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Ejector for the World: simplified ejector-supported CO_2 refrigeration systems for all climates.

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ABSTRACT

The novel configuration presented in this work simplifies the layout of ejector-supported booster systems while maintaining all the benefits of an ejector implementation. The basic version of the solution is based on: i) MT and LT compressor suction groups, ii) flooded MT evaporation with increased evaporation temperature, and iii) ejector utilization throughout the year. The ejector is actively operated as a high-pressure-control device at elevated ambient temperatures ('summer mode'). With lower ambient temperatures the ejector is operated passively, and the high-pressure control is performed by individual metering devices upstream of the different evaporators ('winter mode'). The feasibility tests performed in the laboratory proved that energy-wise this novel system configuration outperforms traditional and parallel compression supported booster systems under any condition. The pressure lift measured with active ejector is sufficient for liquid refrigerant distribution to the evaporators, while the pressure drop recorded in passive mode is negligible for practical applications.

Keywords: Refrigeration, Carbon Dioxide, R744, Ejector, Energy Efficiency, Simplicity.

1. INTRODUCTION

In recent years, the use of low Global Warming Potential (GWP) fluids in the refrigeration field registered a wide increase, following the approval of the EU F-Gas Regulation 517/2014 (European Commission 2014) and the consequent progressive ban of commonly used synthetic refrigerant which will occur in the near future.

The establishment of CO_2 units as the preferred choice for commercial refrigeration and supermarket applications, due to their ability to guarantee long-term legal and environmental safety and at the same time better performances compared to synthetic refrigerants units under almost any climatic condition, is widely testified among scientific literature (Gullo, Hafner et al. 2018, Karampour and Sawalha 2018). According to these papers, in order to maintain a high energy efficiency even in warm environmental temperature conditions, the standard booster system needs to be adapted, including for example mechanical subcooling, parallel compression or flooded operation of the evaporators. Another option suggested and investigated in literature is the integration of other demands, such as heat recovery and air conditioning, in a single unit providing also the required refrigerating effect. The first studies based on field data assessing the performance of such units in commercial refrigeration applications are available in literature (Azzolin, Cattelan et al. 2021). In addition, the use of vapour or liquid ejectors, depending on the specific setup, has been suggested and implemented in novel fully integrated configurations to support efficiently the integration of all the demands (Pardiñas, Hafner et al. 2018, Gullo 2019).

These technological advancements increase the investment cost and the level of complexity of the units, hindering their implementation. The novel configuration presented in this work, named Ejector for the World, is aimed at simplifying the layout of a fully integrated CO_2 system, while maintaining all the

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improvements in energy performance given by the ejector implementation, namely reducing CAPEX and OPEX. This paper describes first the Ejector for the World concept, based on a different operation of the ejector depending on ambient temperature. It continues with the description of the experimental setup of NTNU/SINTEF laboratory in Trondheim (Norway) used for the experimental system performance evaluation. Later on, a brief analysis of the collected field data and its validation is presented. Finally, the performance of the ejector and of the whole unit under different operating conditions are presented, discussed, and compared with the performance of traditional booster and parallel compression configuration systems.

2. EJECTOR FOR THE WORLD CONCEPT

Ejector for the World concept is an adaptation of an ejector-supported booster system, focused on simplifying state-of-the-art solutions which accommodate ejectors, parallel-compression, flooded evaporation, etc., while keeping the efficiency enhancement inherent to these technologies. Figure 1 shows a simplified diagram of proposed novel system structure, which is based on a CO_2 booster system with two compressor groups: an LT compressor group serving the load from the LT evaporators and an MT compressor group serving the cooling load from the MT evaporators, the liquid receiver vapour fraction and the discharge of LT compressors. The proposed configuration involves the ejector as a part of the system throughout the year and under any ambient temperature conditions. Consequently, flooded MT evaporation with elevated evaporation temperature can be achieved without risk of liquid hammering of MT compressors, which are always connected to the liquid receiver (functioning also as a suction accumulator).

