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REFLAB: An Interactive Tool for Supporting Practical Learning in the Educational Field of Refrigeration*

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A new interactive tool for supporting practical learning in the educational field of refrigeration is presented in this paper. The application, called REFLAB, is used for on-line representation of the main operating variations in real refrigeration plants, such as cooling capacity, power consumption and coefficient of performance. The implementation of this interactive tool covers two groups of practical lessons, in which students operate with two refrigeration plants (a single-stage and a two-stage) and obtain, by means of its graphical interface, the effects produced by changes in the operating conditions. The use of REFLAB allows a quick comprehension of the theoretical concepts explained in class and an intuitive assimilation of the behaviour of the refrigeration plants. The aim of this paper is to explain how the interactive tool works and which are the main objectives pursued in the practical lessons. The paper includes a series of graphical animations that simulate the practice lessons received by the students.

Keywords: interactive learning, refrigeration, vapour compression plants, practical lessons.

1. Introduction

Nowadays, the most widely used cool production systems are based on vapour compression technology [1], which is employed in all refrigeration and air-conditioning applications and in domestic, industrial, transport and commercial sectors. Given its importance, the theoretical and practical knowledge of the basic principles of operation of refrigeration plants constitute a fundamental subject in the mechanical engineers' education, where the main objective is to achieve sufficient knowledge to design, calculate and operate this type of plant.

Practical training is basic for engineers and artificial cold production (especially vapour compression technology) is one of the most important subjects to be focused in this way. Accordingly, traditional teaching has been complemented with two types of practical lessons:

1. A first group, in which students identify the arrangement and components of the refrigeration plants, analyse and represent the working cycle and calculate the main energetic parameters of operation (cooling capacity, COP, thermal efficiency, etc.).
2. A second group based on the use of computer applications (RefProp© [2] and CoolPack© [3]) in which students calculate several cycle configurations working with several refrigerants.

These practical lessons have several disadvantages that make the connection between theoretical and practical aspects difficult. First, the effects on the main energy parameters of the plants cannot be represented on-line when the operating conditions are modified, and secondly, the stabilisation time related with thermal processes is too long. These problems are often associated with the signal acquisition systems used to monitor the thermal plants that are usually only based on the acquisition of the measured variables (pressure, temperature, flows, etc.). Thermodynamic states and the main energetic parameters of the cycle are calculated afterwards; therefore it is very difficult to analyse the operation of the refrigerating plants and it is impossible to understand its dynamic evolution.

To solve these difficulties, technological progress in computer and electronics sciences [4–7] has been used to develop an educational tool, which we call REFLAB. REFLAB acquires, calculates and performs on-line representations of the main operating parameters of the vapour compression refrigerating plants used in the practical lessons. REFLAB, developed with LabView© [8], contains the refrigerant property libraries of RefProp© [2] and the calculation program MATLAB© [9]. With this computer application, students are able to follow the refrigerating plant and to analyse its dynamic response and the evolution of its main parameters on-line (pressures, enthalpies, mass flows, powers, etc.), as well as the thermodynamic working cycle when the operating conditions are modified.

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The description of this software and several applications developed with REFLAB are presented in this paper. The responses to the software made by both students and the teacher are also presented.

2. Description of REFLAB

Although REFLAB is an interactive tool, its operation requires a complete signal acquisition system, which could be divided into several parts according to the function that each performs.

Group 1: Sensors: Sensors are the elements of the system that convert the physical measured variables (pressure, temperature, mass flow . . .) into an electrical signal (current or voltage). Temperature is measured using surface thermocouples, pressure with piezoelectric gauges, refrigerant mass flow rate with a Coriolis-effect mass flowmeter and power consumption with a digital wattmeter. Compressor speed is registered using different types of sensors depending on the compressor configuration (open-type with a capacitive sensor, and semi-hermetic with accelerometers).

Group 2: Signal acquisition system: This consists of a series of commercial elements from the National Instruments Company© used to condition and sample electrical signals.

Group 3: REFLAB interface: This part allows the representation and analysis of the main operating variables of the refrigerating plants, such as the energy parameters and the thermodynamic working cycle.

Relations between the different groups of elements and different programs used in REFLAB are shown in Figs 1 and 2, respectively.

In order to represent all the measured variables graphically, the program Measurement and Automation©, from National Instruments©, is used to convert the electrical signals to a physical magnitude by means of the calibration pattern of each measuring element. Once all the signals have been expressed as a physical magnitude, the representation and storage of values is performed by the LabView©-based application. This application also connects with MatLab© and it connects with the dynamic libraries of RefProp© for an on-line evaluation of the thermodynamic state of each sampling point in the real cycle, which are then used to calculate different capacities and efficiencies of the refrigerating plant (cooling capacity, heat capacity, COP, thermal efficiency, etc.).

When all calculations of the sample are done, the LabView©-application represents the complete on-line plant behaviour (Fig. 3). In this sense, we can analyse at the same time measurements and all the operating variables of the refrigerating cycle: mass flow rates, powers, efficiencies, enthalpies, the global efficiency of the plant (COP) and its thermodynamic cycle (Fig. 4).

