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Integrated supermarket refrigeration for very high ambient temperature

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ABSTRACT

This paper analytically investigates and compares the performance of a proposed 'all-natural' NH₃/CO₂ cascaded booster system to a conventional R404A direct expansion system as well as to an 'all-CO₂' system with multi-ejector unit and flooded evaporator. Performance comparison is made based on the annual combined COP and Life Cycle Climate Performance (LCCP) for operation in selected cities of Middle East and India. Our results show that in extreme warm climate, the energy efficiency of the proposed configuration exceeds that of all-CO₂ configuration by a maximum of about 12.23% and the total emissions are lower by up to 11.20%. However, the all-CO₂ multi ejector system performs better in cold and mild warm climate. In the NH₃/CO₂ cascade, the high temperature NH₃ system can be designed to be isolated from the accessible locations of the supermarket. The work presented is expected to help adoption of natural refrigerants such as CO₂ and NH₃ for commercial application in extreme warm climate conditions prevailing in many cities of Middle East and India.

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1. Introduction

Supermarkets have massive refrigeration, air conditioning (A/C) and heating load that consume approximately 50% of the supermarket energy consumption [1] and significantly contributes to carbon emissions. Moreover, supermarkets employ large tonnage of HFC refrigerants having high Global Warming Potential (GWP) leading to substantial environmental worries. Various environmental regulations are being enforced to eliminate wholly or partially the use of HFCs. Complying with the changing regulations is a persistent challenge for supermarkets. A possible shift over to all-natural refrigerant can provide a permanent solution to the problem.

Average levels of HFCs supply in Europe is expected to reduce by 79% from 2015 to 2030, as per the EU F-Gas Regulation 517/2014 [2]. Even some European countries such as Denmark, Sweden, Germany and Spain have been taxing the purchase of HFC refrigerants leading to rise in the price of R404A, R410A, and R407C [2]. The US

Environmental Protection Agency had laid the restrictions on the usage of high GWP R404A in new commercial refrigeration system since January 2017 [3]. In 2016, Kigali amendment, to the Montreal Protocol, has resolved to reduce the consumption of HFCs up to 85% by 2050 to restrict the global temperature rise to 2 °C [4]. Consequently, the adoption of natural refrigerants and improvement in the design of existing supermarket refrigeration and air conditioning system has become of paramount importance.

CO₂ has been employed in indirect, cascade and booster configurations for supermarket refrigeration. CO₂ systems have found full acceptance with more than 11000 installations worldwide, mostly the booster configuration and in cold climate [5]. These systems have cost comparison advantage compared to conventional systems [6] specially after the rise in HFC prices. Also, in terms of heat recovery they have greater advantage against traditional solutions, especially in cold regions [7]. Performance of CO₂ booster configuration in a cold climate is better compared to conventional HFC based direct expansion (DX) systems [8]. Various modifications for improvement of performance of CO₂ configuration have been reported in literature. Sharma et al. [9], concluded that adoption of parallel compression in booster system leads to

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Nomenclature

A/C	Air conditioning
B	Standard booster configuration
BV	Bypass valve
CB	NH ₃ /CO ₂ cascaded booster configuration
COP	Coefficient of performance
DX	Direct expansion
E	Emissions (Tons CO _{2eq})
GWP	Global warming potential ($kg_{CO_2,eq} \cdot kg_{refrigerant}^{-1}$)
HC	High stage compressor
IN	India
IP	Intermediate pressure
LC	Low stage compressor
LCCP	Life cycle climate performance
LT	Low temperature
ME	Middle East Asia
MP	Medium pressure
MT	Medium temperature
ODP	Ozone depletion potential
PC	Parallel compressor
$\dot{Q}$	Load (kW)

R	Baseline configuration
RH	Relative humidity
SS	Stand-alone system
T	Temperature (°C)
$\dot{W}$	Power consumption (kW)

Greek letters

ω	Entrainment ratio (–)
β	A/C load to the refrigeration load (–)
γ	Heating load to the refrigeration load (–)

Subscript

A/C	Air conditioning
amb	Ambient
avg	Average
cond	Condenser
evap	Evaporator
EOL	End of life
gc	Gas cooler
H	Heating

increase in performance. Llopis et al. [10] experimentally evaluated the performance of CO₂ refrigeration cycle with and without mechanical sub-cooler. They reported improvement in the cooling capacity and COP by 55.7% and 30.3%, respectively. Gullo et al. [11] suggested a combination of parallel compression with dedicated mechanical sub-cooler as efficient alternative in terms of energy consumption, especially for warm climates. Hafner et al. [12] reported reduction in energy consumption up to 30% for multi ejector configuration over the solution employing parallel compression based on the field measurements at a refrigeration plant located in Spiazzo (North of Italy). Purohit et al. [13] presented an ejector sub cooled trans-critical CO₂ refrigeration cycle and reported a maximum of 10% improvement in COP over parallel compression cycle. Schonenberger [14] compared and reported a maximum of 20% energy savings for CO₂ refrigeration plant assisted with multi ejector unit compared to parallel compression for application in two Swiss stores. Tsamos et al. [15] showed that the configuration with parallel compression consumes 5% less electricity than the basic CO₂ booster configuration in Athens. Purohit et al. [16] reported a maximum of 22.16% energy savings for warm climate operation of a CO₂ booster configuration in conjunction with a flooded evaporator, parallel compression and work recovery expander over standard booster configuration. Further, investment recovery time of fewer than four years for such configuration was reported.

