Avances en Ciencias y Técnicas del Frío - 11

Libro de actas XI Congreso Ibérico y IX Congreso Iberoamericano de Ciencias y Técnicas del Frío Cytef2022

Editores:
Antonio López Gómez
José Ramón García Cascales
Ginés Benito Martínez Hernández
Arturo Esnoz Nicuesa
Asunción Iguaz Gainza
Fernando Illán Gómez
Francisco Javier Sánchez Velasco
José Pablo Delgado Marín
Ramón Antonio Otón Martínez

Universidad
Politécnica
de Cartagena

edicionesUPCT

AVANCES EN CIENCIAS Y TÉCNICAS DEL FRÍO-11

EDITADO POR

ANTONIO LÓPEZ GÓMEZ (IFSA)

JOSÉ RAMÓN GARCÍA CASCALES (MSTE)

GINÉS BENITO MARTÍNEZ HERNÁNDEZ (IFSA)

ARTURO ESNOZ NICUESA (IFSA)

ASUNCIÓN IGUAZ GAINZA (IFSA)

FERNANDO ILLÁN GÓMEZ (MSTE)

FRANCISCO JAVIER SÁNCHEZ VELASCO (MSTE)

JOSÉ PABLO DELGADO MARÍN (MSTE)

RAMÓN ANTONIO OTÓN MARTÍNEZ (MSTE)

Grupos de Investigación en Ingeniería del Frío y la Seguridad Alimentaria (IFSA), y en Modelado de Sistemas Térmicos y Energéticos (MSTE)
UNIVERSIDAD POLITÉCNICA DE CARTAGENA

Actas del XI Congreso Ibérico | IX Congreso Iberoamericano de Ciencias y Técnicas del Frío - CYTEF 2022
Cartagena, España, 17-19 abril, 2022

edicionesUPCT

Plaza del Hospital, 1
30202 Cartagena
Teléfono: 968 325908
ediciones@upct.es
I.S.B.N.: 978-84-17853-55-6

Diseño y maquetación: Eventos en Plural.

EVALUATION OF ZEOTROPIC MIXTURES AS REFRIGERANTS IN A DEDICATED SUBCOOLING SYSTEM OF A CO_2 REFRIGERATION PLANT

Gabriele Toffoletti[1], **Laura Nebot-Andrés**[2], **Manel Martínez-Ángeles**[2], **Giovanni Cortella**[1] **and Rodrigo Llopis**[2]

1: Polytechnic Department of Engineering and Architecture, University of Udine, Italy; 2: Thermal Engineering Group, Mechanical Engineering and Construction Department, Jaume I University, Castellón de la Plana, 12071, Spain

Gabriele Toffoletti
rllopis@uji.es

……

Abstract: *Prof. Baomin Dai suggested in 2018 that the use of zeotropic mixtures with high glide could provide energy improvements as refrigerants in dedicated mechanical subcooling systems for CO_2 plants due to matching of temperature profiles between the evaporation of the refrigerant and the CO_2 during the subcooling. This communication addresses this hypothesis from a theoretical point of view, selecting refrigerant blends that could be used in the subcooling system, and then presents the experimental evaluation of three mixtures in a real plant.*

Experimental evaluation has been done using a water-to-water CO2 transcritical refrigeration plant at three heat rejection levels for an evaporation level of -10 ºC. The work will compare the energy results and highlight the operation of the main components of the cycle.

Keywords: CO_2, energy improvement, dedicated mechanical subcooling, zeotropic mixtures.

