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Design of an Environmentally Friendly Refrigeration Laboratory Based on Cooling Capacity Calculation for Graduate Students*

ADRIÁN MOTA-BABILONI[1], PAVEL MAKHNATCH[2], JOAQUÍN NAVARRO-ESBRÍ[1], FRANCISCO MOLÉS[1] and RAHMATOLLAH KHODABANDEH[2]

[1] GIESTER Educational Innovation Group and ISTENER Research Group, Department of Mechanical Engineering and Construction, Universitat Jaume I, Campus de Riu Sec s/n, E-12071 Castellón de la Plana, Spain. E-mail: mota@uji.es

[2] KTH Royal Institute of Technology, Department of Energy Technology, Division of Applied Thermodynamics and Refrigeration, Brinellvägen 68, 100 44 Stockholm, Sweden. E-mail: pavelma@kth.se

Lower global warming potential (GWP) refrigerants must be used in refrigeration education to integrate the environmentally responsible engineering principles in class. However, most of the refrigeration educational laboratories are still using hydrofluorocarbons (HFCs) as working fluids, which are considered as greenhouse gases. This paper shows the procedure to adapt the new refrigerant R513A in a refrigeration system used for a cooling capacity educational laboratory. First, the paper describes the organization of the laboratory session, and the characteristics of the different methods of cooling capacity calculation taught to the master's degree students. Then, the benefits of including new sensors in the experimental setup to obtain more accurate results are explained. Later, accurate new graphics and an equation to calculate the R513A cooling capacity are provided. Finally, the educational aspects worked with the students in this session, and each cooling capacity method are assessed. The procedure explained in this paper can be used as a guide for introducing lower GWP refrigerants in similar educational refrigeration laboratories.

Keywords: climate change; refrigeration; lower GWP mixtures; R513A; R134a

1. Introduction

The Kyoto Protocol [1] has included the hydrofluorocarbons (HFCs) in the greenhouse gasses basket. Consequently, the European Union (EU) Regulation No 517/2014 [2] have planned their phase down by imposing conditions that facilitate reduction of HFC emissions. HFCs with global warming potential (GWP) between 150 and 2500 are being prohibited in several applications. Most of these applications are within the refrigeration and air conditioning sector, which in fact, is responsible for 17% of the electricity consumption worldwide and contributes to global warming due to direct and indirect emissions of greenhouse gases [3].

In this way, the search for alternatives to HFC refrigerants with high GWP (e.g. R134a, R404A, and R410A) is today a much-debated issue [4]. The studies indicate that the lower GWP alternative refrigerants can be used as a drop-in or retrofit replacements [5]. However, the knowledge is still limited, and there is the need for more research to fully introduce these fluids and hence, reduce the direct contribution to global warming.

The use of environmentally friendly working fluids is also fundamental in engineering education. Hyman [6] states that engineering design education should include considerations such as the environmental, health, safety, ethical, social, and political impact of it. Antón et al. [7] highlight that refrigeration system learning may help students to achieve a deeper understanding of the interrelation between thermodynamics, heat transfer and fluid mechanics. Besides, authors like Cabello et al. [8] or Mendoza-Miranda et al. [9] have developed software for refrigeration education.

Sánchez et al. [10] include in an educational project the objective of instruct the automation, measurement, regulation, and control techniques of complex refrigeration plants. Cooling capacity, which represents the quantity of heat removed from space through the evaporator to preserve the required conditions, is one of the parameters that define the appropriate operation of a refrigeration system. This parameter can be calculated using different methods and varies between the refrigeration applications (domestic, commercial and industrial refrigeration or air conditioning) or purposes (control, maintenance, research, etc.).

This paper shows how an experimental refrigeration setup can be adapted to teach methods of cooling capacity calculation to Master's degree students using R513A, a lower GWP alternative to R134a. The operating and energetic parameters of R134a and R513A are determined and compared using the same installation. Furthermore, graphics and correlations using the R513A are provided for coming laboratory sessions.

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2. General aspects of the subject and the laboratory session

The laboratory session that uses the experimental setup is titled 'Determining cooling capacity' (Fig. 1) and is the second session of 3 (total of 1.5 European Credit Transfer and Accumulation System (ECTS) credits) in the 6 ECTS Applied Refrigeration and Heat Pump Technology course. This course is comprised in the 1st year of the Sustainable Energy Engineering Master's Programme (120 ECTS credits) and is conditionally elective [11]. The laboratory sessions take place between the week 9 and 16 of the course (one group per week), which starts in February (2nd semester).

One of the objectives of the course is to give the ability to independently treat complex problems within the area of refrigeration and heat pump technologies. The target of the experimentation is to determine the cooling capacity of a refrigeration plant using different methods. Therefore, before the start of the lab lesson, the student should be able to answer the following questions:

1. Describe at least three methods for determining the cooling capacity.
2. How can the refrigerant flow be determined?
3. How do the subcooling and superheating influence the cooling capacity?