In the indirect and cascade solutions, CO₂ operates at sub-critical running modes irrespective of outdoor temperature, removing the technical and economic challenges of high pressure operation and have advantages over “all CO₂” system, especially in warm climatic conditions [9]; [17]. The adoption of indirect configuration allows reduction in refrigerant charge [18]; [19]. However, two main disadvantages associated with the secondary loop systems are the need for a pump and an additional heat exchanger. Adoption of CO₂ as a secondary working fluid offers reduced pump work and pipe size and improvement of heat transfer characteristics [20]. Inlow and Groll [21] reported that CO₂ as secondary fluid can counterbalance the drop in COP caused by the additional heat transfer level and the pumping power for secondary loop systems. NH₃ is a prominent primary fluid along with

CO₂ in a cascade system. Getu and Bansal [22] formulated a multivariate relation for NH₃/CO₂ cascade system to estimate maximum COP and the optimal ratio of mass flow rate in the primary circuit to the secondary. Rezayan and Behbahaninia [23] reported that the performance of NH₃/CO₂ cascade system is influenced by condensing temperature of NH₃, evaporating temperature of CO₂, condensing temperature of cascade condenser and approach temperature of cascade condenser. Dopazo and Fernandez-Seara [24] experimentally investigated the performance of NH₃/CO₂ cascaded system. They reported up to 19.5% higher COP for cascaded configuration over the two-stage NH₃ solution. Mosaffa et al. [25] conducted exergoeconomic and environmental analyses for two different NH₃/CO₂ cascaded refrigeration systems, the first one equipped with two flash tanks and the second with a flash intercooler. They reported almost identical performance for both the options.

Integrated “all-in-one” configurations are designed to satisfy mostly or full air-conditioning (A/C) and heating demands for a

Fig. 1. Comparison of typical warm climate in Europe with Middle East Asia as well as with India.

supermarket rather than fulfilling only the refrigeration loads [26]. Such configurations have been already installed in more than ten supermarkets in Sweden, which eliminates the need of alternative working fluid and also, reduces both direct and indirect emissions [27]. Further, in all- CO_2 configurations, CO_2 being a pure fluid avoids the problem related to refrigerant leakage which the conventional HFCs mixture such as R404A, R513A or R450A does possess owing to different normal boiling points of the components in mixture. Reinholdt and Madsen [28] concluded that integration of heat recovery is an efficient modification for booster configurations which can lead up to 25% improvement in COP. Cecchinato et al. [29] claimed that CO_2 booster system integrated with heating and air-conditioning results into comparable or even less energy consumption than the reference R404A system. Funder-

Kriestensen et al. [30] presented a case study of a Danish supermarket employing CO_2 trans-critical booster system with heat recovery. They reported 20% saving in running cost compared to the gas heating system. Karampour and Sawalha [31] reported comparable seasonal performance factor for CO_2 booster system integrated with heat recovery and conventional heat pumps and refrigeration. Sharma et al. [32], studied integrated waste heat recovery in various CO_2 trans-critical supermarket refrigeration systems. They conducted a bin analysis for US climatic zones and concluded that heat recovery could nearly satisfy the desiccant regeneration and water heating demands. Hafner et al. [12], investigated integrated CO_2 system which provides direct space heating and cooling for a small supermarket in Italy and found 15–20% energy saving and considerable cost reduction. Karampour

Fig. 2. (a) Schematic, (b) p-h for winter operation and (c) p-h for summer operation of an integrated all CO_2 booster system with multi-ejectors.

Fig. 3. (a) Schematic and (b) p-h for summer operation of an integrated all-natural NH_3/CO_2 cascaded booster system.

and Sawalha [33] concluded that an integrated CO₂ booster configuration can satisfy the whole refrigeration and A/C demands efficiently, for cold and mild climates. Polzot et al. [34] reported a maximum of 6.5% savings in annual electricity consumption for a CO₂ booster system integrated with heat recovery for space heating in North Italian climate compared to the baseline system comprising of R134a/CO₂ cascade system for refrigeration and R410A heat pump. Gullo et al. [35] reported a comparative study of performance of integrated CO₂ trans-critical booster system equipped with multi-ejectors and parallel compression with a conventional DX R404A system. They reported up to 22% improvement in performance for the CO₂ system when operated in warm climate of Seville, in Europe.

As reported in literature, the integrated CO₂ booster system with multi-jet ejector are exciting development and is claimed to be effective in warm climate of Europe. However, it is important to note that the frequency of ambient temperature over shooting 25 °C in Europe (for example, Seville) is only 20% (Fig. 1). Climate condition in most part of India and Middle East are more extreme. Further in such condition, the A/C load are comparable to the refrigeration load.

Consequently, this paper proposes an all-natural integrated NH₃/CO₂ cascaded booster system for operation in cities with extreme weather conditions like Jodhpur in India and Kuwait in Middle East. The performance is compared with that of an integrated all-CO₂ multi ejector system and a conventional R404A DX system without integration. The proposed system seeks to combine the advantages that NH₃ system has for heat rejection at high ambient with that of CO₂ system operating sub-critically. The three systems are compared against parameters like COP, annual energy consumption and Life Cycle Climate Performance (LCCP).