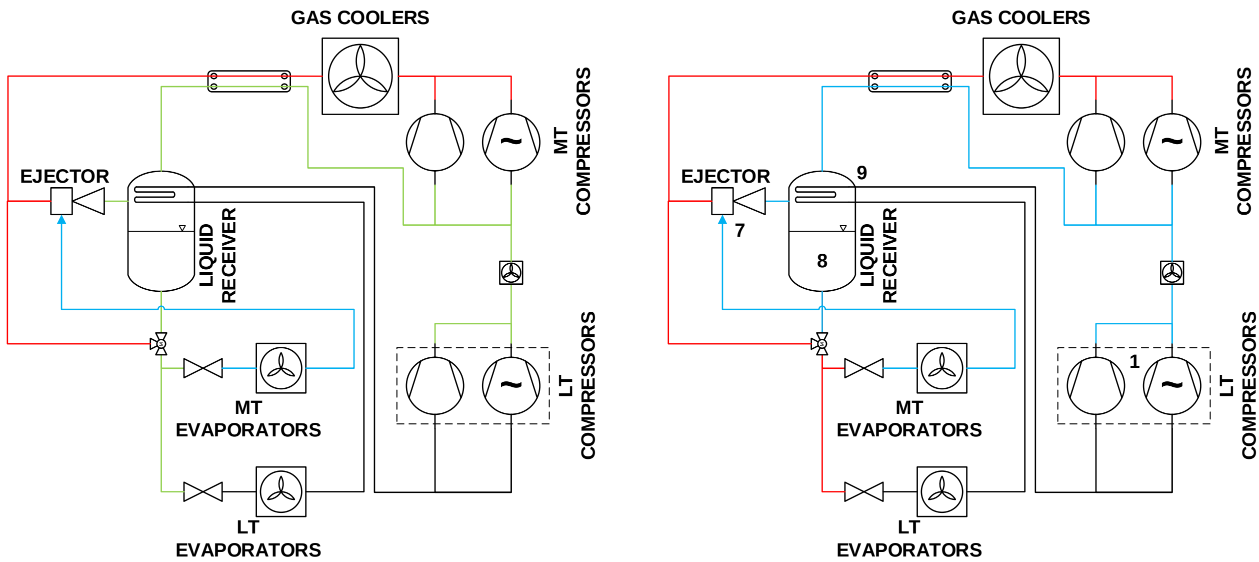

Figure 1. Ejector for the World concept. Left, operation in summer mode. Right, operation in winter mode.

During operation in moderate to elevated ambient temperatures (summer mode, Figure 1 left), the system runs as a classic ejector cycle in transcritical conditions. The ejector acts as the high-pressure control device according to a control algorithm for optimal high-side pressure depending on the outlet temperature of the gas cooler. The ejector is used in a conventional manner to lift the suction pressure of the MT compressor group from the MT evaporation temperature to the pressure of the liquid receiver. The pressure lift achieved by the ejector needs to be sufficient to supply liquid refrigerant from the liquid receiver to the individual expansion valves upstream of the MT evaporators. At low ambient temperatures (winter mode, Figure 1 right), the system is basically a subcritical CO_2 system with low pressure receiver (suction accumulator). The ejector is operated passively and functions as a check valve between the MT evaporators and the liquid receiver. The motive side of the ejector is closed, and liquid refrigerant is supplied to the individual MT and LT evaporators directly from the gas cooler outlet. The high-pressure control is then a consequence of the operation of the expansion valves upstream of the evaporators and the gas cooler outlet conditions. The ejector is a part of the system configuration in all operational conditions, simplifying the overall layout while still retaining the benefits of ejector-supported operation and flooded MT evaporators. For further

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discussions and comparison with more conventional CO_2 system configurations, the following abbreviations are established: Booster System (BS), Parallel Compression supported booster system (PC), Ejector for the World concept Summer Mode (EW SM), Ejector for the World concept Winter Mode (EW WM).

3. EXPERIMENTAL EVALUATION

3.1. Experimental setup

Figure 2 shows a simplified diagram of the experimental setup used, which consists of the CO_2 refrigeration system and several auxiliary circuits. It is versatile and allows experiments to be performed with different system configurations (booster, parallel compression, ejector supported parallel compression, etc.) and for a wide range of operating conditions. A more detailed explanation can be found in (Pardiñas, Hafner et al. 2018).

