A New Pedagogical Paradigm

Introduction

This document presents the new pedagogical paradigm we have developed for teaching applied thermodynamics to energy systems. This evolution is based on a shift in the knowledge acquired by learners in initial or professional training. The writing of equations describing the processes undergone by fluids is drastically reduced, as the calculations are performed by the simulator.

We then show that energy systems rely on only a small number of functions, which can be represented in a graphical environment.

This approach can be implemented in three modes depending on the scientific level of the learners.

Finally, we discuss the advantages and disadvantages of teaching equations.

We then list the main pedagogical improvements.

General Context

The context of initial engineering training has evolved significantly in recent years. Although their scientific and technical knowledge and their ability to mobilize it to solve concrete problems are still some of the characteristics that continue to distinguish them most from other professionals, engineers must, like the latter, increasingly pay attention to the non-technical dimensions of their profession, such as personnel management, project economics, product marketing, and their environmental impact. Under these conditions, the time available to invest in technology and their motivation to do so are now lower than before. Moreover, the time devoted to technical subjects in initial engineering training programs is also gradually decreasing. Additionally, practical work and projects are often reduced compared to the study of theory.

This evolution in the training requirements requires us to renew the pedagogies we implement, but fortunately, we also have new assets because virtual environments offer us new opportunities to do so.

Although applied thermodynamics in engineering can be considered a well-established discipline (its foundations were established more than a century ago), it continues to evolve significantly due to advances in materials and control-command, physical and geopolitical constraints on resources, and the evolution of regulations, which has led to the development of increasingly environmentally friendly devices. Significant technological advancements are still expected in the coming decades. They will require strong skills in applied thermodynamics, particularly for the development of new integrated cycles with high efficiency and low environmental impact.

Our goal is to best prepare our students to meet these challenges.

Specific problems arise for learners in continuing education, or more broadly in professional training, who are very different from traditional engineering students enrolled in initial training within the university system. Even if some have completed higher education, they may have obtained their degree years ago and have often forgotten certain concepts that they have not used regularly, although these concepts are implicit prerequisites for understanding the usual presentation of elementary thermodynamic cycles. Obviously, if their initial training is of a modest level, their foundations in mathematics and physics are even more incomplete. On the other hand, due to their professional practice, they generally know the technologies better than students in initial training. For all these reasons, the pedagogies classically used for the latter are not adapted to their needs.

This observation is not only valid for the teaching of applied thermodynamics but also for many other scientific training programs. It has a much broader scope and implies the need to develop specific pedagogies if we want to meet the needs of learners outside the traditional initial training system.

In college, students are used to moving from one subject to another according to their school schedule without questioning its overall logic (Mathematics from 8 am to 10 am, English afterward...).

Trainees in professional training, on the other hand, expect us to focus more on showing them the relevance of the teachings they follow, especially if they are theoretical. Their concern is to acquire one or more skills, and the link with employment must be clearly explained to them. They may even be unable to engage in the training until the practical objective of the program has been explained to them.

Such learners, therefore, do not fit well into the Cartesian deductive logic, which begins by presenting reminders of mathematics and physics before unfolding the theory to arrive at practice, a logic that underpins the usual scenario of courses in initial training in higher education.

Even for undergraduate students, this mode of presentation is not necessarily the most suitable. Today, learners are more engaged when they perceive the meaning and interest of the courses offered to them.

This is why we have been compelled to profoundly modify the content and sequencing of our course on energy systems in order to reduce the use of mathematical formalism as much as possible and introducing it only contextually and when absolutely necessary.

Difficulties Encountered in Teaching Applied Thermodynamics

It is widely recognized that thermodynamics is a difficult subject to teach. The problem has long been recognized, and many efforts have been made to remedy it, but until recently, solutions were still lacking, despite the efforts of teachers and the evolution of programs.

The theory-application link, essential for understanding any discipline, is much less simple and intuitive in thermodynamics than in other areas of physics. In the classical approach to teaching experimental sciences, such as electricity or mechanics, theory and applications to simple realizations are presented to students at about the same time, with practical work if possible. The relevance of simple models (U = R I, force balance) is then easily verifiable, and the link between theory and technology seems immediate; this is how we speak of the "laws" of elementary physics, whereas these are directly understandable models that can explain the functioning of many very useful technologies known to all (electric lamp, heating resistance, simple machines like the winch, the pulley, the inclined plane, the pendulum...).

For energy systems, it is unfortunately nearly always impossible to find models that are both simple and precise. In a somewhat exaggerated way, one could say that the classical approaches to the discipline are faced with a dilemma, the models they lead to being either unrealistic or incalculable.

In these approaches, given the difficulties in precisely determining the properties of thermodynamic fluids, one must generally either make somewhat oversimplified assumptions or to adopt methods that are cumbersome to implement: for example, in almost all first-cycle training programs taught worldwide, internal combustion engines are analyzed with the assumption that the working fluid is air, itself assumed to behave like a perfect gas. How, with such assumptions, can one hope to motivate learners today who are concerned about the environmental impact of these technologies: an air engine has never polluted and never will!

