Simulation Programs for Teaching Thermodynamics*

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In teaching thermodynamics to engineering students, one often finds that they have difficulties understanding basic concepts like enthalpy or entropy and their use for concrete applications. Simulation programs can help here in several ways in that they visualise the values of abstract properties during thermodynamic processes, allow for a more *experimental* approach complementing theoretical derivations in a lecture and provide examples that show the relation between the thermodynamical state variables and energy forms in context. To prove these claims, six programs are used as examples in a detailed discussion presented in this article. Each example is built around a basic question and supplies concrete tasks that students have to undertake when utilising the program. The introduction of simulation programs has had very positive effects in that students participated more actively in the lecture, experimented with the systems and used the programs at home in order to control the results of their homework exercises. As a consequence, students gained a better understanding of thermodynamic processes and achieved higher scores in the final examinations.

INTRODUCTION

Thermodynamics should be an engaging and enjoyable subject to learn because of the following reasons:

- Its topics are well defined and many good reference books exist (eg ref. [1]);
- The needed level of mathematical sophistication is not too high;
- It provides well-defined procedures for calculations (eg of cyclic processes).

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

- A lack of intuitive understanding regarding the direction of energy flows;
- Difficulties with enthalpy and open systems in general;
- Problems using entropy and its diagrams.

One device to promote understanding is the use of simulation programs to perform *virtual experiments*. Their general usefulness is well-established in that they can provide insights into abstract concepts leading to better mental models, as well as helping students to engage in active learning [2]. Consequently, there exist large collections of simulation programs for many physics subjects, which are based mainly on applets using the following:

- Java and JavaScript [3];
- Java and *Flash* [4];
- JavaBeans [5].

There are even completely worked out course materials, such as for the following topics:

- Teaching optics [6];
- Electric circuits [2];
- Chaotic systems [7].

However, for the subject of thermodynamics, the situation is different: although one can find many applets on the Internet, they mainly address physics courses, and concentrate on the kinetic theory of gases and the statistical origin of macroscopic laws [4][8]. In contrast, the simulations that are presented here are based on the classical approach, which is generally used in courses for engineering students, and examples shown for the wide range of technically relevant applications. They concentrate on the following aspects:

- 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 as follows:

- An experimental approach that complements theoretical derivations;
- The visualisation of abstract properties like enthalpy and entropy;
- The promotion of qualitative understanding, eg of the direction of energy flows;
- The possibility to show more complicated examples like the Isex process.

The applets are included in students' course materials. 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, as well as 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, six programs are presented as detailed examples. More thermodynamics applets can be found on the homepage of the PhysBeans project [9], in ref. [5] and in the forthcoming new edition of ref. [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 a moving piston displaying the momentary temperature, T,

using a blue-to-red colour scheme, and the numeric temperature value. Students can choose the kind of state change and control the animation; they can also measure the pressure, p, and the volume, V, by clicking on the oscilloscope. Students can also change the initial pressure and volume, as well as the final volume (see Figure 1).

This 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 gain an intuitive understanding of the properties of the ideal gas.

Two different class room *experiments* provide further insights, as follows:

- In groups of three, students are asked to find the thermal state equation that connects the state variables p, V and T. Of course, there are many different methods to undertake this using the applet and the discussions within a group about how to organise the measurements deepens their understanding of the relationship between the properties of the gas and state changes;
- Students have to determine the equations for the isothermal and adiabatic using the graph in the oscilloscope. After suggestions are collected, the correct result is derived theoretically. Since students want to know which group was correct, they are more interested than usual in the explanations.

