaporative cooling system with real-time weather data taken from the weather station installed in the institute. Subsequently, the performance of the BBS, BBS-MEC, and R404A systems have been compared in terms of COP, power consumption, and seasonal energy efficiency ratio. The results show that for BBS-MEC, SEER enhances by 28.66% and annual power consumption decreases by 22.89% as compared with BBS. In addition to that, the total environment warming impact is also found significantly lower in the case of the BBS-MEC system.

Keywords: CO_2 refrigeration, booster system, evaporative cooling, R744, natural refrigerator, supermarket;

1. Introduction

Supermarket installations are continuously increasing worldwide, which lead to an increase in the use of R404A as a refrigerant for the supermarket. The refrigerant leakage rate predicted using this refrigerant ranges from 3% to 35% [1], which contributes to direct global warming due to high GWP. Subsequently, the power consumption of the system contributes to increasing global warming indirectly. Several alternative low GWP refrigerants, viz. CO_2, R600a, R32, NH4, R290, and R1234yf, etc. have been proposed to reduce the direct contribution of global warming. However, except CO_2, afore said refrigerants are either toxic and/or flammable. As a natural refrigerant with excellent thermo-physical and heat transfer characteristics, CO_2 has been recognized as an encouraging substitute [2]. Further, safety features i.e. non-flammability and non-toxicity in nature make CO_2 an attractive replacement of the conventional refrigerants. CO_2 has already been effectively commercialized in low-temperature climate regions, however, using in high-temperature climate regions, is still a challenge due to poor system performance at high ambient temperature [3].The lower critical temperature of CO_2i.e. 31.1oC makes the CO_2 cycle trans-critical, consequently, the CO_2 system performs vulnerably at high-temperature climates. Several studies have been carried out on the use of CO_2 as a refrigerant for supermarket applications in different ambient conditions, some of the recent developments are summarized below, The water spray technique was used for reducing gas cooler outlet temperature when operated at high ambient temperatures [4]. The yearly energy savings were limited to 3-5% and stated that saving is significant due to the high cost of electricity in peak summer periods. A theoretical investigation was done on two main trans-critical CO_2 systems centralized with an accumulation tank at the medium temperature and parallel with two separate circuits for low and medium temperature [5]. The performance of the centralized system with two-stage compression was found better in ambient temperature range 10-40ºC.Theoretical analysis is done of the trans-critical booster system for supermarket applications [6].The possible parameters were identified which affect the performance of the system at high ambient temperature. It was concluded that high side pressure, is highly dependent on compressor efficiency, ambient temperature, and suction line heat exchanger.

Comparison is done for different configurations of the CO_2 system with the baseline R404A direct expansion system using bin analyses in the eight climate zones of the

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United States for supermarket applications [1]. It was concluded that the trans-critical booster system with bypass compressor, performance is comparable to the R404A direct expansion system. Later, the oretical analysis was done for the integrated CO_2 trans-critical system with parallel compression, heat recovery, and air conditioning [7]. It was identified that in summer conditions, the performance of parallel compression is better than flash gas by-pass. The CO_2 system as compared HFC system is more efficient in lower ambient temperature (range 20-25°C) and less efficient in high ambient above 25°C. A theoretical investigation was done on the trans-critical CO_2 refrigeration system with an enhanced booster and parallel compression for supermarket applications in warm climatic conditions (35-50°C)[9]. The results indicated that the proposed cycle configuration has an advantage over the other modified cycles in warm climatic conditions. Further, a comparative analysis of five different CO_2 booster systems for supermarket application of four prominent cities based on annual hourly average temperature presented [10]. It was concluded that the performance of the CO_2 booster system with parallel compression with flooded LT evaporator and work recovery expander is better with maximum annual energy savings of 22.16% for New Delhi, India.A discussion was done on the control strategies of the CO_2 refrigeration system for supermarkets application [11]. It was concluded that integrated refrigeration and heating by CO_2 system for the supermarket saves up to 13% of primary energy compared to the conventional heating method. The conclusion derived from the study is that CO_2 is the only refrigerant which can be used as a refrigerant even at high ambient condition [12].A study on the integrated CO_2 trans-critical booster systems showed results indicating the two-stage heat recovery, flooded evaporation, parallel compression, and integration of air conditioning are the most promising features of the state-of-the-art integrated CO_2 system [13]. Subsequently, the booster system with gas cooler evaporative cooling was also investigated and concluded that annual energy saving was 1% and 3% for Stockholm and Barcelona. Results show that using evaporative cooled gas cooler does not contribute much in energy-saving at a moderate and humid place, but performance is better when operated for hot and dry climatic conditions.

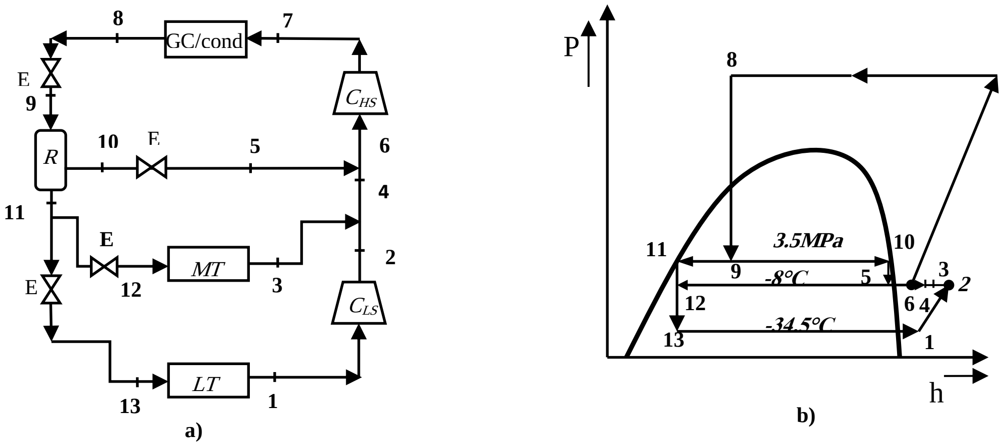
Recently, a comparison was done on the different CO_2 refrigeration systems with an internal heat exchanger, a parallel compression, two-stage compression, and mechanical subcooling [14]. It was observed that the mean COP of a two-stage compression and mechanical subcooling was enhanced by 49.8% and 75.8% respectively. Theoretical analysis is done on the CO_2 booster systems for supermarket applications with dedicated and integrated mechanical subcooling with a thermal load of 41 kW and 140 kW for low and medium temperature respectively [15]. The variation among both investigated systems in terms of annual energy reductions is 1.5-2.9% and 1.4-2.9% for tempered regions, 2.9-3.4%, and 2.9-3.4% for warm, 3.0-5.1%, and 1.3-2.4% for hot regions respectively. Investigation of ten different CO_2 refrigeration systems and its comparison with a conventional R404A system is done [16]. It was concluded that parallel compression, over fed MT and LT evaporators, intercooler, and mechanical subcooling reduced energy consumption by 8.53% yearly compared to the conventional R404A system. It was also concluded that the simple booster CO2 system is found to be less efficient than the conventional R404A system. A study showed R744 refrigeration as an alternative to the supermarket sector in Mauritius and concluded that the R744/R134a cascade system is a feasible solution both from energy efficiency and environmental perspective [17].