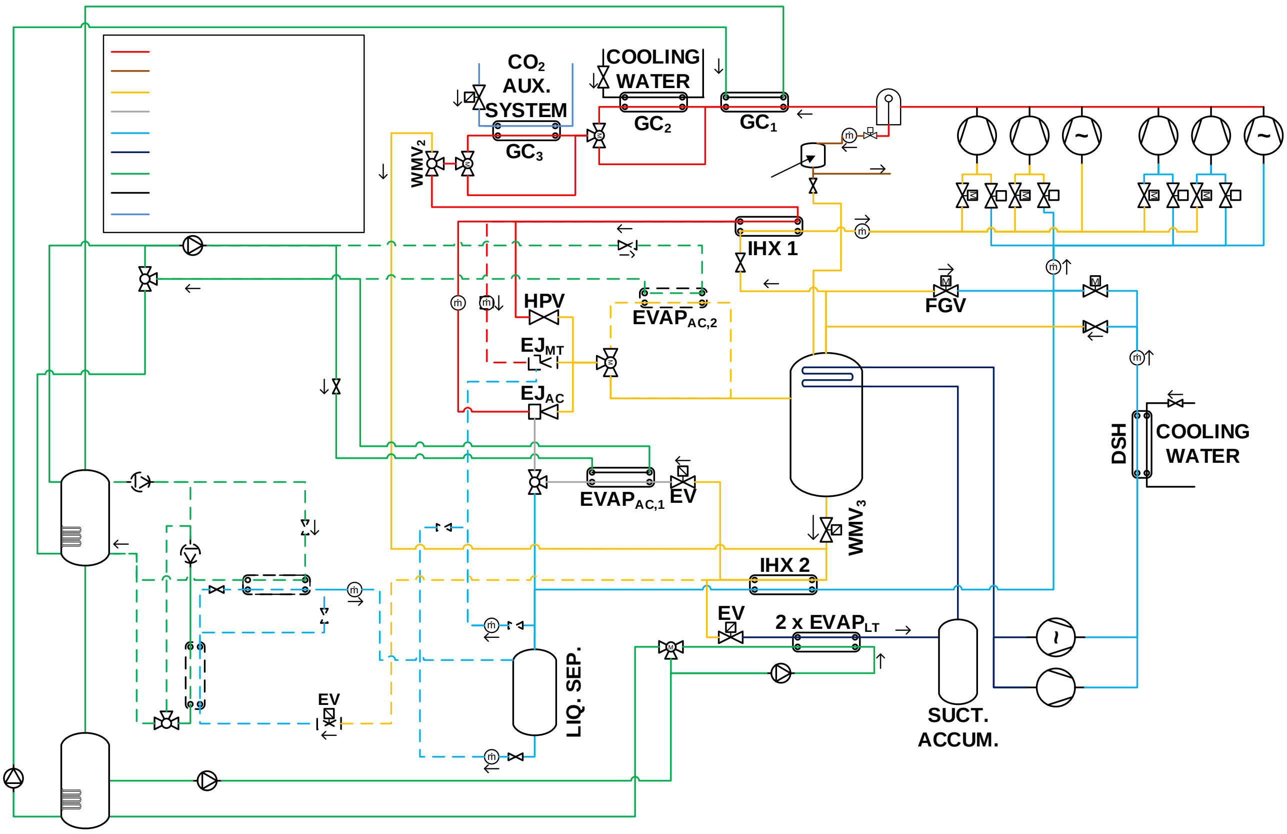

Figure 2. Simplified diagram of the refrigeration system and secondary loops in NTNU/SINTEF laboratory (Trondheim, Norway). Dashed lines and components were not in use during this test campaign.

Eight semi-hermetic piston compressors are installed in the unit (Table 1), all of them manufactured by Bitzer (Bitzer Kühlmaschinenbau GmbH, Sindelfingen, Germany). Table 1 indicates how the compressors were arranged as a function of the system configuration tested.

The high-pressure side of the test facility consists of three gas coolers (plate heat exchangers) that reject heat at different temperature levels against glycol, ice water and an auxiliary R744 refrigeration system, depending on the gas cooler outlet temperature required for each test. WMV_2, is a three-way valve located downstream of the gas coolers that, in combination with the closing of WMV_3, allows changing between summer mode and winter mode in Ejector for the World configuration. Concerning the high-pressure control devices, two of the alternatives were used: the high-pressure valve (HPV) in booster system (BS) and parallel compressor supported (PC) configurations, and the low pressure lift Multi Ejector (LP 935) EJ_{AC} in the Ejector for the World (EW) configuration. Further information about the Multi Ejector can be found (Kalinski 2019).

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Table 1. Characteristics of the compressors utilised in the setup. System configurations nomenclature: Ejector for the World (EW), booster system (BS) or parallel supported booster system (PC).