At this stage, the question, which gas is actually simulated, can be discussed using the numeric constants that have been determined previously. One can elaborate on this point with a slightly extended version of the applet, which allows one to select one of several gas species. On the other hand, the
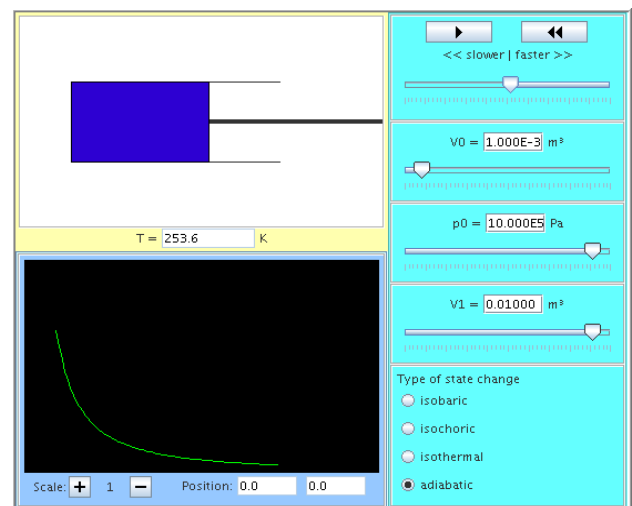

Figure 1: The applet, *StateChange*.

PhysBeans applets are generally designed to have simple user interfaces and 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 that shows 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 of these values can be shown numerically (see Figure 2).

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.

However, the main purpose of this applet is to provide students with a qualitative understanding of what 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.

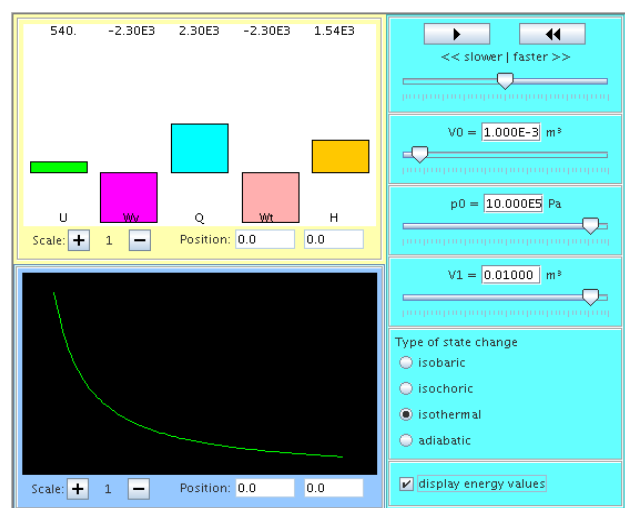Another application is the comparison of the inner energy form and the enthalpy form of the first law. Since U and W_v are usually introduced for closed systems, and H and W_t for open systems, students sometimes believe that they are not defined for the other kind of system. However, in the applet,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

A completely different experiment that can be carried out with this applet is to identify 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 utilises the already known ideal gas equation to determine the canonical form U(T, V). Clever students can shortcut here by noting the constancy 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 vapour. It is crucial to clearly point out which of the 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: *PATHDEPENDENCY*

The third example deals with a two-stage state change given by two polytropics. In order to provide maximal information, it combines the cylinder animation with the display of energy values and contains the inevitable p-V diagram. Sliders are provided for defining the start, intermediate and end points of the two state changes (see Figure 3).

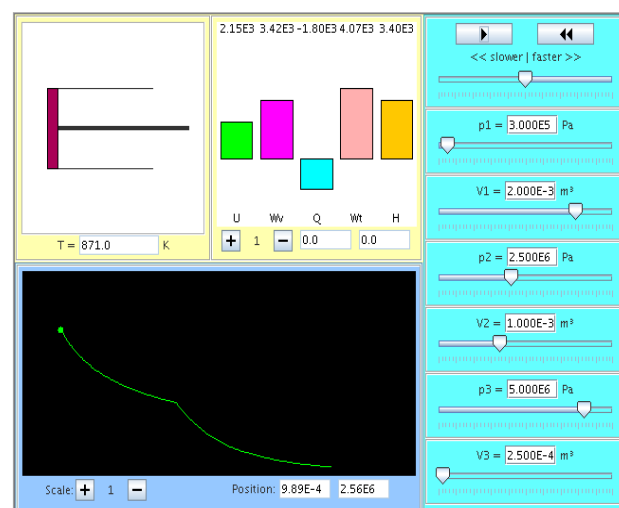Figure 2: The applet, *FirstLaw*.

Figure 3: The applet, *PathDependency*.

