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EXPERIMENTAL ANALYSIS OF THE FREEZING PROCESS IN A HORIZONTAL PLATE FREEZER WITH CO_2 AS REFRIGERANT IN A CASCADE REFRIGERATION SYSTEM

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ABSTRACT

A prototype of a cascade refrigeration system using NH_3 and CO_2 as refrigerants has been designed and built. The prototype is used to supply a 9 kW refrigeration capacity to a horizontal plate freezer at an evaporating temperature of –50 ºC as design conditions. The prototype includes a specific control system and a data acquisition system. The paper describes the prototype and the experimental program carried out to study the freezing process in the horizontal plate freezer. The experimental results include the freezing time, the temperature evolution in the product to be frozen, the refrigeration capacity of the facility, the electric power of the compressors, the COP's of the low and high temperature systems and the overall system COP. The results obtained would confirm that the use of CO_2 in the freezing process represents a viable alternative to the refrigerants currently in use.

INTRODUCTION

Since the synthetic refrigerants (CFCs, HCFCs y HFCs), which have a negative impact on the ozone layer or considered responsible for global warming, have been banned or are in the process of being outlawed or restricted in the near future, the refrigeration industry is witnessing important changes. In this regard, the use of natural substances as refrigerants, such as ammonia, carbon dioxide and the hydrocarbons, seems to be the better long-term alternatives, thus causing a renewed interest in this area. Ammonia is a naturally available old refrigerant used from the middle of the 1800s in absorption and compression refrigeration systems. It has excellent thermodynamic and transport properties as a refrigerant, but it brings with it a few application constraints such as toxicity and flammability [1]. Despite this, ammonia is the most common natural substance used as refrigerant for low temperature applications and it has also been proposed in low power refrigeration and heat pump systems [2]. Furthermore, recently published researches by Lorentzen [3] and Pearson [4] point out that the employment of CO_2 as a refrigerant offers high potential when used in low temperature refrigeration systems.

NOMENCLATURE

COP	[-]	Performance coefficient
h	[kJ/kg]	Specific enthalpy
m	[kg/s]	mass flow rate
T	[ºC]	Temperature
Tin_x	[-]	Related to tin Nº X
P	[kPa]	Pressure
Q	[kW]	Heat flow rate,
W	[kW]	Compressor's power

Subscripts

1-8	State points of the CO_2 system
9-15	State points of the NH_3 system
c	condenser, condensation, condensing
CO_2	Related to CO_2 system
CO_2/NH_3	Related to cascade system
e	evaporator, evaporation, evaporating
ele	Electric
max	Maximum
min	Minimum
NH_3	Related to NH_3 system
sat	Saturation

Included within the advantages of CO_2 is that it is environmentally friendly, non-toxic, non-explosive, easily available and can be used in refrigeration processes within a wide range of temperatures (from -50 ºC). The main disadvantages of CO_2 as a refrigerant are the high work pressures (7.2 MPa at 30 ºC). Lorentzen laid special emphasis on the high potential of reinitiating the use of CO_2 as a refrigerant in transcritical cycles and in cascade refrigeration systems. Regarding the use of CO_2 in cascade refrigeration systems, the pair of CO_2- NH_3 has been the centre of attention of much research developed in recent years, generating high expectations. Eggen and Aflekt [5] and Van Riessen [6] showed practical examples of the use of cascade refrigeration systems for cooling in supermarkets.

Moreover, Sawalha et al. [7] and Litikitthammannit [8] reported the design and construction of an experimental cascade refrigeration system with CO_2 and NH_3, for applications in a medium size supermarket in Sweden. Lee et al. [9], Getu and Bansal [10] showed a thermodynamic analysis of a cascade refrigeration system with CO_2/NH_3. Dopazo et al. [11], presented a theoretical analysis of the design and operating conditions, and the influence of these parameters on the COP system in a cascade refrigeration system with CO_2 and NH_3, including the influence of the compressor's efficiency on the optimum condensing temperature in the cascade heat exchanger. Bingming et al. [12], reported experimental data obtained from a cascade refrigeration system with CO_2/NH_3 when using screw compressors.

