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New capacity control technique for two-phase ejectors in transcritical CO_2 condensing units: Preliminary experimental outcomes

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Abstract

With the ever-growing need for climate change mitigation, CO_2 as the sole refrigerant (R744) has become an appealing future-proof option for several refrigeration and heat pump solutions. Currently transcritical CO_2 systems offer, by far, the best energy and environmental performance in various medium- and large-capacity applications, provided that some of the available expansion work is recovered via two-phase ejectors. However, although similar benefits are expected for small-scale units (e.g. condensing units), at present no appropriate capacity control strategy is available for two-phase ejectors in these solutions. The aim of this work is to bridge this knowledge gap by presenting the first experimental results related to an innovative capacity control technique for two-phase ejectors in transcritical CO_2 condensing units. The novel capacity control methodology is based on the pulse-width modulation (PWM) of the refrigerant flow through the ejector. At the compressor speed of 40 Hz, water temperature at the gas cooler inlet of 35 °C and ethylene glycol temperature at the evaporator inlet of 5 °C, it was found that the high pressure and the cooling capacity can be increased by up to about 20 bar and 17%, respectively. Furthermore, at the optimal operation condition the solution relying on the PWM ejector offered an increase in coefficient of performance (COP) by 14% compared to the unit with passive ejector and by about 29% over the standard system. In addition to the encouraging results obtained, the proposed strategy features low cost, simplicity, low vulnerability to clogging, no need to vary the nozzle throat area for flow control and major potential than its currently available competitors. Having no practical size or application constraints, the suggested capacity control mechanism could possibly lead to lay robust foundations for a significantly more sustainable future in the whole cooling and heating sector.

1 Introduction

Small-format stores, such as grocery and convenience stores, are energy-consumptive applications. Their energy use intensity, in fact, is above 2000 $kWh \cdot m^{-2}$ sales area per year, being significantly higher than that of hypermarkets (i.e. about 700 $kWh \cdot m^{-2}$ sales area per year) [1]. In order to achieve global sustainability targets, particular attention needs to be devoted to the efficiency enhancement of their refrigeration system (i.e. condensing units), which is responsible for 30% to 60% of the electricity used [1]. The need for energy saving in refrigeration applications is even more exacerbated in high ambient temperature countries, where the warm climate represents a considerable challenge for refrigeration technologies. In addition to great energy efficiency, the adoption of low global warming potential (GWP) refrigerants in the refrigeration sector is compulsory nowadays. However, the identification of the most suitable long-term working fluid complying with both the safety and the energy efficiency requirements (i.e. future-proof solution) is still matter of intense debate among experts. In fact, safety on flammability and toxicity is generally imperative in small-format stores, being the refrigeration units easily accessible by the public and the refrigerant charge relatively high.

Two-phase ejectors have emerged as one of the key drivers of ever-wider global approval of CO_2 as the sole working fluid in medium- and large-capacity commercial refrigeration systems [2]. CO_2 is a well-known refrigerant, being virtually ideal from an environmental and safety perspective (i.e. negligible GWP, zero Ozone Depletion Potential, non-toxic, non-flammable). This means that this working fluid will never be subject to any future regulatory liability. Its main drawback, i.e. low energy efficiency at high cooling medium temperatures, can be overcome by recovering part of the available expansion work with the aid of two-phase ejectors [2]. As an example, Nakagawa et al. [3] experimentally experienced a maximum COP enhancement of 27% compared to a conventional CO_2 system at the on-design operation condition. However, the energy benefits from the use of a two-phase ejector are lost, as the ejector capacity is not effectively controlled [4,5], i.e. as both capacity and heat sink temperature substantially vary (i.e. at off-design operation conditions). These running modes are typical for commercial refrigeration applications. The experimental work by Nakagawa et al. [3] also revealed that the system and ejector performance off-design penalties can be quantified as COP decreases of up to 82% and an ejector efficiency reduction of 12% as the gas cooler pressure is 1.25÷1.50 MPa below the optimal operating condition. In order to overcome this drawback and to the best of the authors' knowledge, three capacity control techniques for two-phase ejectors have been implemented. Firstly, the needle-based capacity control mechanism was formulated [6,7]. However, this solution features complicated and costly design and significant vulnerability to clogging [5]. Recently, Zhu and Elbel [5] developed a simpler, possibly less expensive and more reliable technique, i.e. vortex ejector. Nevertheless, it was found that the vortex ejector presents similar or slightly lower performance than the needle-based ejector, although it is still under development. The third option is the multi-ejector concept [8], which is currently leading to a considerable spread of transcritical CO_2 refrigeration systems in medium- and large- applications (i.e. mainly supermarkets) operating in warm climates [2]. However, the multi-ejector arrangement is too complex [9], costly and limited by manufacturing size to be successfully employed in small-capacity systems. Therefore, it is necessary to formulate new capacity control techniques for small-capacity CO_2 vapour-compression systems equipped with two-phase ejectors [10]. This challenge is even more arduous for transcritical CO_2 solutions, since in these applications a two-phase ejector needs to simultaneously be able to recover some of the available expansion work effectively and control the discharge pressure properly.