The operation of REFLAB by the students is quite easy and intuitive because of its simple graphical interface (Fig. 3).

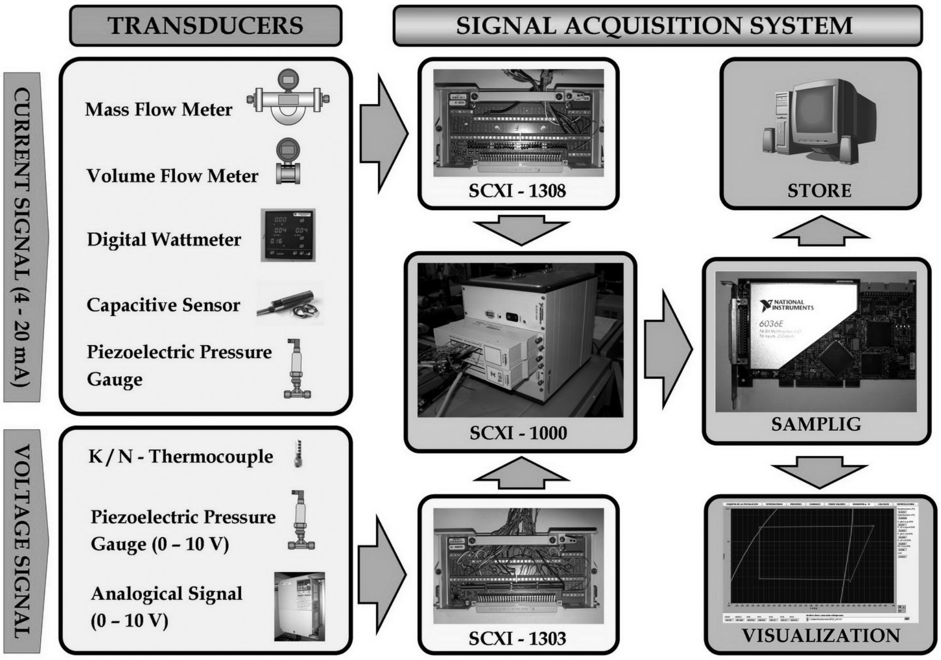


Fig. 1. Relations between the different signal acquisition system elements.

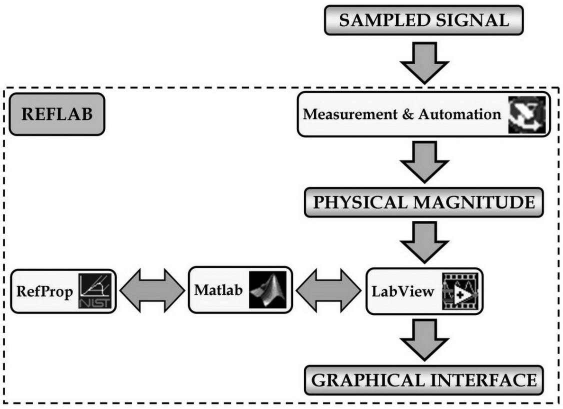
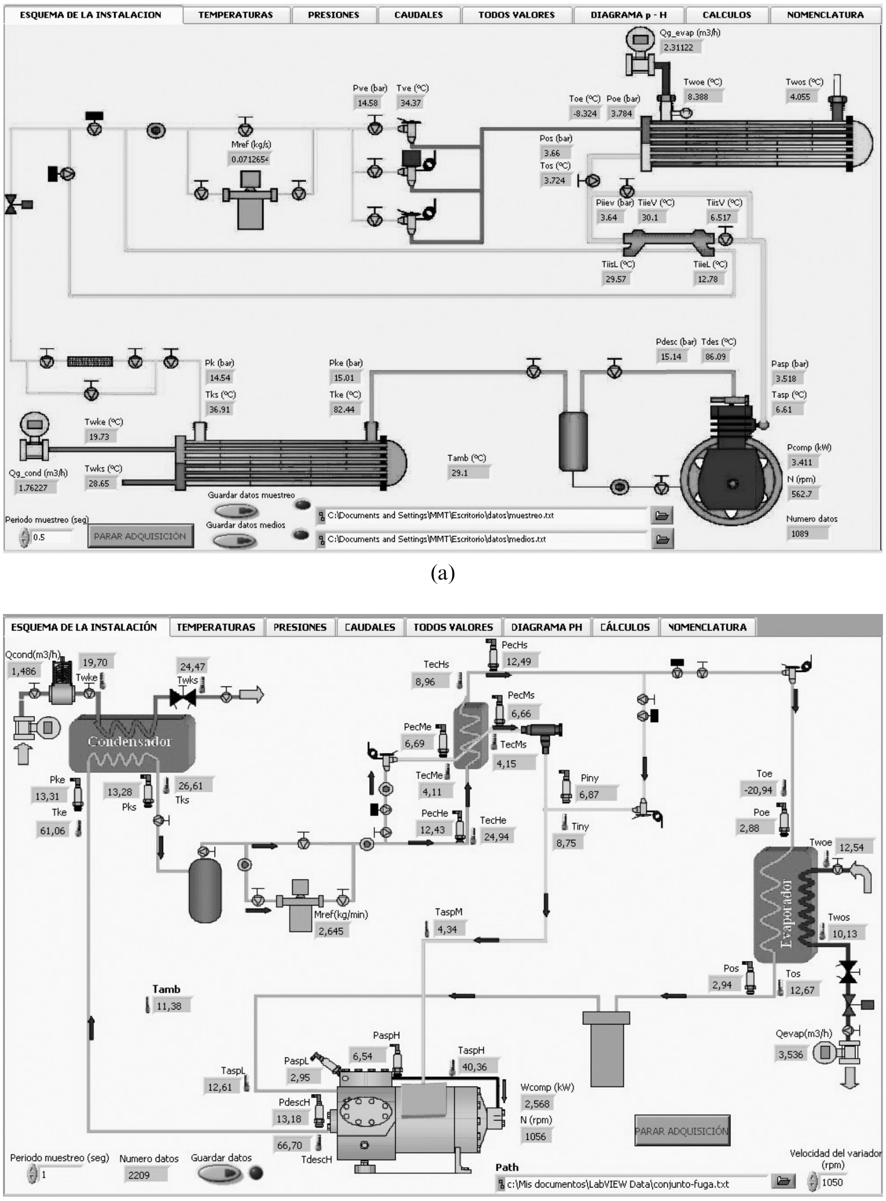