2. Investigated systems

Two integrated systems and one conventional refrigeration system for a typical supermarket are investigated. Along with the conventional R404A DX refrigeration system (abbreviated as 'R'), a separate R410A DX system is also chosen to satisfy the A/C load as well as a R407C DX system to the satisfy heating loads. The

investigated systems are briefly described in the following sub-sections.

2.1. Integrated all CO₂ booster (B) configuration with multi-jet ejector

An integrated "all CO₂" configuration with flooded medium temperature (MT) evaporator, parallel compressor and multi-ejector unit is shown in Fig. 2. This configuration is abbreviated as 'B'. The multi ejector unit consists of a combination of vapor and liquid ejectors [36]. Typically, 4 to 6 vapor ejectors and 2 to 3 liquid ejectors each with fixed geometry but having different sizes are connected in parallel to constitute a multi-jet ejector module. The vapor ejector ensures achievement of optimal gas cooler pressure corresponding to ambient conditions as well as entrain a portion of refrigerant from the medium pressure (MP) receiver and compresses the same to the higher IP receiver pressure. Consequently, there is reduction in required high stage (HS) compressor capacity and power consumption. The liquid ejectors pump liquid back to the IP receiver to ensure overfeeding of the MT evaporators. A parallel compressor is adopted to remove the flash gas from the liquid receiver (IP). These compressors are supposed to be switched off in sub-critical operating mode, and the flash gas from the receiver IP is throttled to the MP via a bypass valve, owing to insufficient volume flow rate of the flash gas. An additional A/C heat exchanger is installed to meet the A/C load, while a de-superheater reclaims the required heating demands following a strategy discussed later in Section 4.1.

2.2. Integrated 'all-natural' NH₃/CO₂ cascaded booster (CB) configuration

The proposed integrated 'all-natural' NH₃/CO₂ cascaded booster configuration, shown in Fig. 3, is abbreviated as 'CB' in this article. The CB configuration is composed of a CO₂ booster system in the low-temperature circuit to cater refrigeration (LT and MT) as well as A/C and heating demands, while ammonia in the high-temperature circuit is used to maintain the CO₂ under subcritical conditions and to perform heat rejection to the environment temperature. At

Table 1
Supermarket configuration and monthly averaged heating & A/C load.

Supermarket configuration	
Floor Area (m ²)	3590
Height (m)	3
Wall Thickness (Stucco/Concrete Block/Insulation/Gypsum Board) (m)	0.025/0.203/0.175/0.0127
Thermal Conductivity of wall (Stucco/Concrete Block/Insulation/Gypsum Board) (W·m ⁻¹ ·K ⁻¹)	0.691/1.31/0.049/0.160
Density of wall (Stucco/Concrete Block/Insulation/Gypsum Board) (kg·m ⁻³)	1858/2240/265/785
Specific Heat of Wall (Stucco/Concrete Block/Insulation/Gypsum Board) (J·kg ⁻¹ ·K ⁻¹)	837/836.8/836.8/830
Thermal Transmittance of wall (W·m ⁻² ·K ⁻¹)	0.26
Void to Solid Ratio (Ratio between opaque and transparent surfaces)	0.30
Thermal/Solar/Visible Absorptance of Stucco (–)	0.90/0.92/0.92
Thermal/Solar/Visible Absorptance of Concrete Block (–)	0.90/0.70/0.70
Thermal/Solar/Visible Absorptance of Insulation (–)	0.90/0.70/0.70
Thermal/Solar/Visible Absorptance of Gypsum Board (–)	0.90/0.92/0.92
Monthly averaged heating & A/C loads	
Avg. Heating Load in January ^a (Tabriz, Middle East) (kW)	158.67
Avg. Heating Load in January (Shillong, India) (kW)	83.85
Avg. Lambda in January (Tabriz, Middle East) (–)	1.3
Avg. Lambda in January (Shillong, India) (–)	0.63
Avg. A/C Load in June ^b (Kuwait, Middle East) (kW)	119.26
Avg. A/C Load in June (Jodhpur, India) (kW)	137.80
Avg. Beta in June (Kuwait, Middle East) (–)	0.87
Avg. Beta in June (Jodhpur, India) (–)	0.94

^a Coldest month

^b Hottest month.

Fig. 4. Year-round climate conditions of Middle East Asia (a) and comparison of typical heating and A/C load to that of European climate (b).

Fig. 5. Year-round climate conditions of India (a) and comparison of typical heating and A/C load to that of European climate (b).

lower ambient (below 18 °C), the CB configuration operates as booster configuration. While at high ambient (above 18 °C), the CB configuration runs in cascade mode. CB configuration also has a parallel compressor installed in CO₂ side to support the A/C evaporator.

Ammonia refrigeration system are known to be most common and efficient technology in industrial installations that are located in isolated place. However, owing to the reduced charge and improved component efficiency, nowadays these systems are also considered as viable alternatives in commercial sector, especially for the warm climate operation [37]. Ammonia units is proposed to be isolated by installing the same in machine room in a supermarket with necessary safety measures. Hydrous ammonia is known to be corrosive to copper, zinc and copper-alloys, while the standard material used in ammonia system is structural steel and aluminium. Typical equipment required for safe handling of ammonia include, ammonia leak detector having visual and audio alarm, spark proof emergency ventilating system, ammonia scrubber, self-closing doors, fire extinguishers, protective goggles, gloves, protective clothing, emergency eye-wash fountain [38] etc.