The target of this work is to fill the aforementioned knowledge gap by presenting the first experimental outcomes associated with a novel control mechanism for two-phase ejectors in a transcritical CO_2 condensing unit. The new capacity control technique is based on the pulse-width modulation (PWM) of CO_2 flow through the ejector. Firstly, the PWM ejector performance has been evaluated. Secondly, this has been compared with the performance of both a passive ejector (i.e. with no capacity control strategy) and a standard CO_2 system (i.e. with flash gas by-pass valve and without ejector). All the assessments have been carried out at the compressor speed of 40 Hz, water temperature at the gas cooler inlet of 35 °C and glycol temperature at the evaporator inlet of 5 °C, leading to a CO_2 evaporating temperature of about -5.5 °C (value characterizing commercial refrigeration applications).

2 Methodology

2.1 Experimental facility

The experimental facility, which is sketched in Figure 1, is equipped with a Dorin CD180H compressor with a variable speed drive (ABB ACS150) and a power analyser (Voltech PM3000A, accuracy: 0.1% of reading). The latter is installed between the drive and the compressor, meaning that the losses related to the variable speed drive in the readings have not been considered. Brazed plate heat exchangers manufactured by SWEP were employed as the evaporator (B17Hx16/1P) and the condenser/gas cooler (B17Hx10/1P). The experimental facility is also outfitted with a suction line heat exchanger (SLHX), being 50 cm stainless steel tubes tin-soldered together. The two-phase ejector is the smallest cartridge installed into the multi-ejector block (motive nozzle/mixing chamber = Ø0.71/Ø2.30 mm). At the inlet of the evaporator, a Danfoss AKV expansion valve relaying on the PWM working principle was adopted. Also, Danfoss ETS stepper-motor valves were employed as the high pressure valve and the vapour by-pass valve. The CO_2 mass flow rate at the high pressure side was measured with the aid of a Coriolis type mass flow meter (Micro Motion DS012, accuracy: 0.2% of reading), which was installed downstream of the SLHX. All the pressure sensors (accuracy: 0.3% of 160 bar) and the temperature sensors (accuracy: ±(0.3+0.005×T in °C)) were provided by Danfoss A/S. Furthermore, the receiver presents a differential pressure transmitter to measure the liquid level. Two Titan turbine flow meters were used in the experimental facility. One had the purpose of measuring the volumetric flow of the water flowing through the condenser/gas cooler (accuracy: 0.36% of 6.5 $l \cdot min^{-1}$), while the other was employed for evaluating the volumetric flow of the ethylene glycol-water (35/65%) mixture flowing through the evaporator (accuracy: 0.74% of 15 $l \cdot min^{-1}$), respectively. An Agilent data logger was employed for logging temperatures, pressures, etc., while Danfoss controllers were used for logging and monitoring the controlled variables. Finally, National Instruments cDAQ module 9411 was utilized for counting the volume flow meters. Inlet temperatures of water and ethylene glycol were respectively controlled with the aid of a 3-way valve and an electric heater, whereas the flows were controlled by 2-way valves.

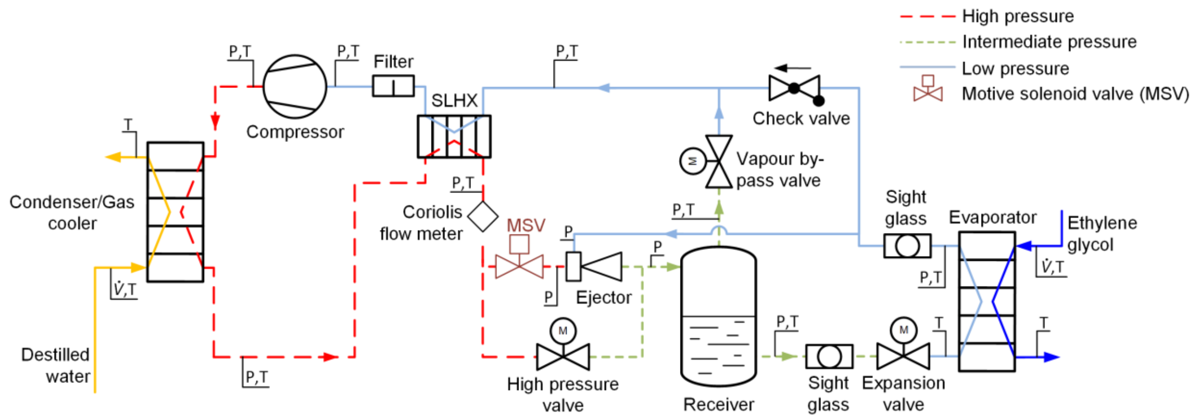

Figure 1: Schematic of the experimental facility (colour/dash for ejector mode, hand-operated valves omitted)

