PAPER ID: 1001
DOI: 10.18462/iir.gl.2020.1001

Preliminary experimental investigation on a transcritical R744 condensing unit using the novel PWM ejector

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ABSTRACT

In this work the preliminary experimental performance study on an innovative control technique for two-phase ejectors in transcritical R744 condensing units is presented. Currently two-phase ejectors cannot be properly capacity controlled without sacrificing ejector and system efficiency in these units. The novel capacity control methodology involves the pulse-width modulation (PWM) of the refrigerant flow through the ejector. At the compressor speed of 50 Hz, water temperatures at the gas cooler inlet between 30 °C and 40 °C and R744 evaporating temperature of roughly -5.5 °C, the collected data revealed that the discharge pressure can be appropriately controlled as well as increased by up to about 28 bar. Also, at the optimum operation conditions the unit with the PWM ejector presented enhancements in coefficient of performance (COP) by between 10.0% and 12.1% over the system using the passive ejector and by between 23.7% and 31.2% compared to the solution with flash gas by-pass valve. Finally, the proposed methodology presents low cost, simplicity, low vulnerability to clogging and much more significant potential than its today's available competitors.

Keywords: Carbon Dioxide, Commercial Refrigeration, Expansion Work Recovery, Gas Cooler Pressure Control, Small-capacity System.

1. INTRODUCTION

Grocery and convenience stores, i.e. small-format stores, are accountable for significant energy demands. As showed by Tassou et al. (2011), in fact, small-format stores feature an annual energy use intensity per sale area being about 3 times higher than that of large-format stores, such as hypermarkets. Being up to 60% of their energy demand employed for refrigeration purposes (Tassou et al., 2011), the efficiency improvement of their condensing units is therefore a key factor to accomplish the sustainable development goals. To further enhance the carbon footprint of these crucial applications, the use of low global warming potential (GWP) refrigerants, such as R744, has become mandatory. Similarly to medium- and large-format stores, transcritical R744 refrigeration systems equipped with two-phase ejectors for expansion work recovery are expected to play a central role as long-term solutions in grocery and convenience stores too (Gullo et al., 2018). However, nowadays two-phase ejectors cannot be suitably controlled in small-capacity applications, leading to significant penalizations in ejector and system performance. As an example, on the one hand, the experimental study by Nakagawa et al. (2011) revealed that a maximum improvement in COP of 27% can be obtained in comparison with a conventional R744 unit at the on-design operation condition. On the other hand, the same study also showed that COP can be reduced by up to 82% as an appropriate capacity control of the ejector is not performed. Therefore, to the best of the authors' knowledge three capacity control mechanisms for two-phase ejectors have been formulated so as to surmount this drawback. Firstly, the needle-based capacity control technique was implemented (Elbel and Hrnjak, 2008; Liu and Groll, 2008). Nevertheless, this strategy involves a complex and expensive design as well as considerable vulnerability to clogging (Lawrence and Elbel, 2019; Zhu and Elbel, 2020). Secondly, Zhu and Elbel (2020) recently formulated the vortex ejector concept. On the one hand, this solution is characterized by more simplicity, possibly lower cost and more trustworthiness. On the other hand, at the current status the vortex ejectors offer similar or slightly worse performance than the needle-based ejector. Thirdly, the multi-ejector concept (Gullo et al., 2019) is currently available. However, this alternative is not suitable for small-format stores, being too complicated (Elbel and Lawrence, 2016), expensive and limited by manufacturing size. Consequently, it is essential to implement novel capacity control mechanisms for two-phase ejectors installed in transcritical R744 condensing units (Gullo et al., 2020a).

