

Teaching Thermodynamics Using Simulations

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ABSTRACT: In teaching thermodynamics to engineering students one often finds that they have difficulties to understand basic concepts like enthalpy or entropy and their use for concrete applications. Simulation programs can help here in several ways: They visualize the values of abstract properties during thermodynamical processes, they allow for a more "experimental" approach complementing theoretical derivations in a lecture, and they provide examples, which show the relation between the thermodynamical state variables and energy forms in context.

To prove these claims four example programs are discussed in detail:

- Program StateChange introduces the p-V diagram and helps to explore the state equation of the ideal gas using the usual state changes.
- Program FirstLaw visualizes the basic energy forms for closed and open systems during the state changes.
- Program Stirling displays the principal mechanism of a Stirling engine and shows the corresponding cyclic process in a p-V diagram.
- Program Isex allows to explore the properties of the technically important Isex process, which is used for gas turbines.

Each example is built around a basic question and is supplied with concrete tasks the students have to do using the program.

The introduction of the simulation programs had very positive effects: The students participate more actively in the lecture, they experiment with the systems and use the programs at home to control the results of homework exercises. As a consequence they gain better understanding of thermodynamical processes and higher scores in the final examinations.

INTRODUCTION

Thermodynamics should be a nice subject to learn:

- Its topics are well defined and a lot of good books exist (e.g. [1]),
- the needed level of mathematical sophistication is not too high,
- it provides well defined procedures for calculations (e.g. of cyclic processes).

But at least for mechanical engineering students it is one of the best hated subjects. This is due to the rather abstract concepts that lie at the heart of thermodynamics, and shows up in generally poor results of the final examinations. Among the main deficiencies one finds:

- lack of intuitive understanding of the direction of energy flows,
- difficulties with the enthalpy and open systems in general,
- problems to use the entropy and its diagrams.

One device to promote understanding is the use of simulation programs for performing "virtual experiments". Their general usefulness is well established [2]: They can provide insights into abstract concepts leading to better mental models and help to engage the students in active learning. Consequently there exist large collections of simulation programs for many physics subjects, based mainly on applets using Java and JavaScript [3], Java and Flash [4] or JavaBeans [5]. There are even completely worked out course materials, e.g. for teaching optics [6], electric circuits [2] or chaotic systems [7].

But for the subject of thermodynamics the situation is different: Though one can find many applets in the internet, they mainly address physics courses and concentrate on the kinetic theory of gases and the statistical origin of macroscopic laws [8],[4]. In contrast the simulations that are presented here are based on the classical approach that is generally used in courses for engineering students, and show examples for the

wide range of technically relevant applications. They concentrate on

- the definition and connection of the basic state variables p, V, T and S,
- the graphical representation of processes in p-V and T-S diagrams,
- the significance of the different energy forms and their behaviour during state changes,
- the illustration and quantitative comparison of important cyclic processes.

Their main advantages in a thermodynamics course are

- an experimental approach complementing theoretical derivations,
- visualization of abstract properties like enthalpy and entropy,
- promotion of qualitative understanding, e.g. of the direction of energy flows,
- possibility to show more complicated examples like the Isex process.

The applets are included in the students' course material. They are used for preparations to motivate a concept before its formal introduction in the lecture, for illustration purposes or active explorations during a lecture and for homework tasks. Furthermore the simulations of cyclic processes can be used as "example generators" during the preparation for the final examinations.

In the next sections four example programs will be discussed in detail. More thermodynamics applets can be found on the homepage of the PhysBeans project [9], in [5] and in the forthcoming new edition of [10].

PROGRAM STATECHANGE

The first example demonstrates the usual state changes (isobaric, isochoric, isothermal and adiabatic) for an ideal gas.

It shows the p-V diagram in an x-y scope, an animation of a cylinder with moving piston displaying the momentary temperature T using a blue-to-red color scheme, and the numeric temperature value. Students can choose the kind of state change and control the animation, they can measure the pressure p and the Volume V by clicking in the oscilloscope and they can change the initial pressure and volume and the final volume.