Model	Name	Swept volume [$m^3 \cdot h^{-1}$] at 50 Hz	Inverter driven?	Configurations
2JME-3K	LT_1	3.5	Yes	All
2GME-4K	LT_2	5.0	No	None
4MTC-10K-40S	MT_1	6.5	Yes	BS, PC
	MT_2		No	BS, PC
2KTE-7K-40S	PAR_1	4.8	Yes	EW, PC
	PAR_2		No	EW
4JTC-15K-40P	MT_3 /	9.2	No	EW, BS
	PAR_3		No	None

Downstream of the high-pressure control devices is the liquid receiver, which in Ejector for the World (EW) configuration operated also as suction accumulator. Liquid CO_2 from the bottom was fed to the MT and LT evaporators under all configurations except EW in winter mode, when liquid would come directly from the gas coolers as mentioned above. The control of the conditions (pressure) in the receiver was different depending on the system configuration tested. In BS it was controlled by the flash-gas bypass valve (FGV) opening degree, throttling vapour back to the MT compressors. In PC by the capacity control (inverter) of the parallel compressor. In EW system configuration, the liquid receiver pressure was a consequence of the control of MT evaporation pressure, which was achieved adjusting the MT compressor capacity (inverter + number of compressors in operation). The difference between MT and liquid receiver pressure levels would be the Multi Ejector pressure lift.

$EVAP_{AC,1}$ was used as MT evaporator in this test campaign instead of the dedicated MT evaporators already installed in the system for two reasons. First, because it was already connected to the low-pressure lift (high entrainment ratio) Multi Ejector needed for EW configuration. Second, because it was possible to avoid any influence of the liquid separator in Ejector for the World configuration. For the sake of fairness in the comparison, also $EVAP_{AC,1}$ was utilized in the BS and PC by shifting the position of the three-way valve, disconnecting the evaporator from the Multi Ejector and leading the refrigerant to the MT compressors.

One of the LT evaporators available in the system was sufficient to meet the LT load intended in this test campaign. The stream from the LT evaporators in the system, after superheated and compressed by the LT compressors, was desuperheated in DSH to a temperature between 20 °C and 30 °C. Then, the refrigerant stream was directed either to the MT compressors in BS and PC system configurations, or joined the stream of vapour from the liquid receiver in EW configuration.

The data acquisition system of the experimental setup is based on a combination of two solutions, which data are synchronized for data processing. The first is based on Danfoss controllers (sampling rate of 5 s), logging data from industrial quality sensors while controlling the system components according to these measurements and the different setpoints. The second is based on LabVIEW (sampling rate of 1 s), which retrieves data from more precise measurement equipment and adjusts the conditions of the secondary loops (glycol, water, and auxiliary CO_2 loop) to establish the boundary conditions for the main refrigeration system (in terms of cooling and freezing loads or operating temperatures). Since the data analysis was based on LabVIEW sensors, only these are listed in Table 2.

Table 2. List of measurement equipment and accuracy.

Type	Manufacturer and model	Accuracy
Mass flow meters	Rheonik RHM	±0.2 % of reading
Pressure transducers	Endress+Hausser PMP21	±0.3 % of set span
Differential pressure transducers	Endress+Hausser PMD75	±0.035 % of set span
Temperature sensors	Pt 100 Class B DIN 1/3 on tube	±1/3(0.3 K + 0.005*temp(°C))
Volumetric flow meter	Endress+Hausser Picomag	±(0.8 % of reading + 0.2 % of set span)
Active power meter (compressors)	Schneider Electric A9MEM3150	±1 % of reading

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3.2. Test conditions

The aim of the study presented in the current paper is a proof-of-concept of the novel ejector-based CO_2 refrigeration system by carrying out an experimental test campaign. The successful operation of the system must be proven in both summer and winter modes, with relevant loads set at MT and LT levels under different operational conditions. The selected test conditions for the experimental campaign are as shown in Table 3. It is worth pointing out that, even if the MT expansion valve operated according to superheat, the evaporator was performing very close to saturated vapour at its outlet, as could be observed at the sight glass located downstream of the MT evaporator.

Table 3. Test conditions for Ejector for the World

Parameter	Range	Observations
MT loads [kW]	18 / 24 / 30	Share MT to LT load equal to 3, 4 and 5
MT evaporation temperature [°C]	-2	Expansion valve control: Summer Mode, superheat @ 5 K setpoint; winter mode, low superheat and subcooling at gas cooler outlet ≈ 1 K
LT loads [kW]	6	
LT evaporation temperature [°C]	-25	Expansion valve control: Superheat @ 8 K setpoint
Gas cooler outlet temperature [°C]	10 / 15 / 20 / 25 / 30 / 35 / 40	Covers cold and warm climate regions
Desuperheater temperature [°C]	20 / 20 / 20 / 25 / 30 / 30 / 30	Shown according to the gas cooler temperatures above

In addition, the performance of the novel system is then compared to a conventional CO_2 booster system (BS) and parallel compressor supported system (PS) by performing test campaigns considering: the same ranges of gas cooler outlet and desuperheater temperatures as in the table, same LT evaporation temperature, expansion valve control and load, MT load at 30 kW with evaporation temperature at -8 °C and expansion valve control with 10 K superheat, and liquid receiver pressure setpoint 41 bar.

