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Power Plant Optimisation Simulator Using Catalogues: A Case Study with Student Assessment*

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A study was carried out using a power plant simulator with optimisation and catalogues to teach Rankine cycles to undergraduate engineering students. To do this, a classic textbook power cycle problem and the tools to optimise it were created. The aim was to bring real world problems closer to students by giving them problems where there is not always a solution and they have to adapt. One of the means used to achieve this was to include real devices as inputs (i.e. catalogues by Siemens Turbine and Carver Pumps). After using the simulator, students provided a thorough assessment. The conclusion of this article is that the simplicity and clear objectives of this multimedia laboratory exercise were effective in teaching thermodynamic cycle optimisation.

Keywords: simulator; Rankine cycle; optimisation; catalogue use

1. Introduction

In recent years the use of computer-based educational technologies has increased significantly. Using simulators helps students to understand the topic at hand and it makes learning more enjoyable and interesting [1, 2]. Another reason that is driving the use of simulators is the fact that modern universities need to prepare students to enter industry. For the majority of technical careers, this can be done through simulation [2]. However, studying only through computers and virtual laboratories can make students feel lonely and isolated, which in turn causes them to become unmotivated [3]. For this reason, building teams and facilitating interaction between students is also a very important factor for their motivation and the learning process. Moreover, combining in-class sessions with group work can encourage students to engage with course content [4].

Students are used to learning by rote and being rewarded for this type of learning from the very beginning of their education. As a consequence, students often do not acquire concepts in any deep or real way [5]. A well-designed educational tool (for example, a simulator or multimedia laboratory exercise), however, introduces students to the major concepts behind the equations and processes, while at the same time giving them the opportunity to practice skills outside the classroom [6]. Simulation games are one way for students to experience the impact of their decisions in real time and validate their prior 'common sense' perspective in relation to a specific situation [7].

Studies suggest that there are six characteristics that simulation games must have in order to fully achieve their potential: storytelling, players as problem solvers and explorers, feedback, challenges that fit student characteristics, competition, and appropriate graphics and sounds [8]. Some of these characteristics will be included in the simulator that will be presented in this study, but since this multimedia laboratory exercise is not exactly a game, we can expect some deviation from what other authors call 'full potential'.

Given this context, this paper presents a simulator that teaches second year engineering students about Rankine cycles. The two main teaching objectives of the simulator are for students to be able to optimise a Rankine cycle and read manufacturer documentation. With these objectives in mind, other simulators are contrasted in the following paragraphs.

Real life power generation facilities make extensive use of simulators, either to practice emergency protocols or to train regular operators [9]. Rheinmetall Defence, GSE Systems and Yokogawa Electric Corporation are three companies devoted to the creation and implementation of simulators across several industries, including power generation [9, 11]. For example, GSE Systems has more than forty years of experience in simulation technology and eleven hundred installations that are related to power generation in fifty different countries. They can tailor specialized simulators that meet the specific needs of a refinery, coal power plant, combined cycle power plant or nuclear power plant [10, 12, 13].

Knowing that this type of solution is not suitable for a beginning undergraduate course in thermodynamics, we developed a real life simulator that not only provides an effective teaching–learning experience but also teaches students the specific skill of optimising the pressures of a power plant,

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which is related to the most cost-effective operating condition.

Some realistic simulators do exist at the intermediate level of learning. This is the case of the Interactive Plant Simulator [14], which uses the software from the José Cabrera Nuclear Power Plant (Spain), which ceased operating in 2006. By using this type of tool, students learn how to operate a Nuclear Power Plant in several situations. However, these kinds of simulators are very specific in what they teach, which in this case is nuclear power plant operations; students at this level already know about thermodynamic cycles. Our aim, in contrast, is to teach thermodynamics to beginners, which is why a carefully-designed multimedia simulator approach works better.

Stepping down from the intermediate level real life simulators to simple, undergraduate level simulators, one can encounter many options. Focusing just on simulators that teach thermodynamic cycle principles rather than the electric or economic aspects [15], the three characteristics of most modern simulators are the following: they work online, they are designed for a particular teaching objective and they have a very easy interaction environment.