1. INTRODUCTION

Subcooling has become a reliable method to enhance the performance of CO_2 refrigeration systems when they are subjected to high heat rejection temperatures. Among all the methods, dedicated mechanical subcooling (DMS) is the one which provides highest energy improvements now [1, 2]. Nebot-Andres et al. [3] presented the experimental optimization of a CO_2 single-stage transcritical refrigeration plant hybridized with a DMS cycle operating with R-152a as refrigerant, where the optimum operating parameters (heat rejection pressure and subcooling degree) were determined. They rated the performance of this cycle in relation to the CO_2 transcritical cycle with parallel compression, which is the state-of-the-art system in Europe, and measured at -10ºC of evaporating temperature COP increments between 7.8% and 17.5% at 25.0ºC and 35.1ºC heat rejection temperatures, respectively [4]. In addition, Catalán-Gil et al. [5] predicted for a medium-sized supermarket that the DMS system could provide energy consumption reductions in relation to the parallel compression between 2.9 to 3.4% in warm regions and between 3.0 to 5.1% in warm regions.

Optimum subcooling degrees are relatively high, reaching values up to 16.5ºC (t_o=-5ºC, t_{env}=30ºC), implying poor temperature match between CO_2 and the operation of the pure refrigerant in the DMS evaporator. Attempting to enhance even more the hybridization, Dai et al. [6] launched an hypothesis about the use of zeotropic refrigerants with matching glide (between CO_2 subcooling and mixture evaporation in the subcooler) to reduce the temperature difference between both fluids to reduce irreversibilities. Dai et al. found that mixture R-32 with R-152a promised 6.5% COP enhancement in relation to the use of R-152a as refrigerant. This hypothesis, was verified by Llopis et al. [7] in an experimental plant. However, they found notable differences in relation to Dai's work.

This communication summarizes the theoretical and experimental approaches to validate Dai's hypothesis using a CO_2 transcritical refrigeration plant with a dedicated subcooling cycle.

2. THERMODYNAMIC APPROACH

Selection of binary mixtures to select the candidates to be evaluated experimentally were done using a close model to the existing refrigeration plant, as detailed by Llopis et al. [7]. Pure R-152a and its mixtures with R-32, CO_2 and R-600 were evaluated theoretically using COP, Eq. (1), as optimization parameter. The thermophysical properties were evaluated using the last version of Refprop v.10 [8]. Figure 1 summarizes the COP results for an operating temperature of the CO_2 refrigeration cycle using the zeotropic mixtures in the DMS cycle at an evaporation temperature of -14 ºC, a water inlet temperature to the gas-cooler and DMS condenser of 35ºC with useful superheat in both evaporators of 5 K and a subcooling degree in the DMS condenser of 2 K. Approach temperature in the gas-cooler was set to 2 K, whereas the temperature difference in the DMS condenser was assumed to be 15 K.

$$COP = \frac{\dot{Q}_o}{P_{C,CO2} + P_{C,DMS}} \tag{1}$$

Results of Figure 1 indicated that mixture R-600/R-152a [60/40%] was the best mixture and the unique that theoretically could improve the performance of the hybridization. However, also R-152a, R-152a/R-32 [60/40 %] and R-152a/CO_2 [90/10 %] were included in the study to evaluate high temperature glide refrigerants.

