Report:

ANALYSIS OF RS51 REFRIGERANT PERFORMANCE IN COMMERCIAL REFRIGERATION APPLICATIONS

OBJECTIVE

The objective of this work is the experimental analysis of the performance of the refrigerant RS-51 (R470B) in commercial refrigeration applications and the validation of the most suitable thermostatic expansion valve to be used as *a drop-in* type replacement.

JOB DESCRIPTIONS

The work consists of analyzing the operation of the RS-51 fluid through samples provided by the company under the following working conditions (Table 1). These tests are intended to simulate and analyze the operation of a commercial refrigeration system.

Table 1. Working conditions for both refrigerants

Condition	T_evaporation	T_condensation
Condition 1	-20 °C	40 °C
Condition 2	-10 °C	40 °C

The aim is to simulate the operation of a commercial refrigeration system on a test bench based on a vapor compression circuit. Both tests consider a moderate ambient temperature based on the Mediterranean climate, between 25 and 30 °C. Depending on the evaporator design, the two evaporation temperatures cover a food preservation/freezing range between 0 °C and -15 °C.

The thermostatic expansion valves *(TXVs) of* different traditional refrigerants will be used with the RS-51, and the ISTENER research group will analyze the behavior of the new refrigerant and its proper or non-operation.

METHODOLOGY

To carry out the tests set out in the previous section, the following tasks agreed between the company and the university have been followed:

Task 1: *Installation preparation and pre-analysis*.

Task 2: *Testing with the R404A TXV.*

Task 3: *Tests with the R22 TXV.* Task 4:

Tests with the R134a TXV. Task 5:

Testing with the R449A TXV.

Task 6: General conclusions *and recommendations*.

RESULTS

Task 1: *Installation preparation and pre-analysis*.

Test bench

Tests have been carried out in a fully monitored vapor compression system connected to two secondary circuits that allow the evaporation and condensation conditions to be fixed. Figure 1 shows a photograph of the primary circuit, and Figure 2 shows the schematic diagram with all the components. Also shown are the location of pressure and temperature measurements and other secondary components required for operation.

Figure 1. Photograph of the test bench

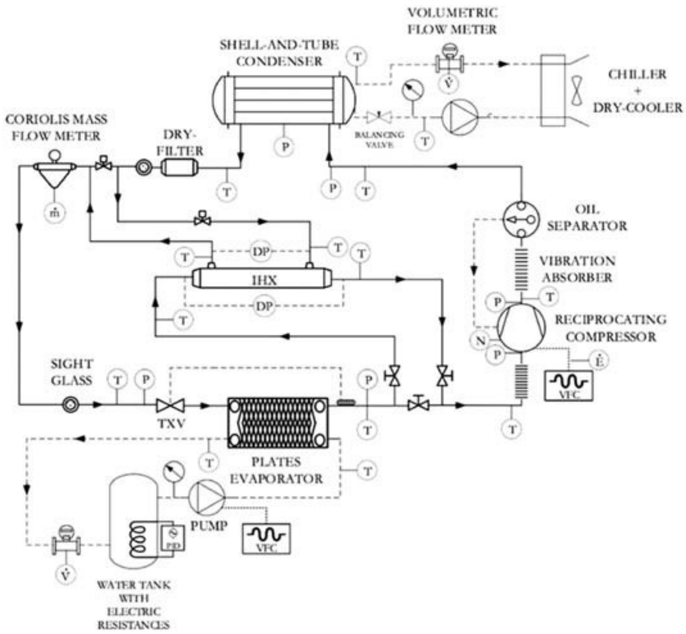

Figure 2. Representation Schematic Diagram

The facility was originally built to experimentally compare R22 and its hydrofluorocarbon (HFC) alternatives, so the correct functioning and suitability of the components for both refrigerants were considered in the design and construction phase. Other alternative refrigerants to R134a and R404A have been validated in the past, as can be seen in the following link (ordered chronologically according to publication in scientific journals):

- R134a, R1234yf y R1234ze(E): https://www.sciencedirect.com/science/article/pii/S1359431114005365
- R134A and R450A: https://www.sciencedirect.com/science/article/pii/S0140700714003569
- R404A and R448A: https://www.sciencedirect.com/science/article/pii/S0196890415007803
- R404A, R454C and R455A: https://www.sciencedirect.com/science/article/pii/S0140700718301762

Tables 1 and 2 describe the main circuit components and the sensors used.