The goal of this work is to bridge this knowledge gap by further study the so-called pulse-width modulation (PWM) ejector experimentally, which was previously formulated by the same authors (Gullo et al., 2020b). The first experimental data revealed that the PWM ejector is capable of properly controlling the gas cooler pressure simultaneously with an effective recovery of the expansion work. Also, at the compressor speed of 40 Hz, water temperature at the gas cooler inlet of 35 °C and evaporating temperature of around -5.5 °C, Gullo et al. (2020b) showed that the gas cooler pressure and the cooling capacity can be varied by up to around 20 bar and 33%, respectively. In addition, at the optimal running mode the unit employing the PWM ejector presented a COP rise by 14% over the system with passive ejector and by about 29% in comparison to the standard solution. The present work extends the one by Gullo et al. (2020b) by studying the effect of the water temperature at the gas cooler inlet on the performance of both the PWM ejector and the condensing unit.

2. METHODOLOGY

2.1. Experimental setup

The experimental setup (Figure 1) presents a Dorin CD180H compressor with a variable speed drive (ABB ACS150) and a power analyser (Voltech PM3000A, accuracy: 0.1% of reading). The evaporator (B17Hx16/1P) and the condenser/gas cooler (B17Hx10/1P) are both brazed plate heat exchangers manufactured by SWEP. A suction line heat exchanger (SLHX), being 50 cm stainless steel tubes tin-soldered together, was also installed. The two-phase ejector is the smallest cartridge belonging to the multi-ejector module (motive nozzle/mixing chamber = Ø0.71/Ø2.30 mm). A Danfoss AKV expansion valve (i.e. relying on the PWM working principle) was used for controlling the degree of superheating at the outlet of the evaporator, whereas Danfoss ETS stepper-motor valves were used as the high pressure valve and the vapour by-pass valve. A Coriolis type mass flow meter (Micro Motion DS012, accuracy: 0.2% of reading) was installed downstream of the SLHX (high pressure side) to measure the R744 mass flow rate. All the temperature sensors (accuracy: ±(0.3+0.005×T in °C)) and the pressure sensors (accuracy: 0.3% of 160 bar) were given by Danfoss A/S. A differential pressure transmitter was employed for measuring the liquid level in the receiver. The Titan turbine flow meters installed in the test rig were used for evaluating the volume flow of the water in the condenser/gas cooler (accuracy: 0.36% of 6.5 $l \cdot min^{-1}$) and measuring the volume flow of the ethylene glycol-water (35/65%) mixture in the evaporator (accuracy: 0.74% of 15 $l \cdot min^{-1}$), respectively. An Agilent data logger was used for acquiring temperatures, pressures, etc., while Danfoss controllers were utilized for logging and monitoring the controlled variables. Finally, National Instruments cDAQ module 9411 was employed for counting the volume flow meters. Inlet temperatures of water and ethylene glycol were respectively controlled by using a 3-way valve and an electric heater, whereas the flows were controlled with the aid of 2-way valves. Additional specifics on the test rig can be found in the work by Kærn et al. (2018).

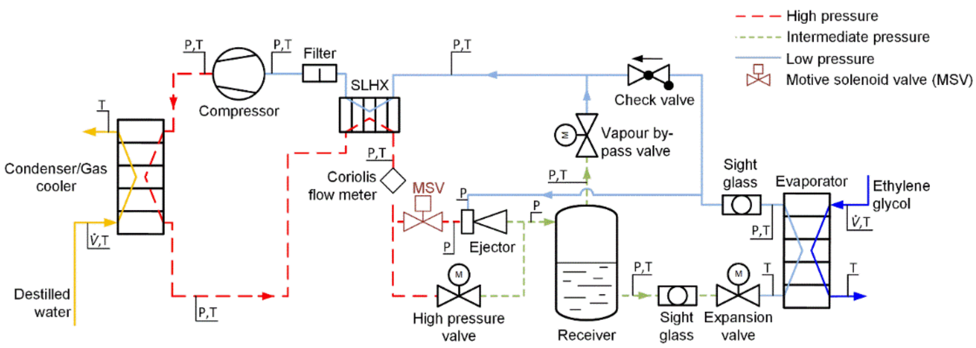

Figure 1: Schematic of the experimental setup (colour/dash for ejector mode, hand-operated valves omitted)