The main scope of this research was the description and experimental evaluation of a cascade refrigeration system prototype for freezing applications, using NH_3 and CO_2 as refrigerants, to supply a horizontal plate freezer with 9 kW of refrigeration capacity at -50 ºC of evaporating temperature. The prototype design includes a data acquisition system based on a 16-bits data acquisition card and a PC which allows real time readings and storage of the necessary variables to calculate and analyze the operating parameters that outline the performance of the prototype. The discussions on the experimental results include the freezing time, the temperature evolution in the product to be frozen, the refrigeration capacity of the facility, the electric power of the compressors, the COP's of the low and high temperature systems, and the overall system COP.

EXPERIMENTAL PROTOTYPE

The experimental cascade refrigeration system prototype has been designed to supply a horizontal plate freezer, with refrigeration capacity of 9 kW, at -50 ºC of evaporating temperature. The schematic diagram of the experimental prototype of the cascade system is shown in Figure 1, and a real view of the experimental facility can be appreciated in Figure 2.

The cascade refrigeration system is made of two single stage systems connected by a heat exchanger (cascade heat exchanger). CO_2 is used as refrigerant in the low temperature system and NH_3 is the refrigerant for the high temperature system. In the low temperature system CO_2 is evaporated in a stainless steel horizontal plate freezer.

An ejector is used to overfeed the plate freezer with CO_2 liquid coming from the CO_2 gas-liquid separator. The ejector acts as an expansion device, and also allows the liquid to recirculate. In the plate freezer, the CO_2 at evaporating temperature absorbs the cooling duty ($Q_{e,CO2}$) from the cooling tins, commonly used in the food refrigeration industry, and enters the CO_2 gas-liquid separator.

The CO_2 is suctioned from the gas-liquid separator and compressed in a semi-hermetic compressor. The discharged superheated CO_2 flows from the compressor unit and enters into the cascade heat exchanger where it is condensed, ejecting the heat into the cold refrigerant (NH_3), and then enters into a liquid reservoir tank. From the liquid reservoir, the flow of CO_2 enters into a sub-cooling process through a coil located inside the gas-liquid separator.

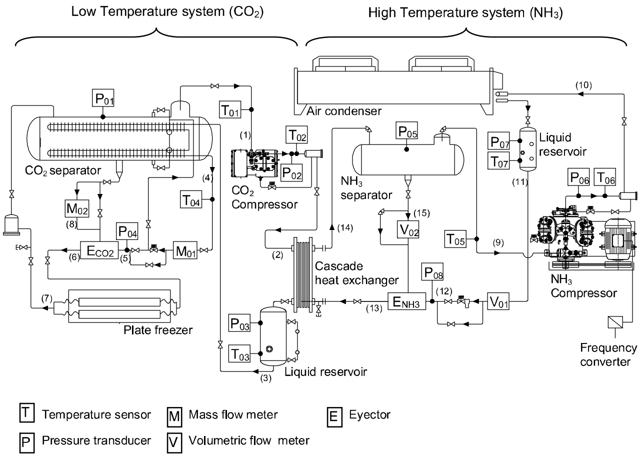

Figure 1 Schematic diagram of the CO_2/NH_3 cascade refrigeration system.

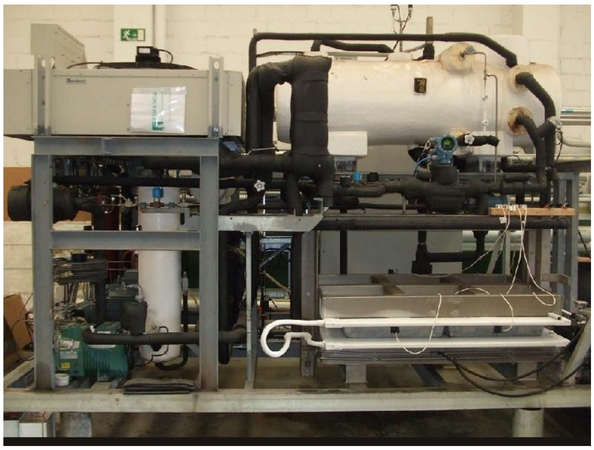

Figure 2 Photograph of the experimental prototype of the cascade refrigeration system with CO_2 and NH_3 built