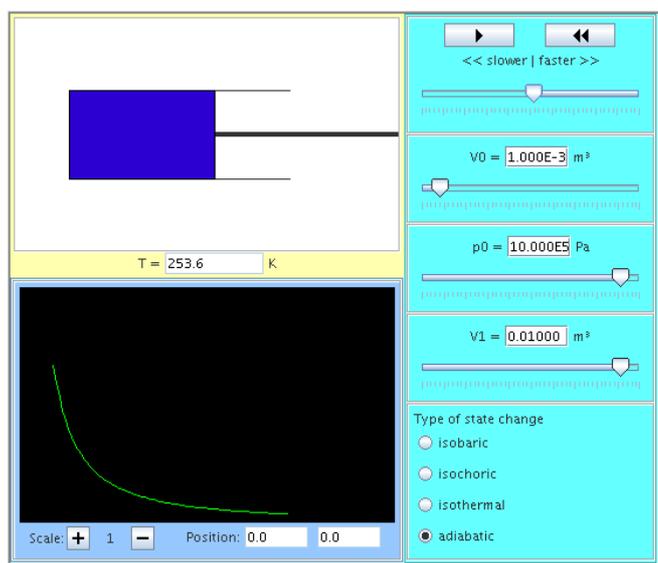


Figure 1 Applet "StateChange"

The applet is helpful for introducing the p-V diagram and the concept of state change, especially the difference between isothermal and adiabatic processes, and to get an intuitive understanding of the properties of the ideal gas. Two different class room "experiments" provide further insights:

- 1 The students – in groups of three - are asked to find the thermal state equation that connects the state variables p, V, and T. Of course there are many different ways to do this using the applet, and the discussions within a group about how to organize the measurements deepens their understanding of the relationship between the properties of the gas and the state changes.
- 2 They have to find equations for the isothermal and the adiabatic using the graph in the oscilloscope. After a while suggestions are collected and the correct result is derived theoretically. Since the students want to know, which group was correct, they are much more interested in the explanations than usually.

At this stage the question, which gas is actually simulated, can be discussed using the numeric constants that have been found before. One could elaborate on this point with a slightly extended version of the applet that allows to choose one of several gas species. On the other hand the PhysBeans applets generally are designed to have simple user interfaces and to focus on special questions. Therefore this idea has been abandoned.

A common misconception at this point is the idea that the four examples more or less exhaust all possibilities for state changes. The situation gets even worse with the introduction of the unifying polytropic, which now clearly defines "the general state change". Consequently one should spend a few minutes here to think about different state changes with a common start and end point.

PROGRAM FIRSTLAW

The next program again shows the well known state changes of the ideal gas, but now the focus is on energy and work. Accordingly the simple cylinder animation has been replaced by a bar graph showing the values of the inner energy U, the expansion work W_V , the heat Q, the technical work W_t and the enthalpy H. In addition all values can be shown numerically.

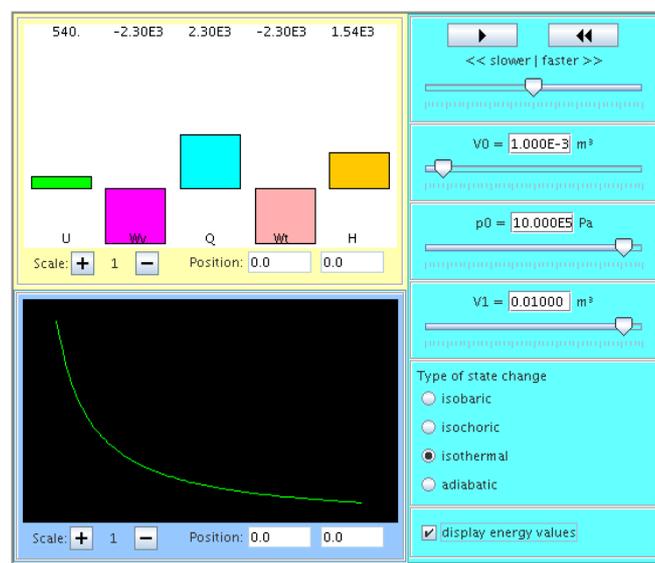


Figure 2 Applet "FirstLaw"