It has been observed from the above literature that there are limited studies available in the evaporative cooled CO_2 refrigeration system, some of the literature [4, 18] indicate that the evaporative cooling system is preferable for hot and dry climates. In this paper, an attempt has been made to investigate the yearly performance of the BBS and BBS-MEC and, compared with the conventional R404A system for supermarket application. The year-round performance has been analyzed using hourly ambient air condition (DBT and RH) real-time data, which is taken from the weather station (installed at institute lab) Ahmedabad city India. Subsequently, the reduced temperature is calculated using the experimentally investigated and validated MEC. These hourly data are used to generate temperature-bin hour's profile for the performance analysis of the aforesaid systems.

2. Description of the systems

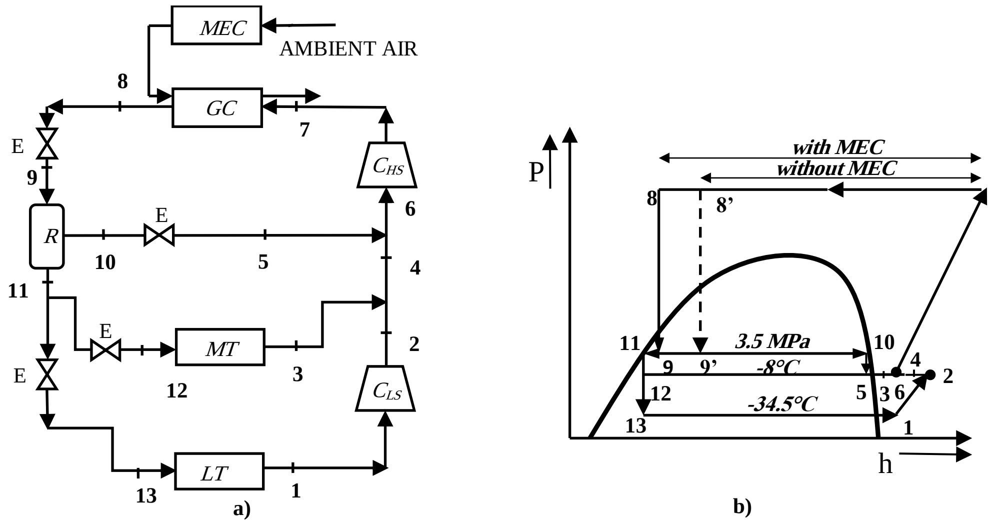
The refrigeration systems selected for the study are BBS, BBS-MEC, and conventional R404A system. The BBS system includes LT and MT loads, and the system operates in three pressures i.e. high, intermediate, and low pressure. The refrigerant from the HS compressor at high pressure enters into the gas cooler to reject heat and then passes through an expansion device to the R at the intermediate pressure. The refrigerant flows in two streams from the receiver i.e. in liquid and gaseous forms. The gaseous refrigerant is bypassed to the suction line of the HS compressor and the liquid form enters into the MT and LT evaporators through the expansion devices. The gaseous refrigerant from the MT evaporator mix with LS compressed gaseous refrigerant from the LT evaporator (low pressure). Subsequently, it mixes with the bypass refrigerant (gaseous form) from the receiver and enters into the HS compressor at the end of the cycle. The schematic and p-h diagrams of the BBS system are shown in Fig. 1.

The BBS-MEC system works similarly as the BBS system with an additional system (MEC) to the gas cooler. The MEC reduces the temperature of ambient air and supplies it to the gas cooler. Subsequently, the refrigerant temperature at the gas cooler outlet gets further reduced, which enhances the performance of the booster system. This can be seen clearly in Fig. 2(b) by point 8 (exit of the gas cooler), while point 8' describes the exit of the gas cooler when MEC was not used. Process 8'-9' represents the expansion process without using MEC and process 8-9 represents the expansion process using MEC. The schematic and p-h diagrams of the BBS-MEC system are shown in Fig. 2. (BBS-MEC) a) Schematic b) p-h diagram.



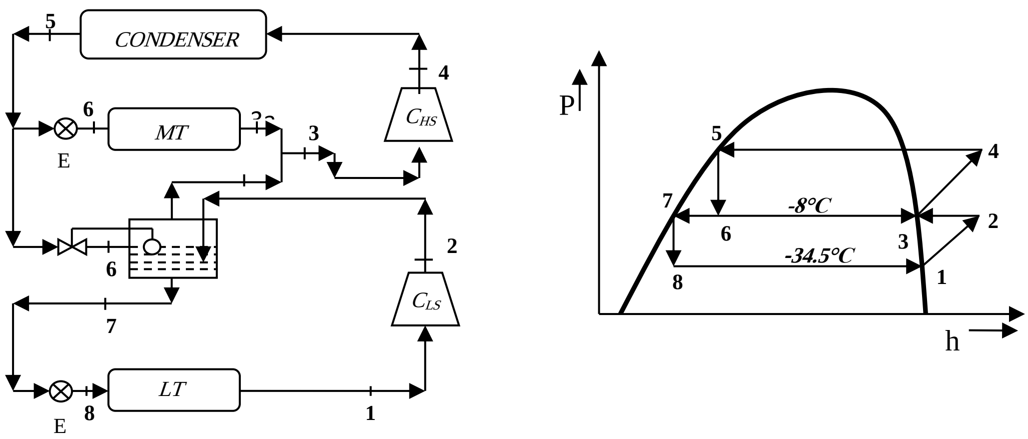
a) Schematic Diagram b) p-h diagram

Figure 1. CO_2 Basic Booster System (BBS)



a) Schematic Diagram b) p-h diagram

Figure 2. CO_2Basic Booster System with the integrated Modified Evaporative Cooling system (BBS-MEC)



b) p-h diagram

a) Schematic Diagram

Figure 3. Conventional R404A system

In the present scenario, the conventional R404A system is mostly used for supermarket refrigeration applications. Fig. 3 shows the schematic and p-h diagrams of the conventional R404A refrigeration system.