Fig. 2. Programs and their relationships used in REFLAB.



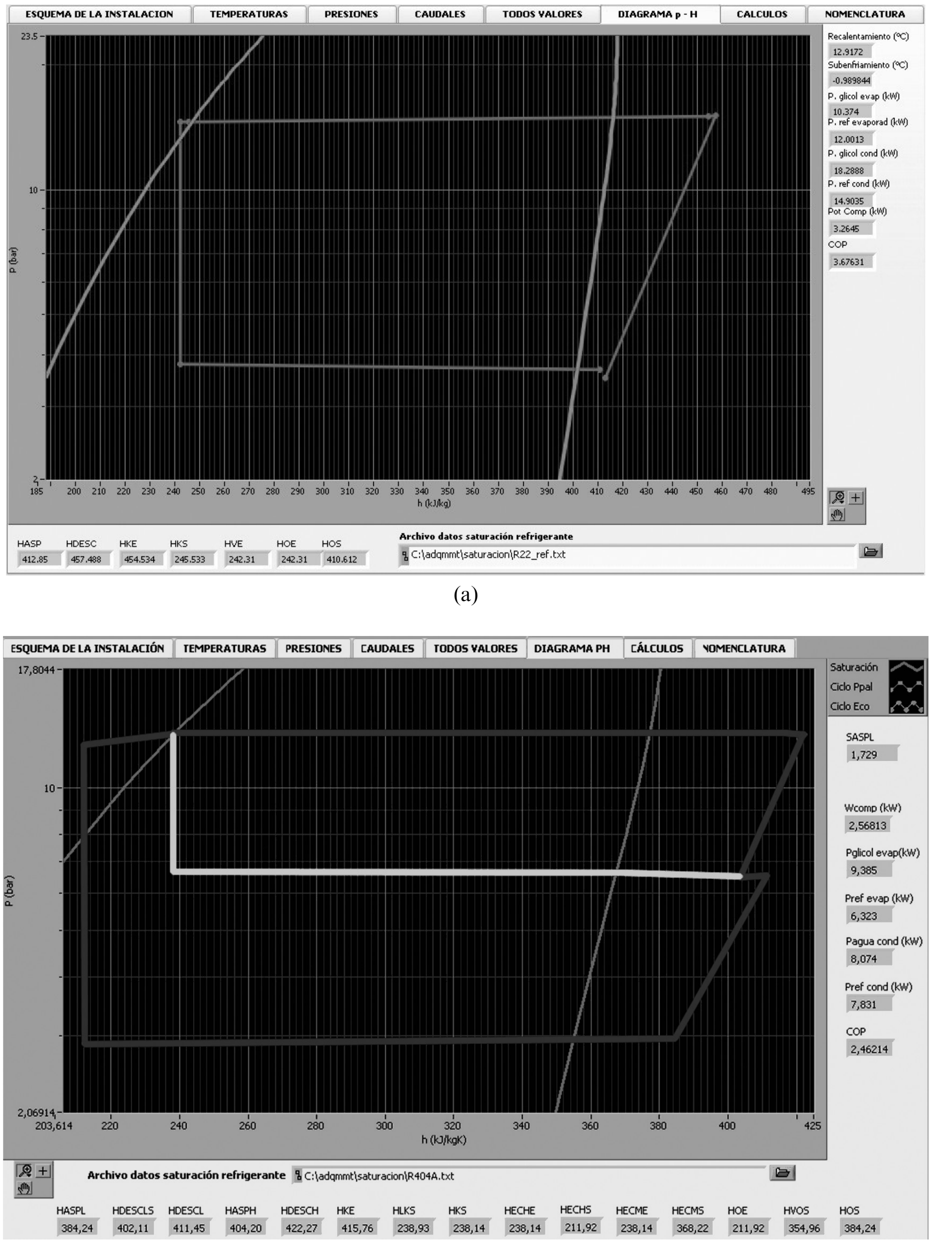
Qg_evap (m3/h) 2.31122
Pve (bar) 14.58
Tve (ºC) 34.37
Toe (ºC) -8.324
Poe (bar) 3.784
Twoe (ºC) 8.388
Twos (ºC) 4.055
Mref (kg/s) 0.0712654
Pos (bar) 3.66
Tos (ºC) 3.724
Piiev (bar) 3.64
TiieV (ºC) 30.1
TiisV (ºC) 6.517
TiisL (ºC) 29.57
TiieL (ºC) 12.78
Pdesc (bar) 15.14
Tdes (ºC) 86.09
Pk (bar) 14.54
Tks (ºC) 36.91
Pke (bar) 15.01
Tke (ºC) 82.44
Pasp (bar) 3.518
Tasp (ºC) 6.61
Twke (ºC) 19.73
Twks (ºC) 28.65
Qg_cond (m3/h) 1.76227
Tamb (ºC) 29.1
Pcomp (kW) 3.411
N (rpm) 562.7
Periodo muestreo (seg) 0.5
C:\Documents and Settings\MMT\Escritorio\datos\muestreo.txt
C:\Documents and Settings\MMT\Escritorio\datos\medios.txt
Numero datos 1089