2.2. PWM working principle

The new capacity control technique relies on the pulse-width modulation (PWM) of R744 flow through the ejector. This technique has been widely used by Danfoss A/S in expansion valves installed in several refrigeration, air conditioning and heat pump applications. An expansion valve relying on the PWM working principle is regulated as follows:

- within a period (i.e. PWM period) of typically between 3 s and 6 s, a voltage signal from the controller is transmitted to and removed from the valve coil, resulting respectively in the opening and closing of the coil (i.e. in the flow of R744 through the valve or not);
- the relation between the opening and closing time of the valve coil defines the delivered capacity.

Therefore, considering the case of 3 s as the PWM period, if it is necessary to deliver 67% of the full capacity, the valve coil will be open for about 2 s out of the aforementioned 3 s (i.e. 67% of 3 s) and will be closed for about the following 1 s. The same principle was applied to the motive solenoid valve (MSV) mounted upstream of the PWM ejector motive nozzle (see Figure 1) and employed for controlling the on/off state of the expansion work recovery device. In the present work, the time period of the PWM ejector and that of the AKV expansion valve were 2 s and 3 s, respectively. A suction check valve (see Figure 1) was also installed to avoid that the pressure lift was short-circuited upon closing. Further details regarding the PWM ejector can be found in the work by Gullo et al. (2020b).

2.3. Data reduction

The data reduction in relation to COP involved the energy balance equations at steady state conditions and the heat absorption taking place through the ethylene glycol-water (35/65%) mixture. The motive nozzle, suction nozzle and diffuser pressures, whose sensors were installed directly on the ejector housing, were acquired at 1000 Hz, whereas the other data were logged 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. The ejector efficiencies were calculated as suggested by Elbel and Hrnjak (2008). Also, the uncertainty propagation was assessed with the aid of Engineering Equation Solver (EES) (F-Chart Software, 2019). Finally, it was found that the average discrepancy in terms of heat balance between R744 and the secondary fluid were of about 8% within the evaporator and 5% within the gas cooler. It is important to highlight that the large differences in the heat exchanger energy balance do not compromise the evidence of the PWM ejector working principle. In addition, the present work involves a preliminary experimental investigation on the PWM ejector.

3. RESULTS AND DISCUSSION

3.1. Results related to the PWM ejector

Different time series stitched together representing the effect of the opening degree (OD) of the MSV on the motive nozzle, suction nozzle and diffuser outlet pressures of the ejector are showed in Figure 2 for the case involving $t_{water,gc\ in}$ = 35 °C. For instance, OD = 90% describes the case in which MSV is closed for 10% of the PWM period (i.e. 0.2 s out of 2.0 s), whereas it is open for 90% of the PWM period (i.e. 1.8 s out of 2.0 s). Consequently, a fluid hammer effect occurred during the MSV closing, followed by a pressure wave propagation as the MSV opened. The MSV closing also resulted in the decay of the diffuser outlet pressure, leading to the equalization with the suction nozzle pressure. Nevertheless, the pressure lift was found to be above 3 bar for OD ≥ 40%, as R744 was allowed to flow through the ejector. In addition, it is important to highlight that, despite the aforementioned pressure equalization, the compressor was still able to draw R744 from the intermediate pressure rather than from the low one. The lower the OD, the more noticeable the previous phenomena appeared. It is thought that the pressure drop between the diffuser and the receiver could result in the decay of the diffuser outlet pressure as the MSV was closed. Similarly, the suction pressure and receiver pressure could equalize possibly through the expansion device.

