

Performance evaluation of CO₂ ejector system with parallel compressor for supermarket application

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ABSTRACT

Evolution in modifications for CO₂ system configuration came across from the last two decades has proven to hold the potential in order to improve the overall performance of the CO₂ cooling system for various applications. However, performance of the CO₂ system at high ambient context is not promising and comparable with popular conventional refrigerants. Due to its unique properties, the CO₂ system possesses substantial losses at high ambient temperature due to the throttling process. System configuration with parallel compressor is proven as the most popular and efficient configuration for high ambient temperature (up to 46 °C). In this study performance evaluation of a CO₂ multi-ejector based supermarket cooling system of 33 kW cooling capacity with compressor configuration is experimentally evaluated at high ambient temperature (up to 46 °C). Test facility is equipped with two-phase multi-ejector resulting in pressure lift due to the expansion work recovery. Removed flashes in flash gas tank or separator after passing through two-phase ejector, are further compressed with the help of auxiliary compressor configured in parallel but with an additional possession of low compression ratio. High stability with high gascooler pressure and CO₂ system consistency at high gascooler outlet temperature is observed. Maximum reduction in the AUX compressor energy consumption observed is 8% for 46 bar & 10.7% for 48 bar receiver pressure at 36 °C gascooler outlet temperature. Also, the Exergy efficiency of the system observed is 0.315 corresponding to 3.2 PIR at 46 °C gascooler outlet temperature.

Keywords: Parallel compressor, Ejector; CO₂; Supermarket, Flash tank; PIR.

1. INTRODUCTION

Supermarkets as a part of the HVAC applications which requires enormous amount of energy to sustain and correspondingly are also responsible for the high emission of greenhouse gasses. The popular refrigerants used in developing countries in the present scenario are HFCs and these are being released into the atmosphere at astonishing rates i.e. about 30% of the total amount charged in the system, leaked every year (Austin and Sumathy, 2011). The synthetic refrigerants not only possess high GWP but also have concerning level of ODP. Hence it is imperative that an alternative solution must be proposed such as natural refrigerants which must not only be eco-friendly but also must be applicable to such a huge energy consumer i.e. supermarkets. Apart from this energy demands all over the world are rapidly growing especially in developing countries and improving the energy efficiencies of the HVAC systems which are an integral part of services that are necessary for everyday life could greatly impact the sustainability of the future. Developing an energy efficient system can overall reduce the unused energy which may result in reduction of future power plants and other cost heavy infrastructure associated with it (Hafner et al., 2014). Therefore, it is essential to develop systems which are both environmentally friendly and energy efficient. Also, a versatile application such as a supermarket requires cooling at various levels of temperature and designing such a system has several intricacies to it and the working fluid or the refrigerant which is preferred in such scenarios are fluids which have lower boiling point (Sarkar, 2017).

Several modifications for the conventional cycle configuration have been proposed which will improve the efficiency of the cycle. However, the use of an ejector has grabbed the attention of many researchers because of its unique attributes which include low cost, huge recovery potential, the absence of moving parts, etc. (Groll et al., 2011). It was reported that the utilization of ejectors can improve the performance of the system by up to 15%, relying on the

temperature of the ambient (Elbel, 2010). Another study depicted an increment of 20% in COP of the system at high ambient temperature. It was also reported that with such an improved performance, it may lead to an energy efficient solution for the commercial refrigeration (Hafner et al., 2014). Later, it was observed that a maximum COP improvement of 7% for the conditions close to the critical point is possible. Also, an exergy analysis was performed and it has been found that by incorporating the ejector expansion system, the exergy efficiency has improved by up to 13% (Haida et al., 2016). Shifting completely to the ejector expansion technology, the dynamic characteristics of the system can be retained and also control of the high side pressure based on varying load can also be smoothly performed (Banasiak et al., 2015).

The present experimental study aims to evaluate the gainful improvement in the overall performance of the system with parallel compressor configuration of a CO₂ multi-ejector based system for supermarket applications at high ambient context.

2. SUPERMARKET DESCRIPTION

A fully instrumented CO₂ test facility of 33 kW cooling capacity is designed to maintain three different temperatures such as for freezing (-29°C), refrigeration (-6°C) and air conditioning (7-11°C). The test facility is equipped with a heat recovery system with water-glycol solution to maintain a constant heat load demand (Figure 1).