The experimental facility can be used in either ejector mode or standard mode. In ejector mode, the refrigerant is condensed/cooled down in the condenser/gas cooler and subcooled in the SLHX before expanding in the two-phase ejector (motive nozzle stream). Consequently, CO_2 is entrained from the evaporator (suction nozzle stream) and thus pre-compressed to an intermediate pressure (i.e. receiver pressure). This leads to a higher suction pressure of the compressor and thus to a better performance compared to the solution without the ejector. From the receiver, the refrigerant is split into its liquid and vapour components. The liquid stream is isenthalpically expanded and evaporated in the evaporator, providing the required cooling capacity. The vapour is superheated in the SLHX before it is drawn by the compressor. In standard mode, CO_2 leaving the condenser/gas cooler is subcooled in the SLHX and then isenthalpically expanded in the high pressure valve. The resulting liquid/vapour mixture is separated in the receiver: the liquid is evaporated in the evaporator, whereas the vapour is isenthalpically expanded through the vapour by-pass valve. Finally, the two streams are mixed and further superheated in the SLHX before being drawn by the compressor. Further details regarding the test rig can be found in the work by Kærn et al. [11].

2.2 PWM concept

The PWM methodology has been widely used in expansion valves by Danfoss A/S in various refrigeration, air conditioning and heat pump applications. An expansion valve is regulated by means of the PWM concept as follows:

- within a period (i.e. PWM period) of generally 3÷6 seconds, a voltage signal from the controller is transmitted to and removed from the valve coil, leading respectively to its opening and closing (i.e. to the flow of the refrigerant through the expansion valve or not);
- the relation between the opening and closing time of the valve coil determines the provided cooling capacity.

Thus, taking the case of 3 seconds as the PWM period into account, if it is necessary the full capacity, the valve coil will remain open during the aforementioned 3 seconds. As it is needed to provide 67% of the full capacity, the valve coil will be open for about 2 seconds out of 3 seconds (i.e. about 67% of 3 seconds) and will be closed for about the following 1 second. In case of 33% of the full capacity is required, the valve coil will remain open for about 1 second out of 3 seconds and will be closed for about the following 2 seconds.

The same principle described above was applied to the motive solenoid valve (MSV) installed upstream of the ejector (see Figure 1). In the current work, the time period of the PWM ejector and that of the AKV expansion valve were 2 seconds and 3 seconds, respectively. The time periods cannot to be too fast to ensure the lifetime of the check valve. In addition, this period of time avoided too slow PWM, which could result in large transients, deteriorate system stability and result in spurious system level pressure oscillations. Referring to Figure 1, the suction check valve ensured that the pressure lift was not short-circuited upon closing.

2.3 Data reduction

The data reduction in terms of COP (Eq.(1)) was based on the energy balance equations at steady state conditions as well as on the heat absorption occurring in the secondary side of the evaporator. The motive nozzle, suction nozzle and diffuser pressures, whose sensors were mounted directly on the ejector housing, were logged at 1000 Hz, while the remaining data were logged at every 2.5 seconds for 5 consecutive minutes (steady state temperature tolerance = ±0.2 °C, steady state wait time = 60 s) and then averaged over the collection period.

$$COP = \frac{\dot{Q}_{eg,evap}}{\dot{W}_{compressor}} = \frac{\dot{V}_{eg} \cdot \rho_{eg} \cdot \left(h_{eg,evap\,in} - h_{eg,evap\,out}\right)}{\dot{W}_{compressor}} \tag{1}$$

The ejector efficiency was computed by using Eq.(2), as suggested in [6]. Also, the pressure lift and the mass entrainment ratio (Φ_m) referred to the pressure difference between the diffuser outlet and the suction nozzle inlet and to the ratio of the suction nozzle mass flow rate to the motive nozzle mass flow rate, respectively.

$$\eta_{ejector} = \Phi_m \cdot \frac{h\left(p_{diff\,out}, s_{sn\,in}\right) - h_{sn\,in}}{h_{mn\,in} - h\left(p_{diff\,out}, s_{mn\,in}\right)} = \frac{\dot{m}_{sn}}{\dot{m}_{mn}} \cdot \frac{h\left(p_{diff\,out}, s_{sn\,in}\right) - h_{sn\,in}}{h_{mn\,in} - h\left(p_{diff\,out}, s_{mn\,in}\right)} \tag{2}$$

Furthermore, the uncertainty propagation was evaluated by using Engineering Equation Solver (EES) [12]. Finally, it was found that the average discrepancy in terms of heat balance between CO_2 and the secondary fluids were of about 12.5% within the evaporator and 8.0% within the gas cooler. It is worth remarking that the large differences in the energy balance within the heat exchangers do not threaten the proof of the PWM ejector concept.

3 Results and Discussion

All the results presented in this Section were obtained at the compressor speed of 40 Hz, water temperature at the gas cooler inlet of 35 °C and glycol temperature at the evaporator inlet of 5 °C (i.e. CO_2 evaporating temperature of about -5.5 °C).