As for ejector-based transcritical R744 units, the expansion work recovery device becomes crucial to control the high pressure in order to maximize the COP as a function of the refrigerant temperature at the gas cooler outlet in transcritical regime (Gullo et al., 2018). Figure 3 shows that the high pressure could be varied from 75.97 bar (OD = 100%, i.e. passive ejector) to 104.33 bar (OD = 30%) at $t_{water,gc\ in}$ = 30 °C, from 84.41 bar (OD = 100%) to 108.38 bar (OD = 30%) at $t_{water,gc\ in}$ = 35 °C and from 91.32 bar (OD = 100%) to 107.58 bar (OD = 40%) at $t_{water,gc\ in}$ = 40 °C with the aid of the PWM ejector. Furthermore, the best COP values were obtained, i.e. 2.30 at OD = 90% for $t_{water,gc\ in}$ = 30 °C, 1.93 at OD = 90% for $t_{water,gc\ in}$ = 35 °C and 1.54 at OD = 80% for $t_{water,gc\ in}$ = 40 °C. Consequently, it could be stated that the PWM ejector can appropriately control the gas cooler pressure, allowing a condensing unit to attain the best COP in transcritical regime. It is worth mentioning that the low values of COP showed in Figure 3 were due to the use of an old compressor. In addition, an increase in cooling capacity by up to 4.9% was also evaluated. Furthermore, ejector efficiencies between 0.25 and 0.32 as well as mass entrainment ratios between about 0.52 and 0.63 were experienced at optimal operating conditions.

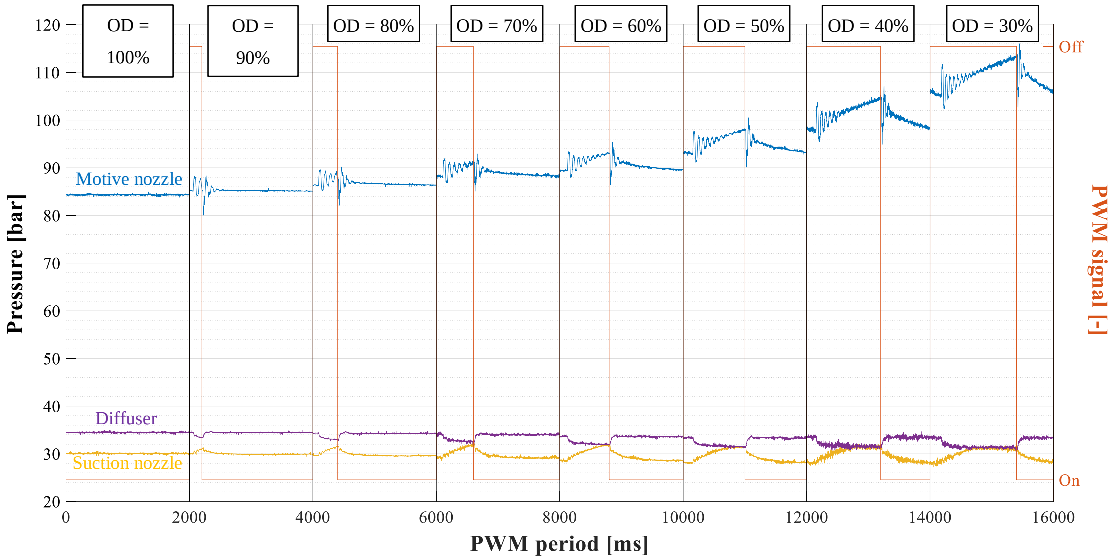

Figure 2: Effect of the opening degree (OD) of the MSV on the motive nozzle, suction nozzle and diffuser outlet pressures of the ejector (compressor speed = 50 Hz, $t_{water,gc\ in}$ = 35 °C, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