One of these simulators is 'TermoGraf' [16], a commercial simulator designed for teaching thermodynamics. Its main advantages are that it allows different cycles, and it can be easily modified in situ while teaching the class, enabling students to learn the differences between each cycle. It also has an integrated evaluation system that teachers can use to test students. Our Multimedia Simulator differs from TermoGraf in that in TermoGraf students do not know the code of the program or how to manipulate it. TermoGraf is a complete simulator about thermodynamics, while our simulator focuses on only one Rankine cycle. As a consequence, it is simpler, and because students will have already learned how to use the Engineering Equation Solver (EES) [17], they can also see and understand how it works out the optimisation process. This allows the teacher and the students to have a guide and an example of what is going to happen, step by step. Although this multimedia laboratory exercise has a reduced scope, at the same time it has a profound impact because it excels in fulfilling its objective.

Similar multimedia laboratories exist, but not with the same scope. REFLAB, for example, teaches students to understand a specific refrigeration cycle and the parameters involved by using a LabView graphic interface [18]. One of the main advantages of REFLAB is that a real refrigeration system exists for students. It is based on a real device that students can see and touch, a factor the plays an important role in motivating students. However, this same advantage presents an inconvenience—since the refrigeration system is already built, students are not able to choose how they would have built it. They can optimise the refrigeration cycle, but the use of product catalogues cannot be included as teaching objectives. Edibon is a company dedicated to the construction of real minicycles for teachers [19]. Students can, for example, combine one of the Rankine cycles created by Edibon with the methods used by REFLAB and learn how to optimise the cycle. Nevertheless, by doing this, learning how to read catalogues is again put aside.

An online eBook created by the University of Oklahoma [20], used mainly for distance education, is a simulator/book for beginners in thermodynamics. It teaches ten different topics, dividing each into four sections: theory, examples, practical cases and a simulator. One of the chapters is dedicated to Rankine cycles. It is at the same level as our multimedia laboratory exercise, and it teaches the same Rankine cycle principles. However, it is theory-based and catalogues that are not used in the eBook. Also, the cycles cannot be optimised. Nevertheless, the interface and its online availability make it a very useful stand-alone tool for distance education [20].

The use of similar software (CyclePad) to teach Rankine cycle analysis has been described by various authors [21]. However, the use of catalogues is not included in these exercises, so they are based on theoretical devices. CyclePad is also used in other simulators [22] in order to define the parameters of a Rankine cycle: through the manipulation of the boiler pressure and condenser pressure, an upper bound is set for the power generated. Using this bound, the rest of the cycle is designed. Nonetheless, designing a cycle is a different exercise from optimising it. Also, the use of catalogues is not included.

The Scottish Qualifications Authority has created a module in order to certificate a student's ability to read manufacturers literature, focusing on industrial pipelines and vessels. This module is part of a course in Thermal Isolation; while it is not related to our topic of power generation in Rankine cycles, it is related to the use of catalogues. By the end of the module, students are expected to select the proper thickness of a thermal isolation for a range of appliances. However, this module is related to our simulator because, prior to the sessions, theoretical lessons are given to the students. This module does not include optimisation of the parameters prior to the selection of the device, which is another difference from our simulator [23].

The optimisation of a cycle is a complicated subject and thus it is difficult to teach it to students. A complex refrigerating cycle simulator, uniting different branches of science (heat transfer and fluid mechanics) and making all parameters change with respect to each other was previously created by Antón et al. [24]. From this experience, the authors conclude that creating a complex problem has advantages (an integrated approach to the problem when mixing several sciences makes the simulator realistic) and disadvantages (the level of complexity is too high for second year engineering students). In terms of our case study, creating a simple problem will help students to grasp major concepts. Also, making a realistic optimisation procedure will teach them aspects of the complexity of real life. Simplicity is of inherent interest because the aim is to teach optimisation and the use of catalogues.

To the extent of our knowledge, no simulator of a Rankine cycle that includes catalogues and optimisation has been thoroughly assessed, making our case study a useful addition to the body of knowledge. In this article, a study of a textbook power cycle problem simulator with optimisation and catalogues is described. Also, an assessment of the simulator by students is presented. The idea of exposing students to real world problems is a key objective in this simulation. One of the means used to achieve this was to include real devices as inputs (i.e. Siemens Turbine catalogues [25] and Carver Pump catalogues [26]). A thorough assessment presents the aspects that students feel they learned best. Also, a comparison between the results and student opinion is presented.

2. Description of the simulator

In order to propose a cycle for the students to solve, it needed to be at the appropriate level. It was also desirable that the cycle showed major concepts without adding complications that could confuse the students. For this reason, full-scope plant simulators are not the best for initial teaching objectives [14].