The sub-cooled CO_2 flows through a expansion valve and enters the ejector, in which it is expanded to evaporating pressure. A secondary flow of saturated liquid of CO_2 coming from the gas-liquid separator, passes into the ejector and the two flows are mixed inside. The resultant mixture enters into the plate freezer where it is evaporated.

In the high temperature system, the flow of NH_3 coming from the gas-liquid separator is compressed in an open type compressor coupled to an electric motor with a pulley system. The superheated flow of NH_3 enters into the air condenser and ejects the heat into the atmospheric air. The condensed stream of NH_3 coming from the air condenser is channelled into a liquid reservoir tank. The NH_3 liquid leaves the reservoir tank and flows through a expansion valve and enters into the NH_3 ejector, where it is expanded until it reaches evaporating pressure and then mixed with a secondary flows of liquid NH_3

coming from a gas-liquid separator. The resulting flow mixture enters into the cascade heat exchanger, in which it evaporates and returns to the gas-liquid separator. Employing the method used for the low temperature system, the evaporation process of the NH_3 was also designed using liquid overfeed.

Data acquisition system

The experimental cascade refrigeration system prototype was equipped with a data acquisition system based on a 16-bits data acquisition card and a PC. In the low temperature system with CO_2, the suction temperature and the discharge temperature of the CO_2 compressor unit are measured by using two sensors located in the refrigerant line close to each compressor (T01 and T02, in Figure 1). The condensed CO_2 temperature is measured by using the sensor T03, (refer Figure 1), located in the CO_2 liquid reservoir tank. The CO_2 sub-cooled liquid temperature is measured by using the sensor T04 located in the outlet sub-cooler line. The suction pressure of the CO_2 system is measured by using the pressure transducer P01 located on the gas-liquid separator. The discharge pressure of the CO_2 compressor is measured by using the pressure transducer P02 installed in the discharge line, close to the compressor. In addition, the CO_2 condenser pressure is measured by using the pressure transducer P03 (refer Figure 1). The pressure at the CO_2 ejector inlet is measured by using the pressure transducer P04. The main mass flow of CO_2 is measured in the outlet sub-cooling line, by using the mass flow-meter M01, whilst the secondary mass flow of CO_2 is measured by using the mass flow-meter M02, located at the auxiliary outlet of the gas-liquid separator (refer Figure 1).

In the high temperature system with NH_3, the suction and discharge temperatures are measured by using the sensors T05 y T06, located on the suction and discharge lines of the NH_3 compressor, respectively (refer Figure 1). The NH_3 condenser temperature is measured by using the sensor T07, located in the NH_3 liquid reservoir tank. The suction pressure is measured by using a pressure transducer located in the gas-liquid separator (P05). The discharge pressure of the NH_3 compressor is measured by using the pressure transducer P06, located in the discharge line of the NH_3 compressor. The condensing pressure of NH_3 is measured by using the pressure transducer P07, installed in the liquid reservoir tank of NH_3. The pressure at the NH_3 ejector inlet is measured by the pressure transducer P08. The main volumetric flow of NH_3 is measured by using the volumetric flow-meter V01, (refer Figure 1). The secondary flow of NH_3, used to overfeed the NH_3 evaporator, is measured by using the volumetric flow-meter V02, located at the auxiliary outlet of the NH_3 gas-liquid separator (Figure 1).

All the temperature sensors used in the experimental facility are A Pt100 inserted in 3 mm diameter stainless steel pockets. The pressure transducers are WIKA ECO 1 type, with an accuracy of ± 0.5% of the full scale (40 bar). The refrigerant mass flows of the CO_2 system are measured by using Coriolis flow meters, with an accuracy of ±0.25% of the measured value. The volumetric flows of the NH_3 system are measured by using electromagnetic flow-meters, with an accuracy of ±0.25% of the measured value. The electric power of each compressor is measured by using watt-meters, with an accuracy of ±2% of the measured value.