3. MEC System

There is an additional component which has been integrated into the BBS system to analyze the BBS-MEC system. The schematic and actual experimental setup fabricated in the laboratory is shown in Fig. 4 (a and b), and Thermo-Anemometer (Model 8912) in Fig. 3 (c), the measuring instrument used for measuring DBT, WBT, and velocity at the inlet, supply, and exhaust section of the MEC system. Experimental and theoretical analysis of the MEC system has been carried out on the laboratory scale. Initially experimental set up is tested to measure the RAT, subsequently, a steady-state mathematical model has been developed in MATLAB® and the results are validated using the experimental data. The results show good agreement with a maximum error of 3.66% for RAT and 8.89% for the TD. Further, the validated model has been used to obtain the RAT, throughout the year, which is given as input to the gas cooler.

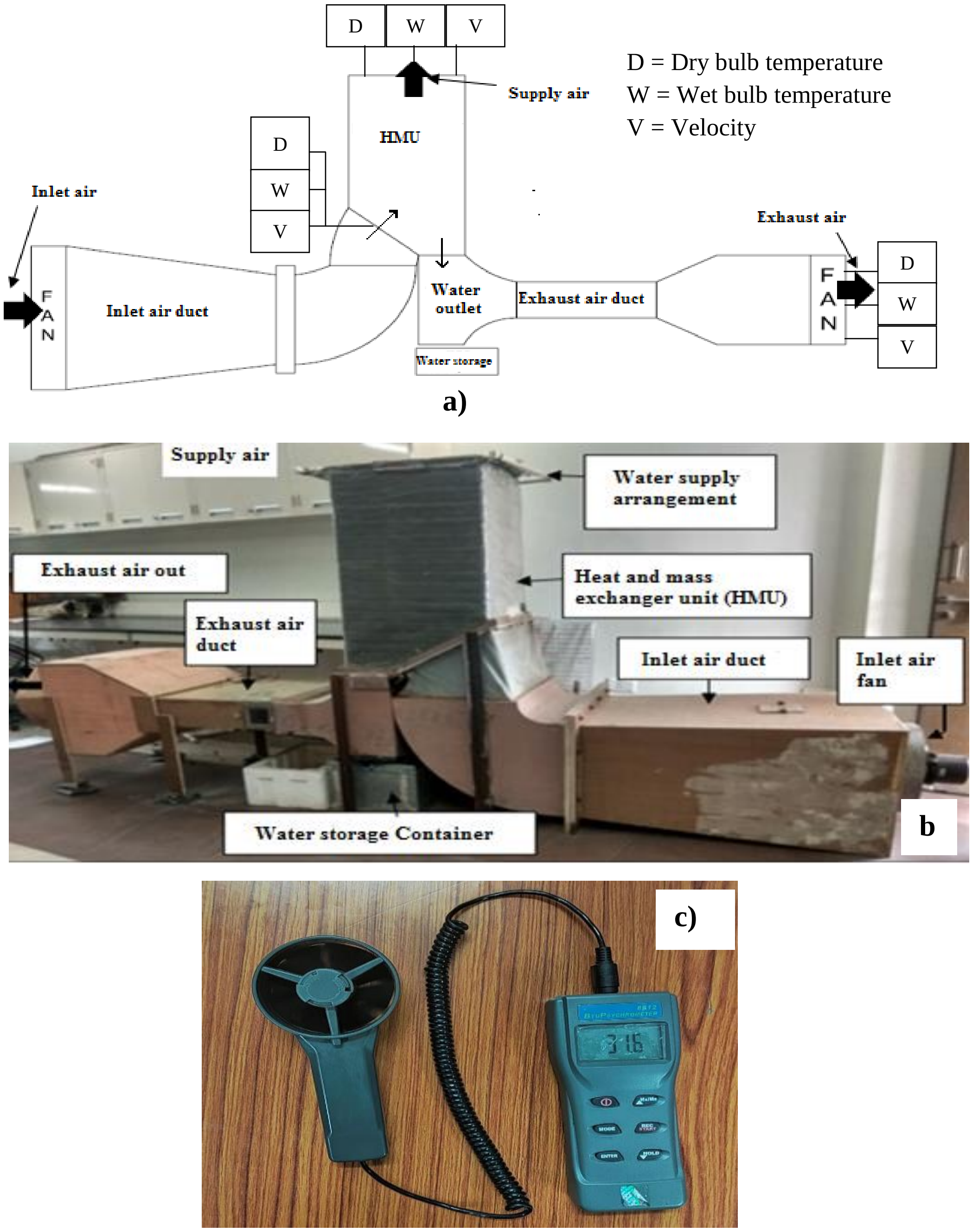
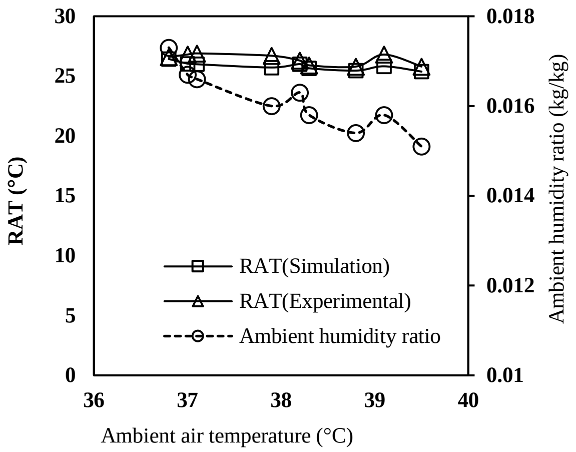


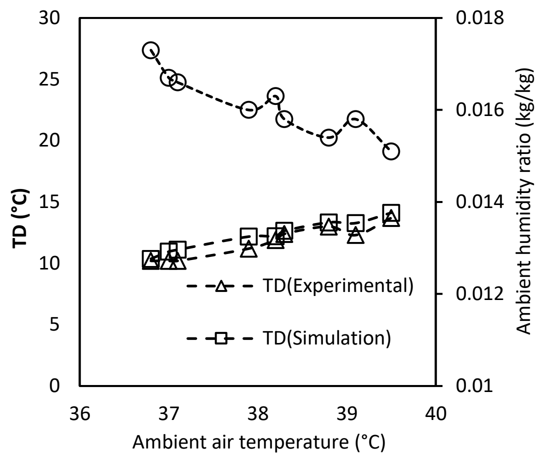
Figure 4. Experimental Facility (MEC) in Laboratory a) Schematic Diagram b) Actual Experimental Setup c) Measuring Instrument Vane Thermo-Anemometer (Model 8912)

Fig. 5 (a and b) shows the variation of RAT (exit or supply air temperature from MEC, which is reduced ambient temperature), and TD (temperature drop of supply air after passing through MEC) measured after the process of cooling in MEC with actual environment conditions i.e. DBT and Ambient humidity ratio as input variables. The results included the experimental as well as the simulation results at the respective operating conditions. It has been observed that there is a very good agreement between the experimental and simulated results. Moreover, the model has been used as a subroutine for the integration with the BBS for modeling the BBS-MEC systems.