(a)

Qcond(m3/h) 1,486
Twke 19,70
Twks 24,47
TecHs 8,96
PecHs 12,49
PecMs 6,66
PecMe 6,69
TecMs 4,15
TecMe 4,11
Pke 13,31
Tke 61,06
Pks 13,28
Tks 26,61
PecHe 12,43
TecHe 24,94
Piny 6,87
Tiny 8,75
Toe -20,94
Poe 2,88
Twoe 12,54
Twos 10,13
Mref(kg/min) 2,645
TaspM 4,34
Pos 2,94
Tos 12,67
Tamb 11,38
PaspH 6,54
PaspL 2,95
TaspH 40,36
TaspL 12,61
PdescH 13,18
TdescH 66,70
Qevap(m3/h) 3,536
Wcomp (kW) 2,568
N (rpm) 1056
Periodo muestreo (seg) 1
Numero datos 2209
Path c:\Mis documentos\LabVIEW Data\conjunto-fuga.txt
Velocidad del variador (rpm) 1050

(b)

Fig. 3. Measured values in the REFLAB interface: (a) simple vapour compression plant; (b) two-stage vapour compression plant.



Recalentamiento (ºC) 12.9172
Subenfriamiento (ºC) -0.989844
P. glicol evap (kW) 10.374
P. ref evaporad (kW) 12.0013
P. glicol cond (kW) 18.2888
P. ref cond (kW) 14.9035
Pot Comp (kW) 3.2645
COP 3.67631

HASP	HDESC	HKE	HKS	HVE	HOE	HOS
412.85	457.488	454.534	245.533	242.31	242.31	410.612

Archivo datos saturación refrigerante: C:\adqmmt\saturacion\R22_ref.txt

(a)

SASPL 1,729
Wcomp (kW) 2,56813
Pglicol evap(kW) 9,385
Pref evap (kW) 6,323
Pagua cond (kW) 8,074
Pref cond (kW) 7,831
COP 2,46214

Archivo datos saturación refrigerante: C:\adqmmt\saturacion\R404A.txt

HASPL	HDESCLS	HDESCL	HASPH	HDESCH	HKE	HLKS	HKS	HECHE	HECHS	HECME	HECMS	HOE	HVOS	HOS
384,24	402,11	411,45	404,20	422,27	415,76	238,93	238,14	238,14	211,92	238,14	368,22	211,92	354,96	384,24

(b)

Fig. 4. Thermodynamic working cycle in the REFLAB interface. (a) simple vapour compression plant; (b) two-stage vapour compression plant.

3. Description of the refrigerating plants used in the practical lessons

The refrigerating plants used in the practical lessons are presented in this section. The plants, a single and a two-stage vapour compression refrigerating machine, cover the most widely used technology in small- and medium-scale applications.

3.1 Single-stage refrigerating plant

Most of the refrigeration systems used nowadays are based on a single-stage vapour compression cycle, mainly because of its simplicity. The single-stage plant used in the lesson is shown in Fig. 5, and its sensor locations and the general diagram are depicted in Fig. 6. It consists of an open-type compressor, a condenser, an evaporator and a thermal expansion valve. The plant works with HCF refrigerants (R-134a and R-407C) and has a nominal cooling capacity of 11.2 kW working with R22 at 0°C of evaporating level.