Control System

The control system installed in the cascade prototype is like the common systems used in facilities of the local refrigerated fish industry. The operating control is made using a PLC. The controlled variables are: the condensing pressures of NH_3, the evaporating pressure of NH_3 and the evaporating pressure of CO_2. The condensing pressure of NH_3 is controlled by modifying the velocity of the fans of the air condenser. There are three options: fans off, fans at velocity 1 (less velocity) and fans at velocity 2 (high velocity). To control the evaporating pressure of CO_2, a flow line which connects the CO_2 compressor discharge line to its suction line was installed, thus allowing the recirculation of a small portion of the mass flow of compressed CO_2. The recirculation of the mass flow of CO_2 is controlled using a valve installed in the flow line previously mentioned. The evaporating pressure of NH_3 is controlled by varying the capacity of the compressor's high temperature system; in the same manner, three values of capacity for this compressor are available: 100% of the capacity, 50% of the capacity and compressor when off (0% of capacity). In addition, the experimental facility was fitted with a frequency converter, Danfoss VLT 2800, which permits the modification of the electric motor's velocity, and consequently the gradual variation of the NH_3 compressor's capacity.The mass flow of the liquid refrigerant is controlled by means of the valves located at the ejectors inlet lines of each system.

Any time the experimental prototype becomes non functional, the pressure of the low temperature system will be controlled using an auxiliary refrigeration unit. This auxiliary unit will cool the CO_2 of the low temperature system with a coil located in the gas-liquid CO_2 separator.

EXPERIMENTAL PROCEDURE AND DATA REDUCTION

Experimental Procedure

The experimental evaluation of the cascade system prototype was made using 94 kg of potable water as the product to be frozen. Four (4) aluminium tins, similar to those commonly used in the local refrigerated fish industry, were filled with the potable water (23.5 kg p/tin) and put in the plate freezer. The tin's dimensions are 0.55 m x 0.45 m x 0.095 m. Each tin was equipped with one A Pt-100 type temperature sensor, inserted in 3 mm diameter stainless steel pockets, located at the tin's geometrical centre. The water temperatures are recorded and stored with the prototype's data acquisition system. The tins are numbered following the trajectory of the CO_2 in the plate freezer. Figure **3** shows the positions of the tins in the experimental evaluation.

The test was conducted for two hours (7200 seconds), recording all the variables measured each 5.5 seconds, approximately. The test time started when the compressors were switched on. The experimental evaluation of the prototype was initiated fixing the control variables as follow:

- The CO_2 compressor's capacity was established at 5.8 bar for the "on recirculation" condition, and 6.0 bar for the "off recirculation" condition. The liquid control valve was fixed at 1/8 open.

- The NH_3 compressor's capacity was established at 2.1 bar for the "0% capacity" condition, 2.3 bar for the "50% capacity" condition, and 2.7 bar for the "100% capacity condition". The compressor's re-start was fixed at 2.9 bar. The liquid control valve was fixed at ¼ open. The frequency converter was fixed at 50 Hz.
- The NH_3 condensing pressure was established at 12.0 bar for the fans at "less velocity" condition, and 13.0 for the fans at "high velocity" condition.

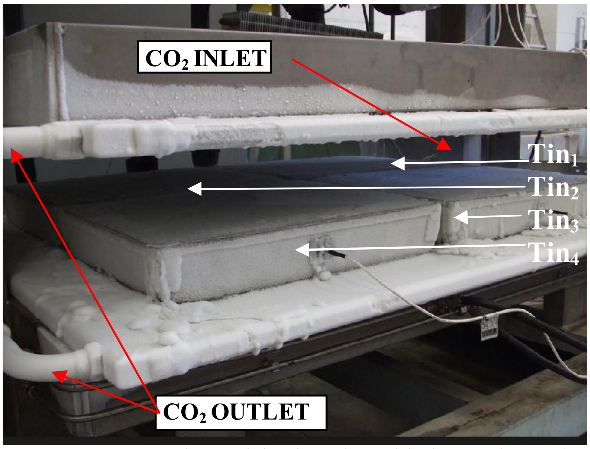

Figure 3 Locations of the four tins with the product to be frozen in the plate freezer, used during the evaluation.