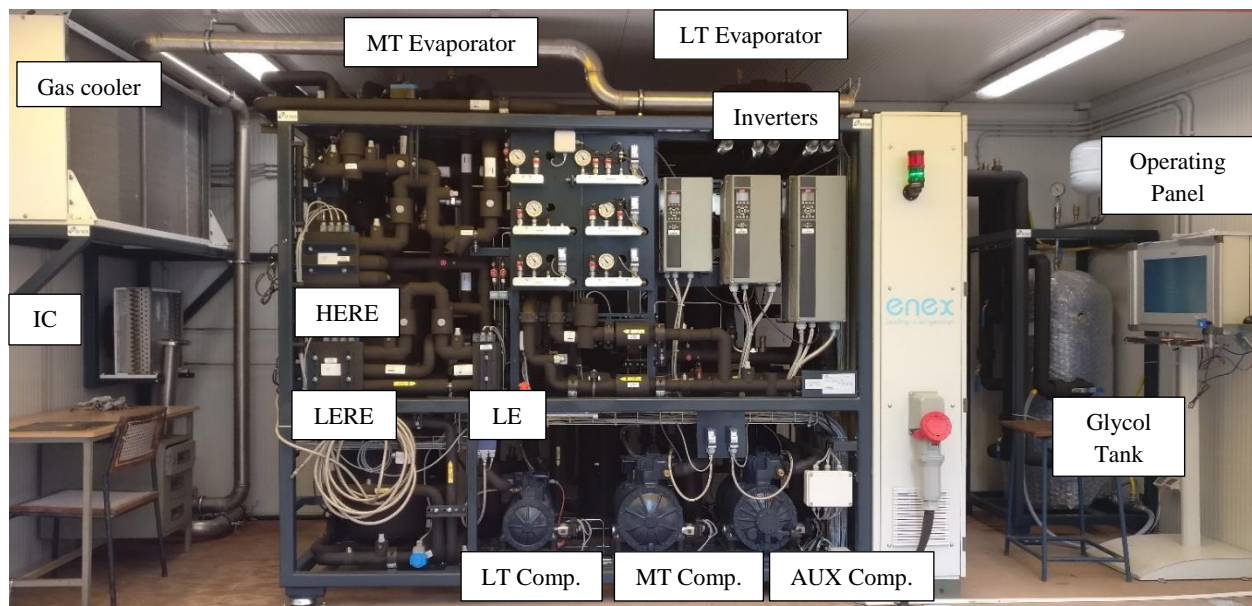


Figure 1: CO₂ supermarket test facility.

Load of medium temperature (MT) and low temperature (LT) evaporators on water side are controlled by manually controlled EEV installed before the suction port to the evaporators. However, AC evaporator temperature is controlled by both adjusting the receiver pressure and employing a set of vapour ejectors. Two glycol loop circuits are arranged with different glycol concentrations; 42% for MT & AC load and 56% for LT load. Shell-tube design evaporator and air-cooled gascooler with tube-fin design is installed in the supermarket facility. Three compressors are arranged, LT & MT compressors and an additional AUX compressor is installed to handle high amounts of flash gas from the receiver which also enables the parallel compression operation. Two ejectors are installed with low ejection ratio (LER), high ejection ratio (HER). One liquid suction accumulator is also installed in order to provide an excess feed to over feed the evaporators throughout the year. Temperature sensors, pressure sensors and energy meters are installed at various locations to evaluate the performance of the system and examine the various parametric variations.

Uniqueness of the parallel configuration, is the separation of flashes with the support of flash tank after the expansion process at an intermediate pressure which further prevents unwanted flashes entering into the evaporator which provide zero useful refrigeration effect.

