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Refrigerating Cycle Simulator: System Modelling, Educational Implementation and Assessment*

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To teach and explain system modelling in a Thermal-Fluid application is a challenge: learning how one component or even the surrounding conditions can influence the performance of the rest of the components of the system and the system itself is not an easy task. However a suitable educational implementation may help students gain a deeper understanding not only of the system itself but of the existing interrelation between the Thermal-Fluid fields: Thermodynamics, Heat Transfer and Fluid Mechanics. In this study a refrigerating cycle simulator is used. The simulator is prepared in such a way that the interrelation between each component, the system and the surroundings can be analysed *by the students. This case study is found to be very useful due of its ability to study system performance. A three-step educational implementation, the simulator being the third step, has been used and found to be enriching both for students and instructors.*

Keywords: refrigeration cycle; virtual lab; simulator and system modelling

INTRODUCTION

IN THE LAST FEW YEARS, the use of virtual labs and simulators for teaching in engineering courses has spread. Their application as an educational tool allows students to learn to use the programs with which they look at engineering problems in a faster and more efficient way not only at university but in their professional career. On the other hand, these simulators and virtual labs can be used as tools to help students to understand the performance of the whole simulated system, of each separate component and of the relations between the components. In this sense it is essential that the simulator allows parametric studies to be performed.

A refrigerating cycle is a system, the implementation of which in a simulator would fulfil the two previously stated educational objectives: to learn how to use the simulator to model the whole cycle and to study and understand the relations between the components of the system. Moreover, in a refrigerating cycle the three main Thermal–Fluid courses (Thermodynamics, Heat Transfer and Fluid Mechanics) are involved, so it would be very interesting if the student could manage to see their relationship using the simulator.

In the specialized bibliography we can find several simulators of a refrigerating cycle in a 'learning and understanding' environment as mentioned above. One of the first is that developed by Smith *et al.* [1] in order to help students to understand the performance of the refrigerating cycles. In this sense, the program stands out because it takes into account the real effects of all the components (pressure drops, subcooling, superheating, irreversibilities), but it exhibits a limitation in the variety of the components modelled and in the types of cycles.

Klein [2] implements a refrigeration cycle as a main example of the application of its EES program (Engineering Equation Solver). EES is an equation-solving program designed to solve problems in the thermal sciences (thermo–physical properties of commonly used fluids are built-in) and within a classroom context. It allows students to solve more problems within a reasonable time, releasing them from the mathematics and the thermo-physical property data calculations. As an example of the application of the program, Klein uses a refrigeration cycle where students perform parametric studies, altering some of the

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parameters of the cycle. One drawback of this application is that it only pays attention to the thermodynamic aspects of the cycle but not to the heat transfer relations, which are treated in a simplified way.

In a similar way, Tan *et al.* [3] developed a refrigeration cycle simulator to be used by students as an optimization and design tool. From an educational point of view, the program helps in reinforcing the thermodynamic concepts learnt in the classroom. From a design point of view, the program optimizes the cycle in order to obtain the maximum value for the coefficient of performance (COP). As in the previous case, this simulator fails to take into account the heat transfer aspects of the cycle and, specifically, the influence of the surroundings.

Another educational simulator of thermodynamic cycles, and not only of refrigeration, is CyclePad [4], which was developed at the Northwestern University. The program is described as a virtual laboratory that can be used as a training tool by students and that provides theoretical explanations. Its strong point is that it extends the understanding of the thermodynamic cycles not only to the refrigeration but also to other types (power cycles). Its weakness is that, as in the former cases, it studies only the thermodynamic aspects of the systems and not their interactions (heat transfer) with their surroundings.

The same can be said of CoolPack [5], a collection of programs implemented in EES and used to optimize and analyse refrigeration systems. It has been developed at the Department of Energy Engineering of the Technical University of Denmark. The software has been conceived as an aid to engineers in the task of designing refrigerating cycles with a higher efficiency. It allows a sequential process design, beginning with the choice of the type of cycle and its dimensions, followed by the simulation of the specified working conditions, and finally the analysis of the energetic results. From this working methodology it can be inferred that the program is more a design tool than a 'learning and understanding' tool.