4. DATA ANALYSIS AND VALIDATION

The loads at the different evaporators in operation were calculated for both the CO_2 side and the glycol side, following Eq. (1) and Eq. (2), respectively. The enthalpies for the refrigerant were found using the REFPROP 10 database (Lemmon, Bell et al. 2018), while the properties of the glycol (DowCal 200, 30%) were taken from the ASHRAE Handbook Fundamentals (2009) (ASHRAE 2009). A comparison between CO_2 and glycol side cooling loads revealed a very good agreement whenever the liquid line (CO_2) stream was slightly subcooled, and an underdetermination of the CO_2 mass flow rate when it was not subcooled, showing that the liquid line Coriolis mass flow meter is very sensitive to two-phase flow. Consequently, the loads obtained by calculation from the glycol parameters were used for the rest of the study.

$$\dot{Q}_{\text{ref, evap}} = \dot{m}_{\text{ref, evap}} \cdot (h_{\text{ref,out,evap}} - h_{\text{ref,in,evap}}) \quad \text{Eq. (1)}$$

$$\dot{Q}_{\text{glycol,evap}} = \dot{V}_{\text{glycol,evap}} \cdot \rho_{\text{glycol}} \cdot cp_{\text{glycol}} \cdot (T_{\text{glycol,in,evap}} - T_{\text{glycol,out,evap}}) \quad \text{Eq. (2)}$$

The Energy Efficiency Ratio (EER) was chosen as the system performance indicator to compare the different system configurations. The EER is the ratio of useful cooling output produced (MT and LT) to the amount of work spent by the compressors and is presented in Eq. (3). P_{comp} is the total power consumption of the compressors in the system. A higher EER represents a more effective system i.e., providing the required cooling and requiring less power to the compressors.

$$EER = \frac{\dot{Q}_{\text{MT}} + \dot{Q}_{\text{LT}}}{P_{\text{comp}}} \quad \text{Eq. (3)}$$

The performance of the Multi Ejector was defined with ejector efficiency, as shown in Eq. (4) (Elbel and Hrnjak 2008). ϕ_m is the mass entrainment ratio of the ejector, which is the ratio of the mass flow rate on the suction side of the ejector (secondary flow) to the mass flow rate at the motive nozzle (primary flow).

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$$\eta_{ej} = \phi_m \cdot \frac{h_{s(suct),p(disc)} - h_{suct}}{h_{mot} - h_{s(mot),p(disc)}} \quad \text{Eq. (4)}$$

Two critical factors proving the successful operation of the novel system concept are the obtained pressure lift from the ejectors during summer mode and the pressure drop over the ejector during winter mode as a result of being operated as a check valve. Figure 3 shows the pressure lift of the ejector during operation in summer mode (left) and pressure drop over ejector during operation in winter mode (right). For both cases, the pressure differential between the discharge port and the suction port of the ejector is obtained by a differential pressure sensor. A successful validation of these measurements was achieved by comparing them with the differences between the MT suction pressure sensor (ejector discharge) and the MT evaporation pressure sensor (ejector suction). From Figure 3 (left) it can be seen that there is a near-linear trend of increasing pressure lift of the ejector with increasing gas cooler outlet temperature, ranging from around 1.3 bar at 20 °C up to about 6 bar at 40 °C. For winter operation (Figure 3, right), the pressure drop from the suction port to the discharge port of the ejector is below 0.1 bar for all test conditions, which is clearly acceptable.