3. Supermarket configuration

EnergyPlus [39] is used to formulate the refrigeration, A/C and heating loads in the climate regions of the Middle East and India. A standard supermarket with a floor area of approximately 3590 m² is assumed, which is divided into four zones vestibule, deli, sales, and backroom. The LT, MT and A/C evaporation temperature levels assumed, are −35 °C, −10 °C and 5 °C, respectively. The model is

developed based on detailed weather and building construction data, including internal loads consisting of lighting, average foot fall, electric and gas loads. The exterior wall construction for the conceptual design consists, from the exterior to the interior stucco, a concrete block, a layer of insulation, and gypsum board. The details of the supermarket configuration and A/C as well as heating load calculated from the model on monthly basis are listed in Table 1. For the article, Beta (β) is defined as the averaged A/C load to the total averaged refrigeration load while Lambda (λ) is the ratio of averaged heating load to the total averaged refrigeration load. The discussion on the typical climatic conditions and refrigeration as well as A/C and heating loads prevailing in Middle East Asia and India are presented in the following subsections.

3.1. Climate zones in Middle East Asia

Middle East Asia has two major climatic zones, Midlatitude represented by Tabriz and Damascus, and Dry Arid/Semi-Arid, as in Tehran, Cairo, Kuwait and Abu Dhabi. As reported in the literature [43], LT load is nearly constant for all the locations, while MT load, as well as A/C and heating loads are dependent primarily on the ambient temperature and secondly on the relative humidity only if the cabinets are open-type, if they have doors the dependence to the HR is very low, since the supermarkets are generally air conditioned (Fig. 4a). With increase in average ambient temperature, the MT load and A/C load are found to rise. On the contrary, the heating load is found to increase with a decrease in ambient. The average ambient temperature in winter (January) is recorded to be minimum of −2.65 °C in Tabriz in lower side and 18.15 °C in

Table 2
Operating parameters of the investigated natural systems.

Parameter	Assumed value
Minimum condensing temperature of CO ₂	7 °C
Condensing temperature of CO ₂ in CB	10 °C
Minimum condensing temperature of NH ₃	25 °C
Minimum condensing temperature of DX R404A	25 °C
CO ₂ gas cooler/condenser outlet temperature	$T_{amb} + 3\text{ °C}$ ($4\text{ °C} < T_{amb} \leq 17\text{ °C}$) $(0.9 \times T_{amb}) + 4.7\text{ °C}$ ($17\text{ °C} < T_{amb} \leq 27\text{ °C}$) $T_{amb} + 2\text{ °C}$ ($T_{amb} > 27\text{ °C}$)
Approach temperature for NH ₃ condenser	10 °C
Approach temperature for DX R404A condenser	10 °C
Approach temperature for cascade condenser	5 °C
Internal/External superheating (Dry evaporator)	5 °C/5 °C
Vapor quality at outlet of flooded evaporator	0.9
Air cooled gas cooler/condenser fan power	3% of the gas cooler/condenser load

Table 3
Relations utilized to simulate compressor isentropic efficiency.

Compressor	Isentropic efficiency
CO ₂	
LT	$\eta_{LT} = (-0.0012 \times (P_{MT}/P_{LT})^2) - (0.0087 \times (P_{MT}/P_{LT})) + 0.6992$
MT (sub-critical)	$\eta_{MT} = (-0.1155 \times (P_{cond}/P_{MT})^2) + (0.5762 \times (P_{cond}/P_{MT})) - 0.0404$
MT (transition)	$\eta_{MT} = (-0.1155 \times (P_{gc}/P_{cond}/P_{MT})^2) + (0.5762 \times (P_{gc}/P_{cond}/P_{MT})) - 0.0404$
MT (trans-critical)	$\eta_{MT} = (-0.0021 \times (P_{gc}/P_{MT})^2) - (0.0155 \times (P_{gc}/P_{MT})) + 0.7325$
PC (sub-critical)	$\eta_{PC} = (-0.172 \times (P_{cond}/P_{IP})^2) + (0.7095 \times (P_{cond}/P_{IP})) - 0.0373$
PC (transition)	$\eta_{PC} = (-0.172 \times (P_{gc}/P_{cond}/P_{IP})^2) + (0.7095 \times (P_{gc}/P_{cond}/P_{IP})) - 0.0373$
PC (trans-critical)	$\eta_{PC} = (-0.0788 \times (P_{gc}/P_{IP})^2) + (0.3708 \times (P_{gc}/P_{IP})) + 0.2729$
NH ₃	
NH ₃	$\eta = (-0.00097 \times (P_{cond}/P_{evap})^2) - (0.01026 \times (P_{cond}/P_{evap})) + 0.83955$
R404A	
R, LT	$\eta_{LT} = (-0.0075 \times (P_{cond}/P_{evap})^2) + (0.0652 \times (P_{cond}/P_{evap})) + 0.5609$
R, MT	$\eta_{MT} = (-0.0004 \times (P_{cond}/P_{evap})^2) - (0.0021 \times (P_{cond}/P_{evap})) + 0.6989$

Kuwait in higher side. For summers (June), the maximum averaged outside air temperature is 21.55 °C in Tabriz in the lower side and 36.92 °C in Kuwait in higher side. Yearly averaged ambient temperature is 12.15 °C in Tabriz and 26.63 °C in Kuwait. Being a relatively cold place, Tabriz has the highest heating load of 158.67 (kW) and minimum A/C load of 28.40 (kW). While Kuwait has high A/C load of 119.26 (kW) and comparably low heating load of 43.36 (kW). Fig. 4 (b) compares the climatic conditions in a few cities in Middle East to that in Europe. Referring to Fig. 4 (b), λ in Tabriz goes up to 1.3, which is well above the maximum value reported in Europe. While the β is significantly higher and goes up to 0.87 for Kuwait. The average MT and LT refrigeration loads for Middle East Asia are 97.21 (kW) and 38.35 (kW), respectively.