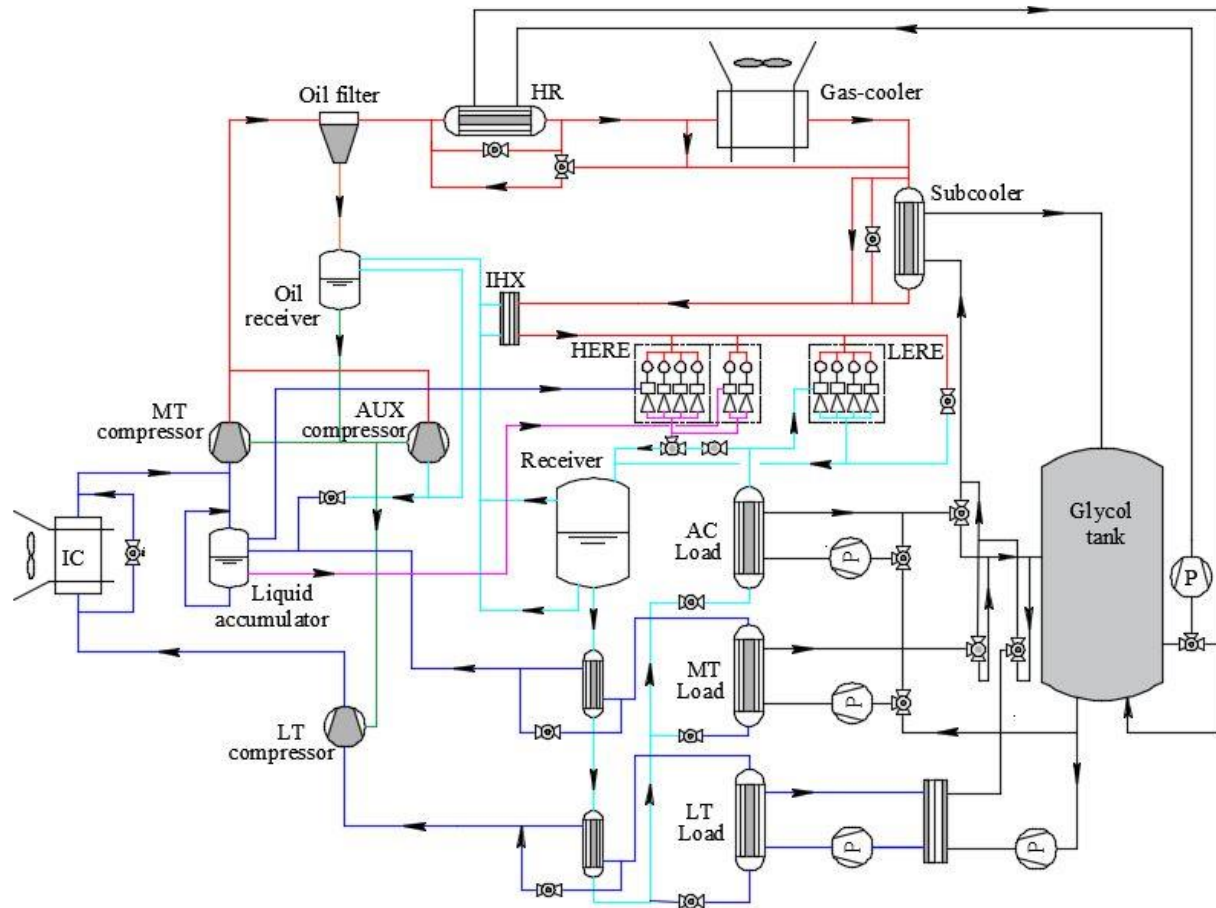


Figure 2: Schematic of the CO₂ supermarket facility.

3. PERFORMANCE EVALUATION AND DATA REDUCTION

Performance of the CO₂ supermarket test facility is evaluated for various gascooler outlet temperature after achieving the steady state which needs ~45 minutes. Data is extracted for a particular gascooler outlet temperature and averaged value of the parameters are used for the performance calculation. Range/value of various parameters used during experimental performance evaluation are tabulated in Table (1).

Table 1: Parameters used for performance evaluation.

Parameter	Unit	Value/Range
Gascooler outlet temperature	°C	36, 41, 46
Gascooler outlet pressure	bar	80 to 120
AC evaporator temperature	°C	7 to 11
MT evaporator temperature	°C	-6
LT evaporator temperature	°C	-29
Receiver pressure	bar	44 to 48

Exergy efficiency is computer using Eq. (1).

$$\eta_{ex} = \frac{B_{MT} + B_{LT} + B_{AC} + B_{HR}}{P_{MT} + P_{LT} + P_{AUX}} \tag{1}$$

where, for heat recovery (HR): $B_{ex,i} = \dot{Q}_{ex,i} * (1 - \frac{T_{amb}}{T_{ut,i}})$

and for cooling (AC, MT & LT) $B_{ex,i} = \dot{Q}_{ex,i} * (\frac{T_{amb}}{T_{ut,i}} - 1)$

and heat transfer is computed using $\dot{Q}_{ex,i} = \rho_i * V_i * \Delta h_i$

T_{ut} and T_{amb} is the temperatures of the heat source and ambient in K respectively.