Table 1. Description of Main Components

Component	**Description**
Compressor	2-cylinder open piston, geometric volume of 681 cm3 and rotational speed of 573±2 rpm at 50 Hz connected to a frequency inverter and 7.5 kW motor

Component	Description
Condenser	Casing-tubes, 2-1 heat exchange area of 2.87 m2
Evaporator	Welded plate type, 20 plates, 1.13 m2 heat exchange area
Expansion rack	Multiple TXVs in parallel and selectable via ball valves

The evaporator and condenser exchange heat with secondary closed circuits in which a commercial mixture of ethylene glycol/water (prevent freezing) and water circulates. A set of variable resistors immersed in a tank (provides thermal inertia) and a fan coil with a frequency inverter allows the power exchange to be adjusted, respectively. The circulation pumps have an integrated frequency inverter that adjusts the temperature difference between the inlet and outlet of the exchanger.

After discussions with the company and following their recommendations, it has been decided to use the reheating-subcooling (IRS) heat exchanger to ensure a minimum degree of reheating (GR) in the compressor and avoid liquid shocks in any condition and with any TXV.

Table 2. Measured Parameters and Uncertainty

Measured Parameter	Sensor	Uncertainty
Temperature	Type K Thermocouple	±0.3 K
Pressure	Pressure Transducer	±0.7 kPa
Cooling Mass Flow	Coriolis Mass Flow Meter	±0.22% measurement
Compressor Power Consumption	Analog Drive Output	±0.45 kW

Calculated Parameters

The thermodynamic calculations necessary for calculating the parameters required by the project are based on REFPROP v10. The RS-51 simulation file was obtained by generating the mixture with REFPROP, according to the composition provided by the company.

The cooling capacity is obtained on the refrigerant side by multiplying the mass flow rate obtained by the Coriolis flowmeter and the cooling effect based on the enthalpy of the evaporator's inlet and outlet. The cooling capacity must be maintained so that the system can counteract the thermal loads of the environment to be controlled.

Both enthalpy values are obtained with pressure and temperature measurements. Due to the impossibility of determining the enthalpy of the evaporator inlet, an isoenthalpic expansion is assumed, and the input enthalpy is taken to the TXV.

$$Q'_o = m'_{ref} * (hos - h_{TXV,e})$$

The side of the secondary circuit could also determine the cooling capacity. However, it is considered less accurate because the vane flowmeter measurement is less expensive than the Coriolis flowmeter in the coolant circuit. Between the secondary and the primary circuit, heat loss always makes the value not match.

The evaporation temperature value was based on the following criteria recommended by other refrigerant manufacturers, as agreed at the GRIT/UJI meetings (Figure 3). In the same way, it is obtained in condensation.

Condensing mid temperature:	$t_{2m} = (t_{2f} + t_{2d}) / 2$
Sub-cooling:	$Dt_{sub} = t_{2f} - t_5$
Evaporating mid temperature:	$t_{1m} = (t_{1e} + t_{1d}) / 2$
Gas Superheat at the compressor inlet	$t_{sh} = (t_1 - t_{1d})$

The above temperature conversion provides more than a rough comparison of *compressor performance data.*