All the necessary knowledge to answer the previous questions and to follow the laboratory session is explained in the theory, exercises and study visit sessions [12]. The length of the laboratory is 2 hours and a preparation control will take place during it. At the end of the session, the teacher considers the assistance and the participation of the students and gives them a grade scale between Pass/Fail.

3. Initial experimental setup

3.1 Experimental setup

The experimental setup (Fig. 2) used for the realization of the laboratory session is located in the laboratory of the Division for Applied Thermodynamics of the KTH Royal Institute of Technology (Stockholm, Sweden). Given the available space and to pay the appropriate attention to the students, every group is composed of five persons maximum.

The experimental setup consists of the main circuit, based on a vapor compression system and two secondary circuits connected to the condenser and the evaporator. The experimental unit represents a typical small capacity refrigeration system, which is the most appropriate for laboratories due to the low cost, construction simplicity, possibility of modifications [13].

The refrigerant gas is compressed in a hermetic rotory compressor and delivered to the discharge port. In the discharge line, the oil is separated from the refrigerant and leads back to the suction side of the compressor. The refrigerant continues to the condenser where it condenses into liquid and then it is subcooled. Cooling water removes the condensing heat (open loop heat removal circuit) and a water regulating valve controls the condensing pressure. Further, the subcooled refrigerant continues through the mass-flow meter, filter, and sight glass

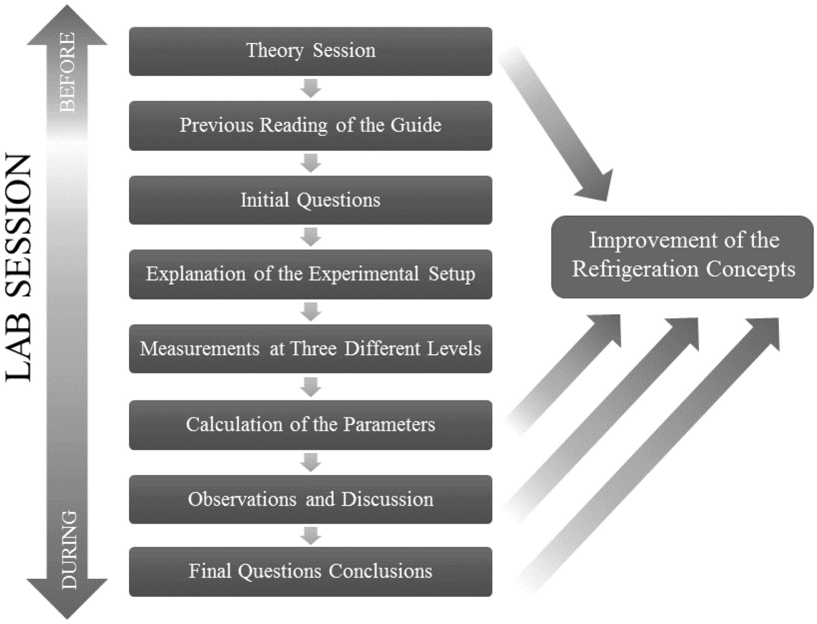


Fig. 1. Structure of the laboratory session.

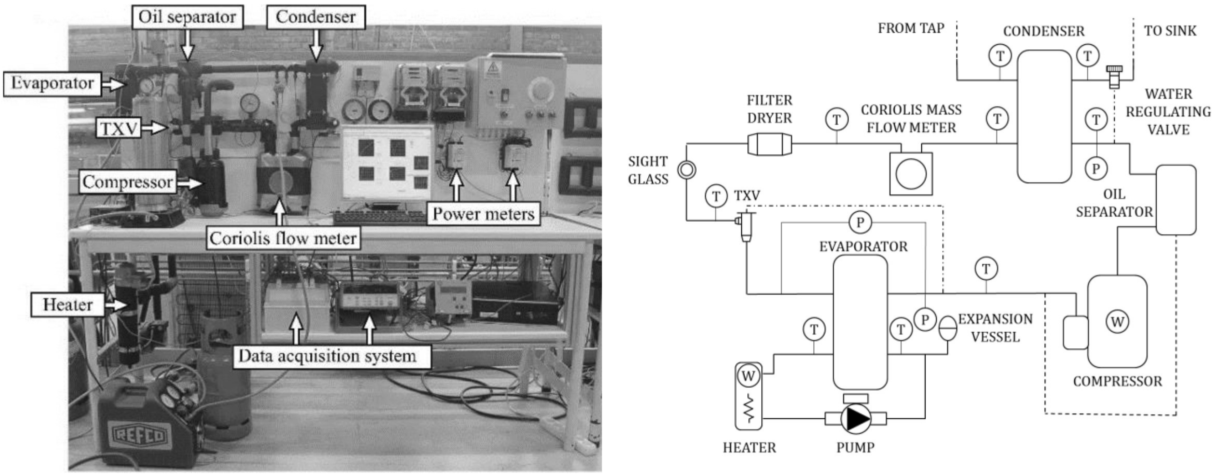


Fig. 2. Experimental setup and schematic diagram of its main components.

and enters to the thermostatic expansion valve. After the valve, the refrigerant is throttled down to the low evaporation pressure. On the other side of the plate heat exchanger, a secondary fluid for heating (43% ethylene glycol based) is pumped and heated by a set of resistances that simulates the heat load (closed loop heat load circuit). The refrigerant is fully evaporated and superheated and continues back to the compressor. The refrigerant pipelines (nominal diameter of 3/8 inch for liquid and discharge lines and $\frac{1}{4}$ for suction line) and the heat exchangers are completely isolated using closed cell elastomeric nitrile rubber foam (thermal conductivity of 33 mW m^{-1} K^{-1} at 0 °C). All the components have been designed for R134a operation, and the main characteristics of them are shown in Table 1.