3.2 Two-stage refrigerating plant

When the difference between evaporating and condensing temperature is below 50K, single-stage vapour compressions are appropriate. If an increase

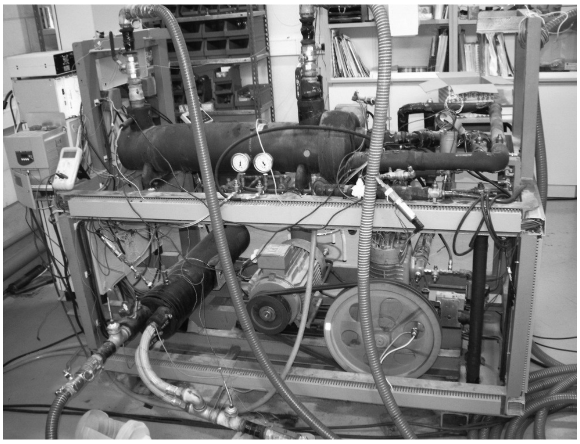


Fig. 5. Single-stage vapour compression plant.

on this difference appears, cooling capacity and COP could be reduced drastically, hence two-stage vapour compression cycles are used for high compression rates.

The two-stage refrigerating plant used in practical lessons (Fig. 7) performs a two-stage cycle, working with a compound compressor (compressor with two compression stages), two brazed plate heat exchangers for the evaporator and condenser, and two different inter-stage configurations between the compression stages: liquid injection system and sub-cooler system. The nominal cooling capacity of this facility is 5 kW working with R-404A at –30°C of evaporating level. Schematic diagram of the refrigeration plant, are shown in Fig. 8.

4. REFLAB application in the practical lessons

Three objectives are pursued in practical lessons of 'artificial cold production':

1. Identify all the elements that make up a real refrigerating system and understand their function and operation.
2. Understand the operation of each plant.
3. Comprehend the variables of operation and their effects on the energetic behaviour of the plants when they are modified.

The first two objectives can be achieved by classical teaching methods, but REFLAB application is required to complete the third. This software allows the student to observe directly the modifications on the main operating parameters of the plants by means of on-line graphics at the exact moment when the operating conditions are being modified. Therefore, the REFLAB interface allows the understanding of the mathematical relations of these changes in the plant by using their graphical evolution, which is a more intuitive and entertaining way of teaching and learning.

In order to achieve those objectives, some practical exercises using REFLAB have been developed, of which we have selected several in order to show just how useful REFLAB is.

All practical lessons start with a brief explanation of the theoretical basis made by the teacher, where the expressions used to calculate cooling capacity, COP and thermal effectiveness are analysed. The refrigerating plant is switched on and, while it is

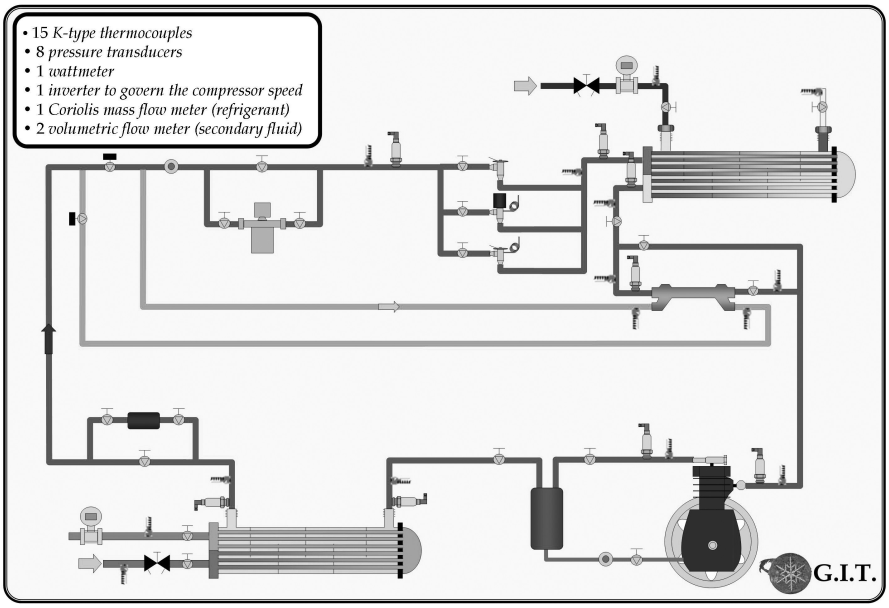


Fig. 6. Single-stage vapour compression plant. Schematic diagram and sensor locations .