The ambient temperature was measured at 14 ºC. The initial temperature of the water to be frozen was the ambient temperature.

Subsequently, taking into account the results of the initial test (Test 01), the performance of the freezing process in the experimental prototype was evaluated at three different control conditions of the NH_3 compressor's capacity, keeping constant the rest of the prototype's control variables, in order to obtain lower evaporating temperatures of CO_2. In table 1 are shown the operating conditions of the prototype during the experimental evaluation carried out.

Table 1

Operating conditions during the experimental evaluation.

Test Nº	CO_2 comp capacity (on-off) (bar)	NH_3 comp capacity (50-100%) (bar)	(0% re-start) (bar)	$P_{c,NH3}$ (01-02 fans vel) (bar)
01	5.8 – 6.0	2.3 – 2.7	2.1 – 2.9	12.0 - 13.0
02		1.9 – 2.3	1.7 – 2.5	
03		1.5 – 1.9	1.3 – 2.1	
04		1.1 – 1.5	0.9 – 2.7	

Data reduction

Several operating parameters for each of the main components of the facility during the experimental evaluation of the cascade refrigeration system, as well as the global COP, were calculated from the data experimentally measured. The calculations from the previously mentioned parameters were formulated from the mass and energy balances applied to each one of the main prototype components. Thermodynamic properties of the CO_2 and NH_3 were obtained from the Refprop Database [13]. The calculated parameters are detailed as follows, according to Figure 1.

The cooling capacity of the plate freezer can be expressed as:

$$Q_{e,CO_2} = m_1 \cdot (h_{1,sat} - h_3) \quad (1)$$

The condensing capacity in the cascade heat exchanger with CO_2 (the low temperature system) and the evaporating capacity of the high temperature system with NH_3 are calculated in equations (2) and (3), respectively.

$$Q_{c,CO_2} = m_1 \cdot (h_2 - h_3) \quad (2)$$

$$Q_{e,NH_3} = m_9 \cdot (h_{9,sat} - h_{11}) \quad (3)$$

The condensation capacity of the air condenser is calculated in equation (4).

$$Q_{c,NH_3} = m_{11} \cdot (h_{10} - h_{11}) \quad (4)$$

The cascade refrigeration system COP is defined as:

$$COP_{CO2/\ NH3} = {Q_{e,CO2}} \Big/ {\left(W_{ele,CO2} + W_{ele,NH3}\right)} \quad (5)$$

The COP of the high temperature system with NH_3, and the COP of low temperature system with CO_2 are determined respectively, as follow:

$$COP_{NH3} = {Q_{e,NH3}} \Big/ {W_{ele,NH3}} \quad (6)$$

$$COP_{CO2} = {Q_{e,CO2}} \Big/ {W_{ele,CO2}} \quad (7)$$

On the other hand, an analysis of the experimental uncertainties was carried out according to ISO [14]. This analysis revealed that the maximum for typical uncertainties was estimated to be 0.35% for $Q_{e,CO2}$, and 1.67% for $COP_{CO2/NH3}$.

RESULTS AND DISCUSSION

The four tin's temperatures and the evaporating temperature of CO_2 recorded during the test 01 are shown in Figure 4. In addition, Figure 5 shows the COP values of the high and low temperature systems, and the overall COP, obtained in this test.

In Figure 4, the high similarity between the evolution of the temperature measured in the tin_1 and the temperature measured in the tin_2 can be appreciated. The same behaviour can be observed between the temperatures measured in tins 3 and 4. This was expected due to the trajectory followed by the CO_2 mass flow in the plate freezer and the location of the tins in it. In general, all of the tins' temperatures that were measured showed the same evolution. In the initial period, the tins' temperatures decrease from the initial temperature until reach the frozen water temperature of 0 ºC. Then the temperatures remain constant during the second period due to the phase change of the water contained in the tin. Once the water is frozen, the temperatures decrease again until the end of the test.