Eight T-type thermocouples measure the temperature at the inlet and the outlet of each main component. The pressure at the suction and the discharge (low and the high refrigerant pressures) of the compressor is measured using absolute pressure transducers. The thermodynamic states of the circuit can be calculated using thermodynamic properties tables or software REFPROP v9.1 [14]. The mass flow rate is measured using a Coriolis flow meter in the liquid line. Table 2 contains the details of the measurement devices. Additionally, the heater and the motor-compressor power consumption are manually measured through electric meters.

The Agilent 34970A data acquisition system collects the sensor measurements and brings them to a personal computer. The software displays and records the measured data and the students can consult the evolution of them, Fig. 3. There is a possibility to transfer data into a spreadsheet file, where the data is presented in columns at 10 seconds time intervals.

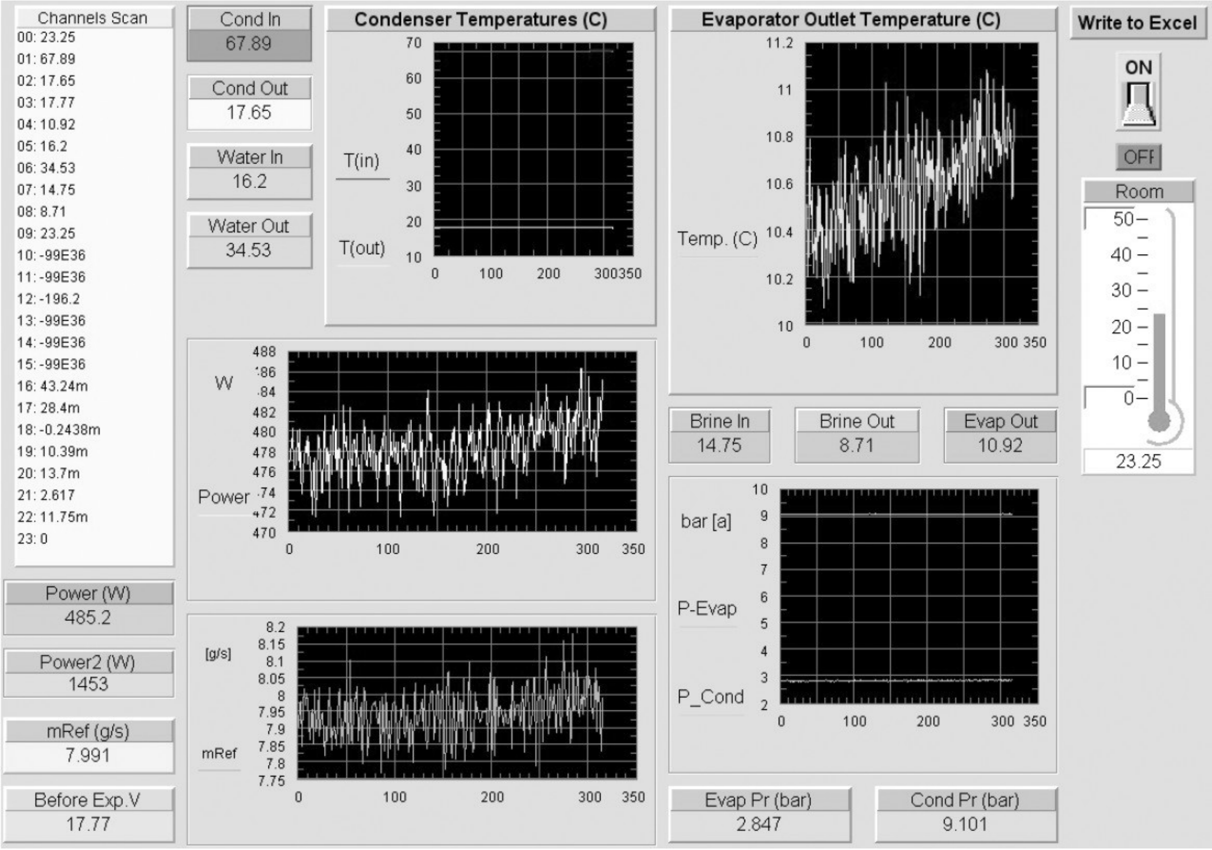
Table 1. Main components of the experimental setup