Power Input Ratio (PIR) of the CO₂ system is compute using Eq. (2).

$$PIR = \frac{P_{MT,act} + P_{AC,act} + P_{LT,act} + P_{H,act} + P_{SAW,act}}{P_{MT,Carnot} + P_{AC,Carnot} + P_{LT,Carnot} + P_{H,Carnot} + P_{SAW,Carnot}} = \frac{\sum_i P_{i,act}}{\sum_i P_{i,Carnot}} \tag{2}$$

where, $P_{i,c} = \frac{\dot{Q}_{ex}}{T_{ut,i}} * (T_{amb} - T_{ut,i})$

4. RESULTS AND DISCUSSION

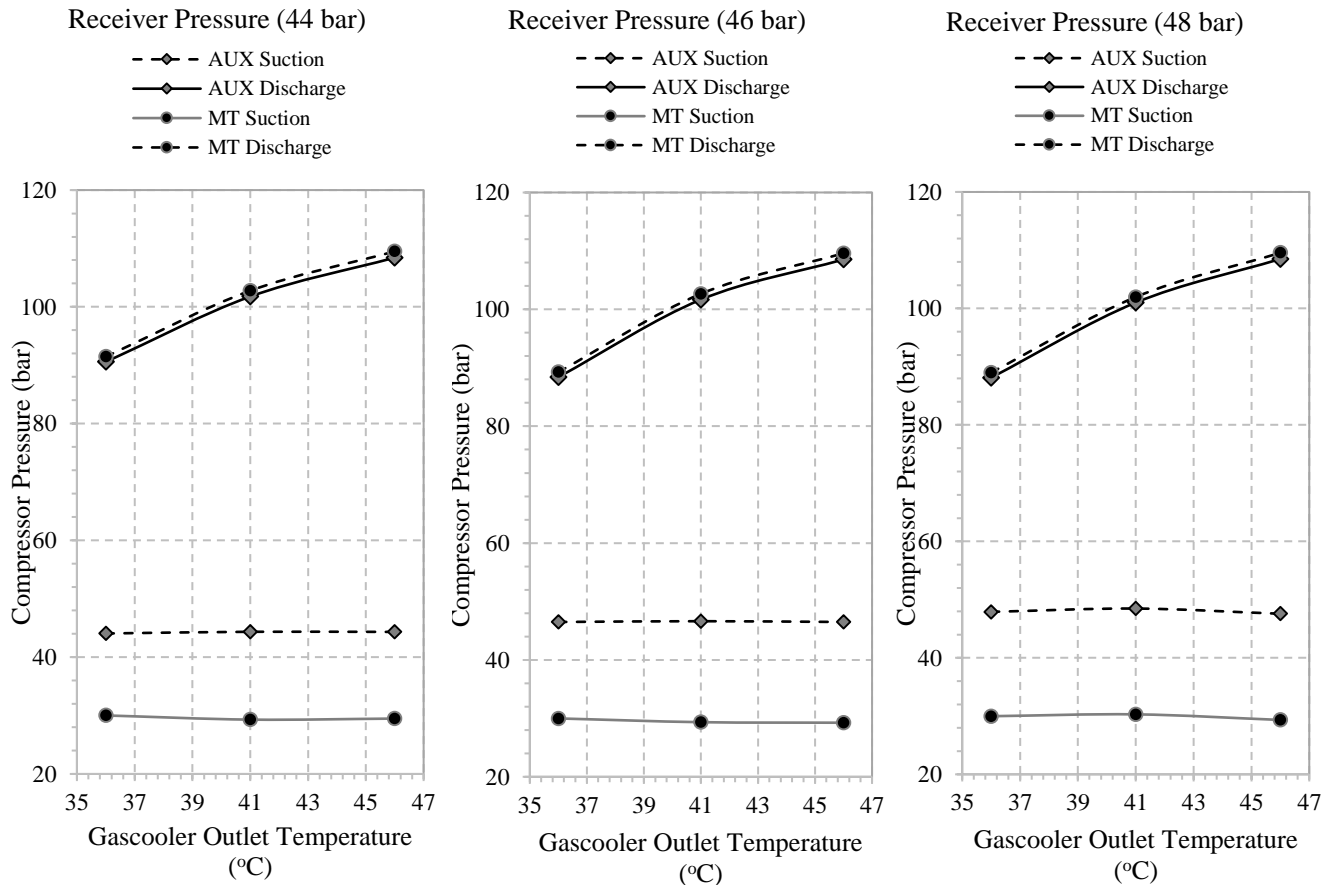


Figure 3: Compressor pressure variation at various receiver pressure with gascooler outlet temperature.

Figure (3) shows the variation of AUX and MT compressors pressure at suction and discharge port for various receiver pressure (44 bar, 46 bar and 48 bar) with respect to gascooler outlet temperature (36°C, 41°C and

46°C). Suction pressure of MT compressor and discharge pressure of AUX and MT is more or less constant because the performance evaluation is carried out at constant MT evaporator temperature (-6°C) and three gascooler outlet temperatures (36°C, 41°C and 46°C). It is observed that, as receiver pressure or suction pressure of AUX