The purpose of this applet is twofold:

- It explicitly shows the path dependency of work and heat, this time for different state changes with common start and end points. This complements the findings of the example *FirstLaw*, where the end points changed with the choice of the state change;
- It prepares students for an analysis of the technically relevant cyclic processes that follow later in the course.

At first, a program run is shown in a classroom presentation, using predefined values. The intermediate point is then moved and students are asked for their expectations of how the different energy forms will change accordingly. The results are explained using the rather involved formulae for the polytropic, which, in this way, prove their practical relevance.

In a subsequent group task, students have to find the intermediate points that maximise or minimise the transferred amount of heat or mechanical work. This prepares the groundwork for a deeper understanding of cyclic processes, especially the question on how they have to be designed for practical applications.

An additional task, usually assigned as a homework exercise, is identifying the exponent of a polytropic that is given by its start and end points. The question as to whether such a polytropic always exists sheds light on the special role of the isochoric in this context.

PROGRAM: *CARNOTTSCYCLE*

Usually, the Carnot process is the first cyclic process introduced in a thermodynamics course. This is partly due to its simplicity – all relevant values can be calculated easily – but mainly due to its relevance to the theoretical foundations. It is often used for the definition of the entropy, which surely is the most *scary* of all thermodynamic properties, not only because its definition is rather abstract, but its unit is very strange. This makes it more difficult than the enthalpy, which at least can be interpreted as *some kind of* energy.

The simulation program shown here contains sliders to define all corner points of the Carnot cycle by giving a start point and the volumes of the intermediate points. It displays the p-V and the T-S diagrams, and marks a corresponding point in both diagrams (see Figure 4).

Students are asked to use the applet to find the entropy at a given point in the p-V diagram. After that, the common derivation of the entropy of an ideal gas is demonstrated. The simple fact that the entropy
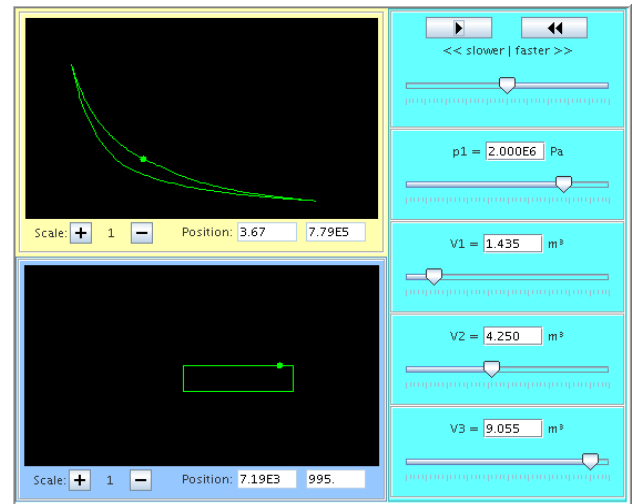

Figure 4: The applet, *CarnotTSCycle*.

can be calculated from the other state variables helps to make it less mysterious to students.

In another application, the program is used for the computation of the efficiency of the Carnot cycle. At this stage, students already know the connection between a state change drawn in the T-S diagram and the heat needed for it. Since the volumes are used here to define different processes, the results are hard to interpret. When students are advised to use both diagrams to obtain the corresponding temperature values, they can deduce a simple formula for the efficiency.

Usually, when drawing p-V diagrams to illustrate the Carnot process, the difference between an isothermal and an adiabatic is greatly exaggerated. This is simply necessary to make the diagram readable at all. But the applet shows a correct graph, an elongated cycle with a very small area. This can be used as a starting point to explain why the Carnot cycle is not used in technical applications. An interesting, although not easy, exercise is to find the intermediate volume such that the area is maximal.

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 it is the subject of current research due to its almost ideal thermodynamic properties. It for this reason that 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 realisation 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 to the relevant parameters, namely: the reservoir temperatures, the initial volume and the compression ratio (see Figure 5).

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 one 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 homework.

The efficiency results are much worse than 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 animation, while the quickly re-evaluated 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 10 basic state changes, which makes the usual computations rather time consuming.

The applet deviates from the design principles utilised before. Instead of focusing on a special question, it is a general laboratory that combines all available information about the Isex system. This involves an animation showing the components (compressors, turbines, coolers and heaters) and the display of a control volume going around the cycle, the temperature, two oscilloscopes with the p-V and T-S diagram, and a bar graph for the energies and works (see Figure 6).