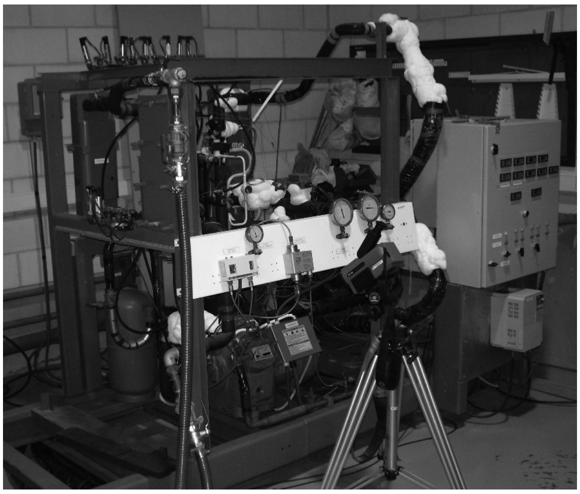


Fig. 7. Two-stage vapour compression plant.

reaching the steady-state operation, all the components that constitute the plant are explained to the students. At the same time the teacher presents REFLAB, explaining its operation and use. When the steady-state operation is reached, the student follows the software and operates the refrigerating plant using the regulation and control elements to complete the practical exercises.

4.1 Internal Heat Exchanger effect on a single-stage vapour compression plant

The objective of this exercise is to understand the purpose of the Internal Heat Exchanger (IHX) installed in a single-stage vapour compression plant. This element, whose main task is to prevent liquid at the compressor suction port, has a positive effect in the energetic behaviour of the cycle since the liquid at the exit of condenser is subcooled and the cooling capacity is increased [10]. However, it has a negative effect since the vapour at the compression suction is superheated and therefore the compression process is worsened. The student connects or disconnects the internal heat exchanger by using a set of solenoid valves.

REFLAB allows the student to follow the refrigerating cycle evolution on-line when this element is connected in the plant by means of the refrigerant *P–h* diagram. The subcooling and superheating degrees, the cooling capacity (Q_o) and COP are also shown at the same time. Figure 9 presents the refrigerating cycles of the plant working with and without IHX. The on-line effect, as seen by the student in the practical lesson, is presented in the associated animation.

4.2 Effect of compressor speed variation on a single-stage vapour compression plant

In this exercise, the basic operating principle of the technology known as the 'inverter' in air conditioning systems is explained and analysed. This control method is commonly used to adjust the compressor speed by focusing on the cooling capacity required in the evaporator.

Using the software, the student selects different speeds in the compressor, and the consequences in the plant are shown in the REFLAB graphics, Fig. 10. As shown in the animation, students can observe the changes in the refrigerant mass flow rate and the cooling capacity, and they can notice that the efficiency of the plant is practically neither reduced nor improved.

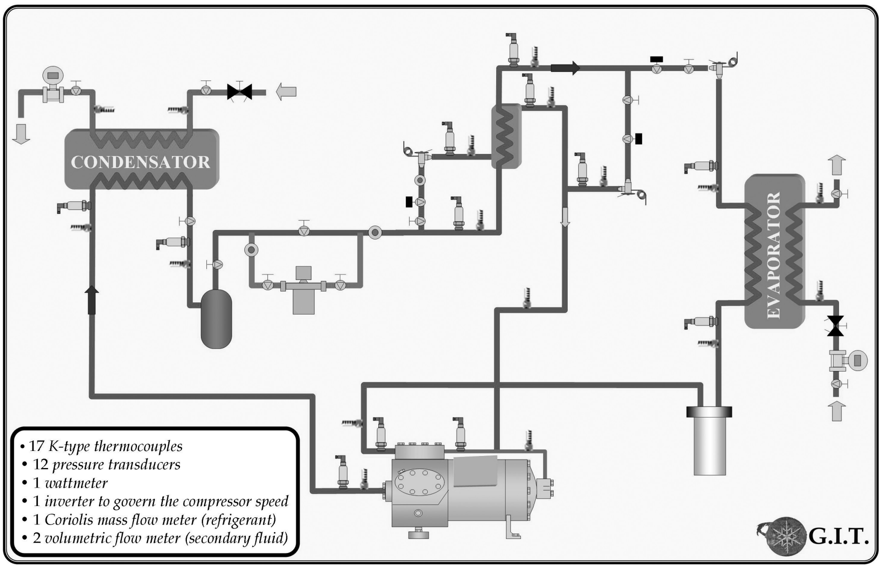


Fig. 8. Double-stage vapour compression plant. Schematic diagram and sensor locations.