As for the calculations of refrigeration or steam cycles, they are performed either with numerical tables requiring cumbersome interpolations or with relatively imprecise paper diagrams.

This approach has two major pitfalls that have the effect of demotivating learners:

- Given that the assumptions are too simplistic, they do not understand the practical relevance of the models presented to them, which are far from reality;
- Given that precise cycle calculations are cumbersome, they are discouraged by the discipline.

If classical approaches present such limitations, it is, in our opinion, because they originated in an era when the engineer had only their slide rule and their table of logarithms, and they have remained largely unchanged for several decades.

Moreover, the time devoted to developing equations describing the properties of fluids and the behavior of elementary components represents the majority of the course, with the result that learners can only work on the basic examples of the discipline, without being able to study innovative cycles, for which they are not equipped in terms of methodology.

Pedagogical Issue

Our approach originates from the difficulties we encountered when we began teaching the discipline: we found ourselves in a situation of failure in relation to the objectives we set for ourselves and that traditional pedagogical approaches could not achieve, namely making our learners capable, by the end of the curriculum, of addressing current energy challenges: reducing the environmental impact of technologies, improving efficiencies under economically acceptable conditions...

The pedagogical paradigm shift we have introduced is based on a shift in the knowledge acquired by learners. The writing of equations describing the changes undergone by fluids is drastically reduced, as the calculations are performed by a simulator like Thermoptim, without the learner needing to know the details, at least initially. They devote the bulk of their work, on the one hand, to learning technologies and, on the other hand, to reflecting on the architecture of both conventional and innovative thermodynamic cycles, by graphically constructing and parameterizing models of various energy technologies.

The keystone of our pedagogical evolution is undoubtedly the use of a simulator, the software Thermoptim, which allows for the graphical modeling of energy systems. A brief presentation will illustrate the paradigm shift that this tool enables.

Brief Presentation of Thermoptim

Let us look at the difference between a classical presentation of a gas turbine model and one that can be made with Thermoptim[1].

Figure 1.1 shows the twenty-two main equations that must be introduced to study, with reasonable precision, the performance of the simplest gas turbine in a classical curriculum. It is, of course, possible to simplify, but the model then becomes caricatural.

The equations describing compression appear at the top left and those for expansion at the top right. These equations are the simplest.

The most complicated ones are located at the bottom left: they determine the composition of the exhaust gases exiting the combustion chamber.

And yet, to simplify, we have on the one hand considered a very simple fuel and on the other hand omitted the equation for calculating the final combustion temperature, which is an implicit equation containing an integral with one unknown boundary.

In all cases, the properties of the gases require equations of the type presented at the bottom of this figure. They are necessary for calculating their energy properties.

[1] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/presentation-thermoptim.html