3.1 Results associated with the PWM ejector

The influence of the opening degree (OD) of the MSV on the motive nozzle, suction nozzle and diffuser outlet pressures of the ejector is showed in Figure 2, which indicate different time series stitched together. As an example, OD = 90% means that the MSV was closed for 10% of the PWM period (i.e. 0.2 seconds out of 2.0 seconds), whereas it was open for 90% of the PWM period (i.e. 1.8 seconds out of 2.0 seconds). The MSV closing resulted in fluid hammer phenomenon and, consequently, in pressure wave propagation downstream as the MSV opened. In addition, a decay of the diffuser outlet pressure, which was found to lead to the equalization with the suction nozzle pressure, was also experienced. However, as the MSV was opened, the pressure lift was reinforced (i.e. around 4 bar). Furthermore, it is essential to highlight that, despite the aforementioned pressure equalization, the compressor was still capable of drawing R744 from the intermediate pressure rather than from the low one. The lower the OD, the more marked the previous phenomena became. It is believed that the pressure drop between the diffuser and the receiver could result in the decay of the diffuser outlet pressure as the MSV is closed. Similarly, the suction pressure and receiver pressure seems to equalize possibly through the expansion device.

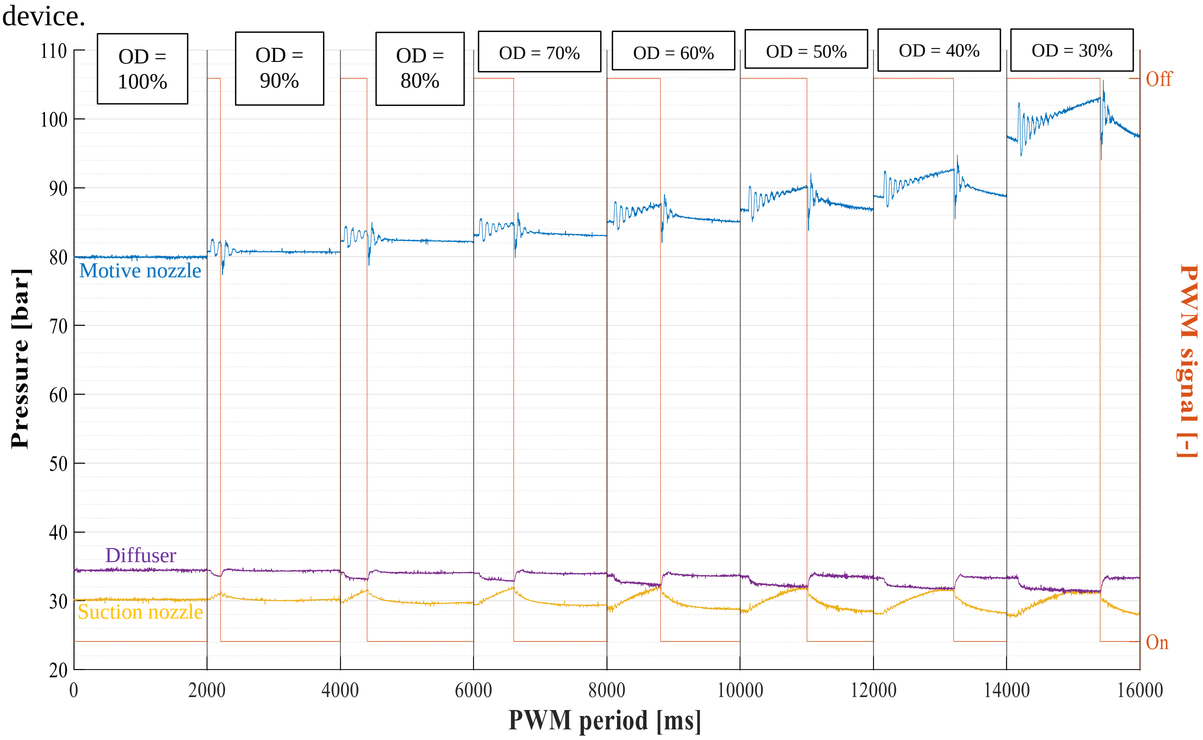

Figure 2: Influence of the opening degree (OD) of the MSV on the motive nozzle, suction nozzle and diffuser outlet pressures of the ejector (compressor speed = 40 Hz, $t_{water,gc\ in}$ = 35 °C, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

As showed by Lorentzen [13], transcritical CO_2 vapour-compression systems feature an optimum heat rejection pressure maximizing the COP with respect to the refrigerant temperature at the gas cooler outlet as soon as the transcritical regime is established. Therefore, it is of vital importance for transcritical CO_2 units that their high pressure is accurately controlled. This target is achieved with the aid of the high pressure valve in standard transcritical CO_2 systems, whereas the adoption of a two-phase ejector in transcritical CO_2 units need to contemporarily guarantee an appropriate expansion work recovery and an effective high pressure control. The results presented in Figure 3 (based on Eq.(1)) highlight that the high pressure can be varied from 79.89 bar with an OD of 100% (i.e. passive ejector) to 99.32 bar with an OD of 30%. Consequently, a COP of 1.63 was attained by using the passive ejector, whereas the use of the PWM ejector allowed obtaining the maximum COP of 1.85 at OD of 80% down to 1.58 at OD of 30%. Therefore, it could be claimed that the PWM ejector is capable of properly controlling the heat rejection pressure and permitting the system to accomplish the best COP at the evaluated operation condition. Also, it is worth highlighting that the low values of COP showed in Figure 3 were due to the use of an old compressor.