Component	Model	Main Characteristics
Compressor	Mitsubishi RB-154 VNF	Hermetic rolling piston type rotary Number of cylinders = 1 Displacement (V_G) = 15.4 cc rev^{-1} N = 2840/2860 rpm at 220/240V
Condenser	SWEP B10-20	
Evaporator	SWEP B10-10	
Expansion valve	Danfoss TEN 2	Thermostatic expansion valve Designed for R134a
Pressure switch LP/HP[a]	Danfoss KP15	LP/HP Regulation range = [–2, 75]/[80,320] kPa LP/HP differential Δp = [7,40]/40 kPa
Water regulating valve	Danfoss WVFX 10-25	Max condenser working pressure = 4.5 MPa Media temperature range = [–25,130] °C
Secondary fluid pump	Grundfos A4 25-6U/130	Connection DN 25 Height = 130 mm
Resistances	Backer	Three-phase power 2 × 810 W (fixed) and 1× 970 W (adjustable)

[a] LP = low pressure, HP = high pressure.

Table 2. Characteristics of the measurement devices of the system

Sensor	Model	Accuracy	Range
Thermocouple	Omega special limited edition TT-T-24-TWSH-SLE	±0.11 K	[–60,100] °C
Pressure sensor	PDCR 4060	±0.08% Full scale best straight line	Max 110 kPa suction Max 210 kPa discharge
Mass flow meter	Micro Motion DS012S	±0.15% reading	Not available



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Channels Scan
00: 23.25
01: 67.89
02: 17.65
03: 17.77
04: 10.92
05: 16.2
06: 34.53
07: 14.75
08: 8.71
09: 23.25
10: -99E36
11: -99E36
12: -196.2
13: -99E36
14: -99E36
15: -99E36
16: 43.24m
17: 28.4m
18: -0.2438m
19: 10.39m
20: 13.7m
21: 2.617
22: 11.75m
23: 0
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Cond In 67.89

Cond Out 17.65

Water In 16.2

Water Out 34.53

Power (W) 485.2

Power2 (W) 1453

mRef (g/s) 7.991

Before Exp.V 17.77

Brine In 14.75

Brine Out 8.71

Evap Out 10.92

Evap Pr (bar) 2.847

Cond Pr (bar) 9.101

Room 23.25

Fig. 3. Visualization of measured parameters of refrigeration system operation.

3.2 *Experimental procedure*

In the laboratory session, the students compare the cooling capacity results determined by five experimental methods. The variety of methods prepare them for different possible situations in the refrigeration industry.

3.2.1 *Method 1: Using supplied electrical power measurement*

The cooling capacity of the system is calculated using the electricity amount supplied to the electric heater during 1 minute and considering the evaporator heat balance. Domestic refrigerator studies usually apply this method because of the low cost of the device. Mohanraj et al. [15] used this method (energy meter ±0.5% accuracy) to compare a hydrocarbon mixture with R134a. Hammad and Alsaad [16] determined the cooling capacity through the length of the heating coil inside a freezer.

3.2.2 *Method 2: Condenser heat balance*

The heat exchanged at the condenser is calculated using the Equation (1).

$$\dot{Q}_{cond} = \dot{m}_{water} c_{p,water} \Delta T_{water} \qquad (1)$$

The students obtain the mass flow rate of the water (in kg s^{-1}) accumulating the water thrown to the sink with a deposit (in dm^3) for a certain time of filling, and then they apply Equation (2). Then, the refrigerant mass flow rate in the system can be obtained from the heat load of the refrigerant side, Equation (3), and the condenser heat balance. Finally, the cooling capacity can be obtained as shown in Equation (4).

$$\dot{m}_{water} \frac{V_{water}}{1000} \frac{1}{t_{filling}} \rho_{water} \tag{2}$$

$$\dot{Q}_{cond} = \dot{m}_{ref} \Delta h_{ref,cond} \tag{3}$$

$$\dot{Q}_{evap} = \dot{m}_{ref} \Delta h_{ref,evap} \tag{4}$$

Methods 1 and 2 are the most interactive ones of all proposed and involve the students in the laboratory session. However, due to the human interaction, these methods are not accurate enough to be used in most of the real cases. For instance, Method 2 requires an accurate secondary fluid flow meter to calculate the cooling capacity. Thus, Kabeel et al. [17] use a hot wire anemometer that measures the air velocity that goes through the condenser, according to the ASHRAE procedure.

3.2.3 Method 3: Using the Coriolis flow meter

The cooling capacity can be calculated through the refrigerant mass flow rate measured using a Coriolis flow meter installed in the liquid line, Equation (4). These values are supposed to be the most accurate ones for the cooling capacity. Besides, Da Riva and Del Col [18] obtained a maximum deviation around 5% and the standard deviation of 1.0%, considering the condenser balance; and a maximum deviation around 3% and a standard deviation of 0.9%, considering the evaporator balance. Hence, the evaporator balance gives more accurate results than the condenser balance.

Several cases of cooling capacity calculation through this method can be found in the recent literature for small and medium capacity systems. Righetti et al. [19] in a domestic refrigerator (±0.1% uncertainty, reading), Sethi et al. [20] in a commercial vending machine system, Mota-Babiloni et al. [21] in a refrigeration experimental setup (±0.22% uncertainty, reading) and, Li et al. [22] in an indirect automotive air-conditioning system (±0.05% uncertainty, reading).