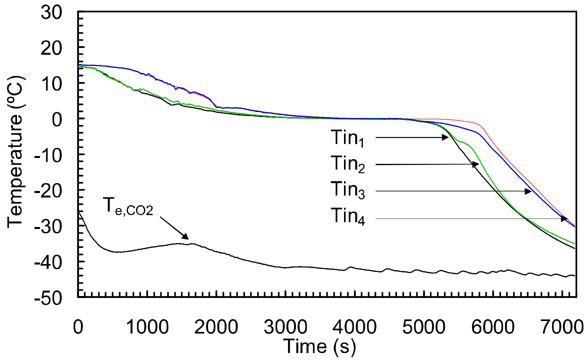

Figure 4 Instantaneous CO_2 evaporating temperature and tin's temperatures. Test 01.

The lowest temperature obtained was -36.36 ºC, measured in the tin_1 at the end of the test. The highest final temperature was measured at -29.98 ºC, in the tin_4. So a difference of 6.38 ºC was observed between the temperatures of tin 1 and 4.

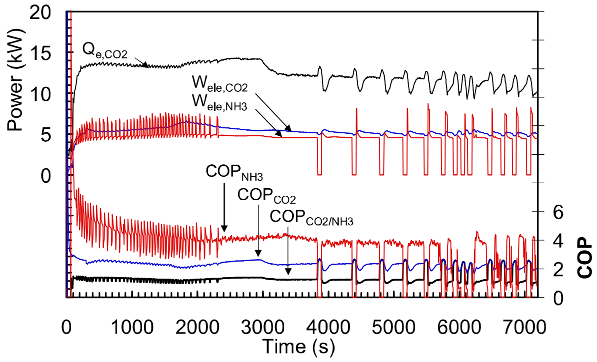

Figure 5 Instantaneous $Q_{e,CO2}$, $W_{ele,CO2}$, $W_{ele,NH3}$, COP_{CO2}, COP_{NH3} and $COP_{CO2/NH3}$. Test 01.

On the other hand, the evolution of $T_{e,CO2}$ shows a decreasing trend during the test. The lowest evaporating temperature obtained was -44.33 ºC at 7044s. The fluctuations observed are associated, mainly, with the operation of the control capacity of the NH_3 compressor. The influence of this capacity control on $Q_{e,CO2}$, $W_{ele,CO2}$ and $W_{ele,NH3}$ can be appreciated in Figure 5. The instantaneous COP_{NH3} values observed are almost always higher than COP_{CO2} ones. The $COP_{CO2/NH3}$ values fluctuates around 1.3.

In Figure 6 are depicted the instantaneous temperatures measured in the tins 1 and 4 during the four test performed, and in Figure 7 the instantaneous evaporating temperatures of CO_2 are shown.

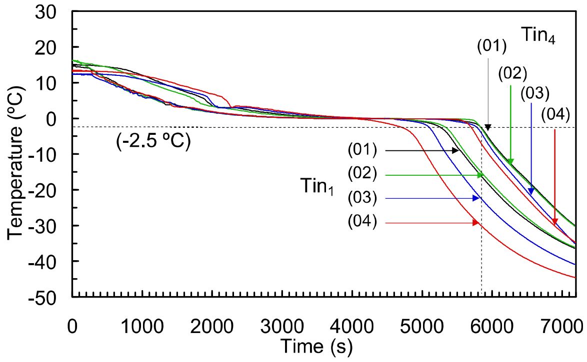

Figure 6 Instantaneous tin_1 and tin_4 temperatures measured during the tests (01-04).