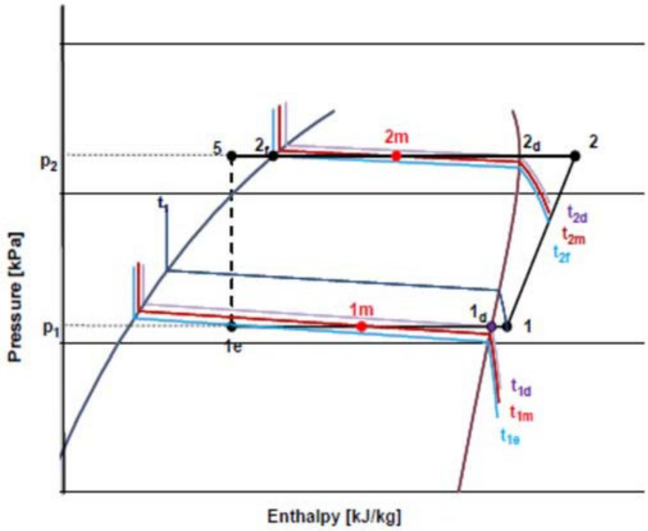

Figure 3. The criterion for Determining Operating Temperatures for a Zeotropic Mixture

To determine the RES, the cooling capacity described above is divided by the electrical consumption of the compressor (motor, frequency inverter). It is also known as a COP if the system only provides cooling. The EER is widely used to quantify the energy performance of installations based on vapor compression systems.

$$EER = \frac{Q'_o}{Pot}$$

Set-up of the system

All the necessary tasks were completed to fine-tune the installation and verify its correct condition. In this way, the following actions were carried out in the set-up:

- The correct data collection by the data acquisition system and its registration on a computer equipped with the recommended software was verified.
- The lubricating oil in the installation and the filter were changed (Figure 4).

Figure 4. Filter installed for testing

- Ball valves with nitrogen-leaking ball valves were replaced.
- Installation of ball valves to section and lose less refrigerant charge when replacing orifices. TXV is more accessible to change holes or adjust screws if required (Figure 5).

Figure 5. Compensator bridge for R404A and R22 TXV (right) and TXV

- The absence of leaks was verified by pressurization with nitrogen at the maximum working pressure (22 bar), and a vacuum was carried out to eliminate any remaining previous gas in the installation.

Preliminary calculations

A simulation was carried out with fixed and equivalent compressor performances, GR, and subcooling degree to have a reference point when analyzing the validity of the tests.

The facility was designed to operate with R22 and its alternatives but has been used with R404A and R134a and their alternatives. However, it was validated that the proposed points could be simulated in the experimental installation by paying attention to the following factors in RS-51:

- The maximum working pressure does not exceed that controlled by the pressure switch (2 bar below the safety valve (28 bar), consistently below the maximum permissible pressure for any component).
- The minimum circuit pressure corresponding to RS-51 shall also not be less than the minimum pressure controlled by the pressure switch so as not to work idle.

- The discharge temperature in the worst conditions will not affect the lubricating oil.
- The suction temperature shall not exceed the maximum intake of the compressor.

- Secondary equipment has sufficient power to provide the charge (evaporator) and stir (condenser).
- The power consumed by the compressor is not greater than the engine can provide.
- The measuring range of the sensors is adjusted to the operating parameters of the refrigerants.

After carrying out the theoretical analysis, it has been decided to use the compressor frequency inverter at 35 Hz when both refrigerant fluids are used and to have a power margin in both secondary circuits. The orifice of the TXV is suitable for this range of operating conditions and frequency for the TXV reference refrigerants, R-404A (7.2 and 4.8 kW), R134a (4.4 and 2.8 kW), and R22 (7.3 and 5 kW) for condensing temperatures of 40 °C and evaporation of -10 °C and -20 °C, respectively.

The following TXVs are available to test *drop-in* replacement with R470B, and the following orifices will be tested on the following Danfoss valves:

- R404A TS2 valve, without a compensator, orifice 06 and 05. It was later replaced by the TE2 valve of R404A, with a compensator and orifice 05.
- R22 TEX2 valve, with compensator, orifice 05.
- R134a TE5 valve, with compensator, orifice 01 and 02.

The TXVs are connected in parallel and share the same measurement point for compensation. The TXV is selected for testing using a ball valve at the inlet. All holes and TXVs have been validated using *Danfoss* CoolSelector2 software (https://www.danfoss.com/es en/service-and-support/downloads/dcs/coolselector-2/).