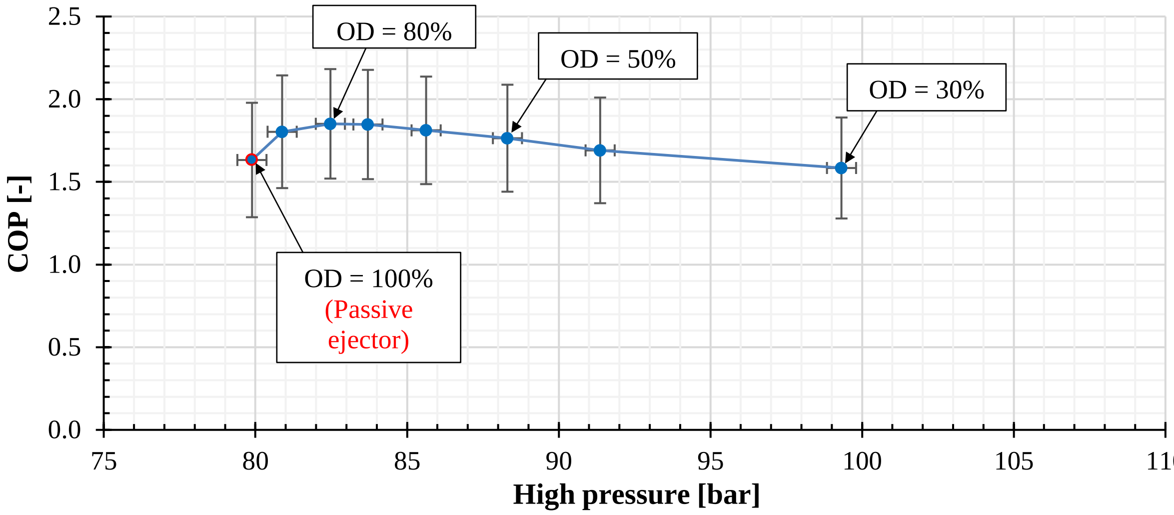

Figure 3: COP as a function of high pressure/opening degree (OD) (compressor speed = 40 Hz, $t_{water,gc\ in}$ = 35 °C, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

The cooling capacity of the investigated solution, being equal to the numerator of Eq.(1), is showed in Figure 4 with respect to the high pressure (and OD). A cooling duty of 1.60 kW was obtained by using the passive ejector at the high pressure of 79.89 bar, whereas this value was increased up to 1.88 kW with the aid of the PWM ejector. In the latter case, a high pressure of 82.47 bar was reached, corresponding to an OD of 80%. A decreasing trend was experienced at OD ≥ 70%, resulting in a cooling capacity of 1.77 kW at OD of 30%. The evaluated behaviour is consistent with the experimental data presented in [6]. Figure 4 also highlights that, as OD reduces, the CO_2 mass flow rate flowing though the motive nozzle decreases as well. Consequently, since the cooling capacity raised at high pressures up to 82.47 bar and then slightly changed, the gas cooler pressure increased.

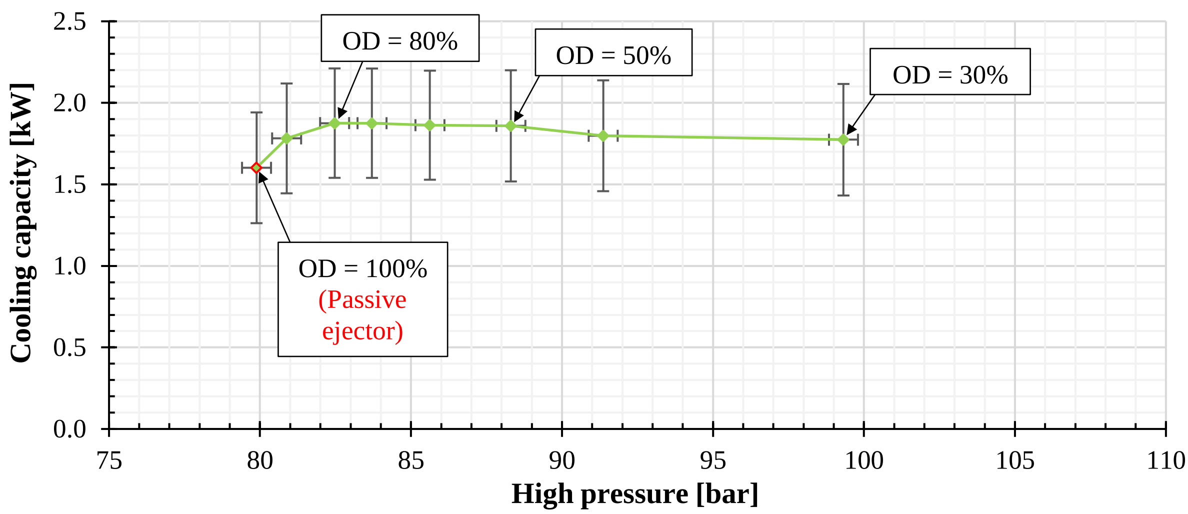

Figure 4: Cooling capacity as a function of high pressure /opening degree (OD) (compressor speed = 40 Hz, $t_{water,gc\ in}$ = 35 °C, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