The yearly data of Ahmedabad city is taken from the weather station data installed at the institute lab in IITRAM Ahmedabad, India. Fig. 6 shows the variation in bin hours of the ambient air conditions (DBT and RH) throughout the year (2017-18). The ambient air temperature is represented on X-axis. Y-axis (right) indicates ambient relative humidity and Y-axis (left) represents bin hours. The annually, DBT and RH range vary between 8°C-44°C and 23%-100 % respectively.



(a) Variation of RAT with ambient conditions



(b) Variation of TD with ambient conditions

Figure 5. Comparison of experimental and simulation results at different ambient air conditions

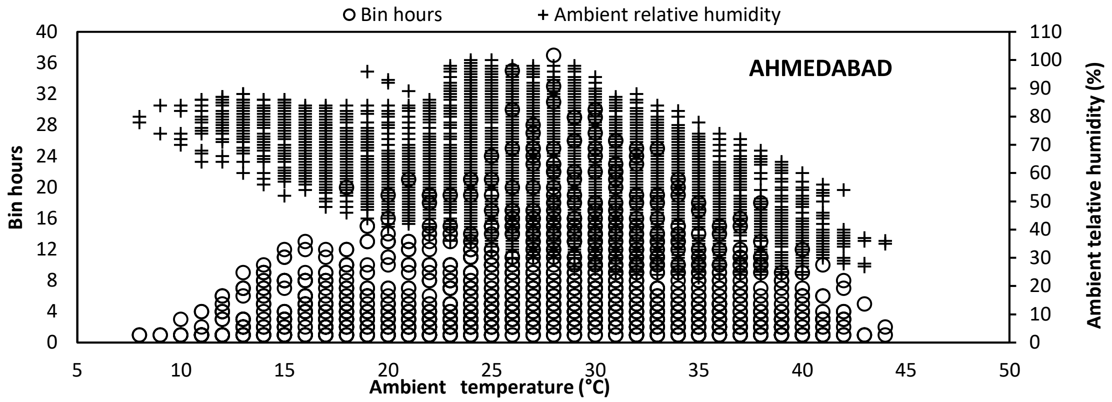


Figure 6. Bin hours at ambient air conditions

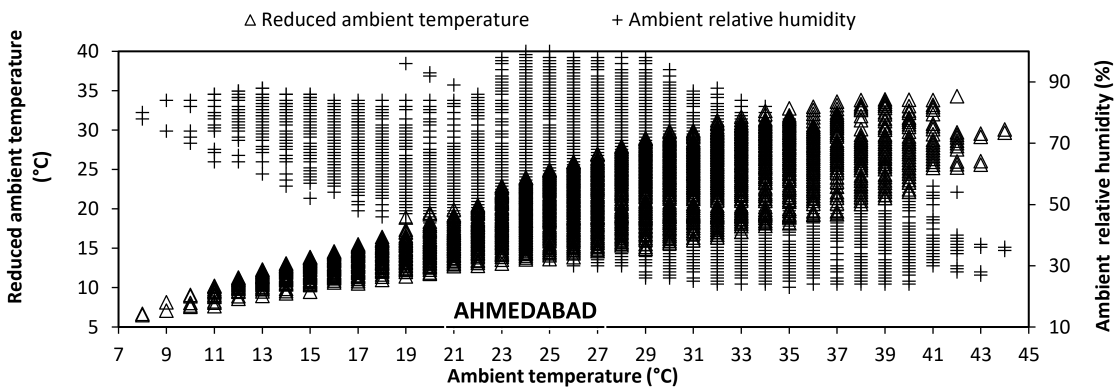


Figure 7. The reduced ambient temperature at ambient air conditions

Fig. 7 depicts the variation of RAT after the cooling process in MEC at different ambient air conditions (DBT and RH) throughout the year evaluated using the validated model of the MEC. The RAT has been evaluated using the mathematical equations of MEC, published elsewhere in Lata and Gupta (2020) [8].The inputs are taken from the ambient conditions as shown in Fig. 6. It has been observed that minimum and maximum reduced air temperature obtained after MEC is 6.52°C at the ambient condition of 8°C DBT and 78% RH, and 34.31°C, at the ambient condition of 42°C DBT and 54% RH, respectively. This RAT has been used as input for the analysis of the BBS-MEC system.

4. Thermodynamic Modeling

The steady-state thermodynamic model of the BBS, BBS-MEC, R404A systems has been developed by considering the following assumptions i.e. throttling process as expansion process, pressure loss, and heat transfer in components and piping are negligible. Table 1, summarizes the mass balance and energy balance equations for the different systems, and these equations have been solved in MATLAB® to evaluate the performances of the systems. The rmophysical properties of the refrigerants, air, and water are taken from REFPROP 9.0 by using the subroutine. Isentropic efficiencies for both the compressor are calculated by using correlations given in the literature [9]. Subsequently, the implementation of the mathematical model of the three systems i.e. R404A, BBS, and BBS-MEC is described in Fig. 8.

5. Operating Conditions and Parameters

The system performance has been analyzed at the ambient temperature of Ahmedabad weather conditions ranging from 8ºC to 44ºC with a gas cooler pressure range from 4.6MPa to 10.6MPa. The correlations of temperature and pressure and the operating conditions for the investigated configurations are taken from the literature [10], as shown in Table 2 and Table 3.