After submitting the first version of the report, the company requested to carry out experimental tests with the TXV of R448A/R449A (from now on, only referred to as TXV of R449A for simplicity). The TXV with compensator (TE2) and the hole (No. 05) were selected, and the R449A TXV replaced the R404A TXV. Thus, in addition to the above list of TXVs tested, the following are added:

- R448A/R449A TE2 valve, with compensator, orifice 05.

Testing Methodology

The methodology followed is the same in all tasks. With the IRS activated, conditions are set in the secondary circuits to achieve close conditions of desired evaporation and condensation.

The test will be recorded throughout the operation. And then, the most stable 5 minutes will be selected.

Task 2: *Testing with the R404A TXV.*

The first tests have been carried out with the R404A TXV without compensation. This TXV has been used in the experimental comparisons of R404A, R448A, R454C, and R455A, and its data have been published in scientific journals, as indicated in the previous section. In these experimental tests, the orifice and screw have been adjusted to maintain a GR at the evaporator outlet in the order of 10 K.

In the tests with this TXV, and initially with a hole of 06, it was observed that the GR tended to become negative within a few minutes of starting the machine. The IRS avoided the liquid hit, but it was decided not to hit any stationary under these conditions.

By closing the TXV screw as much as possible, a minimum GR could be achieved in the evaporator. Figure 6 shows the evolution of the suction and discharge pressure and the temperature at the evaporator outlet in the tests.

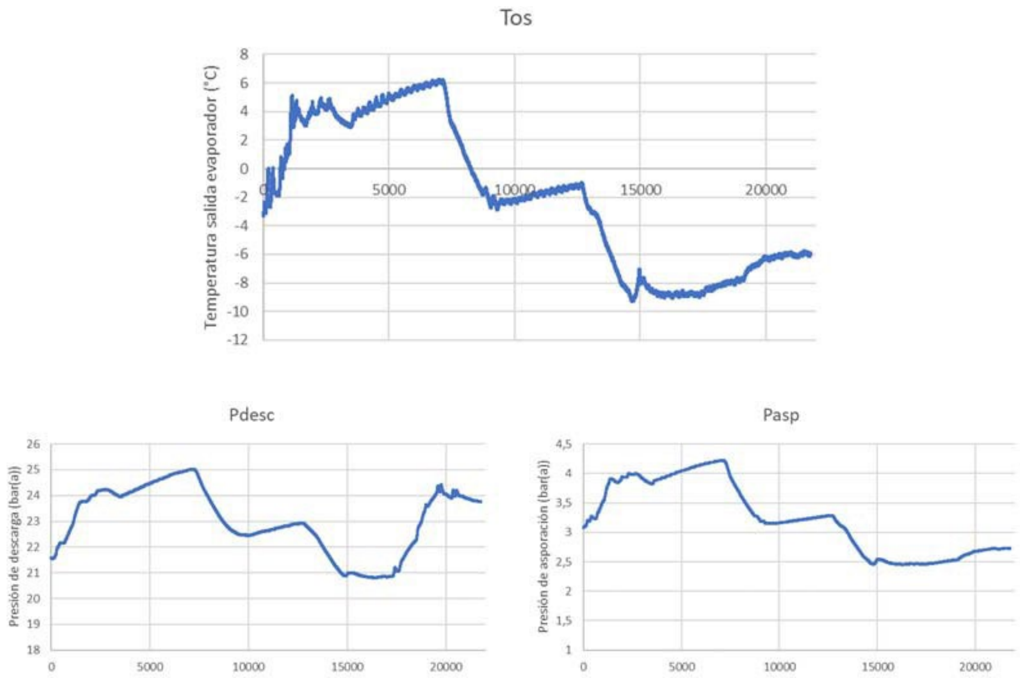

Figure 6. Measuring Representative Parameters with the R404A TXV

The conditions of the secondary glycol circuit were varied to cover different evaporation conditions with the aerothermal of the secondary water circuit at maximum, so the condensing temperature varied slightly following the decrease in the condensation temperature.