compressor increase the compression ratio of AUX compressor decreases which overall results in reduced AUX compressor work. A consistency in compressor discharge pressure is observed as shown in Figure (3) which overall projects the stability of CO₂ cooling system and its operation for high temperature operating context (upto 46°C).

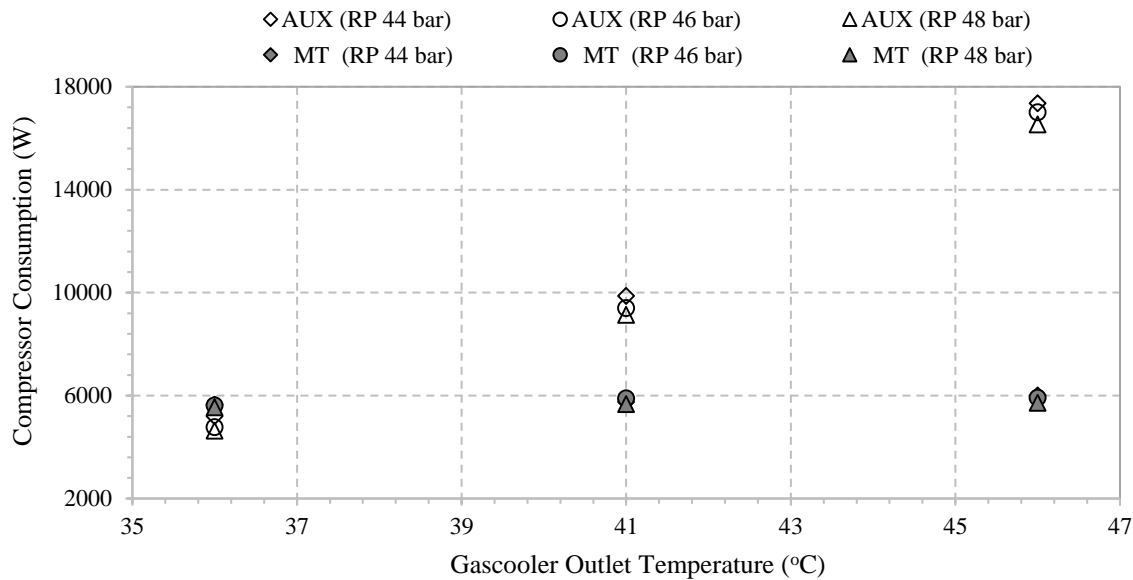


Figure 4: Compressors consumption at various receiver pressure with gascooler outlet temperature.

Figure (4) shows the consumption of AUX and MT compressor at various receiver pressure (44, 46 and 48 bar) with respect to gascooler outlet temperature (36°C, 41°C and 46°C). It is observed that, as the receiver pressure increases the compressor consumption or compression ratio decreases for various gascooler outlet temperature. However, as the gascooler pressure corresponding to gascooler outlet temperature increases the flash from the receiver passing to the AUX compressor increases which further results in high mass flow handling by the AUX compressor and due to which the consumption increased.