A similar trend presented in Figure 5 for the mass entrainment ratio as well as for the pressure lift with respect to the high pressure was also revealed in [14], meaning that lower values of mass entrainment ratio result in higher values of pressure lift and vice versa. Consequently, since the ejector efficiency evaluates the trade-off between how much refrigerant can be lift and the pressure up to which the refrigerant can be lift by the ejector, a maximum value can be found around the point in which the mass entrainment ratio and pressure lift overlap, as showed in Figure 6. Furthermore, it is worth remarking that the values of pressure lift presented in Figure 5 are underestimated compared to those showed in Figure 2. This is due the fact that the values of pressure lift in Figure 5 were averaged over the data collection period, i.e. including the period during which the diffuser outlet and the suction nozzle pressure tend to get equalized. On the one hand, this explains the different values of pressure lift with rise in OD plotted in Figure 2 and Figure 5. On the other hand, as showed in Figure 2, it is important to highlight that the PWM ejector offered values of pressure lift of about 4 bar as the OD was ranged between 100% and 30% at the investigated operation condition.

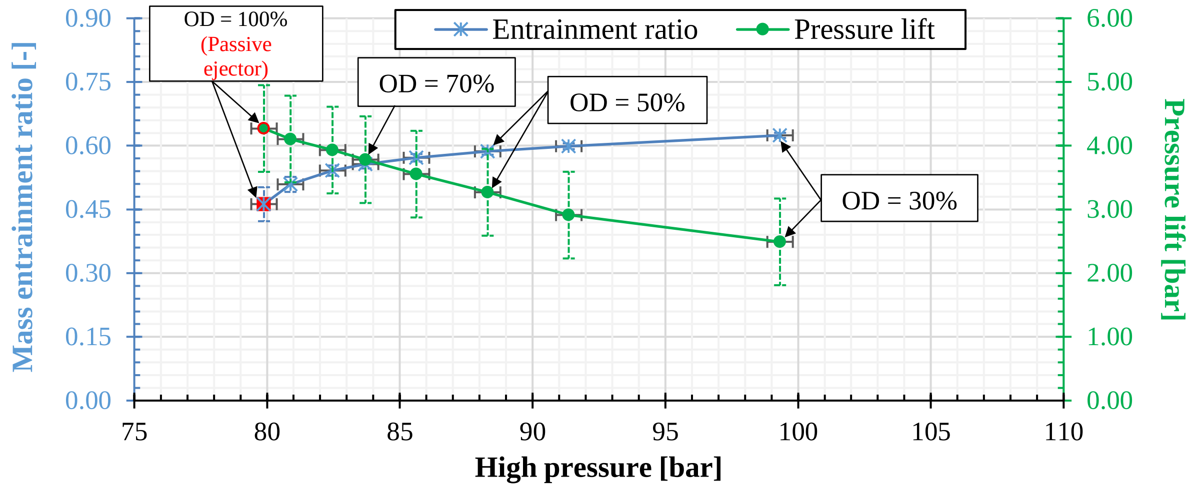

Figure 5: Mass entrainment ratio (left y-axis) and pressure lift (right y-axis) as a function of high pressure/opening degree (OD) (compressor speed = 40 Hz, $t_{water,gc\ in}$ = 35 °C, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

In Figure 6 it can also be noticed that the value of maximum ejector efficiency (calculated via Eq.(2)) does not coincide with that of maximum COP and cooling capacity, meaning that the PWM ejector performance can be improved by enhancing its design. In addition, Lawrence and Elbel [4] experimentally showed that the use of a needle-based ejector in a transcritical CO_2 unit leads to a significant drop in the ejector efficiency as it is necessary to obtain high gas cooler pressures, i.e. the losses caused by the use of the needle are much more considerable than those owing to off-design. This was not the case for the proposed methodology, since the PWM effect allowed the ejector to present higher efficiencies than those of the passive ejector at ODs between 90% and 40%, becoming almost the same at OD of 30%.