Students are taught how to solve simple cycles in classroom sessions. They also learn about each separate process of the cycle. However, real and practical optimisation of power generation is not something that can be learned only by blackboard. By its nature, it involves too many variables that are interdependent in a complex equation system.

Our learning objectives are:

- to teach students how to optimise a Rankine cycle with regeneration and reheating, putting emphasis on the important parameters involved in the optimisation;
- to teach students the limits of using real devices when solving a problem through the use of catalogues.

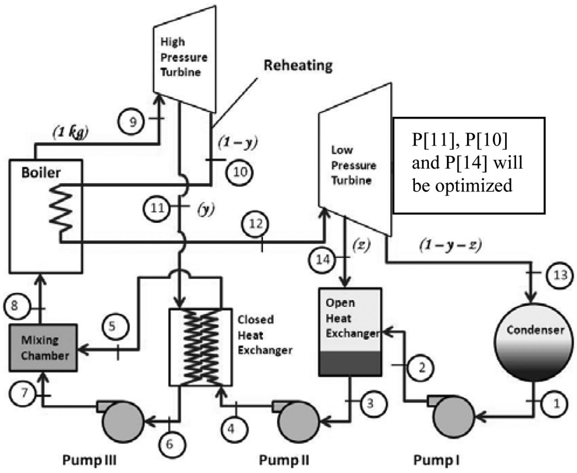

Fig. 1. Rankine cycle diagram.

To tackle the issue of optimising bleedings (which depend on pressure) in a pedagogically sound way, we referred to the textbook and selected an illustrative case [27]. We then modified it to add the possibility of optimisation and changes in input parameters. The selected cycle was a Rankine cycle with reheating, regeneration, two expansion stages and three compression stages (refer to Fig 1). In order to simplify the problem at hand, following the same line of thought that we have previously explained for beginners in thermodynamics, one important assumption and four simple assumptions needed to be made.

The most important assumption was made for the turbines. The real operating point of these devices depends on many variables, some of which are: inlet flow rate, inlet pressure, inlet temperature, bleeding flow rate, number of bleedings, placing of the bleedings in the turbine, and outlet pressure. The students could have been taught how to calculate the operating point of the turbine, but this was not done because the aim of the exercise is to teach cycle optimisation. If the real efficiency of the turbines were included in the problem, it would increase the difficulty of finding the efficiency of the cycle without adding value to what students learn about the overall optimisation of the cycle, which is our objective. As a consequence, it was decided that:

- the turbine efficiency is fixed at a given value, independently of the other thermodynamic parameters. The given value depends on the student's university ID number, so each student has a different turbine efficiency.

This causes students to focus on the optimisation more than in the actual solving of the equation system. The other simplified assumptions are self-explanatory and prevent students from taking the wrong approach in tackling the problem:

- The power plant is working at steady-state.
- Changes in kinetic and potential energies in the fluid are small and do not affect the cycle.
- The efficiency given in the carver pump catalogues is the isentropic efficiency.
- Water coming out of the heat exchangers and condenser is saturated at its corresponding pressure.

Once the cycle was described, the problem that students had to solve had to be defined. When planning the problem, the factors we had to include were: storytelling, players as problem solvers and explorers, and challenges that fit the students' characteristics [8]. These factors were introduced in order to make it work 'closer to its full potential'. The factors were incorporated in the following ways:

- Students are told to assume that they work at the Siemens' power generation department and they have to solve a critical problem for a Volkswagen manufacturing plant, covering storytelling and players as problem solvers and explorers.
- Assumptions were made to bring the problem to their level, covering challenges that fit students' characteristics.

Finally, we decided to make two types of problems. Problem types A and B differ from each other only in the installed capacity. Type A has 250 MW and the Siemens SST-600 and SST-500; problem type B has 28.5 MW and uses SST-100 and SST-150. The problem, as defined to students, was:

> Consider the vapour power plant operating in a Rankine cycle with regeneration and reheating. Initially, the vapour goes into the High Pressure Turbine (HPT) at the maximum pressure and the temperature is allowed by the turbine catalogue specifications. The same applies to the Low Pressure Turbine (LPT). Some vapour is extracted from the HPT to the closed heat exchanger at a pressure we would have to set; the rest of the vapour goes to the boiler to be reheated to a maximum temperature of T12. The fraction of vapour extracted condenses completely in the parallel, counter flow, closed heat exchanger before going through pump III. The vapour going through the open heat exchanger is extracted from the LPT at the pressure P14 to be determined.'