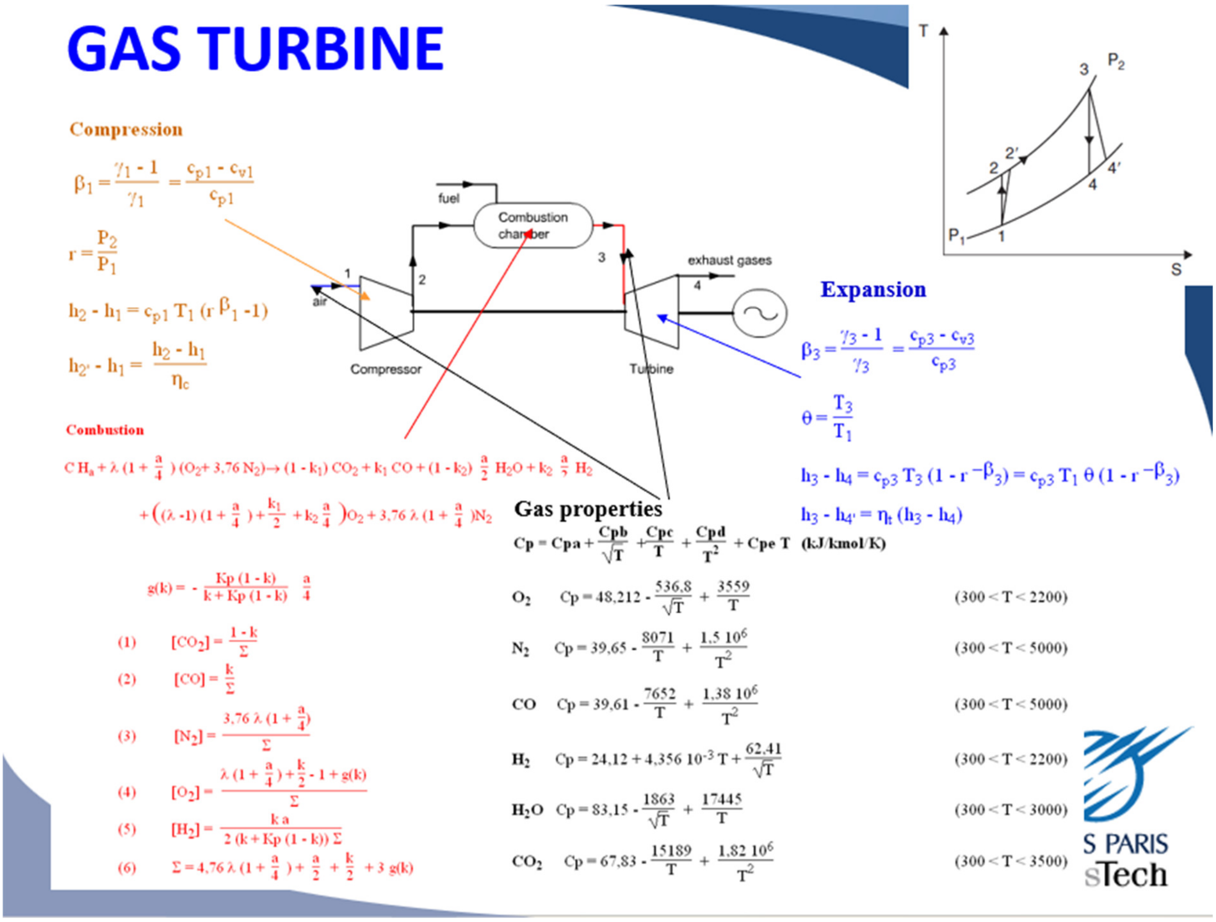

Figure 1.1: Classical Modeling of a Gas Turbine

In total, there are at least forty equations to consider to obtain a realistic model of the gas turbine.

Of course, even if each of the equations is known, the risks of error are numerous in the development of the model and its resolution, especially since they are interconnected and the resolution of some of them must be done iteratively.

Constructing a gas turbine model with Thermoptim is radically different from what was traditionally done: we prioritize, as we have said, a qualitative approach to the phenomena, with the calculations necessary for quantitative studies being carried out by software tools in a transparent manner for the learners: it seems to us that they do not need, at least initially, to know the details.

More precisely, as shown in Figure 1.2, the model is constructed by assembling icons placed on the workspace of the schematic editor: the architecture of the machine is very close to its physical diagram.

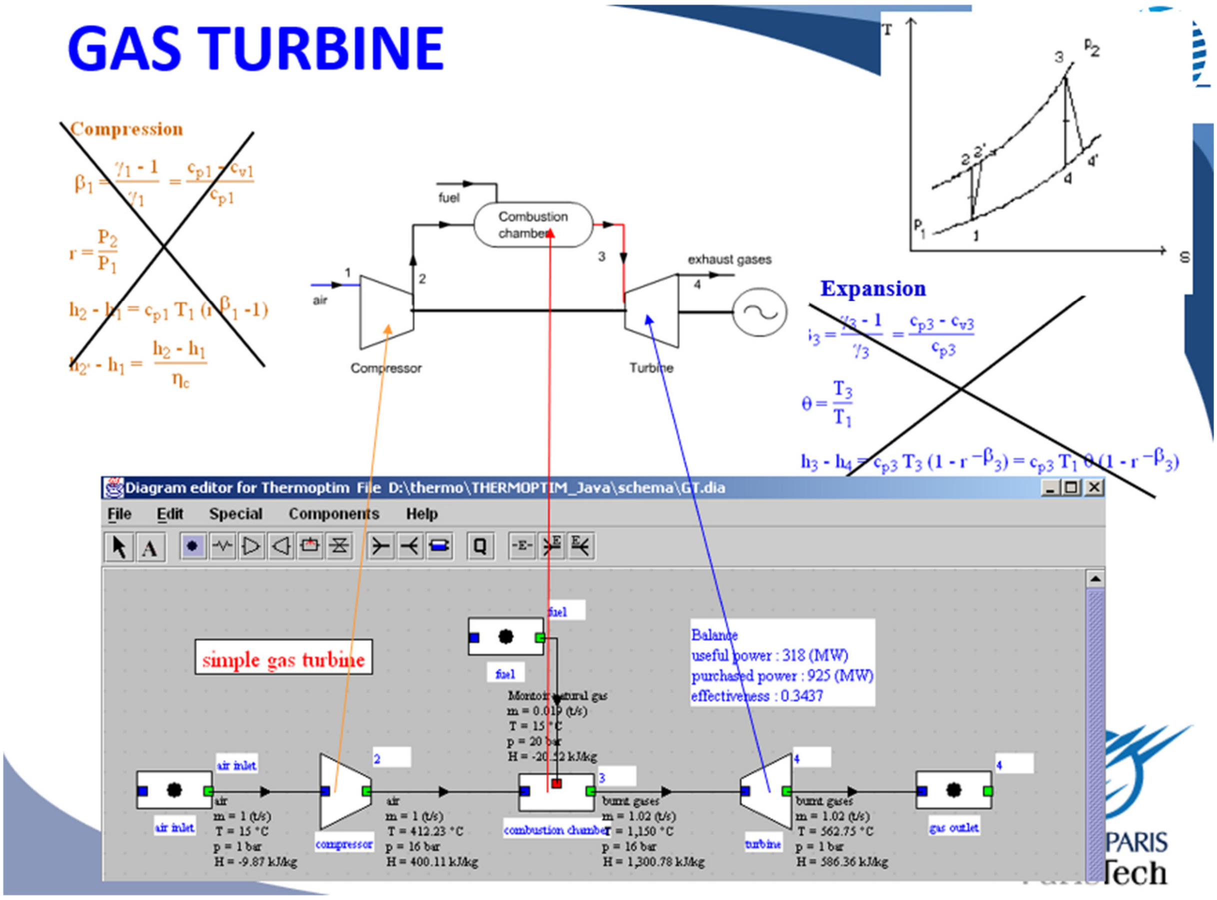

Figure 1.2: New Pedagogical Approach

Each component is then defined with a small number of characteristic quantities. Since the thermodynamic properties of the fluids are encapsulated in the software, the calculation of the machine's performance presents no difficulty, thus offering a precision far superior to that of the traditional approach.