The reason of the absence of the Coriolis flowmeter in real refrigeration equipment is that high accuracy provided by this method does not justify the high initial investment of this component. The accuracy given by other indirect methods is sufficient for this purpose.

3.2.4 Method 4: Calculation based on expected compressor data

In this method, the refrigerant mass flow rate is calculated out of the geometrical data given by the compressor manufacturer. First, the theoretical volumetric flow rate is determined as the product of the geometrical volume of a cylinder, the compressor rotation rate and the number of cylinders. In the real case, the volumetric efficiency should be considered, Equation (5).

$$\dot{V}_{ref} = \eta_{vol} V_G \frac{N}{60} \tag{5}$$

The real volumetric efficiency can be experimentally obtained and plotted against the compression ratio. If the refrigerant considered is commonly used in these systems, as R134a, the regression is available. In this type of hermetic compressors, the second-degree empirical correlation of the volumetric efficiency and pressure ratio for R134a is the Equation (6), with an R^2 of 0.9995.

$$\eta_{vol,R134a} = 0.0038PR^2 - 0.0537PR + 0.9816 \tag{6}$$

This method can be found in several refrigeration studies. In small capacity refrigerating systems, Janković et al. [23] compared the performance of pure HFOs and R134a, and Pisano et al. [24] analyzed the combined effects of capillary tube diameter and refrigerant charge on the performance. In supermarket refrigeration system analysis Makhnatch et al. [25] and Sawalha et al. [26] applied this method.

The major problem regarding this method is that if the refrigerant is recently developed, as the HFO mixtures, this information is not available (only the new compressor models present it). Therefore, the volumetric efficiency can be approximated considering isentropic compression [12], Equation (7). (V_o/V_s) is the dead space ratio, PR the pressure ratio and k the specific heat ratio.

$$\eta_{vol} = 1 - \frac{V_o}{V_s}\left(PR^{\frac{1}{k}} - 1\right) \tag{7}$$

Makhnatch et al. [25] presented another method to approximate the volumetric efficiency for the new refrigerants. They adapted the compressor R404A manufacturer's volumetric efficiency to that of R448A considering the deviation between the isentropic compression volumetric efficiencies (Equation 8).

$$\eta_{vol,new\,fluid} = 1 - \frac{\left(PR_{new\,fluid}{}^{\frac{1}{k_{new\,fluid}-1}}\right)}{\left(PR_{R404A}{}^{\frac{1}{k_{R404A}-1}}\right)}\left(1 - \eta_{vol,R404A}\right) \tag{8}$$

3.2.5 Method 5: Capacity according to the compressor manufacturer's data

In some cases, the manufacturer provides a compressor capacity diagram with different parameters (the supply current, cooling capacity, power input

Table 3. Required measurements and calculations for the laboratory session

Method	Measurements	Calculations
Method 1. Using supplied electrical power measurement	• Turns of heater and compressor electric meters, nr • Time to complete the turn, s	• Cooling capacity = Power to the secondary fluid heater, kW • Power to the compressor, kW • Power to the condenser, kW
Method 2. Condenser heat balance	• Compressor discharge and suction pressure, kPa • Condenser cooling water volume, dm^3 • Time of filling, s – Temperatures, °C – Compressor inlet/outlet – Condenser inlet /outlet – Evaporator inlet/outlet – Water condenser inlet/outlet – Secondary fluid inlet/outlet	• Enthalpies, kJ kg^{-1} – Evaporator inlet (condenser outlet) and outlet – Condenser inlet • Water mass flow rate, kg s^{-1} • Condensing temperature, °C • Evaporating temperature, °C • Condenser capacity, kW • Condenser and evaporator enthalpy differences, kJ kg^{-1} • Refrigerant mass flow rate, kg s^{-1} • Cooling capacity, kW
Method 3. Using the Coriolis flow meter	• Refrigerant mass flow rate, kg s^{-1}	• Cooling capacity, kW
Method 4. Calculation based on expected compressor data	• Displacement volume per cylinder, m^3 • Number of cylinders, nr • Nominal revolutions, rpm	• Refrigerant volume flow, m^3 s^{-1} • Pressure ratio, – • Volumetric efficiency, – • Refrigerant mass flow rate, kg s^{-1} • Cooling capacity, kW
Method 5. Capacity according to the compressor manufacturer's data	• Cooling capacity based on capacity diagram from manufacturer, kW	• Cooling capacity corrected for the exact subcooling and superheating degrees, kW

or flow rate) at common operating conditions and fixed superheating and subcooling degrees. These values present similar accuracy to the previous method, but if the exact condensing temperature is not present or the suction superheating, liquid subcooling, and ambient temperature are different from the mentioned, the cooling capacity value must be adapted [12].

3.2.6 Conclusions of the laboratory session

Table 3 shows a summary of the required measurements and calculations to the students at the end of the session (to be done consequently by the students). After all the calculations, the students should compare the cooling capacity results for the five different methods and discuss the following questions:

- The agreement between the methods. Why are there differences?
- Which is the most accurate method?
- Which methods would you recommend for practical use?