Table 1. Thermodynamic equations for the simulation of the investigated systems

R404A	**BBS**
$\dot{W}_{LS} = \dot{m}_{LT} \times (h_2 - h_1)$	$\dot{W}_{LS} = \dot{m}_{LT} \times (h_2 - h_1)$
$\dot{W}_{HS} = \dot{m}_{MT} \times (h_4 - h_3)$	$\dot{W}_{HS} = (\dot{m}_{LT} + \dot{m}_{MT} + \dot{m}_{F1}) \times (h_7 - h_6)$
$\dot{Q}_{cond.} = \dot{m}_{HS} \times (h_5 - h_4)$	$\dot{Q}_{cond./gc} = (\dot{m}_{LT} + \dot{m}_{MT} + \dot{m}_{F1}) \times (h_7 - h_8)$
$\dot{m}_{F} \times (h_3 - h_6) = \dot{m}_{LS} \times (h_3 - h_2)$	$(\dot{m}_{LT} + \dot{m}_{MT} + \dot{m}_{F1}) \times h_9 = (\dot{m}_{F1} \times h_{10}) + (\dot{m}_{LT} + \dot{m}_{MT}) \times h_{11}$
$\dot{m}_{HS} - \dot{m}_{MT}) \times (1 - x_6) = \dot{m}_{LS}$	$\dot{Q}_{MT} = \dot{m}_{MT} \times (h_3 - h_{12})$
$\dot{m}_{HS} = \dot{m}_{MT} + \dot{m}_{Flash} + \dot{m}_{LS} \times \left(\frac{x_6}{1 - x_6}\right)$	$\dot{Q}_{LT} = \dot{m}_{LT} \times (h_1 - h_{13})$
$\dot{Q}_{MT} = \dot{m}_{MT} \times (h_3 - h_6)$	
$\dot{Q}_{LT} = \dot{m}_{LT} \times (h_1 - h_8)$	
BBS-MEC	
$\dot{W}_{LS} = \dot{m}_{LT} \times (h_2 - h_1)$	
$\dot{W}_{HS} = (\dot{m}_{LT} + \dot{m}_{MT} + \dot{m}_{F1}) \times (h_7 - h_6)$	
$\dot{Q}_{cond./gc} = (\dot{m}_{LT} + \dot{m}_{MT} + \dot{m}_{F1}) \times (h_7 - h_8)$	
$(\dot{m}_{LT} + \dot{m}_{MT} + \dot{m}_{F1}) \times h_9 = (\dot{m}_{F1} \times h_{10}) + (\dot{m}_{LT} + \dot{m}_{MT}) \times h_{11}$	
$\dot{Q}_{MT} = \dot{m}_{MT} \times (h_3 - h_{12})$	
$\dot{Q}_{LT} = \dot{m}_{LT} \times (h_1 - h_{13})$	
$m_p C_p (t_{p\_in} - t_{p\_out}) = h_p dA_s (t_{p\_a} - t_{l\_a})$	
$\dot{m}_w (W_{w\_in} - W_{w\_out}) = h_m dA_s (\rho_{wf\_a} - \rho_{w\_a})$	
$\dot{m}_{wf\_in} - \dot{m}_{wf\_out} = \dot{m}_w (W_{w\_in} - W_{w\_out})$	
$\dot{m}_w (H_{w\_out} - H_{w\_in}) = h_w dA_s (t_{wf_a} - t_{w_a}) + H_{wv} h_m dA_s (\rho_{wf\_a} - \rho_{w\_a})$	
$m_p C_p (t_{p\_in} - t_{p\_out}) + \dot{m}_w (H_{w\_out} - H_{w\_in}) = m_{wf} C_{wf} (t_{wf\_in} - t_{wf\_out}) - \dot{m}_w (W_{w\_in} - W_{w\_out}) C_{wf} t_{wf}$	

Table 2. Correlations for the investigated CO_2 booster configurations[10].

Sub-critical		**Transition**	**Trans-critical**
$T_{amb} < 4°C$	$4°C < T_{amb} < 17°C$	$17°C < T_{amb} < 28°C$	$T_{amb} > 28°C$
$T_{cond} = 9°C$	$T_{cond} = T_{amb} + T_{approach}$	$T_{gc/cond} = 0.9 * T_{amb} + 4.7$	$T_{out,gc} = T_{amb} + T_{approach}$
$T_{out,cond} = 7°C$	$T_{out,cond} = T_{cond} - T_{sub-cooling}$	$P_{gc/cond} = (166.33 * T_{gc/cond} + 2676.3)$ kPa	$T_{approach} = 2°C$
$T_{sub-cooling} = 2°C$	$T_{sub-cooling} = 2°C$		P_{gc} = optimized
	$T_{approach} = 3°C$		