The use of equations is minimized during the introduction of the discipline. The cognitive effort is primarily devoted to understanding the concepts and technologies as well as their practical application, and it is only once the learner has acquired sufficient knowledge of the discipline that the writing of equations becomes possible if it is relevant. If they wish, they can even have the software generate the equations corresponding to the models they are working on. Since these are grouped by component, they can easily analyze them.

Indeed, once a Thermoptim model is developed, its schema and project files contain all the information needed for its complete resolution. It is therefore possible to use it to generate the entire set of corresponding equations[2].

Thermoptim can thus be used as a pre-processor for various applied thermodynamics solvers, such as Interactive Thermodynamics, EES, or Matlab.

By using a tool like Thermoptim, the calculation time for a thermodynamic cycle is very short, and once the model is established, it is possible to perform sensitivity analyses and solve in a few minutes problems that would take hours using classical methods.

[2] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/equations.html

Moreover, there is no risk of programming errors or misreading properties on diagrams. This results in a considerable time saving on a non-essential pedagogical aspect, namely the resolution of numerical problems. In addition to the time saving, the arduousness of the work is greatly reduced, leading to a significant gain in motivation for the learners, who are no longer discouraged by heavy and tedious calculations.

Furthermore, considerable gains in precision are achieved, and therefore in the reliability of calculations: it is not necessary to resort to overly simplifying assumptions solely to make calculations possible.

Energy Systems: A Space of Functions of Reduced Dimension

At the origin of Thermoptim, and this is fundamental, lies the following observation: despite their diversity, energy systems implement only a small number of functions. The functional analysis of these systems shows that even if the technological solutions implemented can be very varied, their components fulfill only a limited number of different functions: the space of functions of energy systems is of reduced dimension.

For example, in all so-called engine cycles for the production of mechanical power, a fluid is first compressed, then heated, then expanded, and finally cooled, which corresponds to only three functions: exchanging heat, compressing the working fluid, and expanding it to produce work. In all so-called vapor compression refrigeration cycles, the working fluid is first expanded, generally without producing work, then heated, then compressed, and finally cooled, which corresponds to two of the same functions and a fourth, expansion without work.

While energy systems are very different technologically, their functional representations use only a small number of elements. It is therefore possible to design modeling environments that exploit this property. It is sufficient that they make available to users this small number of functions and allow them to be easily assembled.

This is precisely what Thermoptim does, which is a modeling software that allows the graphical construction of models of many energy systems thanks to a small number of components corresponding to these elementary functions.

As we said above, the entire set of corresponding equations can be exported and converted to the formats of different solvers, thus allowing it to be exploited in other environments.

Pedagogical Improvements Brought by Thermoptim

Very quickly, it became apparent that the pedagogical use of Thermoptim led to a radical change in the attitude of learners towards the discipline: we hoped for an improvement, but did not imagine it would be so remarkable.

The main pedagogical innovations brought by Thermoptim are as follows:

- Firstly, with tedious calculations eliminated and most quantitative aspects handled by the computer, learners can focus more on acquiring the mental schemas of the discipline;
- The use of the simulator implicitly brings major benefits in structuring the cognitive schemas of learners: the screens of the software allow for the spatial structuring of the different concepts that learners discover and manipulate. For example, the main characteristics of a small fluid particle, such as its state functions and calculation options,

appear together on the screen of a point. By seeing them grouped each time they have a point screen in front of them, the learner gradually gets used to associating them, which helps them structure their knowledge of the domain. By appropriating the logical organization of the software, they structure their own mental schemas much better than if they were only following a classical course. Moreover, they do so in a much more playful manner;

- By using the software, beginners acquire the basic vocabulary and concepts, which are encapsulated in the presented screens and whose design has been carefully done while ensuring that their content is as simple as possible. Once this vocabulary is learned, cooperative learning with peers and teachers is enhanced;
- The schematic/synoptic editor synthetically gathers in a single screen almost all relevant information about a thermodynamic cycle (its structure, the interconnections between its components, the values of state variables, the overall balance...);
- Thermoptim allows learners to solve realistic and non-simplistic models, unlike the classical approach;
- Thermoptim is not just a good tutorial: its functionalities also make it a powerful professional simulator used by companies such as EDF, the CEA, or Framatome;
- It places the reflection of students at a higher conceptual and methodological level, with purely computational aspects being outsourced to the computer. There is not only a reduction in cognitive load (Sweller, 1989) but also a significant increase in problem-solving capacity;
- Thermoptim makes students truly operational, which is a major factor in their motivation and therefore their engagement;
- Finally, Thermoptim is an open environment, with the equations corresponding to its models being exportable to the format of different solvers.