Hole 05 was then changed. The same conclusions were reached as with the other orifice (06). If the hole in the TXV was not closed as much as possible, the GR in the evaporator was non-existent, which could endanger the compressor in the event of liquid impacts. Therefore, the behavior analysis is analogous to hole 06.

Finally, as an additional task and to verify all the possibilities in this project, the R404A TXV without a compensator was replaced by a new one with a compensator. The positive GR could not be secured in any condition or screw position. No steady state could be recorded.

Despite the existence of a minimum GR at the evaporator outlet in the case of the valve without a compensator, it is recommended to discard an R404A TXV to control a machine with RS-51. TXVs are not designed to work closed entirely, and there would be a permanent risk of liquid impact.

Task 3: ***Tests with the R22 TXV.***

R22 TXV with compensator has been used in R22 and R407C trials. The experiments were performed with a hole size of 05, as obtained with the CoolSelector 2 software.

In the tests with the R22 TXV, it is observed that the GR at the evaporator outlet is adequately controlled, although with an oscillation (known as *hunting*, https://www.parker.com/content/da m/P arker-com/Literature/Sporla n/Sporlan-pdf- files/Sporlan-pdf-010/10-9.pdf) if the screw is too closed. In this way, the screw of the TXV was progressively opened from 1 to 5. Figure 7 shows that for the larger opening of the TXV screw, the oscillation is lower, and the behavior of the machine is stabilized. The average value of the main parameters of interest is shown in Table 3.