Sieres and Fernández-Seara [6] developed a simulator of compression refrigeration cycles, where the cycle can be designed using a database of components and refrigerants. The simulator allows students to focus their attention on the study of the influence of the different parameters in working conditions and in the performance of the cycle, instead of on solving the equations and looking for the thermodynamic properties. As in the programs previously mentioned, this gives more weight to the design aspects of the refrigerating system than to the understanding of the interrelations between components, system and surroundings.

Finally, the simulator developed by Rivas *et al.* [7] in Microsoft Excel can be included in this review as another example of a program more centred in the analysis and the optimizing of thermodynamic (power) cycles and piping networks than in contributing to offering students a more 'global picture' of the systems modelled.

A common drawback of all the above-mentioned simulators and virtual labs is the lack of feedback about their use from the students. It is generally agreed that the development of a simulator as a teaching tool for engineering courses is just as important as the assessment of its application by the students. The teacher must wonder: 'I have prepared a program to help the students to learn and understand my subject, but how effective is my simulator in order to achieve this objective? How can I improve it?' Feedback has been collected and reported in subjects as diverse as Strength of Materials [8, 9], Computer Design [10], Heat Exchangers [11] and Process Systems [12]. In these papers surveys were carried out among the students in order to provide the developers with feedback about the validity and effectiveness of their simulators. In all cases, the tools were regarded by the students as an aid to understanding the theoretical concepts and for doing the 'experiments' in a rapid and easy way. They also pointed out their usefulness in conjunction with a real laboratory and valued the availability of the virtual lab at any time of the day.

In this paper, a case study using a refrigerating cycle simulator is presented. The main difference from those simulators mentioned above is that, as well as modelling the interaction of the components of the whole system, it models the interaction of each component (evaporator and condenser, mainly) with their surroundings. The simulator models the heat transfer in the heat exchangers so that the variation of the thermodynamic states of the refrigerant in the cycle is related to the variations (thermal or flow) of the air flows in the evaporator and the condenser. Owing to this outstanding feature of the developed virtual lab, students can acquire an integral picture of the system–components–surroundings interrelationship in a refrigerating cycle and can see the applications of the concepts learned in the Thermal–Fluid Sciences subjects: Thermodynamics, Heat Transfer and Fluid Mechanics. To validate this statement, an assessment of the usefulness and effectiveness of the simulator has been carried out by means of questionnaires distributed among the students of the three previously mentioned subjects. The results of these surveys are also presented in this paper.

INTEGRAL APPROACH

The goal of any engineering educational program is to offer the students 'the global picture' of the engineering courses. A global picture implies the relationships and interactions between knowledge obtained from several courses. A virtual lab that represents a system (a system model) and that contains information related to several engineering courses may be a convenient tool for promoting learning and understanding 'the global picture'. Moreover, a simulator may have the capacity, as in the present case, to relate and analyse the relationships not only between the system and each of the components of the system but also with the system and its surroundings. This interrelation and the integral approach are shown in Fig. 1. There, the three main actors in system modelling are introduced: the components, the system—all the components working together in such a way that the goal of the system is fulfilled—and the surroundings. The bidirectional arrows show the fact that any of them may affect the other two.

SYSTEM MODELLING

To explain system modelling in a Thermal–Fluid application is a challenge. How one component of a system affects the other components in the system, and the system behaviour itself, is often a desired learning outcome in engineering courses. There is however a big difference in understanding how a single component operates on its own compared with how it functions together with other components in a system.

One example is the fact that changing one parameter will influence all the output data. In a system model of a refrigerating cycle it is not always obvious which parameter is the most important. For example: How much is the power of a fan in the evaporator going to influence the cooling load and the performance of the cycle? Working with the simulator permits the student to realize that Thermodynamics, Fluid Mechanics, and Heat Transfer are related, in this case the student captures the global picture not only of the relationship between the engineering courses but of the refrigeration cycle where the knowledge is integrated. The student knows that the heat transfer in the evaporator is a function of the refrigerant mass flow and its enthalpy change or, on the air side, that it is a function of the air mass flow and its temperature change. Hitherto we are moving in the thermodynamics field, however according to heat transfer theory, the heat transfer is also a function of the global heat transfer coefficient in the heat exchangers (i.e. taken into account both sides of the heat exchanger: the refrigerant side and the air side) and thus closely related to the air and refrigerant velocities on the two sides of the heat exchanger (see Fig. 2). In the case of a change of the air mass flow rate due to a change in the fan power, the students can, by using theory and aided by the results of the simulator, investigate the behaviour of the system and gain an understanding of the system.