The potential disadvantage, but this constraint is not specific to this software, is of course the learning time of the tool, which must be as short as possible. The simulator is only a means to serve the teaching of applied thermodynamics, and especially its handling should not take up too much of the available time. The solvers used by other pedagogical approaches share this constraint.

As we will see later, guided explorations of models are an excellent way to reduce the difficulties and time required for this handling.

Guided Explorations of Pre-built Models or Model Construction?

A tool like Thermoptim allows for the complementation of thermodynamics teaching with a wide variety of pedagogical activities, which can be grouped into two main categories:

- Discovery and initiation, notably by exploring pre-built models;
- Model construction, which concerns learners who wish to model energy systems themselves.

Depending on the objectives pursued and especially the available time, the teacher can choose one or the other.

From 1998 to 2015, the main use of Thermoptim in higher education corresponded to the second category. It allows learners to delve deeply into the subject and learn to construct different thermodynamic cycles themselves, which gives them great autonomy, a motivating factor, especially when they are on internship.

However, this approach requires that their first steps in using the software be the subject of tutoring sessions with supervision by teachers who are proficient with the tool, as some manipulations require a bit of practice. Moreover, this approach requires that the learner has a Thermoptim usage license, which, although inexpensive, is not free.

For other teaching contexts, the first category can also present many advantages. When learners do not construct models themselves but explore and parameterize pre-built models, the difficulties of learning the software are considerably reduced, as is the need for supervision. Guided explorations can all be studied using the free demo version of Thermoptim, so it is not necessary in this case to acquire a usage license for the software[3].

The scenario is presented in a specific Java navigator capable of emulating Thermoptim, which offers different activities to learners, such as searching for values in the simulator's screens, parameterizing them to perform sensitivity analyses, etc. Contextual explanations are provided along the way.

Guided explorations are defined in an HTML 5 file, which allows for opening and closing the Thermoptim files corresponding to the studied models, tracing their cycles in thermodynamic diagrams, and proposing small quizzes to learners so that they can verify their understanding of the presented methods.

This ensures that they do not waste time dealing with errors that have no pedagogical interest, which is essential if one wants to make the most of the available time. The risk of error is considerably reduced, and if any occur, learners only need to reset the navigator by reloading the files they have.

Practical Considerations

In practice, we believe that these two ways of using Thermoptim are complementary and that, with students having different learning strategies, one or the other is better suited to each case.

Course Sequencing

A point that we have only touched upon is crucial. This is the sequencing of the course, that is, the way of linking the different concepts so that students can learn them best. We have significantly evolved the pedagogical methods in this regard.

We have already mentioned the limitations of the classical deductive approach where theory is presented before applications. It seems to us that an inductive and minimalist approach (Carroll, 1990, Köppe & Rodin, 2013), especially during the discovery of the discipline, better meets the expectations of today's learners.

We believe that learning is an iterative process, which lends itself well to progressive pedagogy, moving from the simple (but always realistic, which is fundamental) to the more complex. For both cognitive and psychological reasons, it is desirable, and this is particularly true in applied thermodynamics, to start by showing learners how the knowledge presented to them can be applied in practice, while minimizing conceptual difficulties.

[3] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/explor-scenar.html

It seems preferable to us that they quickly realize that there are environments like Thermoptim with which they can learn thermodynamics in a painless way and obtain very precise results without writing a single equation. Once their initial reluctance towards the discipline has been overcome and they have assimilated the basic vocabulary and concepts, it becomes possible to take a new step and, if necessary, introduce more equations.

The experience accumulated over the past decade confirms that once they realize the existence of very effective methods for moving to application, initially very reluctant learners often request additional study material: once the psychological blocks induced by overly axiomatic and impractical presentations of the discipline are overcome, they become much more receptive to equations, no doubt because they no longer fear having to memorize them, nor of finding themselves unable to put them into practice.

From Technology to Theory: Components, Functions, and Reference Processes

Concretely, to present elementary thermodynamic cycles, it is possible to adopt an original sequence, which we call the CFRP presentation for Components, Functions, and Reference Processes, where we start by describing the architectures of different simple machines and some technological solutions implemented. We then show that despite their diversity, their components perform only four main functions, corresponding to three reference processes undergone by the fluids passing through the machines (Figure 1.3).