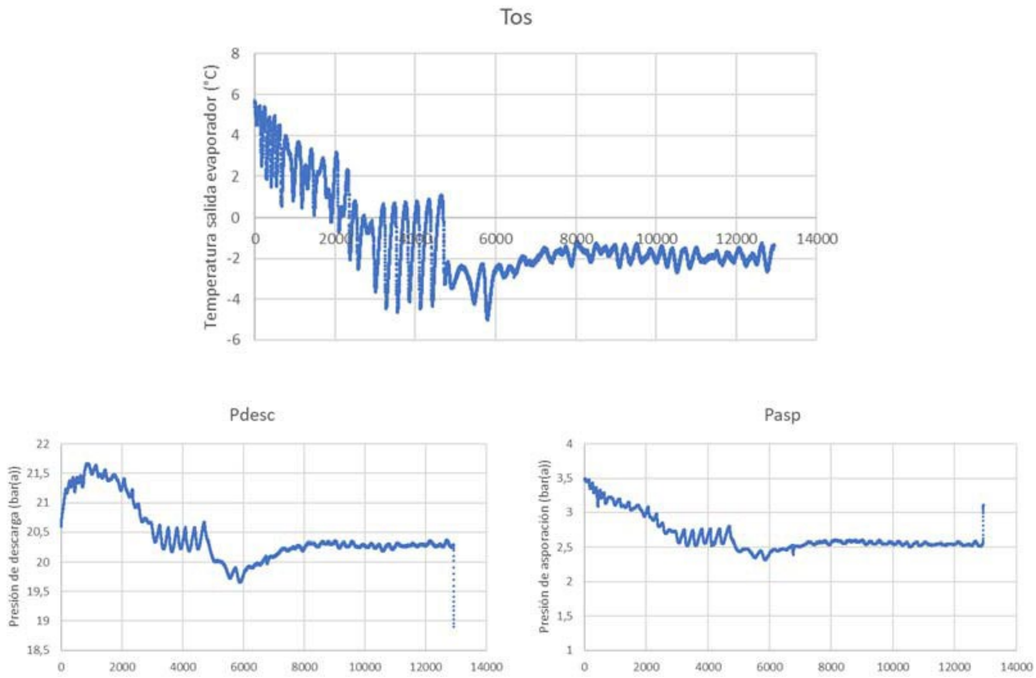

Figure 7. Measurement of representative parameters with the R22 TXV

Table 3. Average Parameters for Stationary Points with the R22 TXV

PASP	Pdesc	Tevap	Tcond	GRevap	GRtot	Qo	EER
bar(a)	*bar(a)*	*C*	*C*	*Towards*	*Towards*	*kW*	-
3,27	21,35	-9,9	45,5	7,21	18,54	5,89	1,76
3,12	21,51	-10,7	45,8	7,34	19,88	5,34	1,64
2,82	20,98	-13,1	44,7	7,28	21,56	4,60	1,53
2,73	20,68	-14,1	44,1	7,70	21,64	4,48	1,53
2,38	19,76	-17,5	42,2	8,15	23,10	3,83	1,48
2,58	20,31	-15,7	43,3	8,14	21,75	4,30	1,54
2,55	20,29	-16,0	43,3	8,09	22,04	4,16	1,51

Given the results, due to the excellent performance of the R22 TXV with the compensator, it was not tested with another orifice. Using this component with the same orifice as the one recommended for R22 is recommended. The GR value at the evaporator outlet is in recommended values, and the oscillation is minimal for an opening equal to or greater than the factory values. In all the tests, it was ensured that the coolant reached the TXV in liquid phase, and therefore, the subcooling at the inlet of the TXV was ensured for proper operation. The IRS ensured this and minimal pressure loss in the liquid line. It was also validated through a viewer at the input of each TXV.

Task 4: *Tests with the R134a TXV.*

The last of the TXVs tested is R134a with a compensator. It is a TXV with great regulation capacity and has previously been used in experiments with this refrigerant and R1234yf as a direct replacement. The experiment started with a size 01 hole.

During the tests, the TXV screw was started with one turn from the closed position. It was gradually increased up to 5 laps and still did not have an acceptable behavior (excessive GR). A test with an initial opening of 10 turns was started again, and the GR at the evaporator outlet was relatively high, so the screw of the TXV was gradually opened, and the GR was reduced from 16 K to 10 K. From there, the oscillations became too large. It was decided to stop the trial. This behavior is depicted in Figure 8. The average value of the main parameters of interest is shown in Table 4.