3.2. Climatic zones in India

There are five climatic zones in India which include Cold

(Shillong), Temperate (Bangalore), Composite (Bhopal and Amritsar), Hot Dry (Nagpur and Jodhpur) and Warm Humid (Bhubaneswar and Chennai). The climatic zones in a set of representative cities in India are shown in Fig. 5 (a) and the same is compared with that in Europe in Fig. 5 (b). The maximum daily averaged ambient temperature in summers (June) is recorded of 19.12 °C for Shillong and 34.03 °C for Jodhpur. For winters, the daily averaged minimum outside air temperature is 6.93 °C in Shillong, and the same goes maximum to 17.01 °C in Jodhpur. Yearly averaged ambient temperature is 19.12 °C in Shillong, while 28.33 °C, 27.03 °C and 26.20 °C in Chennai, Bhubaneswar and Jodhpur, respectively. The reason for such high yearly average ambient temperature in Chennai and Bhubaneswar (both in coastal region), is due to the comparatively higher relative humidity (see, Fig. 5 (a)). Shillong has the highest heating load of 83.85 (kW) and minimum A/C load of 22.80 (kW). Being warm locations, Jodhpur (Hot Dry) and Chennai (Warm Humid) have the maximum A/C load, of 137.80 (kW) and

Fig. 6. Flowchart for simulation of B configuration.

Fig. 7. Flowchart for simulation of CB configuration.

Table 4
LCCP analysis assumptions.

Parameter	Assumed value	Notes
Refrigerant charge (kg/kW)	CO ₂ : MT = 3, LT = 2 Cascade high stage: 0.75 DX/HFC: MT = 2, LT = 4	[43]
Leakage rate (%)	10	Percentage of refrigerant leakage to atmosphere
System lifetime (years)	20	
Service interval (years)	2	[42]
Service leak rate (%)	5	
Reused refrigerant (%)	85	
GWP	CO ₂ = 1, NH ₃ = 0 R404A = 3922 R407C = 1624 R410A = 1924	[45]

128.74 (kW), respectively. Heating loads for Jodhpur and Chennai are 30.23 (kW) and 12.41 (kW), respectively. Bangalore has lower A/C loads as well as lower heating load. Bhopal (Composite) and Jodhpur (Hot Dry) also has similar climatic conditions, except that Jodhpur has higher A/C load as well as heating load, owing to comparatively higher and lower average temperature in summer and winter, respectively. Fig. 5 (b) compares the climatic conditions in India to that in Europe. As observable from the Fig. 5 (b), λ in Shillong is just above 0.6, which is below the maximum value reported in Europe. For Hot Dry/Warm Humid locations and in comparison with Europe, the β in Chennai and Jodhpur is significantly higher and goes maximum up to 0.78 and 0.94. The average MT and LT refrigeration loads for India are 110.65 (kW) and 40.34 (kW), respectively.

4. Modelling

Thermodynamic models are developed using MATLAB, and REFPROP 9.0 (Lemmon et al., 2002) is used to obtain CO₂ and ammonia state properties. Mass and energy balance across each components of the cycles are applied assuming steady-state operation, no heat transfer and no pressure loss in piping and isenthalpic expansion in the expansion valve.

The minimum condensing temperature for CO₂ is 7 °C, while the

same is 25 °C for the NH₃ condensers. In CB configuration, the condensing temperature of CO₂ is 10 °C, while the NH₃ rejects the heat outdoor. Approach temperature of 10 °C is considered for all condenser, except for CO₂ gas cooler/condenser, which are adopted from those reported in Gullo et al., [35]. Approach temperature for cascade condenser in CB system is 5 °C. In the overfed evaporator, the refrigerant enters with a low vapor quality and leaves in two-phase with high vapor quality, owing to the excess liquid circulation for such heat exchangers. As a result, more liquid is transferring heat, allowing the saturation temperature of overfed evaporators to be higher than that of conventional dry evaporators. Consequently, for MT overfed evaporator, an increase of 6 K in saturation temperature is adopted [40]. The internal superheat as well as external superheat of 5 °C each, are assumed for all the dry evaporators. While a vapor quality of 0.9 is assumed at the exit of MT overfed evaporator in B configuration. The air-cooled gas cooler/condenser fan power for both B and CB systems is assumed 3% of the gas cooler/condenser heat duty [43].