Of course an immediate experiment is to verify the first law – or to discover it in the first place. The numerical findings are a good starting point to reconsider the definition of the inner energy – what kinds of energy are stored in a gas? – by having a closer look at the "arbitrarily" defined constant.

But the main purpose of this applet is to provide the students with a qualitative understanding, which energy forms stay constant during the basic processes or in what direction they change. This question is investigated further with a similar applet that shows the energy balance for a general polytropic state change, this time allowing for a variation of the adiabatic coefficient.

Another application is the comparison of the inner energy form and the enthalpy form of the first law. Since U and W_V are usually introduced for closed systems and H and W_t for open systems, students sometimes believe that they are not defined for the other kind of system. In the applet they can see their values coexisting peacefully for the same system. But by looking at their behaviour for different state changes, they can find out, why they are *more useful* at different situations.

A completely different experiment that can be done with this applet is to find the dependence of the inner energy on the thermal state variables (the *caloric equation of state*). Since the temperature is not displayed, one starts with charting U as a function of p and V and then uses the already known ideal gas equation to find the canonical form $U(T, V)$. Clever students can shortcut here by noticing the constance of U for isothermal processes.

Since the situation for the ideal gas is so special, all these findings have to be contrasted later with the corresponding results for real gases or vapor. It is crucial to clearly point out,

which results follow from general laws and which are due to the properties of the ideal gas! This is even more important regarding the well-known tendency of most students to collect useful equations instead of building up basic concepts.

PROGRAM STIRLING

The Stirling engine is a heat engine that converts a temperature difference between two reservoirs into the periodical movement of a piston. It is not only of historical interest – being the oldest heat engine after the steam engine –, but is subject of current research due to its almost ideal thermodynamic properties. For that reason it provides another good example of a cyclic process – after the Otto and Diesel process – in a thermodynamics lecture.

The basic engineering problem that has to be solved for the construction of a Stirling engine is the realization of two isothermal processes. The main task of the applet is to show the principle mechanism, which is more complicated than for the combustion engines. As always the p-V diagram is shown and sliders allow changes of the relevant parameters: the reservoir temperatures, the initial volume and the compression ratio.

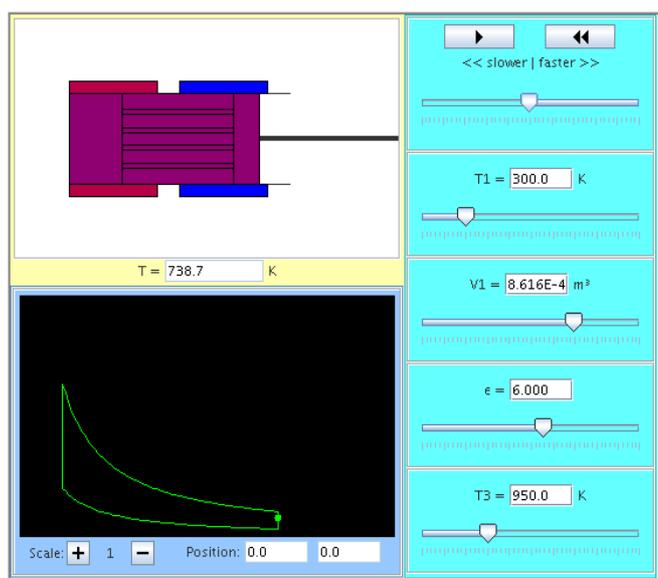


Figure 3 Applet “Stirling”

The first exercise for each new cyclic process is the computation of its efficiency. The applet simplifies this task by giving immediate access to the state variables. This allows to rapidly check several parameter configurations during the lecture, thereby providing some clues about its general behaviour before the theoretical analysis. The task to verify all “measured” values by explicit computations remains as a homework.