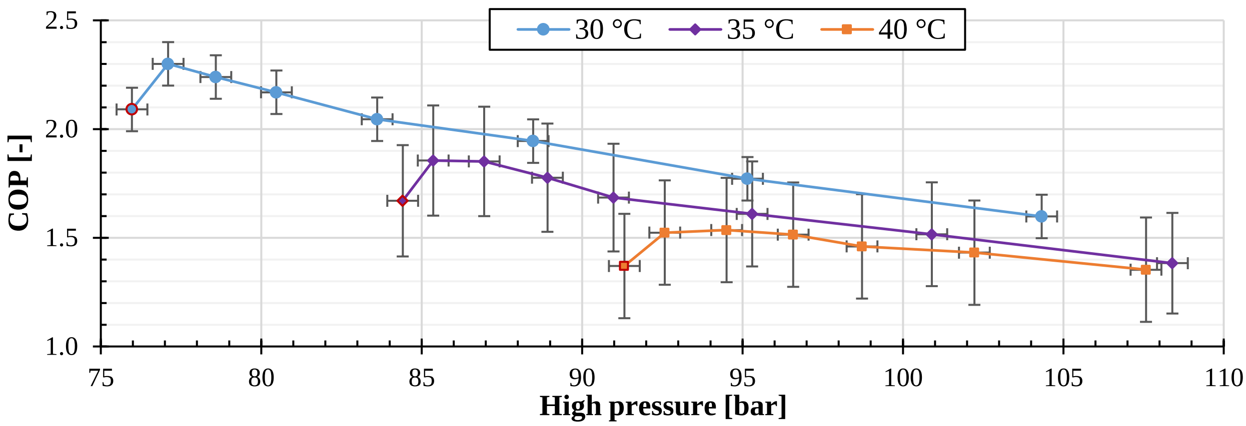

Figure 3: COP at $t_{water,gc\ in}$ of 30 °C, 35 °C and 40 °C as a function of high pressure (compressor speed = 50 Hz, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

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

The COP comparison among the standard system (i.e. with flash gas by-pass valve and without ejector), the solution using the passive ejector (i.e. no capacity control mechanism for the ejector) and the unit outfitted with the PWM ejector is presented in Figure 4. The results obtained showed that, at the selected boundary conditions, the adoption of the passive ejector leads to COP improvements between 12.4% (at $t_{water,gc\ in}$ = 30 °C) and 17.1% (at $t_{water,gc\ in}$ = 40 °C), whereas these were between 23.7% (at $t_{water,gc\ in}$ = 30 °C) and 31.2% (at $t_{water,gc\ in}$ = 40 °C) for the PWM ejector, respectively. Consequently, it was found that the implementation of the latter permits enhancing the COP between 10.0% (at $t_{water,gc\ in}$ = 30 °C) and 12.1% (at $t_{water,gc\ in}$ = 40 °C) compared to the passive ejector at the investigated operation conditions. It is worth highlighting that the outcomes showed in Figure 4 were derived at their corresponding optimum running mode for all the three evaluated solutions, as presented in Figure 3 for the PWM ejector and by Kærn et al. (2018) for the other two units. Also, the needle-based mechanism and vortex-based technique, which are today's available capacity control strategies for two-phase ejectors in small-capacity systems, present a COP improvement by between

2% and 4% in comparison with the passive ejector (Lawrence and Elbel, 2019; Zhu and Elbel, 2020). This additionally suggests the significant potential of the PWM ejector. Finally, it is important to remark that improvement potential of both the PWM ejector and the vortex ejector is still considerable.