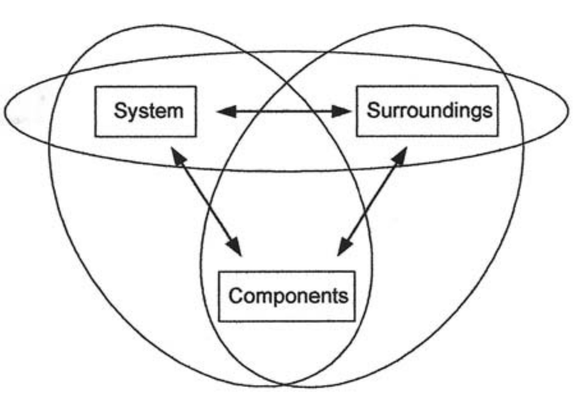


Fig. 1. A global picture. The interrelation in the Thermal–Fluid courses.

$$\begin{aligned} Q &= UA\Delta T_{ml} & u_{air} &= f(\dot{m}_{air}) \\ Q &= \dot{m}_{refrigerant}\Delta h & \dot{m}_{air} &= f(Q) \\ & & Q &= f(UA) \\ Q &= \dot{m}_{air} c_p \Delta T & UA &= f(u_{air}) \end{aligned}$$

Fig. 2. Equations for heat transfer in a (fan coil) heat exchanger. Q: heat transfer. A: heat exchanger area U: global heat transfer coefficient. T_{ml}: log. mean temperature difference. $\dot{m}$: mass flow. Δh: enthalpy change. c_p : air specific heat. u: velocity. ΔT: temperature change on the air side.

Teaching system behaviour is very difficult without some kind of model of the system or access to the actual system itself. However, gaining an understanding of how a system behaves is still not easily achieved—even with the aid of a model of the system (or the actual system). Moreover, many teachers are of the opinion that students will gain understanding of the system behaviour by developing some kind of computational model of the system. Our experience tells us that this is not usually the case. When students are asked to develop a model of a system, they often manage to build a fully functional model, but they seldom get the time to study and understand the behaviour of the system. On the other hand, if the students are given a fully functional model of a system some insight of the system behaviour can be gained. However, the deeper understanding of the system behaviour may be lost because the students may not know how the different components of the system are connected. In both cases the learning outcome is not achieved.

EDUCATIONAL IMPLEMENTATION

It is always interesting to use lab exercises as an aid for understanding the basic theory, as shown for example in [13]. In the educational path for teaching system behaviour that has been followed by the authors, the students have developed small models of components in the system such as a heat exchangers, and a compressor before using the system model. They have understood the components by developing a component model ('learning by doing'). The next step is to understand the system behaviour or the interactions between the components. In this case, it is not realistic to gain an understanding of the system **behaviour** by devel-

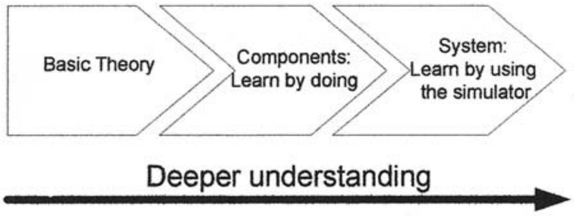


Fig. 3. Proposed educational path.

oping a system model since it would be extremely time consuming for the student, instead a simulator is given to the students in a computer lab ('learning by using a simulator'). The basic idea is that the students, once given the complete model of the system, should know how the various components are modelled and implemented. The intention of the teachers is that the students should now focus on the system **behaviour** rather than on connecting all the components into a system. This educational implementation is shown in Fig. 3.