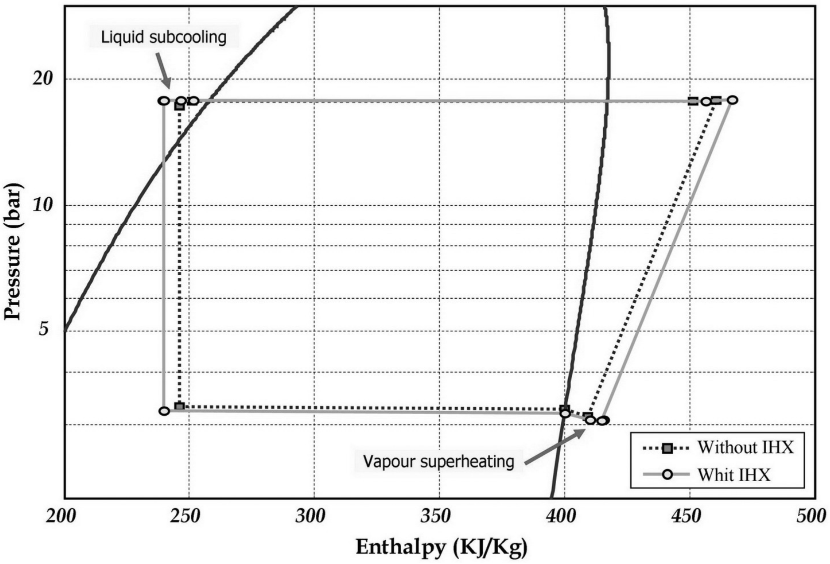


Fig. 9. Internal Heat Exchanger effect in a single-stage vapour compression plant.

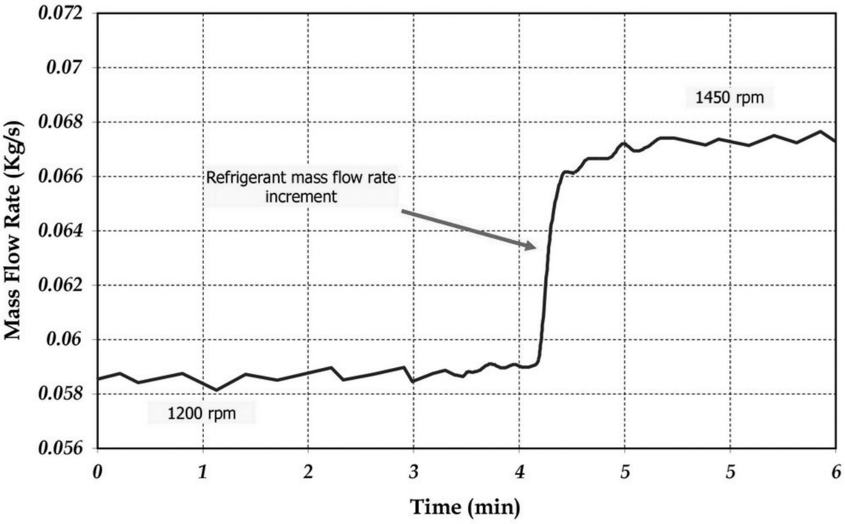


Fig. 10. Mass flow rate decrease by compressor speed reduction.

4.3 Effect of de-superheating in a two-stage vapour compression plant

This exercise and the following are based on the study of a two-stage vapour compression plant (Fig. 7), which attempts to explain the cycle modifications achieved by using two different inter-stage systems. The first one is the liquid injection system, which is used to reduce the discharge temperature of the compressor [11, 13].

The student connects or disconnects the inter-stage system using a set of solenoid valves and analyses the effects in the REFLAB interface on-line. The P–h cycle modification can be seen in Fig. 11 when this system is used. The student could notice the temperature reduction caused at the compressor, as well as the de-superheating effect between stages. The on-line evolution could be seen in the corresponding application.

4.4 Effect of liquid subcooling on a two-stage vapour compression plant

The last exercise of the practical lessons is based on the understanding of the inter-stage system in two-stage refrigerating plants known as the 'subcooler'. This system causes a subcooling in the liquid line at high pressure, as well as a slight de-superheating effect between compression stages [12, 13].

In this exercise, the student shows how the COP of the refrigerating plant is slightly increased and the discharge temperature is strongly reduced.

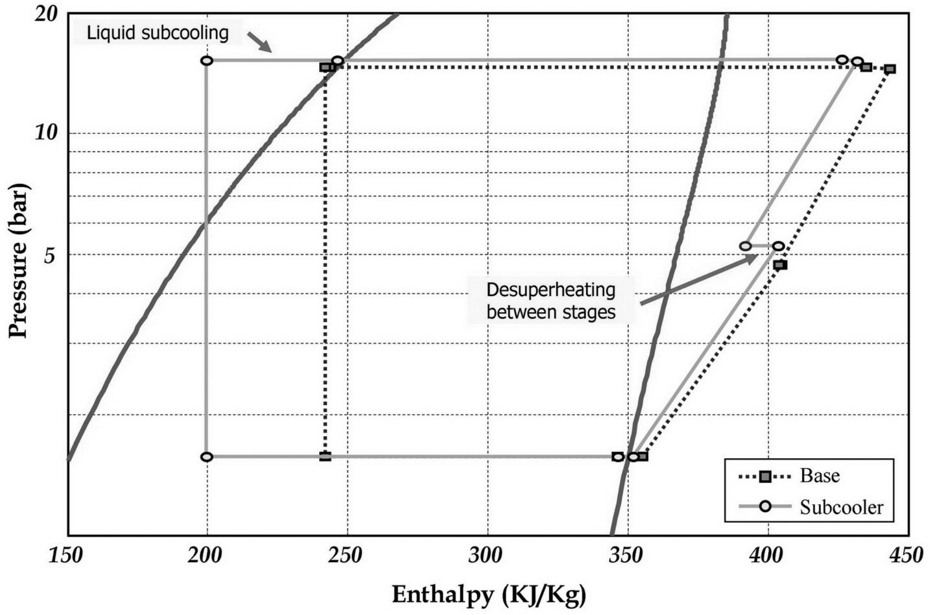


Fig. 11. The effect of liquid injection on a two-stage refrigerating plant.