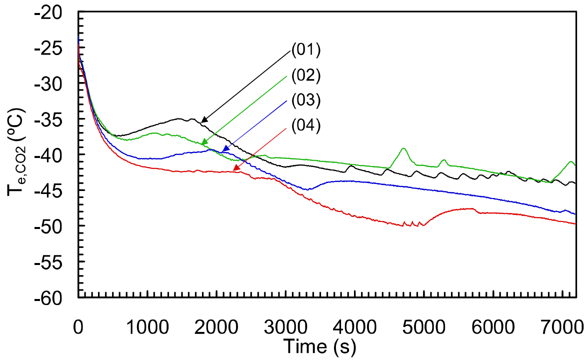

Figure 7 Instantaneous CO_2 evaporating temperatures obtained during the tests (01-04).

In figures 6 and 7 it can be appreciated that the lower the evaporating NH_3 pressure established by the control capacity of the NH_3 compressor (test 01 to 04), the lower the $T_{e,CO2}$ will be and, as a result, the lower the final temperatures measured in both tins (1 and 4) will be. The evolution of temperatures observed in the tin_4 during the tests 01 and 02 are very similar. This behaviour could result from the similarities between $T_{e,CO2}$ obtained in those tests, as can be observed in Figure 7. In test 04 it was observed the lowest tin_1 and tin_4 temperatures, -44.64 and -34.79 ºC, respectively, and the highest temperature difference between those tins, 9.85 ºC. The lowest $T_{e,CO2}$ temperature of -50.07 ºC was measured during test 04 at 4908 s (Figure 7).

In addition, Figure 6 shows that, after 5900 seconds, all the tins' temperatures had reached values less than -2.5 ºC. As a result of the foregoing it can be concluded that, when the temperature in the tin reaches the value of -2.5 ºC the water in the tin will be completely frozen, Figure 6 also shows that the freezing times of tins 1 and 4, obtained in the test 01, were 5341s and 5837s, respectively, whereas the freezing time observed in test 04 the time were 4714s and 5703s for those tins. Varying the capacity control of the NH_3 compressor from test 01 to test 04 (table 1), a reduction of 11.7 % was obtained in the freezing time of tin_1, and 2.3% in the freezing time of tin_4.

The average temperature values of tin_1 and tin_4 (maximum and minimum), $T_{e,CO2}$ and $COP_{CO2/NH3}$ are represented in Figure 8 for all of the tests that were performed. Both tin's temperatures show clearly light decreasing trends. Similar behaviour is observed for $COP_{CO2/NH3}$ values. A difference of 10.45 % was obtained between the highest and lowest average $COP_{CO2/NH3}$, observed in test 01 (1.34) and test 04 (1.20), respectively.

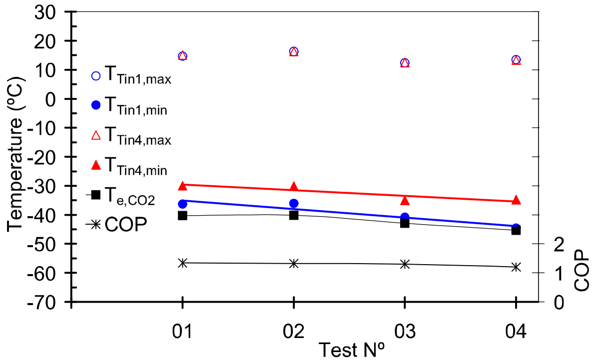

Figure 8 Average values of tin_1 and tin_4 maximum and minimum temperatures, $T_{e,CO2}$ and $COP_{CO2/NH3}$.

CONCLUSION

This paper dealt with the description and the experimental evaluation of an experimental prototype of a cascade refrigeration system with CO_2 and NH_3, to supply a horizontal plate freezer of 9 kW of nominal refrigeration capacity at -50 ºC of evaporating temperature. The experimental evaluation of the prototype was performed by four tests with different operating conditions of the capacity control of the NH_3 compressor in order to obtain different evaporating CO_2 temperatures. Water was used as the product to be frozen. The timeframe of each test was 7200s.