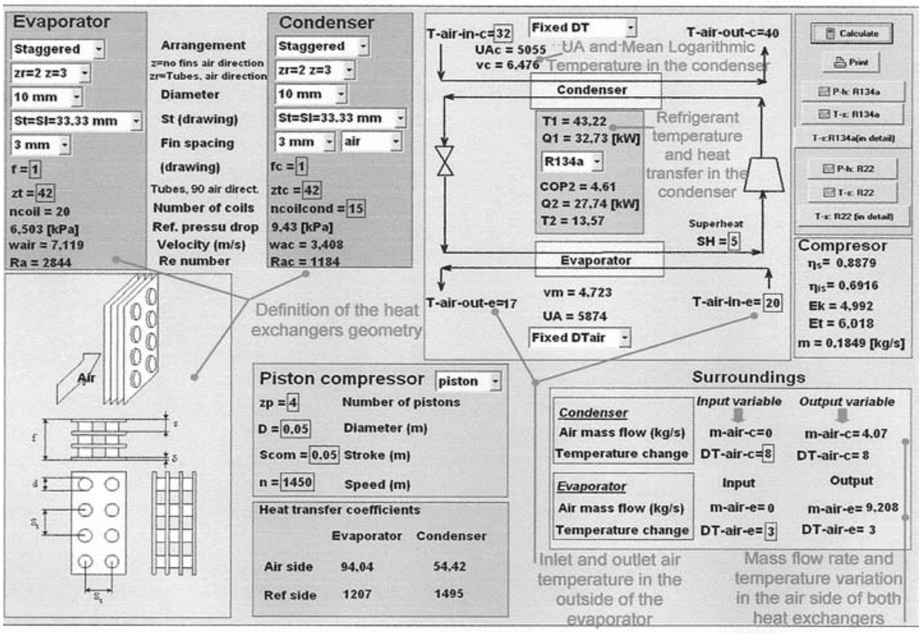
Furthermore, using a system model is beneficial for many educational reasons. Many students, who decide to study engineering long to get a closer understanding of real engineering equipment and to design it. The fact that they not only encounter theory in an engineering course but also analysis and design is always encouraging for students, who develop a more enthusiastic approach to the course. In fact, one of the benefits of using a simulator is that the students get a more realistic view of the system behaviour, one that may be quite different from the view they would obtain from ordinary classroom instruction. In typical textbook problems dealing with this issue, some parameters are treated as constant input data (e.g. the evaporation and condensation temperatures), whereas in reality these parameters are system dependent output data. In fact, this difference is quite an obstacle for the students to overcome. Using a system model will highlight this difference and, once properly implemented in the course, will improve the students' learning about the system's behaviour.

This last step—learn by using the simulator—is to a certain extent something new in thermal–fluid courses. The conventional way of teaching focuses on the first two steps of Fig. 3. In the present case, the third step allows for a deeper understanding. This third step is something that, because it is complex to teach on a board, it does not appear on the syllabuses of these courses. However, this system analysis can be successfully carried out with the aid of a simulator.

Students' approaches to learning are related to the teacher's approach to teaching as stated in [14], where the authors show how teaching in a student-focused way and changing the students conceptions helps students to obtain a better approach to learning. Furthermore, a change in teaching methods towards a more interactive approach would be beneficial to students as expressed in [15]. The authors believe that this educational implementation in which there is interaction with a simulator will foster a useful analytical approach for the students.

THE SIMULATOR

In this paper, a virtual lab that simulates the performance of a vapour-compression refrigerating cycle is briefly described. The theoretical basis of the cycle was described in a previous article by the authors [16]. The simulation tool offers consid-



Evaporator		Condenser
Staggered	Arrangement	Staggered
zr=2 z=3	z=no fins air direction zr=Tubes. air direction	zr=2 z=3
10 mm	Diameter	10 mm
St=Sl=33.33 mm	St (drawing)	St=Sl=33.33 mm
3 mm	Fin spacing	3 mm air
f = 1	(drawing)	fc = 1
zt = 42	Tubes, 90 air direct.	ztc = 42
ncoil = 20	Number of coils	ncoilcond = 15
6,503 [kPa]	Ref. pressu drop	9,43 [kPa]
wair = 7.119	Velocity (m/s)	wac = 3,408
Ra = 2844	Re number	Rac = 1184