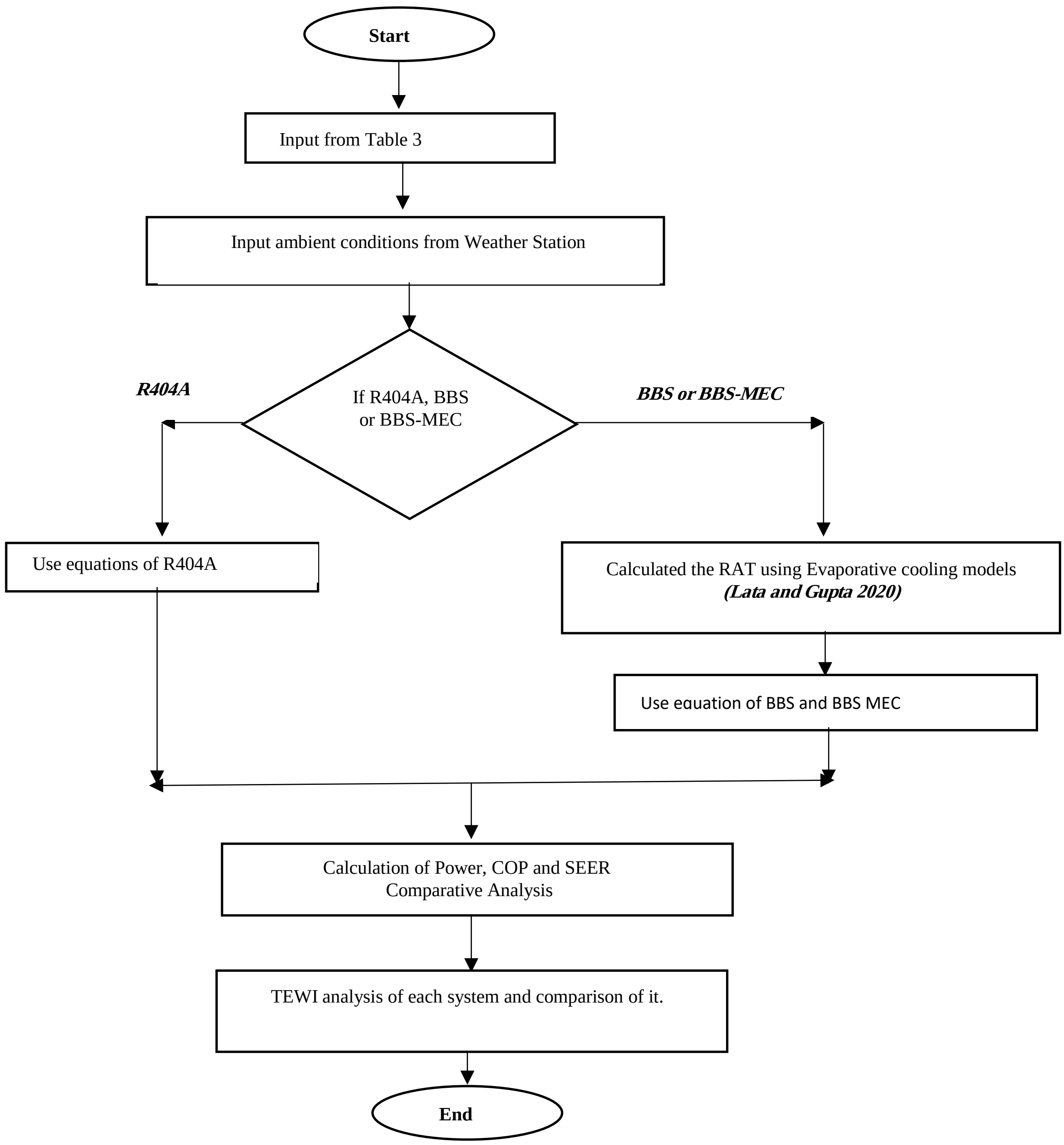


Figure 8. Model implementation of R404A, BBS, and BBS-MEC systems

Table 3. Operating parameters of the investigated configurations [10].

Operating Parameters	Values
MT load	120 kW
LT load	65 kW
Approach temperature for R404A system	10 °C
Approach temperature for gas cooler	2 °C
MT evaporating temperature	−8 °C
LT evaporating temperature	-34.5 °C
Minimum condensing temperature for CO_2/R404A system	9/25 °C
Superheating	5 °C
Circulation ratio(CR) for LT flooded evaporator	2.5
Intermediate vessel (R1) pressure	3.5 MPa
Maximum gas cooler pressure	10.6 MPa

6. Model Validation

The model developed for BBS is validated against published data [10] using the same operating conditions. Fig. 9 and Fig. 10 depict the validation of COP and optimum gas cooler pressure, respectively for the BBS system. The results show good agreement with the published data, the maximum deviation found in COP and optimum pressure, is 10.54 % and 1.6% respectively. There is no data available in the literature for BBS-MEC as it has not been explored much in the past. Hence, the analysis of such a system adds the novelty to this work.

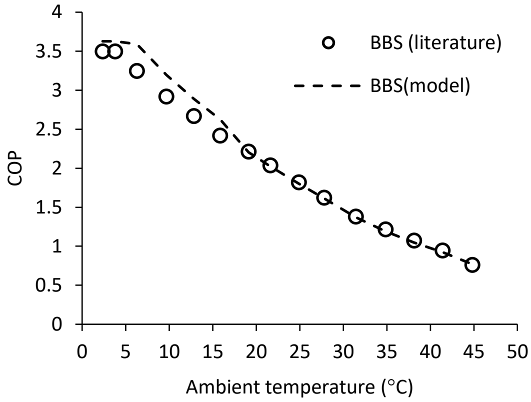


Figure 9. COP comparison of the developed model with published data

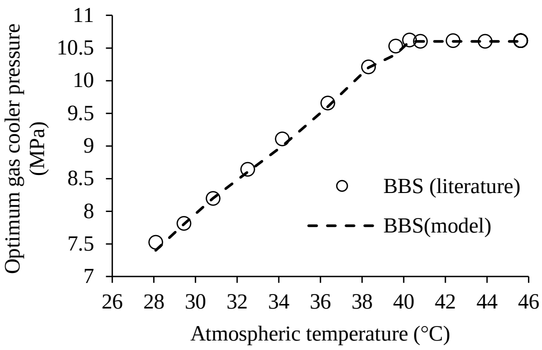


Figure 10. Optimum gas cooler pressure comparison of the developed model with published data

7. Results and discussion

The detailed analysis of all three configurations i.e. BBS, BBS-MEC, and R404A has been carried out using the thermodynamic models. The bin hours with different ambient conditions through a year have been calculated using Fig. 9 and Fig. 10 for the BBS and BBS-MEC system respectively as shown in Fig. 11. It is observed that for the BBS-MEC system, maximum bin hours obtained are 846 at 26°C DBT, whereas for BBS and R404A system, the maximum bin hours is 656 at 28°C DBT. It is a clear indication that the BBS-MEC system operates more at a lower temperature which leads to better performance.

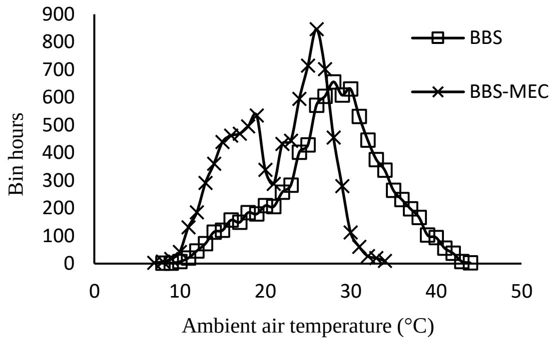


Figure 11. Bin hours at different ambient air temperature

Fig. 12, indicates the variation of COP with the bin hours throughout the year for conventional R404A system, BBS, and BBS-MEC systems. It has observed that maximum bin hour for the conventional R404A system is 656 at COP 2.03, followed by 656 for BBS at COP 1.60 and 846 at COP 1.73 for BBS-MEC system. Similarly, Fig. 13, indicates the variation of power consumption in kW with the bin hours throughout the year for conventional R404A, BBS, and BBS-MEC systems. It is observed that maximum bin hour for the conventional R404A system is 670 with a power consumption of 93.78 kW, followed by 670 for BBS, and 835 for BBS-MEC with the power consumption of 120.83 kW and 106.997 kW respectively. The variations of these bin hours mainly depend on the local ambient temperature and relative humidity at a specific time.

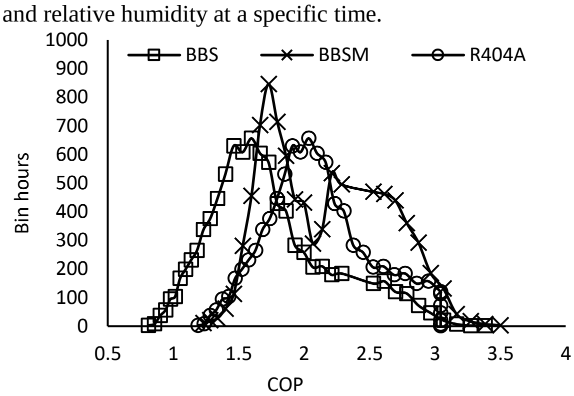


Figure 12. COP with Bin hours at different ambient air temperature

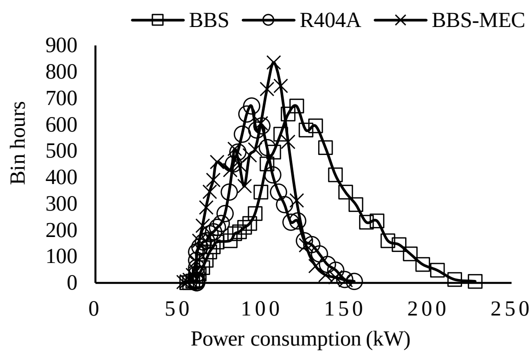


Figure 13. Power Consumptions with Bin hours at different ambient air temperature

Fig. 14 depicts the optimum gas cooler operating pressure with different ambient air temperatures. It has been observed that the maximum gas cooler pressure found is 10.6 MPa for BBS, which reduced to 9 MPa for BBS-MEC systems at the same ambient conditions. This is because optimum gas cooler pressure decreases with a decrease in ambient air temperature, using the MEC system.