3. Optimisation of the cycle and the use of catalogues

The steps students have to follow to complete the optimisation of the cycle are explained in Fig. 2.

The process needs to be carried out one time to obtain the three intermediate pressures of the cycle. After students reach the end of this process, the cycle is considered solved. Students had to understand the meaning of global maximum and local maximum in order to use the integrated optimisation functions of the EES. The first function, using the genetic method, uses a random seed and, through multiple iterations, is able to approach the global maximum. However, in order to be sure, the direct search method is applied, using the result from the genetic method as the initial guess values. This is done because it converges on a more precise value and we are sure it is the global maximum. It would not necessarily converge on the global maximum if we did not use the genetic method result as seed because a local maximum can confuse the direct search method. As a result, the students that successfully calculate the optimum pressures understand the meaning of global and local maximum, optimisation functions and the logical steps that need to be followed.

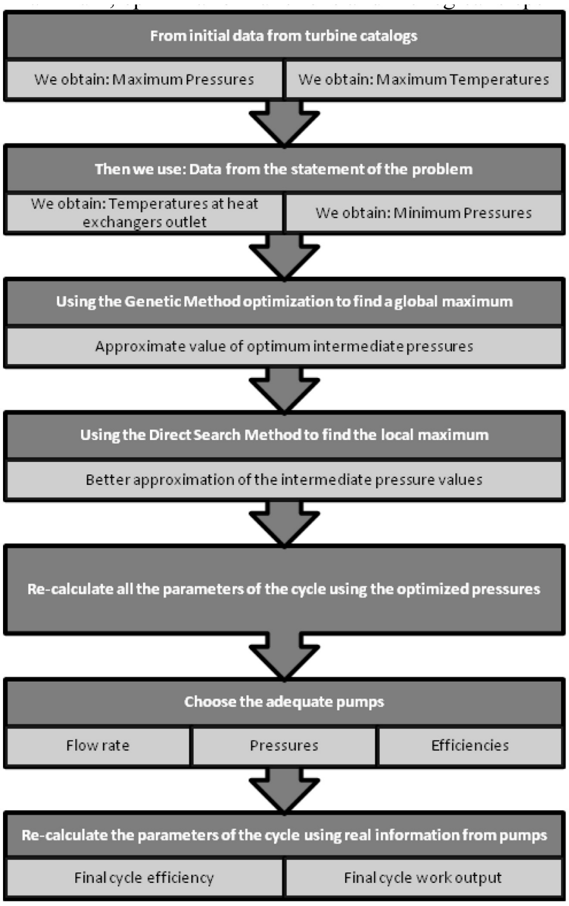

Fig. 2. Flow chart for the optimisation problem.

When reading the initial data from the turbines, students use real catalogues from the Siemens steam turbines SST series. This is the first time many students encounter this type of document and their ability to read and use the data is fundamental to being able to start the exercise. In this step the turbines had been previously selected, and the aim is to familiarize students with what a catalogue is, how the information is displayed and what they should look for when using it.

After optimising the pressures, the catalogues needed to be used again in order to select the pumping devices. Carver Pumps RS Series size A, C and E online catalogues were used. This second use of catalogues requires more than the first because students have to select an operating point for each of the three pumps of the cycle. The aim is for them to understand that even though the optimisation of the cycle gives a theoretical value of the optimum pressure, the value may not exist in the pumps they have available for use. Therefore, students have to try combinations of pumps until they reach an approximate value of the calculated optimum pressure and flow rate.

4. Evaluation of the case study

The problem laid out for each group had different numbers but was equal in reasoning. This was be done by setting the initial data of the turbine efficiency with an algorithm that used the university ID card number as a seed; hence, the problem was different for each group. According to the algorithm, the efficiencies for the High Pressure Turbines (HPT) of each group were between 0.8 and 0.98 and the efficiencies of the Low Pressure Turbines (LPT) of each group were between 0.8 and 0.89.

When students solve the problem using the guide, they answer three online questionnaires. One asks them to upload the results of the optimisation of the power plant to a Google Docs spreadsheet. Another one asks them to measure the technical content they have learned on cycle optimisation and, finally, there is a poll to assess this multimedia laboratory exercise (e.g. a feedback poll). After the questionnaires are submitted, a comparison of the results of what students have learned vs. the assessment of the simulator is made.