Important operating conditions of ejector are entrainment ratio defined as ratio of mass flow rate associated with suction to the mass flow rate at the motive flow, operating gas cooler pressure, receiver pressure (generally fixed) and ambient conditions. They significantly affect the ejector efficiency as well as the overall system performance. Of course, geometry of ejector itself plays a vital

Fig. 8. Monthly COP_{total} for R, B and CB configurations when operated in Midlatitude, Tabriz (a & b) and Dry Arid/Semi-Arid, Kuwait (c & d), climates in the Middle East.

role in predicting its performance on-design as well as the off-design condition. Consequently, multi-jet ejector module in this article is modelled following the methodology adopted by Gullo et al., [35]. The methodology utilizes experimental data in literature to formulate correlations to predict entrainment ratio in terms of pressure lift (difference between pressure of receiver IP and MP) and the gas cooler/condenser outlet temperature. The minimum and maximum values for the pressure lift, adopted from the literature, are 4 bar and 15 bar, respectively. The upper limit of ejector efficiency is kept 0.40 [41]. The ejector module is modelled by optimizing the pressure lift for the varying ambient conditions.

At ambient temperature lower than 18 °C, both B and CB configurations operate similarly, as the ammonia chiller is not operational below 18 °C. The consolidated operating parameters are listed in Table 2. The compressor efficiencies are calculated as a function of pressure ratio as shown in Table 3.

4.1. Integration of A/C load in B and CB configurations

A/C evaporator is switched on above 17 °C ambient temperature. Otherwise, ambient cooling is assumed effective. CO₂ receiver and parallel compressor are designed to satisfy the A/C load for both B and CB configurations. The supply and return temperature for A/C load is taken as 7 °C and 12 °C, respectively, [44].

4.2. Integration of heating load in B and CB configurations

Heat recovery mode becomes active in both B and CB configurations when the ambient temperature is less than 18 °C. The supply temperature for heating loads is considered as 35 °C and 45 °C at the ambient temperature above and below 0 °C, respectively [43]. Any further heating demand is met using auxiliary heaters with assumed electrical to thermal conversion efficiency of 0.95. A de-superheater installed (see, Fig. 2) reclaims the superheat of the CO₂ following the control strategy suggested by Sawalha [7]. Normally, the gas cooler is operated at full capacity for minimum possible gas cooler exit temperature, regulating the high side pressure to meet the required heating and refrigeration load in the integrated system. The increment in high side pressure to meet the heating load is limited to an optimum value corresponding to the system maximum efficiency. To meet the required heating load beyond the maximum operating pressure limit, as a second step, the gas cooler capacity is reduced to increase the CO₂ temperature at the exit of the gas cooler.

4.3. Standalone heat pump and A/C system (SS)

A standalone heat pump is modelled as an air source heat pump (SHP), with R407C as operating fluid. As per Karampour and

Fig. 9. Monthly COP_{total} for R, B and CB configurations when operated in Cold, Shillong (a & b) and Temperate, Bangalore (c & d), climates in India.

Fig. 10. Monthly COP_{total} for R, B and CB configurations when operated in Warm Humid, Chennai (a & b) and Hot Dry, Jodhpur (c & d) climates in India.

Fig. 11. Relative annual average COP_{total} for B and CB configurations in comparison to R configuration.

Fig. 12. Relative total emissions for B and CB configurations in comparison to R configuration.

Sawalha, (2018) following data are assumed: total superheat of 10 °C, defrost energy consumption equals 7% of compressor power, minimum evaporator temperature of −15 °C and evaporator approach temperature of 7.5 °C. For very-low ambient temperature, auxiliary heaters are installed to support the SS to meet the heating load. For space cooling, standalone HFC based A/C, using R410A, is modelled considering evaporation temperature of 3 °C, total superheat of 10 °C and condenser approach temperature of 10 °C. Both the standalone A/C and heat pump are modelled assuming compressor isentropic efficiency of 0.70.

4.4. COP and LCCP calculations

The combined COP, termed as COP_{total} is defined as the ratio of

total load including refrigeration as well as A/C and heating load to the total power consumption expressed as equation (1).

$$COP_{total} = \frac{\dot{Q}_{LT} + \dot{Q}_{MT} + \dot{Q}_{A/C} + \dot{Q}_H}{W_{total}} \quad (1)$$

The parallel compressors are assumed to be large enough to compress all vapor generated owing to the integration of A/C load. COP of A/C integration in the B configuration is calculated as the ratio of A/C load to increase in power consumption for the parallel compressor. While, in CB configuration, COP of A/C integration is calculated as the ratio of A/C load to increase in power consumption for both parallel CO₂ compressor and NH₃ compressor. To calculate the heating COP for both B and CB configurations, the power

Table 5
 COP_{total} , Annual Energy Consumption (MJ) and Total Emissions (TonsCO_{2eq}) for R, B and CB configurations.