The efficiency results are much worse than the students expect after the boastful introduction of the Stirling process. This is the time to introduce the clever device of the regenerator, which will appear again later when considering gas turbines. The basic mechanism can be explained using the animation, and the quickly reevaluated efficiency values, which reach Carnot cycle heights, convince the class of its usefulness.

PROGRAM ISEX

The last example deals with the Isex cycle, a complicated process for gas turbines, which is based on the simple Joule-Brayton cycle, but approximates the ideal Ericsson process by using intermediate heaters and coolers. In the version used here the cycle consists of ten basic state changes, which makes the usual computations rather time consuming.

The applet deviates from the design principles used before. Instead of focusing on a special question it is a general laboratory combining all available information about the Isex system: An animation showing the components (compressors, turbines, coolers and heaters) and displaying a control volume going around the cycle, the temperature, two oscilloscopes with the p-V and the T-S diagram and a bar graph for the energies and works.

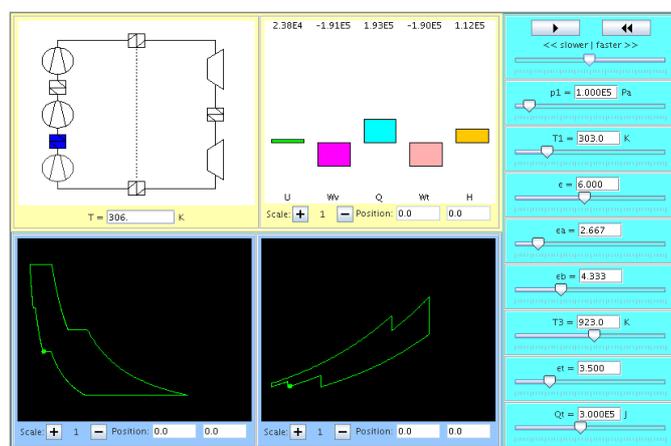


Figure 4 Applet “Isex”

Using the wealth of information provided, all interesting properties can be calculated easily. Especially the simultaneous availability of the p-V and the T-S diagram proves to be helpful. e.g. to quickly get an idea of how parameter changes affect the efficiency. In this way the T-S diagram gets a bit more popular among the students, paving the way for the more abstract diagrams to come.

The Isex simulation with its many parameters opens up interesting experiments, e.g.

- Which compression ratios should one choose for the compressors?
- What is the optimal amount of heat to add between the high and low pressure turbine?
- At which pressure should the reheating be done?

Such questions can be combined with a discussion of constructive constraints: What pressures and temperatures are feasible using standard or expensive high tech materials? In working on such questions the students realize the practical importance of what seemed to be a purely theoretical course before.

CONCLUSIONS

Simulation programs have proved to be a useful tool in teaching thermodynamics:

- Experimenting with parameter changes leads to a good qualitative understanding of thermodynamic processes.

- Visualizing quantities like enthalpy or entropy helps to build up an intuition of their behaviour.
- Sketches of graphs are replaced by exact curves, which can be studied interactively.
- Practically relevant, but complex systems can be analyzed.

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The students' reactions to the applets are very positive: They take a more active part in the lecture, mainly due to the hands-on approach that complements the theoretical parts. They use them to check the results of theoretical homework problems and to create additional examples. As a consequence the average score of the final examinations has increased, though the empirical basis is yet too small for a sound statistical analysis.

All example applets and a few more (about 20 altogether) can be downloaded from the PhysBeans homepage [9], together with their sources. Since the programs are based on the JavaBeans model, they can be easily adapted to own needs [5].

The processes that are simulated at the moment are dealing with the ideal gas. Plans for future extensions include the use of real gases (defined by the van-der-Waals or other, phenomenological equations) and steam (based on the standard equations of the IAPWS [11]).

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