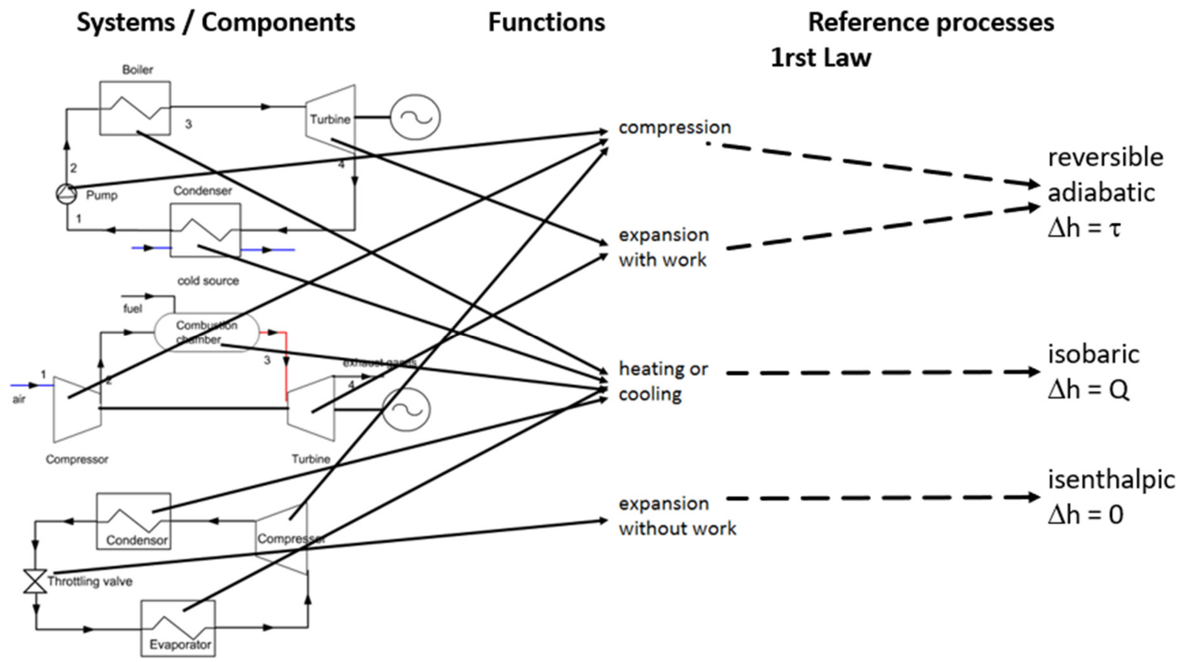

Figure 1.3: From Components to Reference Processes

After introducing some essential notions of thermodynamics, the energy exchanges of a system with its environment and the first principle are presented, and we show that each reference process describes a particular case of application of this first principle.

Reference processes are models of fluid behavior in machines, which naturally lead to questioning the properties of these fluids. This leads to introducing a simple thermodynamic diagram of use in which cycles can be visualized, the (enthalpy pressure diagram). Diagrams indeed play a fundamental role in learning and constitute one of the working environments of the software (Figure 1.4).

The study of energy exchanges taking place in the components of machines also leads to introducing a minimum of thermodynamic notions in a contextual manner and justifying their necessity. This approach has the advantage of avoiding the use of the notion of entropy, which is always difficult for beginners to understand.

The use of the simulator naturally finds its place in this context, as the components it implements correspond precisely to the functions that have been identified previously. The architectures of the cycles are constructed by connecting these components in the schematic graphic editor and their parameterization is easily explained by comparison with the reference evolutions. The cycles can then be visualized in the diagram (enthalpy, pressure), which is one of the easiest to understand and use. In Figure 1.4, we have superimposed on this diagram the schematic of a refrigeration machine, to make the link between the points of the cycle and their representation in the diagram.