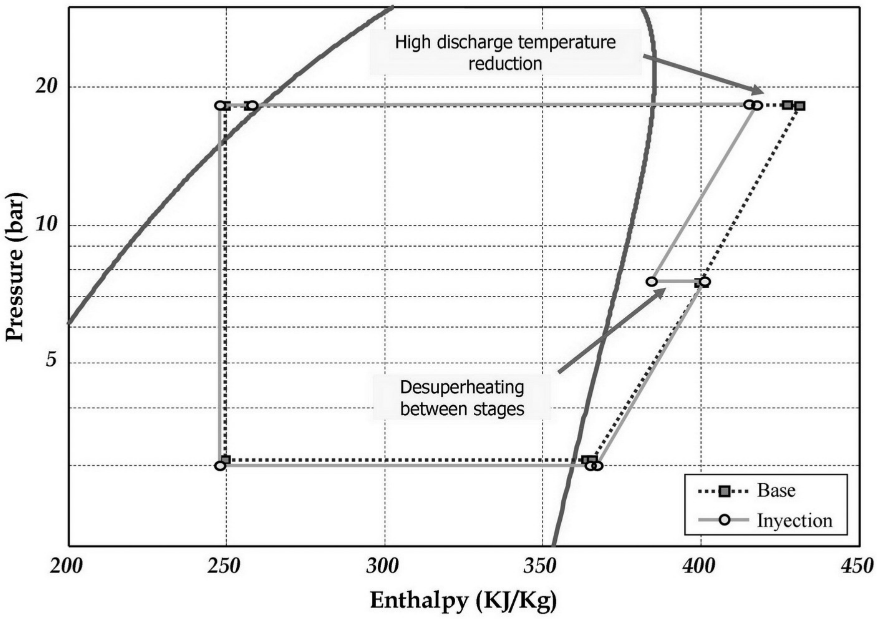


Fig. 12. Subcooler effect on a two-stage refrigerating plant.

5. Application in the course

The practical lessons that are presented in this paper are taught in Industrial Engineering in the 4th academic course (Energetic Technology) and in the 2nd year of Technical Industrial Engineering (Thermal Engineering), where 'cold production' is an important topic. These REFLAB-base practices were introduced in the 2005/2006 academic year with two 2-hours sessions.

The lessons are divided into four parts:

1. Theoretical introduction (15 minutes.): the theoretical concepts of the plants are explained and the refrigerating plants are switched on.
2. Introduction to the plants (20 minutes): here we emphasise the identification of each element that constitutes the plant and we explain their functions.
3. REFLAB presentation (15 minutes): in this section we explain the different elements that constitute REFLAB, such as sensors and their locations, the signal acquisition system and the

graphical interface. The basic principles of REFLAB operation are also explained.

4. Practical exercises (70 minutes): students follow the exercises detailed in manual controlling of the refrigerating plants and analysing the effects of each modification in the REFLAB interface.

To evaluate the use of REFLAB and the practical lessons a survey was distributed to the students with the following results: 87% of the students considered that the new teaching method was more interesting and entertaining than the classical one, 94% stated that the exercises were helpful to understand the concepts explained in the theoretical lessons and 98% considered it necessary to do more practical lessons in order to understand the different topics of the subject in the practice.

In our opinion, the use of REFLAB in the practical lessons has overcome the two main problems of the classical teaching method. The use of REFLAB increases the volume of information analysed in the lessons, at the same time increasing the level of assimilation of the concepts. These facts have been proved from the questions suggested by the students in both practical lessons and tutorial hours.

This experience has been applied to the 2005/2006 year and will continue in the future according to the excellent results. In the future, the procedure of the on-line visualization phenomenon will be applied to other Thermal Engineering topics, such as combustion engines, cogeneration plants, heat exchangers, air-conditioning, etc.

Furthermore, REFLAB will be released as a free executable program to allow other teachers to use it in their practical lessons.

6. Conclusions

A new and interactive teaching tool called REFLAB has been presented herein. This tool uses the latest signal acquisition techniques and four different commercial programs with the objective of improving the learning process in the practical teaching of refrigeration.

This new tool allows on-line visualisation of the real working cycle of refrigerating plants in the refrigerant P–h diagram, and of other operating variables of the plants: pressures, temperatures, flow rates, superheating and subcooling degrees, cooling capacity, compressor power consumption and COP.

REFLAB allows the study of the responses of refrigerating plants when some of the parameters are modified through an on-line representation in a graphical interface. Thus the teaching–learning process is improved and the contents explained in practical lessons are quickly assimilated by the students.

The success of the application in the course has motivated the teachers to continue using REFLAB and to improve the teaching tool.

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