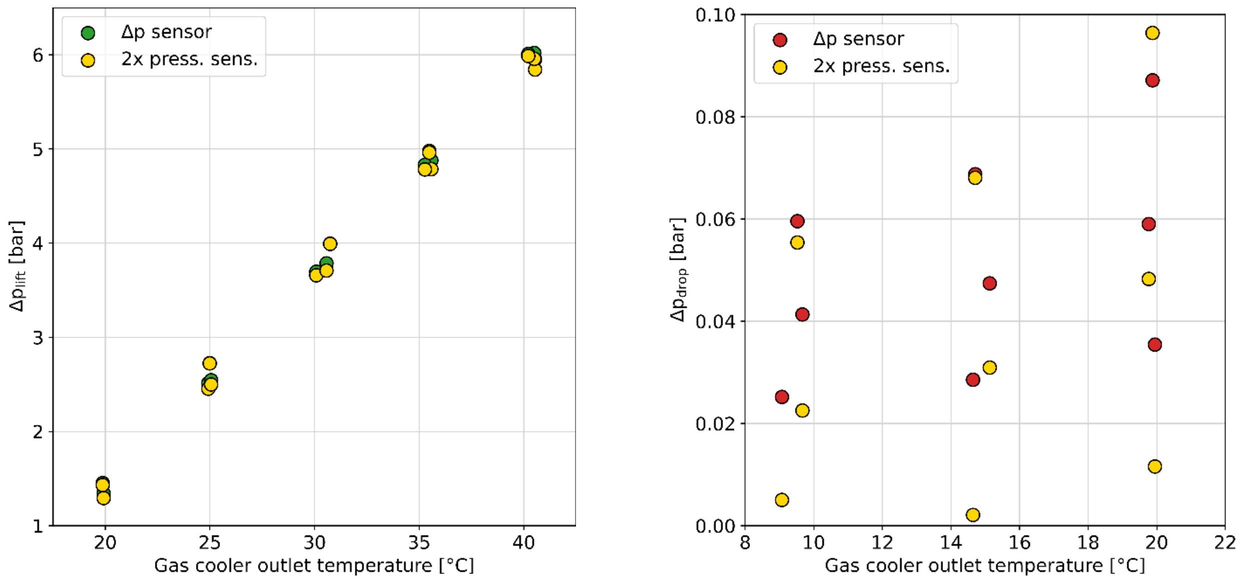

Figure 3. Pressure lift of the ejector during operation in summer mode (left) and pressure drop over ejector during operation in winter mode (right).

5. RESULTS

The first part of this section will focus on the performance of the ejector operation specifically, while the second part will concern the general system performance. Figure 4 presents the ejector performance in summer mode (active operation) as a function of the gas cooler outlet temperature. Figure 4 (left) shows the entrainment ratio of the ejector under various gas cooler outlet temperatures and for increasing mass flow rates at the suction port. It can be observed that the entrainment ratio decreases nearly linearly from about 0.63 at 20 °C to about 0.42 at 40 °C, while there was an increase of pressure lift of the ejector for the same range of gas cooler outlet temperatures (Figure 3, left). Consequently, there is a trade-off between the achievable pressure lift of the ejector and the obtained mass entrainment ratio. The results also indicate that the higher MT load slightly increases the entrainment ratio, up to a maximum of 0.05 from the lowest MT load (18 kW) to the highest MT load (30 kW).

The ejector efficiencies for various gas cooler outlet temperatures and mass entrainment ratios are represented in Figure 4 (right). Here it can be observed that the ejector efficiency is low at high gas cooler outlet temperatures and increasing up to the maximum value of about 0.27 at 25 °C. The ejector efficiency is proportional to the entrainment ratio according to Eq. (4), and Figure 4 (right) confirm that the optimum efficiency is found in the trade-off between mass entrainment ratio and the obtained pressure lift of the

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ejector. For a gas cooler outlet temperature of 20 °C, the ejector efficiency drops significantly due to achieving a pressure lift of only about 1.3 bar, although the entrainment ratio is the highest among all tests.