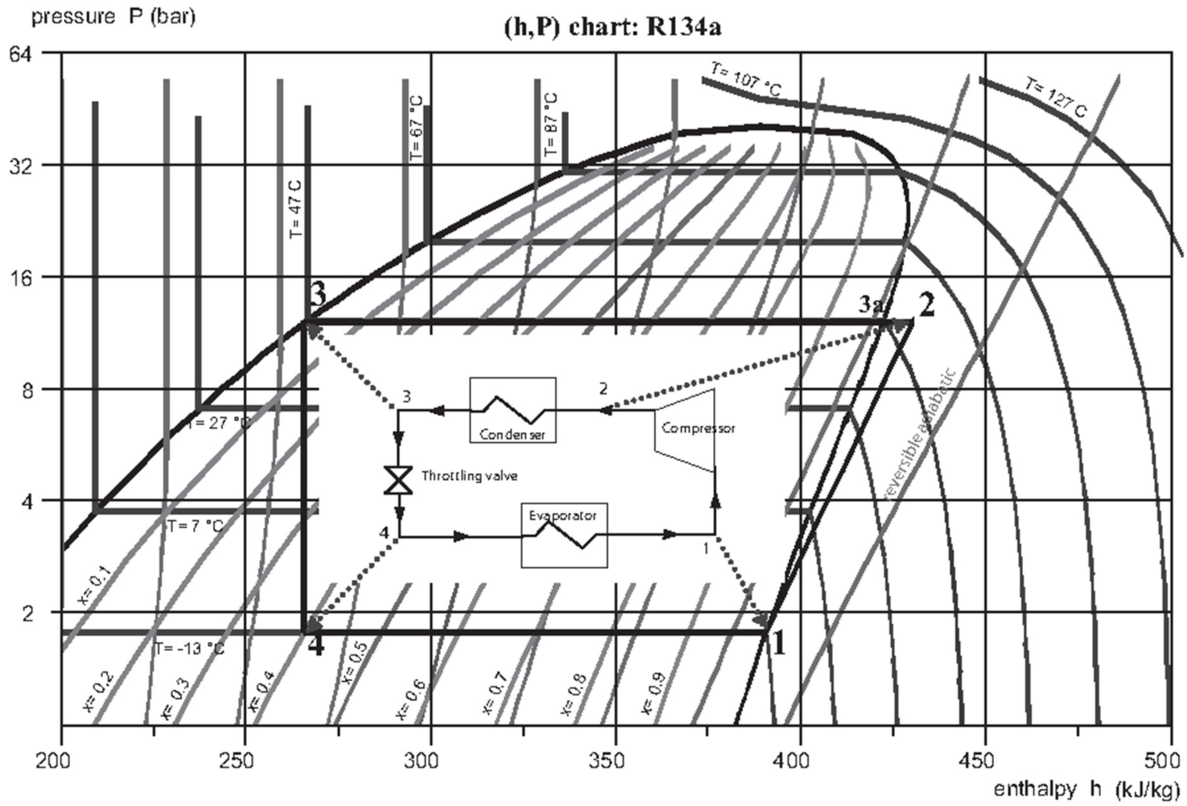

Figure 1.4: Simplified Cycle of a Refrigeration Machine

The distinction between components and systems plays a fundamental role in the pedagogy we advocate. The number of commonly used thermodynamic functional components is relatively small, but the systems that can be imagined by assembling them are extremely numerous and varied: at this level, there is still a considerable field of investigation for the coming decades.

Pedagogical Progression

For the online courses on energy systems that we offer in the Thermoptim-Unit portal, we adapt our pedagogical approach according to three modes[4].

First Mode

The first mode is the **Light** presentation[5], used in our two MOOCs CTC (Thermodynamic Conversion of Heat). The first, Modeling and Simulation, follows the CFRP approach for basic cycles, while the second, Classical and Innovative Cycles, broadens the analyses to many cycles. In both cases, practical work with Thermoptim takes the form of guided explorations.

As we have already indicated, we have also sought to lighten the mathematical baggage used in these MOOCs as much as possible, which led us to avoid using the concept of entropy, the understanding of which can pose difficulties. The only activities that use it are optional and have been included so that those who wish to study this subject can do so.

Second Mode

The second mode, which can be described as **Progressive**[6], is aimed at undergraduate students or active professionals who are not particularly motivated by theoretical aspects but are capable of following them if necessary. It begins with the Light presentation mentioned earlier, which is complemented by introducing an approach to improving cycles based on comparison with the Carnot cycle in the entropy diagram and exergy balances.

It should be noted that the use of these advanced tools does not require learners to manipulate the equations related to entropy and exergy directly. They use entropy diagrams in a visual and qualitative manner, and exergy balances are presented in the form of tables of calculated values. Quantitative reasoning is based only on these values and not on how they are obtained.

Practical exercises use guided explorations of models as well as some Diapason sessions[7] (Diapason = DIAporama Pédagogiques Animés et SONorisés in French). The 2022 course on Energy Systems corresponds to this mode.

Third Mode

The **In-Depth** mode is the third one[8]. It is intended for master's or engineering school students who are familiar with theoretical developments. It differs from the previous ones in three points:

Firstly, these students are accustomed to a "Cartesian" and disciplinary presentation of their teachings, and there is nothing to prevent starting by presenting all the theory before moving on to applications;

[4] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/_Arborescence_web.html
[5] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/mode-allege.html
[6] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/mode-progressif.html
[7] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/pres_modules_diapason23.html
[8] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/mode-approfondi.html

Secondly, since the use of entropy poses no problem for them, (T,s) entropy diagrams and (h,s) Mollier diagrams as well as exergy and exergy balances can be introduced very quickly;

Finally, the use of Thermoptim can be done almost indifferently in the form of explorations or model constructions.

The approach to improving cycles based on exergy balances and comparison with the Carnot cycle can also constitute, in the third mode, the guiding thread for analyzing variants of simple cycles. Practical exercises use either guided explorations, including those using the advanced functionalities of Thermoptim, or Diapason sessions where learners construct their models themselves.

Which Equations Should Be Taught in a Course on Applied Thermodynamics to Energy Systems?

This is a controversial question. Obviously, the answer depends on the type of equations involved: mass and energy balance equations, the First Law of thermodynamics, the Second Law, and so on.

It seems to us that four main categories of equations can be identified:

- Those describing fluid behavior, the simplest being of course the ideal gas equation $Pv = rT$. However, even though simple, this is a hyperbolic equation in P and v, considerably more complex than Ohm's law for electricity, for example.
- Those describing the behavior of the various components found in energy systems, such as compressions, work-producing expansions, combustion processes, or heat exchangers.
- Conservation balance equations such as mass flow rate conservation or enthalpy conservation.
- Finally the equations for entropy or exergy balances, which are much more complex than the previous ones, particularly because the latter are not conserved.