Climate	Location	Annual average temperature °C	Annual average COP _{total}			Annual Power Consumption (MW)			Total Emissions (kTonsCO _{2eq})		
			R	B	CB	R	B	CB	R	B	CB
Middle East											
ME1	Tabriz	12.15	3.18	3.78	3.68	566.35	477.77	488.98	19.26	7.61	7.80
	Damascus	16.69	3.02	3.47	3.45	564.04	489.99	492.91	19.23	7.82	7.86
ME2	Tehran	17.43	3.03	3.45	3.48	574.36	503.88	499.19	19.37	8.03	7.96
	Cairo	21.89	2.84	3.08	3.12	612.10	557.75	564.16	19.91	8.98	8.88
	Kuwait	26.63	2.46	2.49	2.81	771.61	726.26	676.17	22.17	12.11	10.75
	Abu Dhabi	27.31	2.55	2.58	2.80	844.79	834.98	771.03	23.21	13.25	12.24
India											
IN1	Shillong	14.50	3.23	3.90	3.62	504.43	417.18	449.04	18.38	6.67	7.17
IN2	Bangalore	23.73	2.81	3.09	2.96	634.75	577.15	603.85	20.23	9.19	9.61
IN3	Bhopal	25.41	2.58	2.63	2.80	708.45	673.54	656.25	22.69	12.59	11.80
	Amritsar	27.57	2.68	2.81	2.89	807.96	792.72	742.89	21.28	10.71	10.44
IN4	Nagpur	26.95	2.60	2.66	2.83	788.17	770.16	725.25	22.41	12.23	11.52
	Jodhpur	26.20	2.62	2.69	2.87	767.95	747.59	701.35	22.12	11.87	11.15
IN5	Bhubaneswar	27.03	2.70	2.76	2.88	830.13	812.17	778.38	23.00	12.89	12.36
	Chennai	28.33	2.65	2.66	2.85	890.24	886.28	829.08	23.86	14.06	13.16

Bold and Italic means the performance of particular configuration is better with other configurations for the respective location investigated.

Fig. 13. Comparative advantage of a specific system in various climate zones of the Middle East.

required for the heating system is calculated as difference in total power consumed while operating with heating load and power consumed while satisfying only the refrigeration load [43]. Figs. 6 and 7 represents the flow chart for simulation of B and CB configuration, respectively.

LCCP is a very effective tool to assess the environmental impact of a refrigeration system [42]. The parameters include lifetime energy efficiency, the specific refrigerant in use and the lifetime refrigerant emissions. LCCP, expressed as in equation (2), represents the total CO₂ equivalent emissions for a refrigeration system including both direct and indirect emissions. The direct emissions, expressed as in equation (3), include emissions related to leakage/escape of refrigerant from the system, refrigerant loss at the end of life of the system and refrigerant loss during service events [42]. The indirect emissions, given by equation (4), include emissions related to production and distribution of electric energy consumed by the refrigeration system as well as emissions related to manufacturing the machinery and the recycling of the machinery at the end of life. The various parameters assumed to calculate LCCP are consolidated in Table 4.

$$LCCP = E_{direct} + E_{indirect} \quad (2)$$

$$E_{direct} = E_{leakage} + E_{EOL} + E_{service} \quad (3)$$

$$E_{indirect} = E_{energy} + E_{manufacture} + E_{recycle} \quad (4)$$

5. Results and discussion

Fig. 8 presents simulated values of COP_{total} for R, B and CB configurations for two cities in Middle East representative, of the two climate zones, while Figs. 9 and 10 depicts the same for four cities in India, representative of four climate zones. Figs. 8–10 are plotted for an hourly averaged profile of temperature, refrigeration load as well as A/C and heating load for 24 h each for both cold and warm months. On the primary axis, COP_{total}, as well as β and λ, are plotted, while the secondary axis shows variation of ambient temperature.

Owing to relatively cold climate prevailing in Tabriz (Fig. 8a), compared to Kuwait (Fig. 8b) it is observable that, the COP_{total} for B configuration followed by CB, are higher than that of R configuration. The annual average COP for R, B and CB configurations, when operated in Tabriz are found to be 3.18, 3.78 and 3.68, respectively. Similarly, operated in Tabriz, the total emissions for R, B and CB configurations are 19.26 (kTonsCO_{2eq}), 7.61 (kTonsCO_{2eq}) and 7.80 (kTonsCO_{2eq}), respectively. On the contrary, while operating in Kuwait having extreme climate, the performance of CB

Fig. 14. Comparative advantage of a specific system in various climate zones of India.

configuration is found better than that of both B and R configurations. The advantage is apparent for operation during peak summer month of June. There is a decrement in performance of CB during January due to the operational shift in CB system from the booster to the cascade configuration and vice-versa, when ambient is in the range 18 °C–26 °C. For ambient above 26 °C, the performance of CB configuration is found better. The ambient temperature in Kuwait remains higher than 25 °C, for more than 50% in a year and hence the annual COP_{total} for CB configuration is found much better. The total emissions for CB configuration operating in Kuwait are also found lower by 51.5% and 11.2% compared to R and B configurations, respectively.

Fig. 9 presents performance of all three investigated systems for operation in Cold (Shillong, subplots a & b) and Temperate (Bangalore, subplots c & d) climates in India. It is observed that configuration B outperforms in both Cold and Temperate climates. The annual COP_{total} for R, B and CB configurations operating in Shillong are found 3.23, 3.90 and 3.62, respectively, while the same are 2.81, 3.09 and 2.96, respectively, for operation in Bangalore. Compared to baseline R configuration, the reduction in total emissions for B and CB configurations for operation in Shillong is found to be 63.7% and 61.1%, respectively, while the same is 54.5% and 52.5% for operation in Bangalore.

When simulated for operation in Warm Humid (Chennai) and Hot Dry (Jodhpur) climates in India (Fig. 10), it is observed that the CB configuration outperforms both the R and B configurations during the month of June. There is an observable drop in performance for a fraction of duration in the day during the month of January. The same is ascribed to operational shift while the ambient is within range 18 °C–26 °C. However, the extended hours of operation of the refrigeration system at ambient above 25 °C results in higher performance of CB configuration by 6.6% and 6.9% compared to B configuration, when operated in Chennai and Jodhpur, respectively. Compared to R configuration operating in Chennai, the reduction in total emissions for B and CB configurations are 41.1% and 44.9%, respectively. While the same is 46.3% and 49.6%, respectively, for operation in Jodhpur. The performance of R, B and CB configurations in the Composite climate in India are not shown here, as there is no significant deviation.