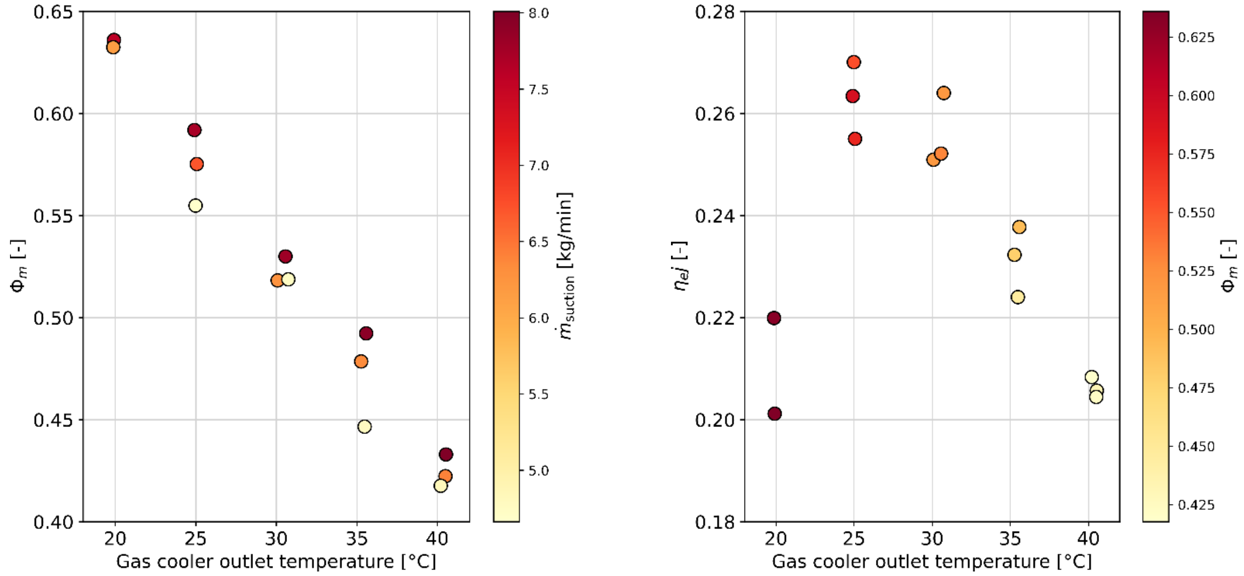

Figure 4. Ejector performance under various gas cooler outlet temperatures in summer mode. Ejector entrainment ratio (left) and ejector efficiency (right).

The system performance, EER, of the novel concept for various gas cooler outlet temperatures is presented in Figure 5. On the left side in Figure 5, the EER for the novel system operating in both winter mode and summer mode is presented as a function of the gas cooler outlet temperature and various MT loads. As expected, the EER decreases for increasing gas cooler outlet temperature (increasing high-side pressure) due to the increase in the pressure ratio that the MT compressors are operating. At a gas cooler outlet temperature of 20 °C, both summer mode and winter mode are tested. It can be observed that the system performs slightly better in the summer mode configuration compared to winter mode configuration for this temperature of summer mode performs better than the corresponding winter mode. However, it is noted from Figure 3 (left) that the pressure lift of the ejector is very limited at this temperature, and some pressure difference is required to supply successfully liquid through the individual MT expansion valves. The drawback of the winter configuration at this gas cooler outlet temperature is mainly the direct expansion of refrigerant into the MT and LT evaporators from the high-side pressure, forming significant amount of flash gas. For the summer mode, the refrigerant is first expanded to the liquid receiver pressure by the ejector and the flash gas is handled at a higher pressure compared to the winter mode. A EER of up to 5.7 is observed for the highest MT load conditions. A higher share of MT load to LT load results in a higher EER for all gas cooler outlet temperatures tested in this study.

To benchmark the performance of the novel CO_2 system concept, a comparison between more conventional CO_2 booster configurations, namely booster system (BS) and parallel-compression supported (PC), and the novel Ejector for the World (EW) in summer mode (SM) and winter mode (WM) is shown on the right side of Figure 5. The conditions chosen for comparison were MT load and LT load of 30 kW and 6 kW, respectively. The performance benefit for the PC system over the BS configuration is clear from 30 °C and higher. Comparing the EER of the novel concept in summer mode (active ejector) to the BS and PC configuration, there is a clear improvement for all gas cooler outlet temperatures in the range of 20 °C to 40 °C. At an outlet gas cooler temperature of 25 °C, the improvement in EER is around 15 % compared to the conventional BS configuration. This is within the range of COP improvements reported in other experimental campaigns (Gullo, Hafner et al. 2018). Regarding operation of the novel system configuration in winter mode, there are large improvements in EER compared to the BS configuration that increase with decreasing gas cooler outlet temperatures. The reason for the improvement is mainly due to the MT evaporators being operated in flooded condition and at higher evaporation temperature. Additionally, the drawback of expanding directly from the high-side pressure to the MT and LT evaporation pressure for the EW WM system compared to the

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receiver pressure in the BS configuration becomes less critical at lower gas cooler outlet temperatures. At 10 °C gas cooler outlet temperature, the improvement over the BS configuration is 38 %. It is worth mentioning that results in the graphs are determined based on averaged values of the measurements recorded during a period of at least 15 minutes at steady state conditions. An uncertainty analysis based on propagation of uncertainties was performed following the recommendations in JCGM (2008). Considering a coverage factor equal to 1, the relative uncertainty (uncertainty divided by average value for each test condition) for the EER was in most cases below 5 %, and only one test had a relative uncertainty above 10 %.