During the experimental evaluation a high similarity between the evolution of the temperatures measured in the tins 1 and 2, and between tins 3 and 4, was observed. Results show that the lower the evaporating NH_3 pressure established by the control capacity of the NH_3 compressor (test 01 to 04) is, the lower will be the $T_{e,CO2}$ and, consequently, the lower the final temperature measured in the tins, will be. The lowest $T_{e,CO2}$ temperature was measured at -50.07 ºC, and the lowest tin's temperature at - 44.64 ºC. Temperature differences from 6.38 ºC (test 01) to 9.85 ºC (test 04) were observed in the temperetures of the tins.

Likewise, after 5900 seconds, all the tin's temperatures had reached values less than -2.5 ºC. Varying the capacity control of the NH_3 compressor from test 01 to test 04 (Table 1), a reduction of 11.7 % was obtained in the freezing time of tin_1, and of 2.3% in the freezing time of tin_4.

On the other hand, the average values of $COP_{CO2/NH3}$ show a difference of 10.45 % between the highest and lowest values observed in test 01 (1.34) and test 04 (1.20), respectively.

The experimental results would confirm that the use of CO_2 in the freezing process represents a viable alternative to the refrigerants currently in use.

REFERENCES

[1] Pearson, A., New developments in industrial refrigeration. *ASHRAE Journal,* Vol 43, 2001, pp. 54-58

[2] Palm, B., Ammonia in low capacity refrigeration and heat pump systems. *International Journal of Refrigeration,* Vol 31, 2008, pp. 709-715

[3] Lorentzen, G., Revival of carbon dioxide as a refrigerant. *International Journal of Refrigeration*, Vol 17, 1994, pp. 292-301

[4] Pearson, A., Carbon dioxide new uses for an old refrigerant. *International Journal of Refrigeration*, Vol 28, 2005, pp. 1140-1148

[5] Eggen, G., Aflekt, K., Commercial refrigeration with ammonia and CO2 as working fluids, *Proceedings of the Third IIR: Gustav Lorentzen Conf. on Natural Working Fluids*, 1998, pp. 281-292

[6] Van Riessen, G.J., CO2/NH3 Supermarket refrigeration system with CO2 in the cooling and freezing section, *TNO Environment, Energy and Process Innovation, Apeldoorn, Netherland,* from:http://www.energie.nl/nel/nl05e1210.html, 2004

[7] Sawalha, S., Suleymani, A., Rogstam, J., CO2 in supermarket refrigerantion, *CO2 Project Report Phase I, KTH Energy Technology*, 2006

[8] Likitthammanit, M., Experimental investigation of CO_2/NH_3 cascade and transcritical CO2 refrigeration systems in supermarkets. *Dissertation, KTH Scholl of Energy and Environmental Technology, Stockholm,* 2007

[9] Lee, T., Liu, C., Chen, T., Thermodynmic analysis of optimal condensing temperature of cascade-condenser in CO2/NH3 cascade refrigeration systems, *International Journal of Refrigeration* Vol 29 (7), 2006, pp. 1100-1108.

[10] Getu, H., Bansal, P., Thermodynamic analysis of an R744-R717 cascade refrigeration system, *International Journal of Refrigeration*, Vol 31, 2008, pp. 45-54.

[11] Dopazo, J.A., Fernandez-Seara, J., Sieres, J., Uhía, J., Theoretical analysis of a CO2- NH3 cascade refrigeration system for cooling applications at low temperatures, *Applied Thermal Engineering* Vol 29 (8-9), 2009, pp. 1577-1583

[12] Bingming, W., Huagen, W., Jianfeng, L., Ziwen, X., Experimental investigation on the performance of CO2/NH3 cascade refrigeration system with twin-screw compressor, *International Journal of Refrigeration*, 2009, doi:10.1016/j.ijrefrig.2009.03.008.

[13] Lemmon, E.W., McLinden, M.O., Huber, M.L., Reference Fluid Thermodynamic and Transport Properties (REFPROP), Version 7.0. *National Institute of Standards and Technology (NIST),* 2004

[14] ISO (Ed.), Guide to the expression of uncertainty in measurements. International Organization for Standardization (ISO), 1995, pp. 9-27