3.3 Problems related to the proposed methods

Table 4 summarizes the main disadvantages of the cooling capacity calculation methods. Two problems highlight, human error and missing information for new refrigerants.

4. Experimental setup modifications and discussion

4.1 New sensors installed

Sanchez et al. [10] highlight that to complete the instructing process is necessary to provide measurement devices and an adequate data acquisition system. For instance, Jarall [27] tested the HFO R1234yf adding the Digital Power Meter Yokogawa WT130 (accuracy of 0.25%, reading) to the experimental setup. In the case presented in this paper, two power meters have been added to the experimental setup. The model is TILLQUIST LQT400, which the accuracy ±0.2% (reading) and the input range is [0,10] A and [0,500] V. The scale of the compressor power meter is set to [0,750] W

Table 4. Main disadvantages of the proposed methods in the laboratory session

Method	Disadvantages
Method 1. Using supplied electricity	• The great influence of human error.
Method 2. Condenser heat balance	• The possible influence of heat losses to the ambient.
Method 3. Using the Coriolis flow meter	• Equipment cost.
Method 4. Calculation based on expected compressor data	• Only available for classic refrigerants (R134a and R407C).
Method 5. Capacity according to the compressor manufacturer's data	• Deviation using the reading from the graphics. • Additional error when using superheating and subcooling degrees at different conditions from rated ones.

Table 5. Main characteristics of R134a and R513A.

Refrigerant	**R134a**	**R513A**
Composition, weight %	R134a, 100	R134a/R1234yf, 44/56
ASHRAE safety classification	A1	A1
ODP / $GWP_{100\text{-}yr}$ (AR5 [28])	0/1300	0/573
Critical temperature/pressure (°C/MPa)	101.1/4.06	97.7/3.86
NBP (°C) and Glide (K) at 100kPa	–26.4 / 0	–29.9 / 0.1
Liquid/vapor density[a] ($kg\ m^{-3}$)	1295.3/14.35	1222.4/17.14
Liquid/vapor c_p[a] ($kJ\ kg^{-1}\ K^{-1}$)	1.34/0.90	1.31/0.92
Liquid/vapor thermal conductivity[a] ($mW\ m^{-1}\ K^{-1}$)	92.08/11.50	79.26/11.72
Liquid/ vapor viscosity[a] (μPa s)	267.0/10.7	227.5/10.5

[a] At 0 °C.

attending to the results of the simulations. The scale of the heater power meter is [0,3000] W, according to the maximum heater power.

One power meter measures the power consumption of the secondary fluid heater and the other that of the motor-compressor set, taking into account the electromechanical losses of it. The output current of both components is 4–20 mA. The power meter connected to the heater, considering steady state and negligible losses to the ambient, directly measures the cooling capacity of the system through the heat balance.

4.2 New research options

The characterization tests were performed retrofitting R513A into the system, to evaluate it as R134a lower GWP alternative in small capacity refrigeration systems. This fluid has been selected because of the comparable characteristics to R134a and the lower GWP, Table 5.

Through several experimental tests after introducing the new power meters, a work comparing R134a and R513A at evaporating temperatures between -15 and 12.5 °C and condensing temperatures of 25, 30 and 35 °C has been published in a scientific peer review journal [29]. Figure 4 shows the motor-compressor power consumption and COP measurements performed for both fluids. The similarity in the measurements indicates that R513A is a promising refrigerant in the R134a current refrigeration system.

4.3 Improvement of the laboratory session

After the experimental tests, the decision was to keep the new power meters in the installation, to extend the options. Therefore, the modified experimental setup offers more methods to determine the cooling capacity and the compressor power consumption and hence, the system performance.

The methods 1 and 2 can now be assessed using values collected by the power meters and compared to that of the electric meters. Then, the volumetric efficiency and cooling capacity data obtained for the new refrigerant can be used during the laboratory session without the necessity of approximations. The linear empirical correlation of the volumetric efficiency and the pressure ratio at different superheating and subcooling degrees for R513A is presented in Equation (9) (R^2 using 60 points is 0.93). Finally, the cooling capacity and mass flow rate curves provided are shown in Fig. 5.