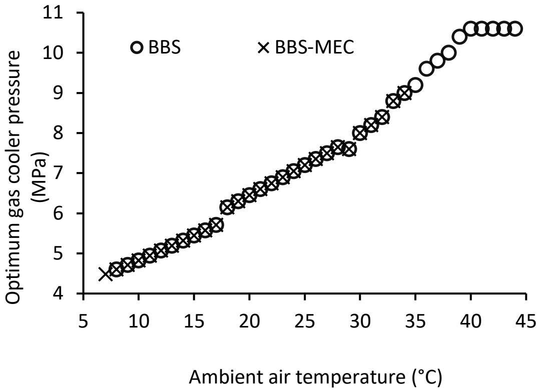


Figure 14. Optimum gas cooler pressure at various ambient temperatures

Further, the overall performance of all three systems has been evaluated in terms of SEER, and annual power consumption, throughout the year. Fig. 15 shows the percentage change in SEER and annual power consumption for BBS-MEC and conventional R404A, with reference to BBS.

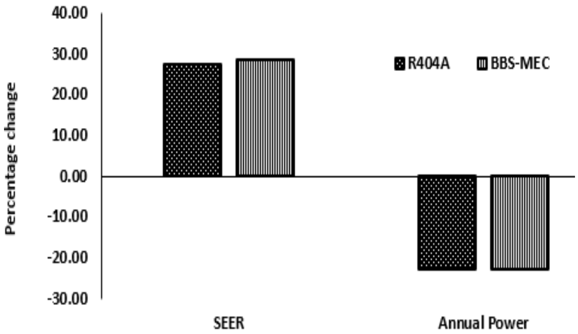


Figure 15. Percentage Change in SEER and Annual Power Consumption

It is observed that as compared to the BBS system, the BBS-MEC and conventional R404A systems, have 28.66% and 27.44% higher SEER respectively. Whereas, annual power consumption decreases for BBS-MEC and conventional R404A systems by 22.89% and 22.72% respectively. However, there is no significant difference in the performance of BBS-MEC and R404A systems. Moreover, the CO_2 BBS-MEC system can be considered as a suitable alternative of conventional R404A systems with comparable performances.

8. TEWI Analysis

The Total Equivalent Warming Impact (TEWI) has been evaluated to analyze the overall impact of the system on the environment. The emission of carbon equivalents (in the form of weight) into the atmosphere of the three systems has been carried out. Subsequently, the comparative analysis of TEWI for the BBS and BBS-MEC systems comparing to the conventional R404A system has also been carried out. The following correlations are used for TEWI evaluations for the corresponding systems, taken from the literature[19].

$$TEWI = TEWI_{direct} + TEWI_{indirect}$$

$$TEWI_{direct} = GWP * L * n + GWP * m * (1 - a_{recovery})$$

$$TEWI_{indirect} = E_{annual} * \beta * n$$

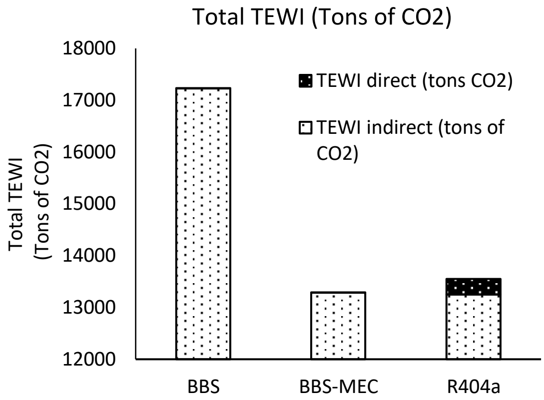


Figure 16. Total TEWI in Tons of CO_2 Equivalent of different systems

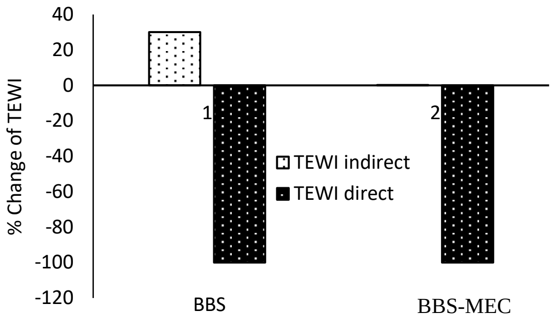


Figure 17. Percentage Change TEWI with reference to R404A system

The TEWI analysis, including direct and indirect contribution, the total TEWI in tons of CO_2 equivalent, are shown in Fig. 16. It is observed that the BBS system has the highest (17224.95 Tons of CO_2) value of TEWI followed by the R404A system (13550.86Tons of CO_2), whereas the value of TEWI is lowest in the case of BBS-MEC system (13285.85Tons of CO_2). Subsequently, the percentage change of TEWI emission with reference to the R404A system, as shown in Fig. 17. It has been found that there is a significant reduction in TEWI direct emissions (99.97%) in both BBS and BBS-MEC systems, moreover, the BBS-MEC system can be considered as an alternative of, conventional and higher GWP R404A system for the supermarket applications in warm climatic conditions.

9. Conclusions

A detailed thermodynamic analysis of the BBS, BBS-MEC, and conventional R404A system has been carried out using the real-time ambient data of Ahmedabad city (hot and dry climate) India. An additional system i.e. MEC has been integrated into the BBS to reduce the gas cooler/condenser outlet temperature, which enhanced the performance of the system. It is concluded that using BBS-MEC system annual SEER has been improved by 28.66% and power consumption has been reduced by 22.89% compared to the BBS. It has also been found that there is a significant reduction in TEWI emissions in the BBS-MEC systems as compared to the conventional R404A and BBS systems for supermarket Applications. These results will help to provide design guidelines for the designer to get better performance using CO_2 as an eco-friendly refrigerant and alternative of the high GWP refrigerant R404A for supermarket applications at different climatic conditions.