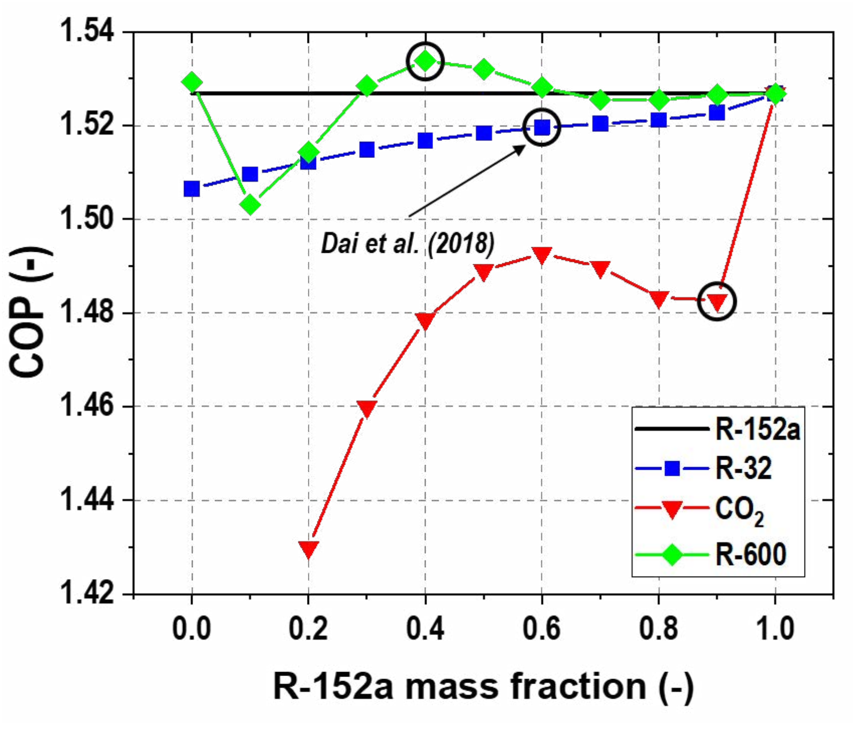

Figure 1. Optimum COP at t_o=-14ºC and $t_{w,in}$=35ºC as R-152a mass fraction

3. EXPERIMENTAL ANALYSIS

3.1. Experimental test bench

Evaluation was done with an experimental CO_2 transcritical refrigeration plant with a DMS refrigeration cycle fully monitored, as described by Figure 2. CO_2 cycle is driven by a 3.48 $m^3 \cdot h^{-1}$ at 1450 rpm semihermetic compressor, uses refrigerant-to-water gas-cooler and evaporator and includes a double stage expansion system to control the high heat rejection pressure and the superheating degree in the evaporator. The DMS cycle is run by a 4.06 $m^3 \cdot h^{-1}$ at 1450 rpm semihermetic compressor designed for R-134a and uses a shell-an-tube condenser and an electronic expansion valve customized for each refrigerant. Heat dissipation in DMS condenser and gas-cooler is performed at the same temperature level using water as heat transfer fluid and the CO_2 evaporator is supplied with a propylene-glycol water mixture at 50 % by volume. Plant is fully instrumented using temperature, pressure, Coriolis mass flow meters and digital wattmeters.

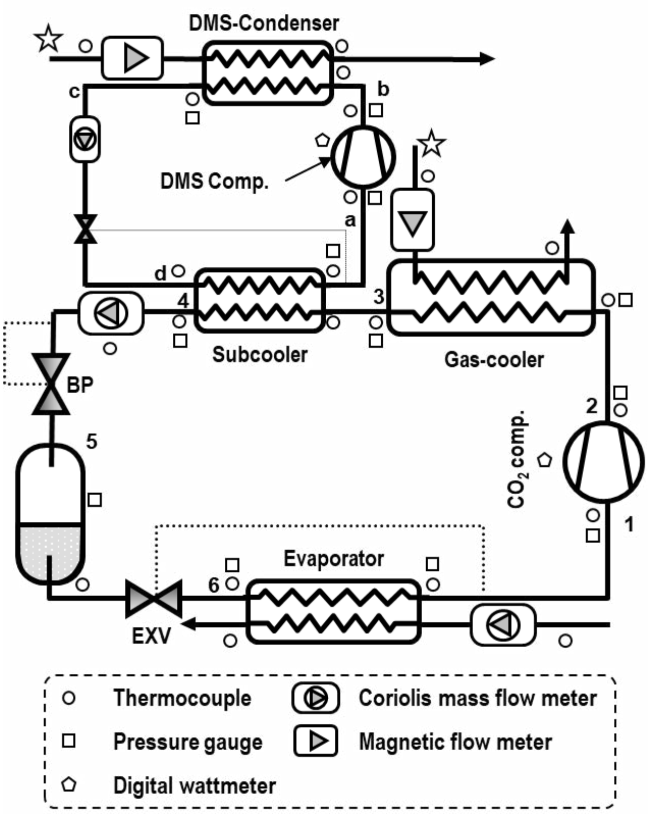

Figure 2. Schematic diagram of the experimental CO_2 refrigeration plant with DMS subcooler