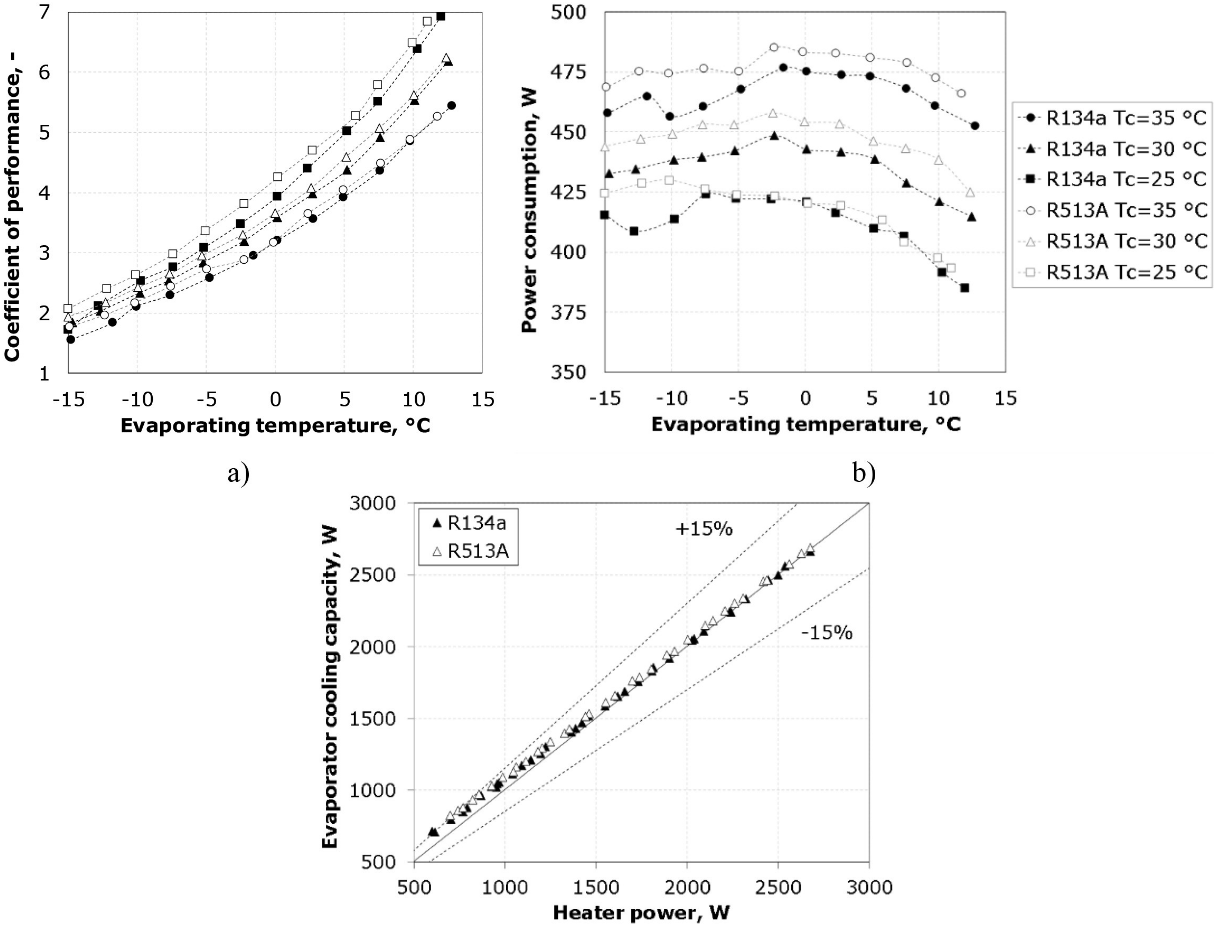
$$\eta_{vol,R513A} = -0.040PR + 1.013 \tag{9}$$

5. Educational aspects determination

The combination of several cooling capacity determination methods in laboratory session has been shown to be advantageous to reach learning objectives. Methods 1 and 2 were seen to be beneficial for initial engagement of students into the laboratory exercise. Although the cooling capacity measurements obtained through these methods are subject to errors, the greater interactivity of these methods led to a higher degree of participation of the students and better overall performance during the laboratory session.

Method 3 is the most accurate method of cooling capacity determination among the discussed methods. However, the lecturers observed that the students are more likely to perform erroneous cooling capacity calculations due to the weaker link between the behavior of the system and its understanding using electronically stored data in a spreadsheet. However, if Method 3 has been preceded by Method 1 and Method 2, the students were more successful in properly performing the calculations. Moreover, in combination with other methods, Method 3 led to a discussion about the measurement uncertainty propagation and measurement techniques in general.

Methods 4 and 5 are the alternative cooling capacity determination methods that open possibility for advancement learning during the laboratory



a) b)

Fig. 4. Experimental measurements using R134a and R513A [29] (a) COP, (b) motor-compressor power consumption and (c) evaporator heat balance.

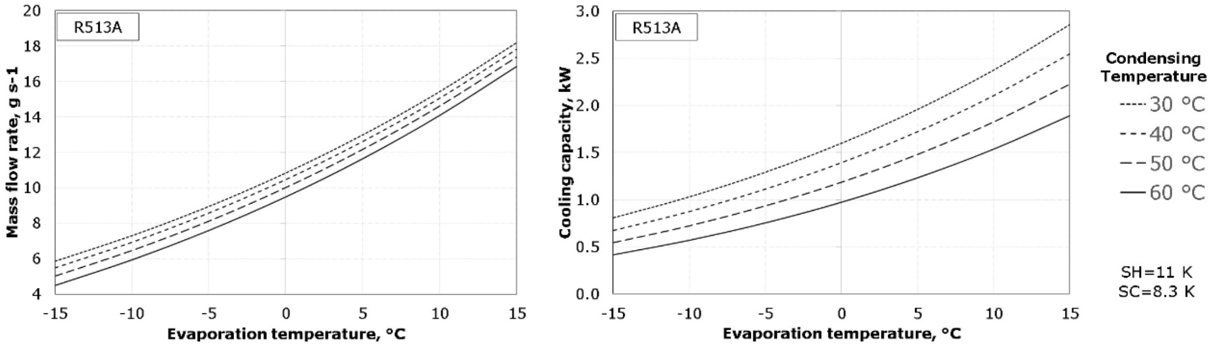


Fig. 5. Graphics for calculation of R513A mass flow rate and cooling capacity.