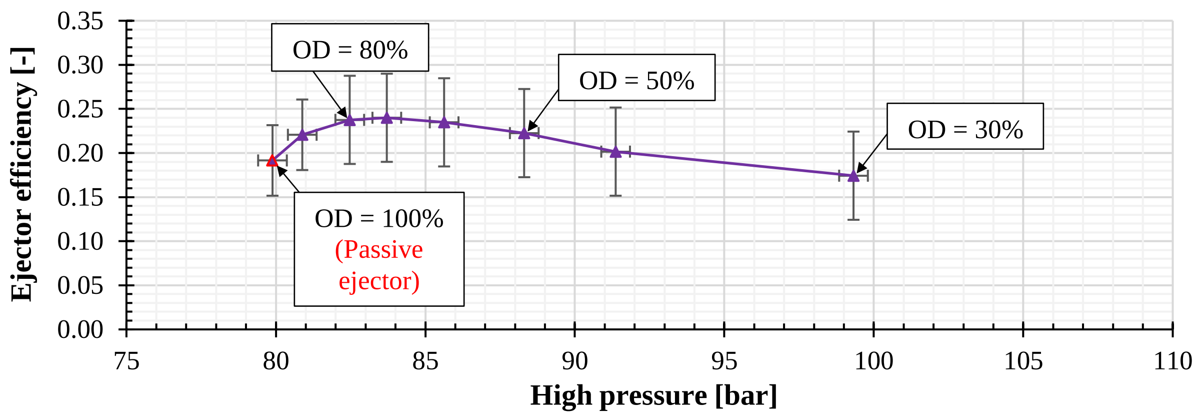

Figure 6: Ejector efficiency as a function of high pressure/opening degree (OD) (compressor speed = 40 Hz, $t_{water,gc\ in}$ = 35 °C, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

3.2 Solution with PWM ejector vs. Solution with passive ejector vs. Standard solution

The results of the comparison among the standard solution (i.e. with flash gas by-pass valve and without ejector), the unit equipped with a passive ejector (i.e. no capacity control strategy implemented for the ejector) and the system relying on the PWM ejector are summarized with the aid of Table 1. It was found that, at the investigated operating conditions, the use of a passive ejector and that of a PWM ejector allow for a COP enhancement by 14.0% and 29.4% in comparison with the standard unit, respectively. This led the proposed capacity control mechanism to a COP improvement by 13.5% compared to the passive ejector. Furthermore, it was revealed that the cooling capacity can be ranged from 1.60 kW up to 1.88 kW thanks to the adoption of the PWM concept (±17.1% compared to the unit with passive ejector). In relation to the standard solution, the cooling duty was enhanced by 13.5% with passive ejector and by up to 33.3% with the PWM ejector, respectively. It is worth remarking that the results listed in Table 1 were obtained at their corresponding optimal operating condition for all the three considered modes, as showed in Figure 3 for the PWM ejector and in [11] for the other two cases.

In addition, the currently available capacity control mechanisms for two-phase ejectors installed in small-capacity units, i.e. needle-based technique and vortex-based strategy, offer a COP enhancement by 2%÷4% compared to the passive ejector [5,6]. This further highlights the considerable potential of the PWM ejector in paving the way for a future-poof refrigeration solution suitable for small-format commercial stores. It is important to highlight that both the PWM ejector and the vortex ejector still need further developments.

Table 1: Comparison among the standard solution (i.e. with flash gas by-pass valve and without ejector), the solution with passive control (i.e. with no capacity control strategy of the ejector) and the solution with PWM ejector (compressor speed = 40 Hz, $t_{water,gc\ in}$ = 35 °C, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

Solution	COP [-]	Enhancement in COP [%]	Enhancement in COP [%]	Cooling capacity [kW]	Enhancement in cooling capacity [%]	Enhancement in cooling capacity [%]
Standard	1.43	Baseline	-	1.41	Baseline	-
Passive ejector	1.63	+14.00	Baseline	1.60	+13.50	Baseline
PWM ejector	1.85	+29.40	+13.50	1.88	+33.30	+17.10

4 Conclusions and Future work

Transcritical CO_2 vapour-compression systems equipped with a two-phase ejector could become the most preferred solution for small-format commercial stores thanks to their ability to considerably attenuate global warming. However, two-phase ejectors cannot be currently appropriately controlled in these applications. Therefore, in the present work the first experimental outcomes associated with a novel capacity control mechanism for CO_2 two-phase ejectors have been presented. The new capacity control technique relies on the pulse-width modulation (PWM) of the refrigerant flow through the ejector. The proposed capacity control mechanism is characterized by low cost, simplicity, low vulnerability to clogging and no need to vary the nozzle throat area for flow control.

At the compressor speed of 40 Hz, water temperature at the gas cooler inlet of 35 °C and CO_2 evaporating temperature of about -5.5 °C, the results obtained have showed that the gas cooler pressure can be augmented by up to about 20 bar, meaning that it can be properly controlled by the PWM ejector. In addition, the cooling capacity can be increased by up to about 17%. Furthermore, at the optimum running mode the solution using the PWM ejector features an enhancement in COP by 14% compared to the system without ejector control and by about 29% in relation to the standard unit. This means that the PWM ejector has a much more considerable potential than its currently available competitors, i.e. needle-based ejector and vortex-based ejector. Although the concept is tailored towards small-capacity vapour-compression systems, it has no practical size or application constraints, potentially allowing for an eco-friendlier future of the whole cooling and heating sector. As possible immediate future work, it will be necessary to:

- investigate the influence of the compressor speed and water temperature at the gas cooler inlet on the performance of both the PWM ejector and the overall system;
- explore an optimal frequency of the ejector PWM;
- evaluate the benefits deriving from the use of mufflers having different size;
- evaluate the potential energy advantageous related to the use of the PWM ejector in air conditioning applications;
- reduce the discrepancy in terms of heat balance between CO_2 and the secondary fluids within the heat exchangers.