3.2. Experimental results

The experimental tests were performed for a fixed evaporating working conditions using an inlet temperature of -1.2 ºC and constant volumetric flow rate of 0.71 $m^3 \cdot h^{-1}$ in the evaporator. Heat rejection was controlled sending different water inlet temperatures to the gas-cooler and DMS condenser, with constant volumetric flow rate to the gas-cooler of 1.16 $m^3 \cdot h^{-1}$ and to the DMS condenser of 0.61 $m^3 \cdot h^{-1}$. Tested water inlet temperatures were of 25.1, 30.3 and 35.1 ºC.

To evaluate the performance of the plant, heat rejection pressure of the CO_2 cycle was optimized using an own PID controller and the subcooling degree was varied through compressor speed variation of the DMS compressor. CO_2 compressor was run always at the nominal speed (1450 rpm). Superheat in the expansion valve of the CO_2 evaporator was set to 10 K and 5 K in the evaporator of the DMS cycle.

Objective function for the optimization was the COP of the combination, as detailed by Eq. (1), where the cooling capacity was that measured in the CO_2 evaporator, as detailed by Eq. (2), where $\dot{m}_{CO2}$ is the measurement of the CO_2 Coriolis, $h_{O,out}$ is the enthalpy at the exit of the evaporator and h_{exp} is the enthalpy measured at the exit of the subcooler (point 4, Figure 2). To optimize the performance of the plant, the degrees of freedom were the heat rejection pressure, which was controlled thanks to the electronic expansion valve working as back-pressure; and the subcooling degree in the subcooler, Eq. (3), which was varied modifying the compressor speed of the DMS compressor.

$$\dot{Q}_o = \dot{m}_{CO2} \cdot \left(h_{O,out} - h_{exp}\right) \tag{2}$$

$$SUB = t_{sub,in} - t_{sub,out} \tag{3}$$

Figure 3 reflects the experimental optimization procedure, where a hand-made spline approach was done to locate the optimum performance conditions. Each black dot in Figure 3 represents an experimental measurement and the colours the COP regions values. The experimental procedure ended when the deviation of the optimum point was less than 1 %, as it can be seen in the experimental results.

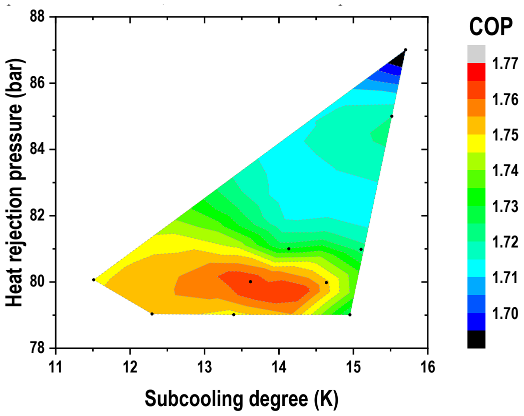

Figure 3. Optimization of CO_2 plant with R-600/R-152a [60/40%] mixture at $t_{w,in}$=30.3°C

The described experimental procedure was extended to the four refrigerants used in the DMS cycle and evaluated for the three mentioned water inlet temperatures (25.1, 30.3 and 35.1 °C) for a constant inlet temperature to the evaporator of -1.2 °C. Figure 4 presents the experimental COP results, where maximum uncertainty is of 0.95 %.