Figure (5) shows the comparative percentage reduction in compressor consumption for 46 & 48 bar receiver pressure with 44 bar receiver pressure at gascooler outlet temperature (36°C, 41°C and 46°C). Variation in receiver pressure is not directly disturbing the suction pressure of MT compressor and due to which very less percentage of reduction is observed in MT compressor consumption at various gascooler outlet temperature. However, in AUX compressor, consumption reduces as compared to 44 bar receiver pressure by 8% for 46 bar & 10.7% for 48 bar receiver pressure at 36°C gascooler outlet temperature. Similarly, consumption reduces by 4.7% for 46 bar & 7.4% for 48 bar receiver pressure at 41°C gascooler outlet temperature and by 2.03% for 46 bar & 4.7% for 48 bar at 46°C gascooler outlet temperature.

Figure (6) shows the Exergy efficiency and Power Input Ratio (PIR) of the CO₂ cooling system with respect to various gascooler outlet temperature. As the PIR of the system decreases due to reduction in energy consumption by the system, also the exergy losses by the system decreases and which further results in increasing Exergy efficiency of the CO₂ cooling system. Maximum Exergy efficiency of 0.315 of the system is obtained corresponding to 3.2 PIR of the system at 46°C gascooler outlet temperature.

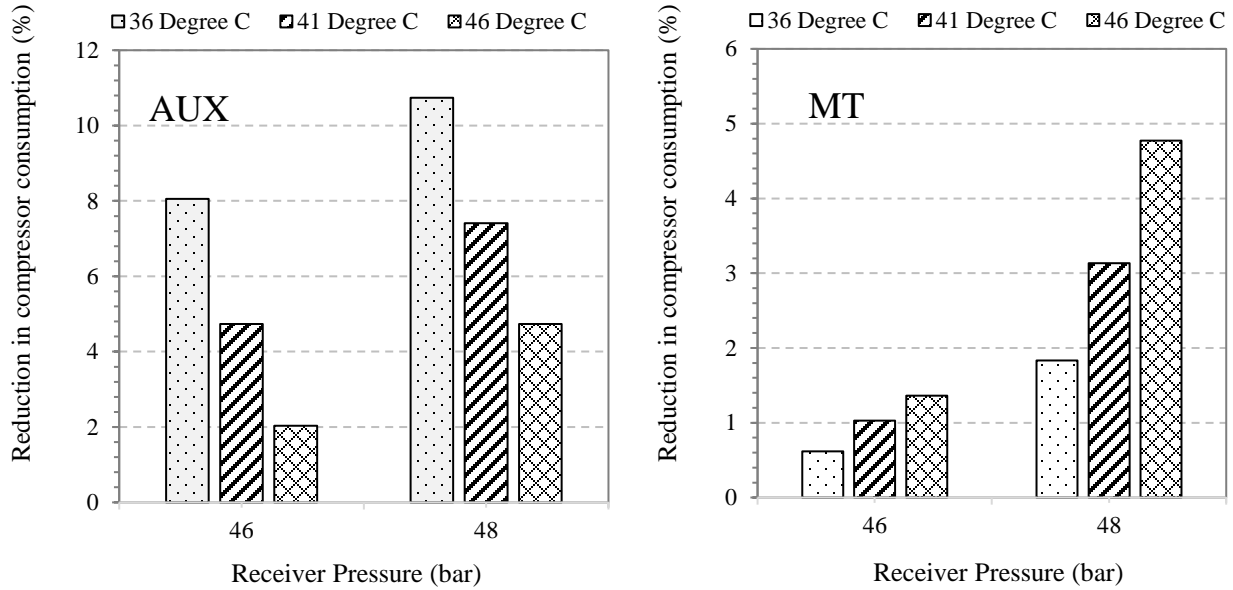


Figure 5: Percentage reduction in AUX and MT compressor consumption with receiver pressure.