T-air-in-c=32
Fixed DT
T-air-out-c=40
UAc = 5055
vc = 6.476
T1 = 43.22
Q1 = 32.73 [kW]
R134a
COP2 = 4.61
Q2 = 27.74 [kW]
T2 = 13.57
Superheat SH = 5
T-air-out-e=17
vm = 4.723
UA = 5874
Fixed DTair
T-air-in-e= 20

Compresor
η_s= 0.8879
η_{is}= 0.6916
Ek = 4.992
Et = 6.018
m = 0.1849 [kg/s]

Piston compressor piston
zp = 4 Number of pistons
D = 0.05 Diameter (m)
Scom = 0.05 Stroke (m)
n = 1450 Speed (m)

Heat transfer coefficients

	Evaporator	Condenser
Air side	94.04	54.42
Ref side	1207	1495

Surroundings

	Input variable	Output variable
Condenser		
Air mass flow (kg/s)	m-air-c=0	m-air-c=4.07
Temperature change	DT-air-c=8	DT-air-c=8
Evaporator	Input	Output
Air mass flow (kg/s)	m-air-e=0	m-air-e=9.208
Temperature change	DT-air-e=3	DT-air-e=3

Fig. 4. The graphical user interface of the simulator (parameters with squares are inputs).

erable flexibility in terms of the ability to choose between different designs of heat exchangers (evaporators and condensers), and working media and hence the possibility to evaluate different solutions. To a certain extent, there is also the flexibility to define the 'inputs' that define the surrounding boundary conditions. The simulator takes into consideration not only the thermodynamics of the cycle but also the heat transfer and pressure drop that occur in the components of the system. Therefore, the model does not separate the refrigeration cycle from the component models: this feature is essential in order to show the interaction between the cycle (the system), the components (condenser, compressor . . .) and the surroundings of the system. In fact, the heat exchangers are modelled in detail, i.e. the heat transfer is calculated on both sides. The simulator has a graphical user interface that allows the student to see how the changes in one parameter of a component influence the rest of the components and the global system. In brief: the simulator is able to answer all the 'what happens if' questions that students may have. The simulator also allows the student to do parametric studies in a very easy way. Furthermore, the fact that the geometry of the heat exchangers and the compressor should be provided gives the student the chance of designing a cycle that is suited for a particular application that requires a specific cooling or heating load.

The system model is developed using EES (Engineering Equation Solver) [17], a programming environment that gives the thermo–physical properties for the working media used, as well being a powerful implicit solver. This environment provides not only the aforementioned graphical interface, but also give students access to the system model source code that they can review and, if they so desire, edit. The user graphical interface is presented in Fig. 4.

EES also makes the cycle in *T*-*s* and *P*-*h* diagrams (see Fig. 5) easy to represent, which helps the students to grasp what is happening in each of the changes.

ASSESSMENT OF THE CASE STUDY

The present simulator has been used for the last five years in the course Sustainable Energy Utilization, at the Royal Institute of Technology (KTH),