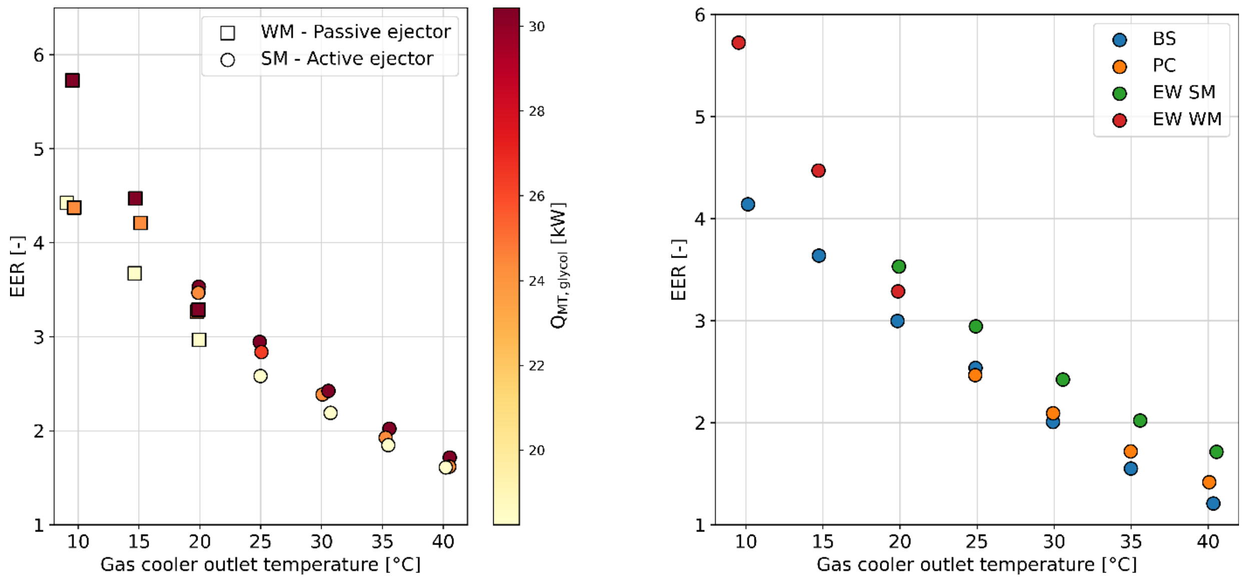

Figure 5. System performance for the novel concept under various gas cooler outlet temperatures for summer and winter mode. EER depending on MT load (left) and EER comparison with conventional system configurations (right) BS = Booster System, PC = Parallel Compression supported booster system, EW SM = Ejector for the World concept Summer Mode, EW WM = Ejector for the World concept Winter Mode.

6. CONCLUSIONS

This paper has presented the novel Ejector for the World concept – a simplified ejector-supported CO_2 booster refrigeration system that still maintains the benefits of implementing ejectors in the system. During operation in transcritical mode at high ambient temperatures (summer mode), the ejector lifts all the evaporated refrigerant in the MT evaporators to the liquid receiver pressure. During operation in subcritical conditions at low ambient temperatures (winter mode), the ejector functions as a check valve for the refrigerant to flow from the MT evaporators to the liquid receiver, which operates as suction accumulator and enables the MT evaporators to run in flooded condition with elevated evaporation pressure. The basic version of the proposed system configuration is tested experimentally, and it is proven that the novel concept outperforms the conventional booster system and parallel compression supported booster system under any conditions. The pressure lift achieved by the ejector during summer mode is sufficient to supply the individual evaporators in the system with liquid refrigerant, while the pressure drop over across the ejector during winter mode is negligible for practical applications with less than 0.1 bar. The novel concept shows improvement in EER up to 40 % compared to conventional CO_2 booster systems, depending on the gas cooler outlet temperature. Further experimental work on the topic will focus on i) adapting conventional system controllers to this new configuration, particularly in winter mode, so that the system follows different load profiles and switches between summer and winter mode, and ii) monitoring oil management.

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dedicated projects supporting the Indian refrigeration and Air Conditioning sector in the transition towards more environmentally friendly technology.

NOMENCLATURE

BS	booster system		$\dot{m}$	mass flow rate (kg s^{-1})		s	entropy (J kg^{-1} K^{-1})	
comp	compressor(s)		mot	motive		SM	summer mode	
c_p	spec. heat cap. (J kg^{-1} K^{-1})		MT	medium temperature		suct	suction ejector	
disc	discharge ejector		out	*outlet*		T	temperature (K, °C)	
ej	ejector		p	pressure (Pa)		$\dot{V}$	volumetric flow rate (m^3 s^{-1})	
evap	evaporator		P	power (W)		WM	*winter mode*	
EW	Ejector for the World		PC	parallel-compression supported		η	efficiency (-)	
h	specific enthalpy (J kg^{-1})		$\dot{Q}$	load (W)		Φ_m	mass entrainment ratio (-)	
in	inlet		ref	refrigerant (R744)		ρ	density (kg m^{-3})	
LT	low temperature							

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