The optimised result of the power plant includes the final values for the five optimised pressures, inlet temperatures to the turbines, pump selection from the catalogues, global efficiency, net work output and bleeding fractions.

Students also had to submit a series of questions about the content to measure the technical abilities they have learned using the simulator. This type of question has a correct answer that is not subject to comparison and is evaluated with the classical right or wrong method.

The feedback poll measures the opinion of the students about the simulator. The focus of this poll was on finding out if they actually had learned how to optimise and read catalogues. Our objective with this simulator was not that much on the technical knowledge but in the reasoning in order to apply the knowledge. The assessment consists of multiple choice questions about what they have learned and of an open question for them to write their opinion about the simulator. An evaluation of the simulator is useful to determine the effectiveness of what we are trying to teach and reveal areas of improvement [28].

This simulator was done in a computer lab and students were graded by their attendance to the classes and by responding ‘logically’ to the content questionnaires. This means that answers were revised, but only the overall conclusion of each group was evaluated. Students could get 100% or 0% of the grade; it was sufficient that the answer fitted the catalogue output parameters of the turbines and pumps for the student to obtain 100% of the grade (this is the meaning of responding ‘logically’). However, the answers were thoroughly analysed in order to evaluate the first year of experience with the simulator.

5. Pedagogical methodology

In this multimedia laboratory (or Simulator), a class of one hundred and forty four engineering students is presented with an optimisation exercise of a power generation facility. The exercise will be handed to them after regular in-class sessions where the teacher has explained the theory behind thermodynamic cycles. It is to be solved by the students in groups of two people (making a total of seventy-two groups) and, following a guide, which is focused on the objective of teaching power generation optimisation. One purpose of the simulator is to develop the intuition of what affects a Rankine cycle. Furthermore, it is intended to show students the limitations of using real devices, by providing real catalogue information of the turbines and pumps involved in the power plant. Most of the students have never had any contact with catalogues before. This will bring them closer to the real world problems, where not everything has a solution as clean as in a blackboard.

Throughout the entire exercise of the multimedia laboratory, different teaching methods are used. Before students can receive the package with the files that make up the exercise, they receive classic teaching sessions in a classroom. In this stage they are taught thermodynamic principles of the Rankine cycle and the characteristics of each device. Learning by thinking and analysing is critical in this part of the curve that ends using the simulator [29]. Without the previous student comprehension of the concepts it is impossible to use the optimisation techniques that the simulator tries to teach.

When students learn the basics of cycle thermodynamics, they also receive practical lessons using the EES program. They learn how it works and how to write the code of different solutions to basic problems. In these lessons, they learn by doing and playing with the program. After acquiring that basic knowledge, the multimedia laboratory exercise is distributed in a regular class session. In that moment they also receive an explanation on how it works and how it will be evaluated.

After the files are distributed, students can freely work with the EES program using university computer rooms. Peer to peer collaboration exists at this stage, introducing a discussion between the different opinions that groups may have. It was important for us to include teamwork in order to achieve a better comprehension of the concepts in the simulator; different studies suggest that when working in groups students learn more [30]. Furthermore, two out of three guidelines to minimise interactional problems in cooperative learning are followed: the work load required to solve the optimisation problem was enough for two students and a guide has been prepared for them to solve the problem [30].

The chart presented in Fig. 3 shows how students are unconsciously using at least five different learning processes when they use the simulator. Each inner circle is required in order to move to the next outer circle.

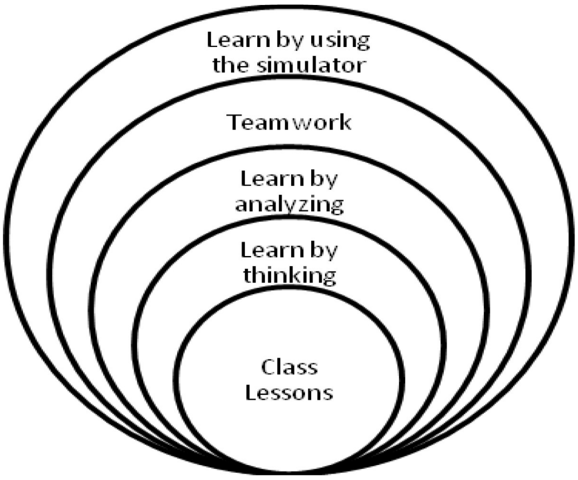

Fig. 3. Learning methods applied by students along a course.