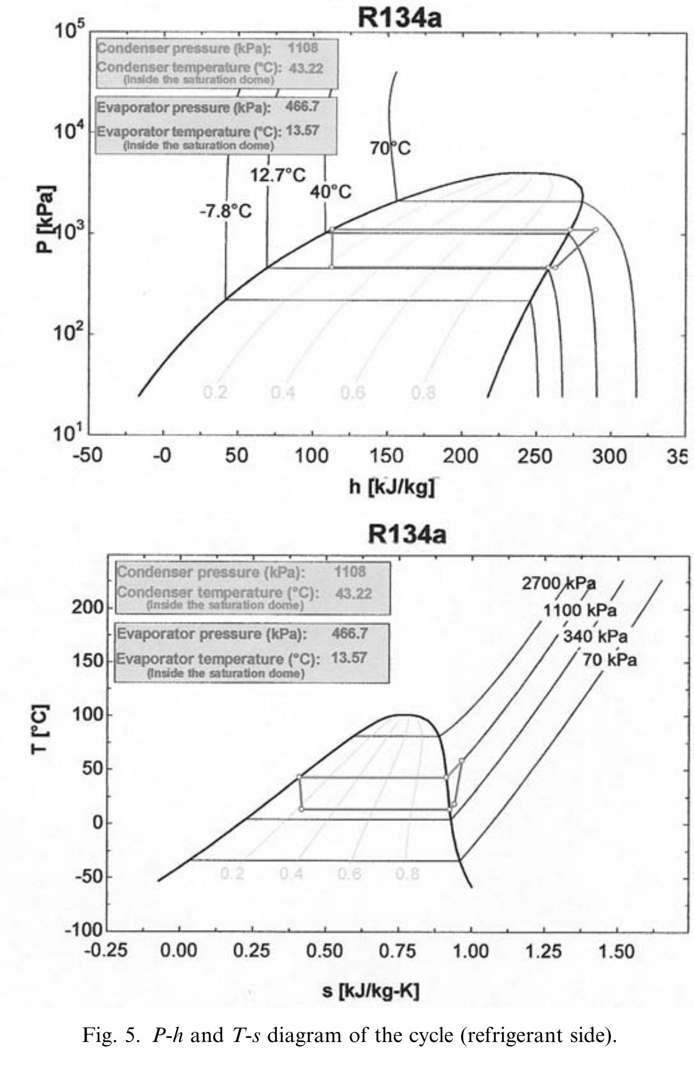


Fig. 5. *P*-*h* and *T*-*s* diagram of the cycle (refrigerant side).

Sweden. In the first four years of its use at KTH, instructors have observed a shift in the students' understanding of the system behaviour. It has however been very hard to assess this shift systematically. The measure of the shift in the students' understanding is hence based on the professional knowledge and experience of the instructors. To investigate the impact of using the simulator statistically, a control group of students would have had to be used. However, the main task of the instructors is to provide a good education and deliver the course at a high and consistent quality level for the students. To isolate a control group of students that could be given less or alternative instruction has hence not been carried out. In the authors' view, it would have been unethical to do so.

The impact of the simulator during the first four years is hence based on the observations of the instructors. From course evaluations, the instructors have been able to see clear trends. However, these trends are dependent on the general level of understanding of the students. Some students have learnt more than others as expected in any group of students. Below, a few quotes from the course evaluations are presented and commented on.

> It is hard to see what happens when I change one parameter since everything in the system changes.

Here, the student clearly doesn't understand the concept of a system. The student is still focused on class instruction where one parameter is changed, and the change of an output variable can be seen.

> The only labs this term that required written analysis = the only labs that made me think about what was happening and why.

The assessment chosen, in this case a written report, also influenced the learning.

> It was hard to separate primary and secondary effects. This wasn't clear enough. The computer does not act as a real system.

Here the student has understood the concept of a system, even though he/she does not trust the model. The system not always behaves in an intuitive way.

> Hard to analyse (everything is linked).

This is one of the most common remarks. However, when assessing the student's report it is clear that the system concept and the system behaviour are understood to a very large extent.

During the fall semester 2007, the simulator was also introduced at TECNUN-University of Navarra, Spain. Thus the authors had the chance to compare the impact between two student groups. The feedback given by students in questionnaires allows the authors to assess the usefulness of the simulator as a teaching tool. The feedback from the students also allows the authors to assess the level of deep understanding gained by the students. The same questionnaires were used at both universities.

The assessment was done for two very different students groups. Students who are taking a course in Sustainable Energy Utilization as part of the master program at KTH, and second year students who are taking the Thermodynamics course as part of their studies in Mechanical Engineering at TECNUN. There is an important difference between these groups: those from KTH had already taken courses both in Thermodynamics and Heat Transfer but those from TECNUN have not taken a Heat Transfer Course previously. Therefore, in the simulator–computer lab at KTH there were issues related to Heat Transfer and Thermodynamics, however at TECNUN, the computer lab focused mainly on some Thermodynamics issues and the relationship of the system with changes in the surroundings.

In the main, two methods to assess student performance can be distinguished: the criterion-based and the norm-based as discussed in [18]. Even if the norm-based method fosters a more competitive atmosphere, the authors have preferred to assess the students using a criterion-based approach that promotes self-reliance in the students and that is defined by the specified contents of the performance criteria.