Clearly, the third category must be thoroughly mastered by learners, if only because these equations will prove useful throughout their professional careers for verifying the consistency of results provided by software. A quick back-of-the-envelope calculation can ensure that mass and energy balances are indeed satisfied.

Fluid equations can be particularly complex for real fluids, and mastering them requires not only knowing them but also being able to invert them in different regions of thermodynamic diagrams, which can be numerically challenging.

As we will see later, even Anglo-Saxon pedagogical approaches that emphasize teaching equations have given up insisting on these, relying instead on solvers to determine fluid properties.

Ultimately, then, it is primarily regarding the second and fourth categories that different approaches exist today.

This question also depends, of course, on the educational level: vocational and technical training, bachelor's, master's, doctoral studies, and so on.

We can start from the idea that the context of engineering education, such as the one that interests us, is highly constrained today. For decades, the time devoted to this type of course has continually decreased, especially for the practical and technological part. At the same time, the level of mathematics and physics of the learners has also decreased.

On the other hand, powerful simulation tools exist today that encapsulate many equations. It is fundamental that learners know how to use them and criticize the results, which assumes that they have a good understanding of the modeled physical phenomena, but it seems less important that they know all the design details, that is, the set of equations, numerical data, and resolution algorithms.

Moreover, it is always necessary to seek to limit the cognitive load of learners, which means that it is counterproductive from a pedagogical standpoint to teach them to write and solve certain equations if they will never be required to manipulate them directly in their professional life.

Two Complementary Pedagogical Approaches to Applied Thermodynamics

Starting from observations similar to those we outlined in the introduction, many applied thermodynamics teachers around the world have evolved their pedagogical practice over the past decades in an effort to overcome the limitations of traditional methods that lead to excessive simplifications, which has the effect of discouraging learners.

To our knowledge, two pedagogical paradigms allow for teaching this discipline while making learners genuinely proficient at the end of the course.

There is the one we have just presented, which relies on the use of Thermoptim, where the emphasis is on a systemic approach, with the equations of the first two categories being "outsourced" to the computer.

There is also the paradigm now widespread in Anglo-Saxon countries, where the emphasis is on learning equations, with only the calculation of the thermodynamic properties of fluids being delegated to the computer.

This second approach aims for learners to be able, at the end of the course, to write by themselves the set of equations for the thermal machines on which they will have to work.

Each of these two paradigms has advantages and disadvantages. Learners, even those with modest scientific levels trained according to the first approach, will be equipped to work on real-world and systems comprised of many components, but the software will often appear to them as a somewhat mysterious black box, while the second group will be perfectly capable of writing the equations of behavior of the components implemented, but in practice will only be able to do so for systems with few components often far from industrial reality.

Can These Two Approaches Be Reconciled?

As we have said, it seems preferable to limit the use of equations as much as possible during the initial stages of training. However, they can still be introduced in a second stage, especially if there is a demand from the learners.

In particular, if we maintain the choice we have made to start by adopting the minimalist CFRP presentation without mentioning entropy, it is clear that all equations involving this state function can only be introduced in a second stage.

Under these conditions, we believe it is possible to reconcile these two approaches by having Thermoptim formally generate the equations corresponding to its models.

Such an activity can be incorporated into the framework of the second and third modes we have presented above.

The learner can start by studying, component by component, the equations implemented in their model, making the link with the theoretical and technological supports they have.

In a second stage, they can work on the complete set of equations, add to them if necessary, and solve them if they have an appropriate solver.

Proceeding in this way allows, in particular:

- To maintain a systemic approach in the description of the model's architecture, while providing access to its equations to exploit them in other environments and perform complementary treatments to those of the software, for example, optimization.
- To ensure the coherence of the sets of equations for large-scale models, which can be difficult in practice if one does not have an appropriate tool.

This synthesis between systemic modeling with a tool like Thermoptim and the manipulation of the corresponding equations is particularly interesting because it allows learners to work on cycles that are much more representative of industrial reality, and therefore more complex, than those that the classical approach allows.

From a pedagogical perspective, this functionality can allow learners to see which equations are associated with each component of the studied system, as well as with the complete system.

From a professional perspective, it can allow for the secure modeling of systems involving a large number of components. Existing thermodynamic solvers have the capacity to solve sets of several thousand equations but do not have an interface allowing for the graphical description of the model and therefore ensuring that the relationships between the equations submitted to them are correct.

In particular, errors in the naming of variables are frequent and difficult to detect for systems with many components, while they disappear if their writing is automated. Similarly, these solvers generally do not have tools for debugging the problem submitted to them, a task that can be very difficult for very large systems, when equations are redundant or, conversely, missing, which the equation generator of Thermoptim is capable of doing.

Having sets of equations can also allow for complementary optimizations to those available in the software.

In Summary

The pedagogy we advocate can take different forms but is based on a few shared principles:

- Reduce the cognitive load of learners by limiting theoretical developments as much as possible;
- Make learners operational thanks to the simulator, which allows them to study real problems and not caricatures of reality due to overly simplistic assumptions;

- Reduce the content of the teaching by limiting the use of equations and emphasizing qualitative explanations related to the physical phenomena occurring in the studied systems;
- Sequence the presented concepts by prioritizing a functional approach.

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