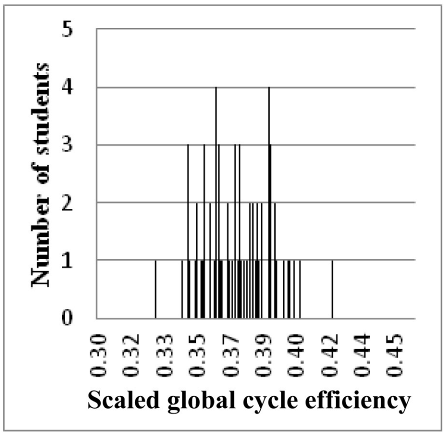

Fig. 4. Number of students who obtained different scaled global cycle efficiencies.

6. Results and discussion

After students optimised the cycle, we compiled the obtained efficiencies to the same scale to compare the values (as seen in Fig. 4). The 'same scale' means that the initial randomisation in the turbines and the difference between the types of problems were removed.

To eliminate the randomisation generated in the turbines, an approximate relation between the efficiency of the turbines and the global efficiency was obtained; then, the equation of the relation was used to generate a correction factor for the global efficiency. This was done for each type of problem. Since type A turbines have better efficiencies than type B, a second correction factor was used. After doing this, a global efficiency independent of the randomisation of the students' university ID number is obtained.

It is interesting to observe the normal distribution around the mean value of 0.37 (Fig. 4). If the students were all equally good, this chart would have to show the entire groups approximately at the same value (because the randomisation of the turbine efficiencies and differences of problems were removed). This means that some students did better than others since they understood the topic at hand better. As a consequence, a superior value for the global efficiency was obtained.

Analysing the information from the individual global efficiencies uploaded by students, the only way to determine if a result is 'correct' is to solve the problem that each student had. Unless this is done, it is impossible to know because each problem was different for each student, and each one of them made a different selection of pumps, a different selection of each pump operating point and different intermediate pressures. Nevertheless, based on the reasoning in the previous paragraph, we can be sure that some did better than others.

Figure 5 measures the percentage of 'how well the students use catalogues' from 0% (students do not use catalogues well) to 100% (perfect use of catalogues). To determine this, we defined the parameters of 'good pump selection' as a pump that:

- Parameter 1: is within a logical efficiency operating range according to the catalogue
- Parameter 2: has a correct number of compression stages according to the catalogue

- Parameter 3: has a flow rate allowed by the pump in the catalogue
- Parameter 4: has the pressures of each compression stage within the range of the pump.

It is interesting to note that over 75% of students chose their pumps such that they complied with at least half of the parameters. Furthermore, none of the students failed all four parameters at the same time.

The pump selection results are close to a normal distribution around the mean value of 0.63 and with a standard deviation of 0.15. Since we considered four parameters, each of the parameters is worth 25% and the mean value tells us that the average student took almost three of them into consideration.

This result is very positive because it is directly related to our main teaching objective of reading catalogues. It shows that the majority of students understood how to use the pump catalogues provided by the teacher.

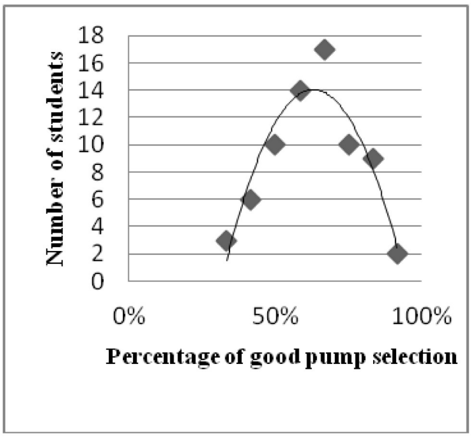

Fig. 5. Number of students vs. a measure of a good pump selection

7. Assessment and discussion

The assessment of the simulator was done by asking multiple choice questions and a yes/no question. We compiled the simulator assessment result in Table 1 where mean values are on a scale of five.

Each learning objective has a reference letter 'Ref', which will be used in the following paragraphs in order to explain what the focus of the question was. The right hand column, entitled 'Std. Dev.', refers to the standard deviation of each aspect assessed.

The analyses of Refs C and E will be further expanded since both of them are referring to the assessment of our main objective of teaching how to optimise a cycle.