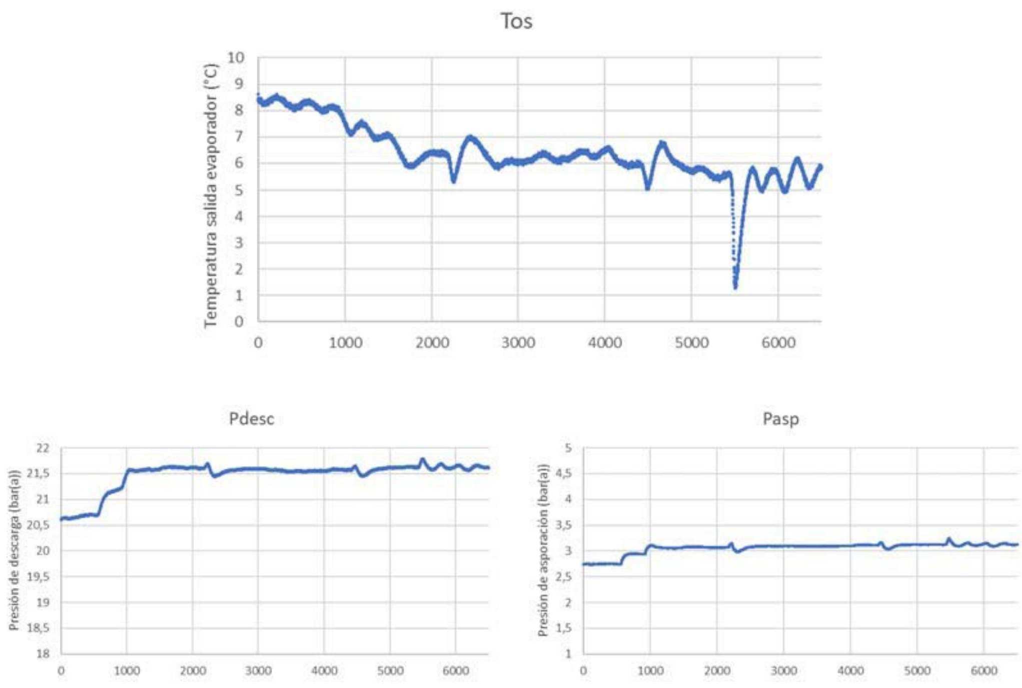

Figure 8. Measuring Representative Parameters with the R134a TXV

Table 4. Average Parameters for Stationary Points with the R134a TXV

	Pasp	Pdesc	Tevap	Tcond	GRevap	GRtot	Qo	EER
	bar(a)	*bar(a)*	*C*	*C*	*Towards*	*Towards*	*kW*	*-*
TXR134a_O1_T11	2,75	20,66	-13,8	44,0	16,43	26,66	4,75	1,61
TXR134a_O1_T13	2,94	21,17	-12,2	45,1	14,45	24,83	5,20	1,66
TXR134a_O1_T15	3,06	21,57	-11,1	45,9	12,60	23,54	5,32	1,65
TXR134a_O1_T17	3,07	21,62	-10,9	46,0	11,41	22,81	5,26	1,63
TXR134a_O1_T18	3,09	21,55	-10,8	45,9	11,38	22,41	5,31	1,63
TXR134a_O1_T19-20	3,12	21,62	-10,6	46,0	10,61	21,87	5,37	1,65
TXR134a_O1_T22	3,13	21,64	-10,5	46,1	10,37	21,46	5,37	1,65

The terminology in the first column of the table above indicates that it is the valve of R134a, with the hole 01, and the number of turns of the screw from the closed position to the maximum (between 11 and 22).

To cover all possible cases, the TXV orifice was replaced, and size 02 was used, which is also acceptable for operation with R134a and this working regime. The result was not acceptable either.

As before, all tests ensured that the coolant reached the TXV in the liquid phase.

In conclusion, working with a TXV of R134a would be possible, but a GR at the evaporator outlet would be higher than acceptable. The orifice could be adjusted to reduce the GR by a few degrees, but it could oscillate too much in the temperature at the evaporator outlet (and other operating parameters).

Task 5: *Testing with the R449A TXV.*

The R448A/R449A TXV replaced the R404A TXV. Tests began with the original configuration in terms of screw turns (2 from the closed position). It was observed that the initial GR in the evaporator was very small, so it was closed 1/4 turn progressively (going from 1 to 4 K every 1/4 turn). The GR increases to the point between 8 and 11 K, oscillating in operation.

This was tested at an evaporation temperature of approximately -10 and -20 °C, and the same conclusions were observed. Figure 9 shows the recorded operation.