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Nomenclature

a	Recovery/recycling factor
A_s	surface area (m/s)
C	Compressor
C	specific heat capacity at constant pressure (J/kgK)
CO_2	carbon dioxide
E	expansion valve
E	Energy consumption (kWh/year)
G	passage gap
h	heat transfer coefficient (W/m^{2}K)
h_m	mass transfer coefficient (m/s)
H	enthalpy (kJ/kg)
H_l	latent heat of vaporization of water at 0 °C (J/kg)
H_{wv}	enthalpy of the water vapor at water film temperature (J/kg)
L	Annual leakage rate (kg/year)
m	Refrigerant charge (kg)
$\dot{m}$	mass flow rate (kg/s)
n	System operating years
P	Pressure
P	Pump
$\dot{Q}$	refrigeration load (kW)
R	Receiver
t	temperature (K)
T_{supply}	temperature of supply air (°C)
$\dot{W}$	compressor work (kW)
W	humidity ratio (kg/kg of dry air)
W_{evap}	Water evaporation rate (kg/s)
x	dryness fraction
ρ	density (kg/m^3)

Subscript

A	Average
amb	Ambient
cond	Condenser
F	flashed at receiver
Gc	gas cooler
HS	high stage
In	Inlet
L	Wall
LS	low stage
LT	low temperature
MT	medium temperature
Out	Outlet
P	Primary air
S	Supply air
W	working air
Wb	wet bulb
w_d	dry working air
Wf	Water film
Wv	Water vapor
Wb	wet bulb
w_d	dry working air
Wf	Water film
Wv	Water vapor

Abbreviations

BBS	Basic Booster System
BBS-MEC	Basic Booster System with Modified Evaporative Cooler
COP	coefficient of performance
DBT	dry bulb temperature
GWP	Global Warming Potential
HMU	Heat and Mass Exchanger Unit
MEC	Modified Evaporative Cooler
RAT	Reduced Ambient Temperature
RH	relative humidity
SEER	Seasonal Energy Efficiency Ratio
TD	Temperature Drop
TEWI	Total Environment Warming Impact

References

[1] S.Vishaldeep, F. Brian, B. Pradeep,"Comparative analysis of various CO_2 configurations in supermarket refrigeration systems". International Journal of Refrigeration, 46, 2014, 86 -99.

[2] K. Man-Hoe, P. Jostein, B.W. Clark,"Fundamental process and system design issues in CO_2 vapor compression systems". Progress in Energy and Combustion Science, Vol. 30, No. 2, 2004,119–174..

[3] N. Petter, W. T. Harald, H. Armin,"CO_2 -a refrigerant from the past with prospects of being one of the main refrigerants in the future". In Proceedings of 9th IIR Gustav Lorentzen Conference, Sydney, Australia 2010.

[4] L. Giovanni, S. Filippini, F. Zoggia,"Using "water-spray" techniques for CO_2 gascoolers". Technological Innovations in Air Conditioning and Refrigeration Industry, Milano, Italy, June 8-9, 2017.

[5] S. Samer, "Theoretical evaluation of trans-critical CO_2 systems in supermarket refrigeration. Part I: Modeling, simulation and optimization of two system solutions".International Journal of Refrigeration, 31, 2008, 516 – 524..

[6] Y.T. Ge, S.A. Tassou, "Thermodynamic analysis of trans-critical CO_2 booster refrigeration systems in supermarket". Energy Conversion and Management, Vol. 52,No. 4, 2011, 1868–1875.

[7] K. Mazyar, S. Samer, "Theoretical analysis of CO_2 trans-critical system with parallel compression for heat recovery and air conditioning in supermarkets". 24th IIR Refrigeration Congress of Refrigeration. IIF/IIR,Yokohama, Japan, vol. 304. 2015.

[8] M. Lata, and D. K. Gupta, Experimental Investigation and Simulation of Modified Evaporative Cooling System; International conference on Advances of mechanical engineering, held at VNIT Nagpur Jan 2020,(paper Id 117) accepted for Scopus book chapter springer publication.

[9] P. Nilesh, G. K. Dileep, D.S. Mani,"Thermodynamic analysis of CO_2 trans-critical booster system for supermarket refrigeration in warm climatic conditions". Proceedings of the 4th IIR Conference on Sustainability and the Cold Chain, Auckland, New Zealand, 2016.

[10] P. Nilesh, G. K. Dileep, D.S. Mani, "Energetic and economic analysis of trans-critical CO_2 booster system for refrigeration in warm climatic condition". International Journal of Refrigeration, 80, 2017, 182–196.

[11] S. Liang, C.I. Ferreira, G. Jan, K. Hendrine, "Control strategies of CO_2 refrigeration/heat pump system for supermarkets". Proceedings of the 12th IEA Heat Pump Conference, 15th–18th May. 2017.

[12] G. Paride, H. Armin, B. Krzysztof, "Trans-critical R744 refrigeration systems for supermarket applications: Current status and future perspectives". International Journal of Refrigeration, 93, 2018, 269-310.

[13] K. Mazyar, S. Samer, "State-of-the-art integrated CO_2 refrigeration system for supermarkets: A comparative analysis". International journal of refrigeration, 86, 2018, 239-257.

[14] B. Evangelos, T. Christos, "A comparative study of CO_2 refrigeration systems. Energy Conversion and Management", 2019, https://doi.org/10.1016/j.ecmx.2018.100002.

[15] C. Jesus, L. Rodrigo, S. Daniel, A.N. Laura, C. Ramon, "Energyanalysis of dedicated and integrated mechanical subcooled CO_2 boosters forsupermarket applications". International Journal of Refrigeration, 101, 2019, 11-23.

[16] M. Georgios, S. Evangelos, T. Dimitrios, B. Evangelos, T. Christos, A. Stavros, "Annual performance of a supermarket refrigeration system using different configurations with CO_2 refrigerant". Energy Conversion and Management, 2019, https://doi.org/10.1016/j.ecmx.2019.100006.

[17] S. Darmanaden, P.Nilesh, M. Romeela, M. Francis, D.S. Mani, "R744 refrigeration as an alternative for the supermarket sector in Small Tropical Island Developing States: The Case of Mauritius". International Journal of Refrigeration, 103, 2019, 264-273. https://doi.org/10.1016/j.ijrefrig.2019.03.034.

[18] B. Riangvilaikul, S. Kumar, "Numerical study of a novel dew point evaporative cooling system". Energy and Buildings, Vol.42, No.11,2010, 2241–2250.

[19] Z. Mylona, M. Kolokotroni, K.M. Tsamos, S.A. Tassou, "Comparative analysis of the energy use and environmental impact of different refrigeration systems for frozen food supermarket applications", Energy Procedia, 123, 2017, pp.121-130.