Ref. A

Students gave a mean value of 3.68 when measuring whether they understood how to use catalogues according to their own opinion. Comparing this value with the mean number of students that 'made a good selection of pumps' using catalogues, we confirm that there is a relation between the defined factors and how much students perceive they learned about catalogues. The mean value given by the result of a 'good selection of pumps' is 63.14%.

Ref. B

Students felt it was impossible to balance all the pumps at the maximum point of efficiency for each one. This is because the pumps were restricted to Carver Pumps RS Series sizes A, C and E. If it were a free parameter, perhaps some students could have found the correct pumps, but since this was a beginners' course in thermodynamics, simplifying the problem helped the students to understand better.

Table 1. Results from the student assessment of the simulator.

Ref.	Learning objective	Mean value	Std dev.
Technical skills			
A	How to read catalogues	3.68	1.13
B	In a real life cycle, it is impossible to have all devices working at the optimum operating point	3.88	1.00
C	An optimum value exists between the W lost in the turbine and the efficiency gained in the boiler	3.85	1.05
D	Problems in real life are different from blackboard problems.	3.89	1.05
E	Have you realized there is an optimum value for the pressures?	3.77	1.17
F	How realistic do you feel this activity was?	3.03	0.99
G	Have some preconceived power generation concepts changed because of the experience from the multimedia laboratory? (yes/no question)	79.60% (Yes)	—
H	The most efficient device is not always the best one, it depends on our global objective.	3.60	1.01
I	Have you realized that real devices have input and output ranges that limit our ability to use a calculated optimum value?	3.76	1.07
Management skills			
J	To hear my team-mate's idea, even if I don't agree.	3.47	1.18
K	To effectively propose an idea to my team-mate for how to solve a problem	3.48	1.02
L	English vocabulary	3.51	1.17

Refs C and E

The mean grade of 3.85 ± 1.05 in Ref. C was obtained when assessing whether students successfully learned the meaning behind the optimum operating point. In the following paragraphs, a statistical analysis of this reference is presented to help us understand the impact that the simulator had on students.

Because a large number of students were involved in the exercise, we can assume a normal distribution in the assessment grades. Doing this for Ref. C will determine an approximate value of how many students understood the optimisation process.

Calculating the probability density function (see Equation 1) for the normal distribution of 3.85 ± 1.05 (Ref. C):

$$fx(x) = 0.38 * e^{0.452*(x-3.95)^2} \tag{1}$$

Then, the cumulative distribution function (see Equation 2):

$$P(X < x) = \frac{1}{2} * erfc(0.673 * (3.85 - x)) \tag{2}$$

The median for the grading range is 2.5, and therefore we will consider the following in order to discuss the results.

- Students who graded less than 2.5 think that they did not learn cycle optimisation.
- Students who graded between 2.5 and 4.16 think they learned optimisation.
- Students who graded more than 4.16 think they learned optimisation very well.

Using the cumulative distribution function with the definitions considered above:

- the probability that a student ‘did not learn cycle optimisation’ is 9.91%;
- the probability that a student ‘learned cycle optimisation’ is 11.60%;
- the probability that a student ‘learned optimisation very well’ is 38.25%;
- finally, the probability that a student ‘learned cycle optimisation’ or ‘learned cycle optimisation very well’ is 89.75%.

Ref. E has a distribution of 3.89 ± 1.17, which is similar to Ref. C. Because Ref. E also refers to cycle optimisation, this result backs up the analysis of Ref. C.

Refs D and F

Almost all students felt they were doing something different from the standard class problems. In particular, it is interesting that they support the idea that ‘problems in real life’ are different from blackboard problems (Ref. D with a grade of 3.89); and at the same time, a score of 3.03 was given to the activity for being ‘realistic’ (Ref. F).

This is a good result because an effort was made to explain the assumptions about the turbine, and students knew the limitations to this problem. They correctly interpreted that a standard blackboard problem is not always ‘realistic’. This simulator brought them closer to real life problems. Two random quotes from students support this result:

- I think this is an easy way to learn how a power plant works because you can see that if you change a parameter the rest of parameters change too and the program shows you all the results to notice it, and in classroom you can’t see that information, you can only imagine it.
- (. . .) It helped me to have an idea of how to read pump catalogues and it brought me closer to seeing what a real power plant is.