Nomenclature

COP	coefficient of performance
EES	Engineering Equation Solver
GWP	global warming potential, $\mathrm{kg}_{\mathrm{CO_{2,equivalent}}} \cdot \mathrm{kg}^{-1}_{\mathrm{refrigerant}}$
h	enthalpy per unit mass, $kJ \cdot kg^{-1}$
$\dot{m}$	mass flow rate, $kg \cdot s^{-1}$
MSV	motive solenoid valve
OD	opening degree, %
p	pressure, bar
PWM	pulse-width modulation¨
$\dot{Q}$	cooling capacity, kW
s	entropy per unit mass, $kJ \cdot kg^{-1} \cdot K^{-1}$
SLHX	suction line heat exchanger
t or *T*	temperature, °C or K
$\dot{V}$	volumetric flow rate, $m^3 \cdot s^{-1}$
$\dot{W}$	power, kW
Greek symbols	
Δ	variation
η	efficiency
ρ	density, $kg \cdot m^{-3}$
Φ_m	mass entrainment ratio
Subscripts and superscripts	
diff	diffuser
eg	ethylene glycol-water (35/65%) mixture
evap	evaporator
gc	condenser/gas cooler
in	inlet
mn	motive nozzle
out	outlet
sn	suction nozzle

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References

[1] Tassou S.A., Ge Y., Hadawey A., Marriott D.: Energy consumption and conservation in food retailing. Appl Therm Eng Vol. 31 Issue 2-3, Feb. 2011, pp. 147-156.

[2] Gullo P., Hafner A., Banasiak K.: Transcritical R744 refrigeration systems for supermarket applications: Current status and future perspectives. Int J Refrig Vol. 93, Sep. 2018, pp. 269-310.

[3] Nakagawa M., Marasigan A.R., Matsukawa T.: Experimental investigation on the effect of internal heat exchanger in transcritical CO_2 refrigeration cycle with ejector. Int J Refrig Vol. 34 Issue 7, Nov. 2011, pp. 1577-1586.

[4] Lawrence N., Elbel S.: Experimental investigation on control methods and strategies for off-design operation of the transcritical R744 two-phase ejector cycle. Int J Refrig Vol. 106, Oct. 2019, pp. 570-582.

[5] Zhu J., Elbel S.: Experimental investigation into the influence of vortex control on transcritical R744 ejector and cycle performance. Appl Therm Eng Vol. 164, Jan. 2020, pp. 114418.

[6] Elbel S., Hrnjak P.: Experimental validation of a prototype ejector design to reduce throttling losses encountered in transcritical R744 system operate. Int J Refrig Vol. 31 Issue 3, May 2008, pp. 411-422.

[7] Liu F., Groll E.A.: Analysis of a Two Phase Flow Ejector For Transcritical CO_2 Cycle. Proceedings of the 12th International Refrigeration and Air Conditioning Conference at Purdue, Jul. 2008.

[8] Gullo P., Hafner A., Banasiak K., Minetto S., Kriezi E.E.: Multi-Ejector Concept: A Comprehensive Review on its Latest Technological Developments. Energies Vol. 12 Issue 3, Jan. 2019, pp. 406.

[9] Elbel S., Lawrence N.: Review of recent developments in advanced ejector technology. Int J Refrig Vol. 62, Feb. 2016, pp. 1-18.

[10] Gullo, P., Kærn, M.R., Haida, M., Smolka, J., Elbel S.: A review on current status of capacity control techniques for two-phase ejectors. Int J Refrig **(*Accepted manuscript, In Press*)**. DOI: 10.1016/j.ijrefrig.2020.07.014

[11] Kærn M.R., Song Y., Markussen W.B., Elmegaard B.: Comparison of a CO_2 refrigeration and heat pump test system with and without ejector. Proceedings of the 13th IIR-Gustav Lorentzen Conference on Natural Refrigerants, Jun. 2018.

[12] F-Chart Software. Engineering Equation Solver (EES), Academic Professional V10.644. Available at: <http://www.fchartsoftware.com/ees/> [accessed 01.06.2020].

[13] Lorentzen G.: Revival of carbon dioxide as a refrigerant. Int J Refrig Vol. 17 Issue 5, 1994, pp. 292-301.

[14] Lucas C., Koehler J.: Experimental investigation of the COP improvement of a refrigeration cycle by use of an ejector. Int J Refrig Vol. 35 Issue 6, Sep. 2012, pp. 1595-1603.