exercise, volumetric compression efficiency, and other related areas of refrigeration system operation. Method 5 provides a greater understanding of the effect of superheating and subcooling on the cooling capacity of a refrigeration system.

By introducing new refrigerant into the lab, it became possible to discuss during the session the environmental effect of the refrigerants and relevant environmental legislation and agreements. Since the original system is designed for the use of refrigerant R134a, the trade-offs in refrigerant selection for a specific application, as well as drop-in refrigerants, can be also discussed with the students.

6. Conclusions

Due to the need of replacement of high-GWP HFCs in refrigeration systems, new synthetic options are being developed. R513A can be a safe and lower GWP (573) alternative to R134a (1430). The use of environmentally friendly fluids should involve consumers and the educational sector. This paper presents an introduction of R513A in the "Determining cooling capacity" laboratory session included in the Sustainable Energy Engineering Master's Programme.

This laboratory session aims to introduce five different methods to the student: using supplied electricity, through the condenser heat balance, Coriolis flow meter, and calculation based on expected compressor's data (volumetric efficiency regression and performance graphs). The two cooling capacity calculation methods based on compressor's data are those commonly used in the refrigeration industry and hence the most interesting for the student. However, both cannot be applied for the lower GWP alternatives because of the lack of the available information.

First, R513A was tested in the experimental setup used for the laboratory session using additional measurement instrumentation. Then, the cooling capacity was calculated and validated (using a Coriolis mass flow rate and a power meter) under a wide range of conditions. The drop-in performance of R513A is comparable to R134a, and therefore it is justified the use of R513A as lower GWP alternative.

Power meters (accuracy of ±0.2%, reading) connected to the motor-compressor set and the heater are included to offer more flexibility and accuracy in some methods. Besides, new curves for the cooling capacity and mass flow rate calculation and the volumetric efficiency regression (R^2 of 0.93) have been provided for further laboratory sessions, in which R513A will substitute the greenhouse gas R134a, and the students will experiment with the next generation of refrigerants.

On the educational point of view, we found that to start the laboratory session with more interactive methods helps to involve the students. Then, Method 3 yields to uncertainty propagation understanding, and Methods 4 and 5 to discuss the effect of volumetric efficiency and superheating and subcooling degrees, respectively.

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Adrián Mota-Babiloni is Postdoctoral Researcher at the Mechanical Engineering and Construction Department at Universitat Jaume I of Castellon. He received the Ph.D. in Mechanical Engineering and Production in 2016 from Polytechnic University of Valencia. His field of interest is the study of the behavior of new lower global warming potential fluids in refrigeration and air conditioning systems and the design and development of high-temperature heat pumps (HTHP). He also gives lectures in heat transfer, refrigeration and air conditioning, and energy-intensive industries.

Pavel Makhnatch is a Ph.D. candidate in energy technology at the Department of Energy Technology at KTH Royal Institute of Technology. He received the degree in Energy Efficient Technologies and Energy Management in 2007, the Master's degree in Energy Systems in 2008 and the Master's degree in mechanical engineering with specialization in Sustainable Energy Engineering in 2011. During his Ph.D. he is involved in research in new refrigerants with low GWP.

Joaquín Navarro-Esbrí is Full Professor at the Mechanical Engineering and Construction Department at Universitat Jaume I of Castellon. He is also coordinator of the Ph.D. Program in Industrial Technologies and Materials at the Universitat Jaume I and Coordinator of the ISTENER research group. His primary research fields are waste heat recovery, ORC systems, HTHP, refrigeration and air conditioning.

Francisco Molés is Associated Professor at the Mechanical Engineering and Construction Department at University Jaume I of Castellón. He received the Ph.D. in Industrial Technologies and Materials in 2015 from University Jaume I of Castellón. His fields of interest are the study of organic Rankine cycle, HTHP and refrigeration systems, regarding both its design and related working fluids.

Rahmatollah Khodabandeh is Docent and Associate Professor of Energy Technology at KTH Royal Institute of Technology and Study Director of the Ph.D. program Energy, Environment and Systems at the Department of Energy Technology. He obtained the Ph.D. degree in Applied Thermodynamics and Refrigeration from the Royal Institute of Technology in 2004. The primary research fields for Dr. Khodabandeh are Refrigerants with low GWP, liquid cooling for electronic components, Heat Transfer in Mini and Microchannels and Nano-Fluids for Enhancement of Heat Transfer.