Ref. G

This was an excellent result because we changed 79.60% of students’ preconceived ideas about power generation. This also means that 79.60% of students had a preconceived idea or perception about how power generation occurs. If the simulator had not included the optimisation and real devices (catalogues), perhaps the preconceived ideas would not have changed since regular in-class exercises are a limited mechanism for illustrating the interconnection between variables that occur in a real cycle. Furthermore, if a thermodynamics course does not have a multimedia tool like a simulator to help students have realistic experiences, then their previous idea of how power generation occurs prevails. A student quote illustrates this point:

> It has been very interesting work, since it has shown me the way things work in a real case or at least, an approximation to it.

Refs H and I

Students were told to choose every device operating point in order to obtain maximum global efficiency in the cycle. However, some of the pumps provided a higher flow rate than others, hence increasing the work output and, as a consequence, the global efficiency even though those pumps were less efficient individually. The students weighed how much efficiency in a pump could be sacrificed in order to increase the flow rate in order to improve global efficiency. It is interesting to note that the high grades of 3.60 and 3.86 were obtained regarding these points. This means most students went through the catalogue process and became aware of the process and problems that exist when selecting a device.

Refs J, K and L

Although they were not part of the initial learning objectives, while running the simulator, some extra learning capabilities appeared. The entire exercise was carried out in English, which is not the mother tongue of the students; this combines the complex issue of learning thermodynamic cycles with language learning. This kind of integration is one of the roles that multimedia laboratories play nowadays [31]. These are positive factors that contribute to students engineering formation. Also, in order to solve the problem, teamwork represented an important part of the process. This is another important positive skill that was developed, as evidenced by a random student quote:

> We consider this a very good initiative, and a great opportunity to put team work in practice and solve problems.

8. Limitations

From our experience, it would have been impossible to teach a thermodynamics exercise for beginners using catalogues if the teacher had not presented a solved example beforehand. This means that students are not able to process an excessive amount of catalogues for the same exercise. Using three catalogues for the pumps and one for each turbine created an intensive workload in terms of answering questions about how to read them.

A lesson that explains how to read a catalogue is necessary to clear up general questions, especially when the group is large. On the other hand, we consider it a success, given that it was a first-time experience. The pedagogical limitations of every simulator depend on the initial knowledge of the students and the simulator's goal.

If the goal is to get a deeper insight, from a technical point of view, in a particular issue, e.g. like the relationship between fluid mechanics, heat transfer and thermodynamics in a Rankine cycle, then the focus should be on this goal only and not on something else, like catalogues. On the other hand, if there is an interest in learning some other tools (like optimisation algorithms and the use of catalogues) applied to a particular case study, then this case study should be something secondary and therefore it should be simple.

The optimisation process is a complex task to teach, and measuring effective learning in students is even more complex. Planning the assessment and the measuring tools for the objectives of the simulator is of utmost importance.

The evaluation method is a limitation. It is not a straightforward task to evaluate individually when the data in the statement of the exercise is different for every student. In other words, to give some data as a function of the ID student number makes it more difficult for students to copy each other but also complicates the evaluation process. It is important for teachers to come up with an idea for evaluation. In the present case, this has been solved by means of the scaling factors applied to the cycle efficiency obtained by each student group.

9. Conclusion

In this article a simple Rankine cycle problem was turned into a realistic optimisation exercise. The simplicity of the cycle made it successful because it was easy for students to understand. Our simulator was complex and novel in the sense that it integrated the use of catalogues and the optimisation of a cycle in the same exercise. Positive results were measured by asking the students questions and by having them assess the simulator. The overall conclusions, after analysing the assessment and results, are as follows.

Students successfully used this multimedia tool to learn what it was intended to teach: Rankine cycle optimisation and the use of catalogues.

Students are motivated by the use of tools that make it easy for them to solve problems that would be difficult to solve by hand (e.g. problems that require optimisation). Furthermore, students now realize that blackboard problems are not that real and that an iterative process is always needed to come up with an optimised solution.

Teachers think that the experience is positive because of the introduction of some interesting contents, which were not in the syllabus of a first year thermodynamics course, thanks to the use of a simulator.

To teach things beyond the typical one-solution-problems solved on a blackboard is possible with the aid of simulators. Thanks to simulators is possible to get closer to the real world. In this particular case study, it is clear that the use of catalogues and optimisation analyses are skills that are not only interesting in thermodynamics; but they are ones that students will apply later on during their career in engineering.

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