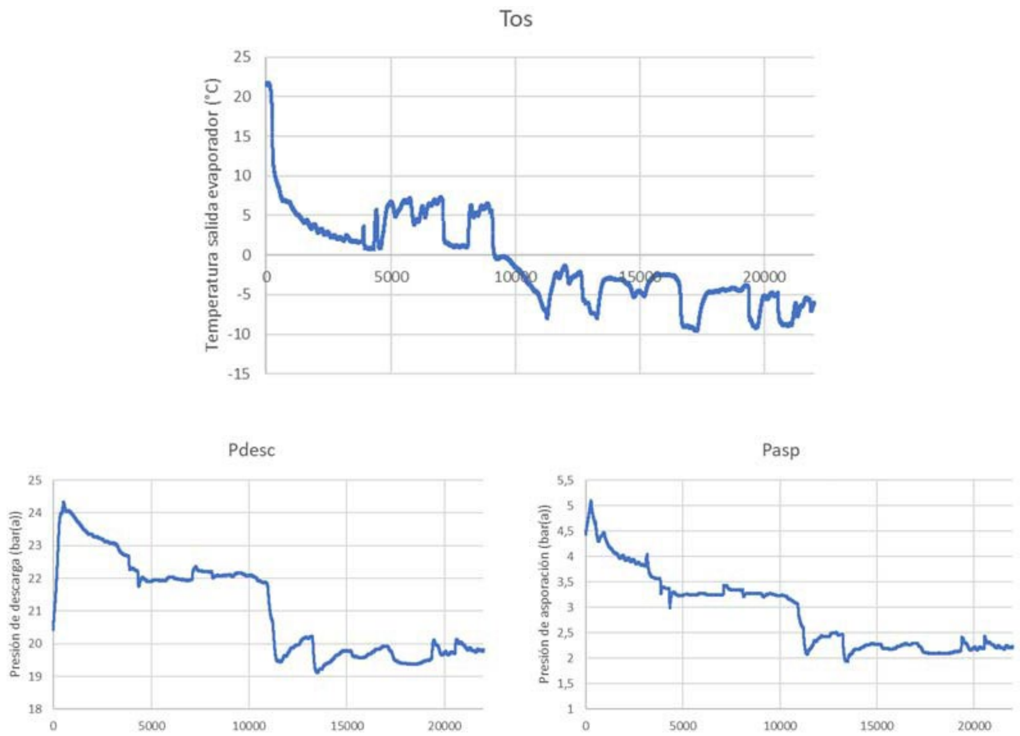

Figure 9. Measuring Representative Parameters with the R449A TXV

It is concluded that the results of the R449A TXV do not improve on those observed with the R22 TXV either. The R449A valve with the factory value provides a very small GR, which, according to errors in thermodynamic calculations, could represent a flooded evaporator and the behavior of the R404A TXV). When adjusted (closed), a value of between 8 and 11 K is reached by oscillating, which is the same as when adjusting the R134a valve. Therefore, although it can work with slight adjustments, its use is not prioritized.

Task 6: *Analysis and conclusions*.
After covering all the cases agreed with the company, an R22 TXV is recommended for RS-51. Suppose the TXV and its orifice are selected for this refrigerant with the screw on the same turns. In that case, it operates with a suitable GR at the evaporator outlet (approximately 7-8 K) and an acceptable oscillation. It could be considered a drop-in replacement (if there is compatibility with the existing lubricating oil).

Next, an R134a TXV and an R448A/R449A TXV might be considered acceptable. Regarding using the R134a TXV with the initial adjustments, the initial GR is high (around 15 K) but does not represent a risk to the installation operation (if the discharge temperature is not at the limit). The screw (open) can be adjusted to reduce the GR, but after a certain point (around 10 K), the behavior becomes unstable and the conditions at the evaporator outlet. The system can be operated this way, but it is not recommended. Additionally, hole change does not fix this behavior.

The following valve in the ranking is R448A/R449A. With factory settings, it gives a very small GR (which could be zero, depending on errors in calculating thermodynamic properties). This would represent a risk in case of *drop-in* or not studying the operation of the machine during start-up. When the screw is tightened (closed), the overheating is between 8 and 11 K with oscillation, but it will still be acceptable to use, although it is recommended to notify the buyer.

An R404A TXV is not recommended because it floods the evaporator and may cause a liquid hit in the compressor. The TXV for R404A is not controlled at any screw setting.

As a final recommendation, it is observed in some cases that thermodynamic calculations indicate the absence of subcooling. Still, gas (bubbles) is not observed in the liquid display. This would suggest that the existing mixture is not accurately calculated, as REFPROP is not yet ready for this type of combination. Therefore, it is recommended not to work with adjusted overheat values so that you can consider that the GR value is lower than quantified.

NOMENCLATURE

EER	*Energy Efficiency Ratio* (-) (energy performance in cooling mode)
GR	Degree of reheating (K)
h	enthalpy (kJ/kg)
IRS	Subcooling Reheat Heat Exchanger (Intermediate Heat Exchanger)
m_{Ref}	Coolant mass flow rate (kg/s)
P	Pressure (bar(a))
Pot	Power absorbed by the compressor (kW)
Q	Exchanged power (kW)
T,t	Temperature (°C)
TXV	Thermostatic Expansion Valve

Subscripts

ASP	Suction comp.
desc	Discharge comp.
e	inlet
k, Cond	Condensation, Condenser
o,EVAP	Evaporation, Evaporator
Tot	total
s	exit