Figs. 11 and 12 compares relative annual COP_{total} and total emissions for R, B and CB configurations, for operation in both Middle East and Indian climatic conditions. While Table 5 comprehensively presents and compares the absolute values for annual COP_{total} , annual power consumption and total emissions for all configurations. It is observable from Figs. 10 and 11 and Table 5 that the B configuration is a better solution in perspective of both

Fig. 15. Heating COP for B and CB configurations, when operated in (a) Midlatitude Climate (Tabriz) and (b) Cold Climate (Shillong).

energy consumption and emissions, for operation in Midlatitude climate in the Middle East and for the Cold and Temperature climate regions in India. While for the Dry Arid/Semi Arid climate in the Middle East and Composite, Warm Humid and Hot Dry regions in India, the CB configuration outperforms others. Figs. 13 and 14 visually illustrates the comparative advantage of the investigated systems in the various climatic regions, within map of Middle East and India, respectively.

Fig. 15 presents the heating COP for the stand-alone R407C based system (SS) and integrated B and CB configurations, when operated in the month of January in a Midlatitude climate of Middle East and Cold climate of India. Both B and CB configurations depict similar heating COPs, at ambient temperature below 17 °C for the major duration of January in Tabriz and Shillong. It is also observed that the heating COP for the SS is comparatively higher than B or CB configuration. The difference on an average is 31.1% and 17.2% for Tabriz and Shillong, respectively. The higher COP for SS is ascribed to the selection of high-performance air source heat pump and is more pronounced in Tabriz, owing to comparatively higher λ . The results obtained are consistent to those reported by Karampour and Sawalha (2018). Despite lower COP for the heating system in the integrated configurations, various other benefits associated with the integration are worth mentioning. The integrated system provides environmental friendly heating and has no limitation for operation in very low ambient. Further, the system is compact requiring only de-superheater and auxiliary heaters to satisfy the annual heating loads.

Fig. 16 presents the COP for a stand-alone R410A based A/C system (SS) and the A/C integration in B and CB configurations, when operated in the month of June in a Dry Arid/Semi Arid climate of the Middle East (subplot (a), for Kuwait) and Hot Dry climate of

India (subplot (b), for Jodhpur). As observed from Fig. 16, the COP for the SS is comparatively lower. The difference, on an average is 12.58% and 36.4%, to that of CB configuration, for Kuwait and Jodhpur, respectively. The A/C COPs for CB and B configurations in Jodhpur are higher compared to that in Kuwait due to higher β values at comparatively lower ambient. Further, benefits associated with the environment friendly integrated A/C system are reduction in space and number of components required as well as ease of control.

6. Future scope

Based on the simulation study, following are future prospect of work.

- Possible improvement in control strategy to improve the heating COP and to reduce the amount of auxiliary power used in cases where λ is greater than unity as well as at low ambient temperatures.
- Improvement in efficiency of CO₂ parallel compressors to make the efficiency of integrating A/C more energetically beneficial, especially for cases where β is high.
- Adoption of ejectors while heat recovery is underway with a suitable control strategy.
- Adoption of ejectors in the cascade configuration where the upper and lower limit of ejector operation would be fixed, promoting better ejector efficiencies.

7. Conclusion

This article investigates the performance of an 'all-CO₂' integrated booster configuration equipped with multi-ejector for operation in extreme warm climate prevailing in the Middle East and India. Further, an integrated NH₃/CO₂ cascaded booster configuration is proposed for operation in same ambient. The performance of both are compared with that of a baseline R404A based direct expansion refrigeration system where the heating and air-conditioning loads are independently taken care by standalone systems. Real-time load profiles for refrigeration, air-conditioning and heating are generated using EnergyPlus. Performance of all systems are compared based on both energy and environmental perspective. The primary conclusion drawn are as following:

- The simulation result reveals that the proposed NH₃/CO₂ cascaded booster configuration outperformance other systems while operating in extreme warm climate.
- In Kuwait (extreme warm climate), the annual COP_{total} for cascaded booster configuration is better than the baseline, and all-CO₂ configurations by a maximum of 14.11% and 12.73%, respectively and the total emissions are lower by 51.5% and 11.2%.
- In Shillong (cold climate), the annual COP_{total} for the baseline, all-CO₂ booster and cascaded booster configurations are 3.23, 3.90 and 3.62, respectively. In comparison to the baseline configuration, the reduction in total emissions for the booster and cascaded booster configurations are 63.7% and 61.1%, respectively.
- The heating COP for the stand-alone system is found higher by a maximum of 31.1% to that of the integrated configurations, while the COP for A/C is found higher for integrated cascaded booster configuration by a maximum of 36.4%.

The work presented in this article offers a broad opportunity for future development in the natural refrigerant-based integrated solutions for supermarket refrigeration system.

Fig. 16. COP of A/C in B and CB configurations, when operated in (a) Dry Arid/Semi Arid Climate (Kuwait) and (b) Hot Dry Climate (Jodhpur).

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