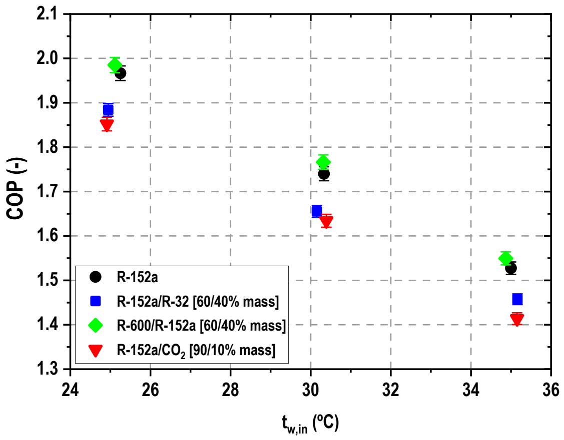

Figure 4. Optimum experimental COP values at $t_{o,in}$=-1.25°C for all evaluated mixtures

As it can be observed in Figure 4, only the mixture R-600/R-152a [60/40 %] is able to enhance the COP in relation to the operation with R-152a as refrigerant for the DMS cycle. Concretely, the improvement with this mixture varies between 1.1 to 1.4 % in relation to R-152a.

Experimental trends are in agreement with the theoretical simulations, thus, it has been verified that it is possible to enhance the performance of a CO_2 DMS subcooled cycle using zeotropic refrigerants as predicted by Dai et al. It needs to be added that for quantifying the real improvements, additional analysis about the heat transfer in the subcooler should be investigated.

4. CONCLUSIONS

This work demonstrates the possibility to enhance the performance of a CO_2 refrigeration plant using a dedicated mechanical subcooling system by using a zeotropic mixture in the auxiliary cycle as suggested by Dai et al. Three refrigerant mixtures, R-152a/R32 [60/40%], R-600/R-152a [60/40%] and R-152a/CO_2 [90/10%] have been tested experimentally against the operation with R-152a as refrigerant using an experimental plant.

It has been observed that only mixture R-600/R-152a [60/40 %] is able to enhance the performance of the plant between 1.1 to 1.4 % in relation to R-152a. It needs to be mentioned that the evaluation was done using a defined subcooler, thus, the possible needed increment in heat transfer surface of the subcooler for large glide mixtures could reduce the improvements.

ACKNOWLEDGEMENTS

Authors acknowledge the Ministry of Science, Innovation and Universities of Spain (RTI2018-093501-B-C21) and Ministry of Education, Culture and Sports of Spain (grant FPU16/00151) and Jaume I University (UJI- B2021-10) for financing this research work.

REFERENCES

[1] Bertelsen, S.K. and S.B. Haugsdal, *Design and measurement of a CO_2 refrigeration system with integrated propane subcooler at high air temperature operations*, in *Department of Energy and Process Engineering.* 2015, Norwegian University of Science and Technology: Trondheim, Norway.

[2] Llopis, R., et al., *Experimental evaluation of a CO_2 transcritical refrigeration plant with dedicated mechanical subcooling.* International Journal of Refrigeration, 2016. 69: p. 361-368.

[3] Nebot-Andrés, L., et al., *Experimental determination of the optimum working conditions of a commercial transcritical CO_2 refrigeration plant with a R-152a dedicated mechanical subcooling.* International Journal of Refrigeration, 2021. 121: p. 258-268.

[4] Nebot-Andrés, L., et al., *Experimental assessment of dedicated and integrated mechanical subcooling systems vs parallel compression in transcritical CO_2 refrigeration plants.* Energy Conversion and Management, 2022. **252**: p. 115051.

[5] Catalán-Gil, J., et al., *Energy analysis of dedicated and integrated mechanical subcooled CO_2 boosters for supermarket applications.* International Journal of Refrigeration, 2019. 101: p. 11-23.

[6] Dai, B., et al., *Energetic performance of transcritical CO_2 refrigeration cycles with mechanical subcooling using zeotropic mixture as refrigerant.* Energy, 2018. 150: p. 205-221.

[7] Llopis, R., et al., *Experimental evaluation of zeotropic refrigerants in a dedicated mechanical subcooling system in a CO_2 cycle.* International Journal of Refrigeration, 2021. 128: p. 287-298.

[8] Lemmon E. W., et al., *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology.* 2018.