The Isex simulation, with its many parameters, opens up opportunities to conduct interesting experiments, for example:

- 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 undertaken?

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, students realise the practical importance of what seemed before to be a purely theoretical course.

CONCLUSIONS

Simulation programs have proved to be a useful tool in teaching thermodynamics, especially regarding the following:

- Experimenting with parameter changes leads to a good qualitative understanding of thermodynamic processes;
- Visualising quantities, such as enthalpy or entropy, helps to build up an intuition of their behaviour;
- Sketches of graphs are replaced by exact curves that can be studied interactively;
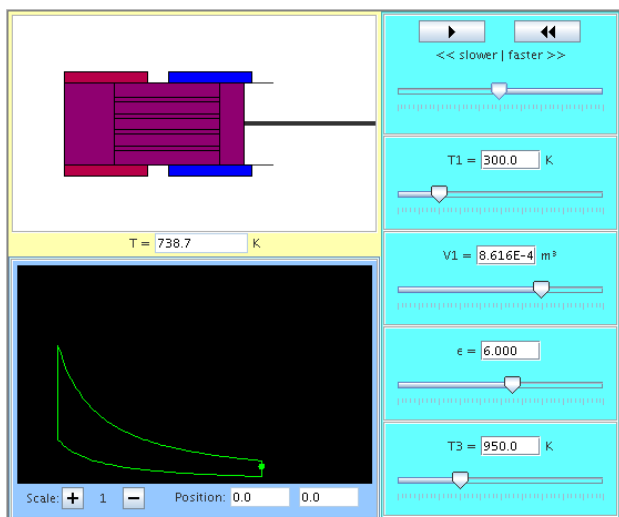

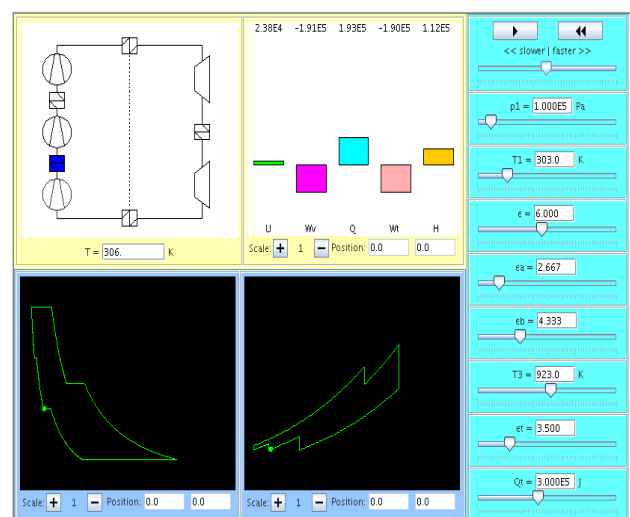
Figure 5: The applet, *Stirling*.

Figure 6: The applet, *Isex*.

- Practically relevant, but complex, systems can be analysed.

Students' reactions to the applets have been very positive. Students take a more active part in the lecture, mainly due to the hands-on approach that complements the theoretical sections. 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, although the empirical basis is still too small for a sound statistical analysis.

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

The processes that are simulated at the moment deal 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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BIOGRAPHY

Peter Junglas was born in 1959. He studied physics in Hannover and Hamburg, and specialised in mathematical physics. In 1987, he received his PhD under Prof. Buchholz at the University of Hamburg that covered general quantum field theory.

After spending time at the University of Göttingen and the MPI for Aeronomy in Katlenburg/Lindau, he worked at the Computing Centre of the TU Hamburg-Harburg until 2000. While there, the emphasis of his activities focused on the fields of scientific computing and parallel programming.

Since 2000, he has been a professor of physics and computer science based in the Department of Mechanical Engineering at Fachhochschule für Wirtschaft und Technik (FHWT), which is a private university of applied sciences in Vechta/Diepholz/Oldenburg.

His present interests cover the development of multimedia techniques for teaching, as well as the broad use of simulation techniques.