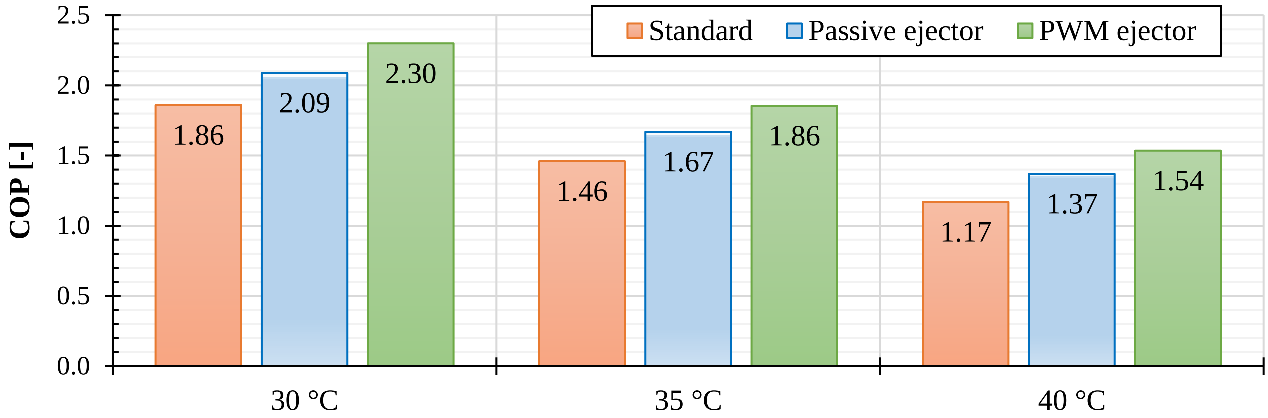

Figure 4: COP comparison of standard solution, unit with passive ejector and system with PWM ejector at $t_{water,gc\ in}$ of 30 °C, 35 °C and 40 °C (compressor speed = 50 Hz, $t_{eg,evap\ in}$ = 5 °C, $\Delta T_{superheating}$ = 10 K)

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

Transcritical R744 condensing units using a two-phase ejector are one of the most promising solutions to mitigate climate change caused by small-format stores. Nevertheless, at present condensing units cannot benefit from the energy benefits deriving from two-phase ejectors, as these devices cannot be properly controlled in small-capacity applications. Thus, in this work the preliminary experimental investigation on a new capacity control technique for R744 two-phase ejectors has been conducted. The novel capacity control mechanism involves the pulse-width modulation (PWM) of the refrigerant flow through the ejector. The PWM-based capacity control technique offers low cost, simplicity, low vulnerability to clogging and no need to change the nozzle throat area for flow control.

At the compressor speed of 50 Hz, water temperature at the gas cooler inlet between 30 °C and 40 °C and R744 evaporating temperature of about -5.5 °C, the collected experimental data suggest that the high pressure can be effectively controlled, allowing for the achievement of the best COP. Furthermore, the gas cooler pressure can be increased by up to about 28 bar. Additionally, at the optimum running modes the solution using the PWM ejector offers COP improvements from 10.0% to 12.1% compared to the unit equipped with the passive ejector and between 23.7% and 31.2% over the standard solution. This leads the PWM ejector to have a much more substantial potential than its today's available competitors, i.e. needle-based ejector and vortex-based ejector. Finally, although the PWM working principle has been thought for small-capacity vapour-compression systems, it has no practical size or application constraints, possibly resulting in an eco-friendlier future of the whole cooling and heating sector. As possible immediate future work, it will be needed to:

- study the effect of the compressor speed on the performance of both the PWM ejector and the overall system;
- evaluate the optimum PWM period as well as the possible advantageous of the adoption of mufflers featuring different size;
- investigate the potential energy benefits of the PWM ejector in air conditioning units;
- decrease the discrepancy related to the heat balance between R744 and the secondary fluids within the heat exchangers.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 844924 (Project: ECO_2-RAPJECT).

NOMENCLATURE

COP	coefficient of performance (-)	*EES*	Engineering Equation Solver
GWP	global warming potential	*MSV*	motive solenoid valve
OD	opening degree of MSV (%)	*p*	pressure (bar)
PWM	pulse-width modulation	*SLHX*	suction line heat exchanger
t or T	temperature (°C or K)	$\dot{V}$	volume flow rate ($m^3 \times s^{-1}$)

Greek symbols

Δ	variation

Subscripts

eg	ethylene glycol-water (35/65%) mixture	*evap*	evaporator
gc	condenser/gas cooler	*in*	inlet

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