The assessment focused on grading the following five issues (A, B, C, D and E):

- A The efficiency of learning stand-alone component behaviour from its modelling by the student in the first computer labs (previous to the simulator-system analysis computer lab).
- B The efficiency of the simulator–computer lab as a way of improving understanding of how the whole system works.
- C If the simulator computer lab has really helped to see the real coupling between Thermodynamics and Heat Transfer that exists in the heat exchangers.
- D Three key questions in relation to the understanding of difficult thermodynamics issues that appear in system modelling: mainly how changes in the surrounding conditions affect the system performance and refrigerant mass flow.
- E The efficiency of the simulator as a tool to get a closer look at real systems.

The students could grade each of the issues between 1 (if it is not efficient or not understood) and 5 (if it is very efficient or very well understood). In Table 1, the mean value of the grading is shown for each issue and group. The standard

Table 1. Mean values of student gradings.

Issue	**KTH (22 Students)**	**TECNUN (59 students)**
A	3.14	4.08
B	3.5	3.24
C	2.77	
D	3.61	3.81
E	3.36	3.9

deviation for each set of data is around one (it ranges from 0.82 to 1.18 depending on the issue and group), which is not large and therefore shows the fairly even opinion that exists.

Several conclusions may be drawn from the assessment results:

Related to issue A:

Both groups of students grade positively to learning the stand-alone component behaviour using the method of 'learning by doing' (the modelling is implemented by the students). We believe that second year students at TECNUN graded it higher because Thermodynamics is a course very focused on that.

Related to issue B:

We believe that the better grading that master students at KTH give to the B issue is related to their broader capacity (they have already taken courses in Heat Transfer and Thermodynamics) to understand the potential of a simulator as a tool to see how the whole system works.

Related to issue C:

Issue C really made sense for KTH students. They needed to handle the real interaction between thermodynamics and heat transfer in the heat exchangers in their computer lab and they had problems in understanding it, as you see in the assessment.

Related to issue D:

Students at both TECNUN and KTH understood the three key thermodynamics questions (the same for both groups) related to system modelling that appeared in their computer labs.

Related to issue E:

Both groups of students think that a simulator is the right tool to help the student to get closer to real systems.

The overall assessment is positive, and it may be concluded that the use of a simulator fosters a deeper understanding. However, from the students' feedback, the following comments may be found: 'It is sometimes hard to isolate the components and see why they are really behaving that way' or 'I think this computer lab is interesting to see the high number of parameters in the system' or 'When one parameter is changed quite all the things change in the functioning characteristics. It is quite difficult to start to explain how the system behaves'.

From these and other similar comments it can be inferred that students realize that in a real system there are more parameters than those of a typical problem, and that many of them are interrelated and that they are somewhat amazed that one component can not be isolated (because a variation in a component parameter actually affects the whole set of components). We believe that the students should have a follow-up session on the simulator in order to clarify some unsolved doubts that were raised during the computer lab and to get the maximum from benefit from it. Otherwise, as it can also be seen from the above comments, there will be students that will not totally understand it.

Furthermore, according to the assessment results, something that can be highlighted is that the computer lab has been useful even for students that have studied only Thermodynamics. It seems to be a good idea for TECNUN students to use the simulator again in the Heat Transfer course so that a deeper and more thorough understanding can be achieved.

From the instructors' point of view, the simulator gives us extra time to discuss the performance of the refrigeration cycle with students. Those discussions have been found to be enriching both for students and instructors.

CONCLUSIONS

A method of fostering greater understanding through the use of a simulator has been presented. This method has been proved to offer an integral approach that actively helps students deal with complex engineering problems. The simulator is not enough and has to be complemented by appropriate handouts on computer lab guidelines and the all-important follow-up session. Altogether this gives the student the necessary tools to understand the system and—even more importantly—to put together content from different courses. The experience has been enriching for students and has generated a more positive attitude amongst them—given that now they can understand complex system problems and not just the prototype component problem usually solved on the blackboard and so commonly found in engineering texts. In this case study, the simulator is also found to be a crossroads for several engineering subjects, giving an integral picture of the thermal–fluid courses.

Some examples of the educational success that can be achieved as a result of this simulation tool have been developed. The feedback from students has been discussed. The overall assessment is positive, and it may be concluded from it that the use of a simulator fosters a deeper understanding in the students and gives an extra opportunity for instructors to discuss system behaviour with the students in a deeper way.

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