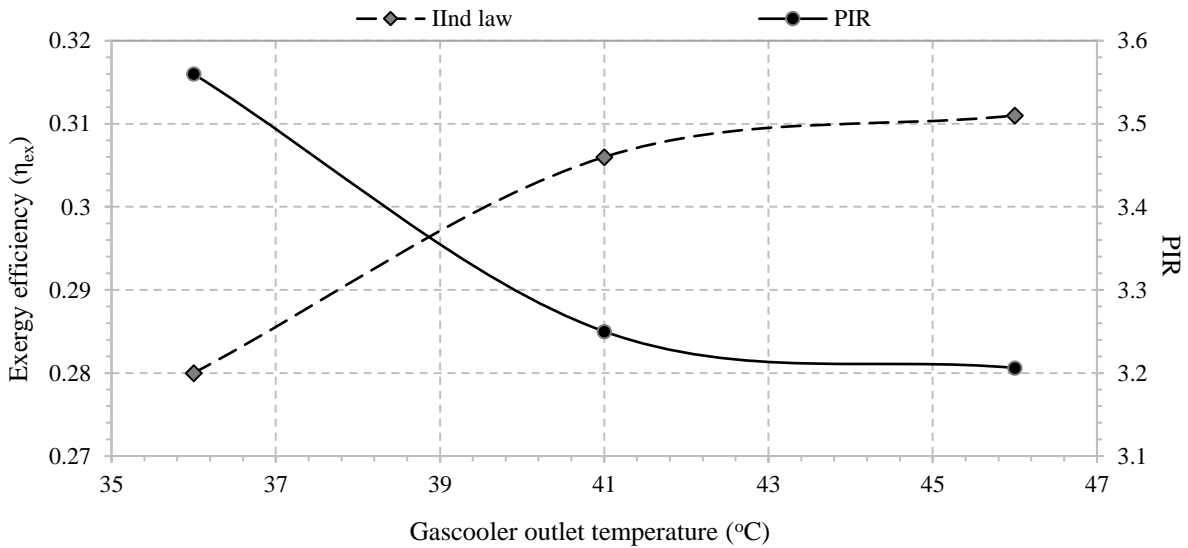


Figure 6: Variation of exergy efficiency and PIR with the gascooler outlet temperature.

5. CONCLUSIONS

An experimental evaluation carried out for a supermarket test facility in order to evaluate the performance of multi-ejector based CO₂ cooling system at high climatic context (36°C, 41°C and 46°C) with parallel compressor configuration. The following conclusions are drawn from the present study.

- High stability and consistency of the CO₂ cooling system is observed at high gascooler pressure and outlet temperature for supermarket application.

- It is observed that, as the receiver pressure increases the AUX compressor consumption decreases for various gascooler outlet temperature due to reduction in compression ratio. However, as the gascooler pressure corresponding to gascooler outlet temperature increases, the AUX compressor consumption also increases due to increase in flash handling through AUX compressor.
- Percentage reduction in AUX compressor consumption is observed, as compared to 44 bar receiver pressure by 8% for 46 bar & 10.7% for 48 bar receiver pressure at 36°C gascooler outlet temperature, 4.7% for 46 bar & 7.4% for 48 bar receiver pressure at 41°C gascooler outlet temperature and 2.03% for 46 bar & 4.7% for 48 bar at 46°C gascooler outlet temperature.
- Maximum Exergy efficiency of the CO₂ cooling system observed is 0.315 corresponding to 3.2 PIR at high gascooler outlet temperature (46°C).

6. FUTURE PROSPECTIVE

A comparative analysis will be carried out with the results obtained from the present experimental study and the synthetic refrigeration system with the support of field data in order to project the actual scenario of both technologies.

Acknowledgements

The work presented is part of an ongoing Indo-Norwegian project funded by the Ministry of Foreign Affairs, Government of Norway coordinated by SINTEF, Norway. The Indian authors acknowledge the additional support received from the Department of Science and Technology (DST) under project: PDF/2017/000083.

Acronyms

<i>CO₂</i>	Carbon dioxide
<i>HR</i>	Heat recovery
<i>HER</i>	High Ejection Ratio ejector
<i>IC</i>	Inter-cooler
<i>LER</i>	Low Ejection Ratio ejector
<i>LE</i>	Liquid Ejector
<i>PIR</i>	Power Input Ratio

Nomenclature

\dot{Q}	Heat transfer rate	(kW)
<i>Vol</i>	Volume flow rate	(kg/s)
T	Temperature	(°C)
<i>C_p</i>	Specific heat	(J/kg K)

Subscripts and Superscripts

<i>act</i>	Actual
<i>amb</i>	Ambient
<i>comp.</i>	Compressor
<i>evap.</i>	Evaporator
<i>in</i>	Inlet
<i>out</i>	Outlet

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