Development and Manufacturing of an Interactive Three-Dimensional Phase Diagram of Carbon Dioxide for Teaching Sessions in Thermodynamics

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Abstract

The p,v,T-phase diagram shows the correlation between the thermal state variables pressure p, specific volume v and temperature T of a certain substance in a three-dimensional plot. Experience showed that many students have difficulties to recognize the derivation and meaning of the three-dimensional phase diagram and its projections. For explaining these phase diagram to the students in a more illustrative and clear way, a special 3D- model for teaching purposes was developed and manufactured. The main objective was to improve the students understanding of complex basics in thermodynamics. Therefore, literature research was done about relevant thermodynamic information of the phase diagram and also topics of physics didactics for getting a better understanding about the effect and arrangement of media in teaching sessions. Creativity techniques were used to develop a concept for the construction and design of the model. Important requirements like portability, durability and clearness were taken care of during this process. By using a computer-aided design (CAD) software a digital reproduction of the p,v,T-phase diagram of carbon dioxide was constructed as a basis for the following production process. Inserting several working screens into the model allowed a division in smaller segments. These segments were printed as hollow bodies by a 3D printer. Small magnets were used for the cohesion between the segments. The main advantage is the possibility to separate and assembly the segments again and again like a puzzle very easily. In addition, a casing was built of plywood panels and acrylic glass for transportation and as an area for the three different projections of two-dimensional diagrams. The projected curves were highlighted by cables fixed onto the acrylic glass allowing to switch illumination of each single line. In case the projection areas would be removed the tree-dimensional phase diagram with its different phase regions and binodals are visible directly. The model can easily be cut open in several levels or certain areas can be taken out for presentation. The designed model was resulting in a significantly better understanding of thermodynamic lectures and turned out to be very useful in an educational film for homeschooling during Corona pandemic.

Keywords: *phase diagram, thermodynamics, teaching sessions, 3D printing*

1. Aims of the project

The p,v,T-phase diagram shows the correlation between the three thermal state variables pressure p, specific volume v and temperature T of a certain substance in a complex three-dimensional plot. Experience showed that many students have difficulties to recognize the derivation and meaning of the three-dimensional phase diagram and its projections. These two-dimensional projections are often used in literature and in thermodynamics lectures.

For explaining these phase diagram to the students in a more illustrative and clear way, a special 3D-model for teaching purposes was developed and manufactured. The main objective was to improve the students understanding of complex basics in thermodynamics. As part of the bachelor thesis a student of mechanical engineering took part in the project as well. The idea that students during their bachelor projects help inventing solutions for next generation of students turned out to be very successful: On the one hand the involved bachelor student knew the typical difficulties of beginner students from personal experience and got an interesting and challenging bachelor project on the other hand [1].

2. Analysis and research

As first step literature research was done about relevant thermodynamic information of the phase diagram and thermodynamic basics like thermodynamic equilibrium [2], state variables [3], Gibbs' phase rule [4] and properties of ideal [3] and real gases [5].

For getting a better understanding about the effect and arrangement of media in teaching sessions research was also done about topics of physics didactics like innovative media in teaching sessions (objective, iconic and symbolic media) [6]. The mechanisms of students' perception and different levels of memory (sensory memory, short-term memory, long-term memory) were analyzed as well [6]. The processes of information recording and preattentive perception (laws of proximity, clossness, similarity and experience) got researched to be considerated in the development process [6].

3. Development of a concept

Several creativity techniques were used to develop a concept for the construction and design of the model in a systematic manner. For getting an overview about the requirements of the model all wishes were listed. Main identified requirements were for example portability, durability, costs, visibility, content, similarity to literature, 2D-projections shown clearly, isolines visible well, binodals and phase areas easily recognizable. The model should be able to be broken down into segments for presentation of certain areas and the isolines inside.
For generating many different ideas the brainstorming method, the Disney method and the Imagine method were used. Rating of the ideas was done using the Morphological Box [7]. All identified requirements were considered as criteria during this process. Following this systematic decision making a check for possible incompatibilities completed this process.

4. Modeling

First step in modeling the phase diagram was the determination of the length ratios of the 3D-phase diagram for Carbon dioxide from literature. By using the computer-aided design (CAD) software Autodesk Inventor [8] a digital reproduction of the p,v,T-phase diagram of carbon dioxide was constructed by modeling of the surfaces. Inserting several working screens into the model allowed a division in smaller segments. Attention was paid to set these slices in every striking area of the model like for instance around the critical point. The model was divided into 94 segments by using four isobars, five isotherms and five isochors as screen cuts. Next step was the generation of thin-walled hollow bodies for each segment. The three different 2D-projections were derivated from the model as well. Converting each of the 94 segments into a printable file format (.stl) for 3D printing terminated the modeling process.

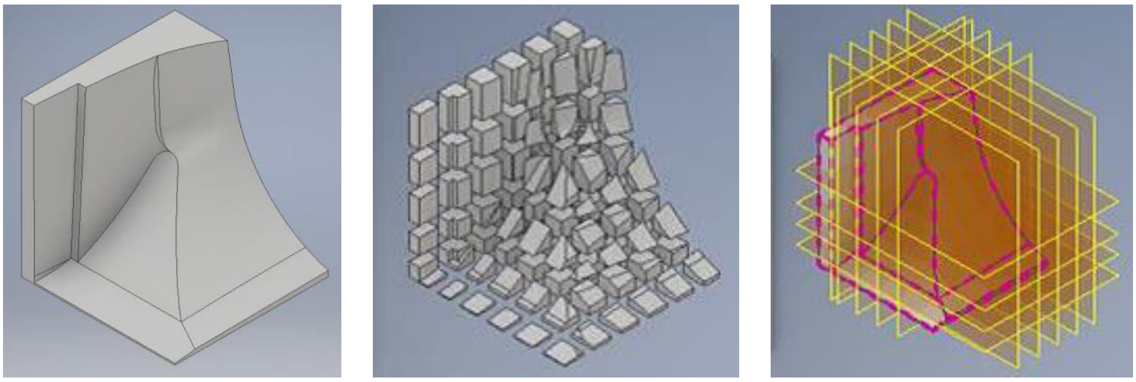

Fig.1: Modeling of the surfaces using CAD software (left); Generation of some division planes following several isolines (middle); Generation of thin-walled hollow bodies for each segment (right) [1].

5. Manufacturing of the model

The manufacturing process was started with 3D printing of all 94 segments. These segments were printed as hollow bodies by a 3D printer using polylactic acids (PLA) [9]. The edges and surfaces were polished with sand paper by hand. For a detachable cohesion between the segments small magnets were glued on the inside of each segments [10]. For some segments special 3-D printed holding structures for the magnets were installed. The main advantage is the possibility to separate and assembly the segments again and again like a puzzle very easily.
Afterwards the printed segments were colored and the isolines were drawn on the inside of every segment. In addition, a casing was built of plywood panels and acrylic glass for transportation on the one hand and, more important, as an area for the three different projections of two-dimensional diagrams on the other hand. The projected curves were highlighted by cables fixed onto the acrylic glass allowing to individually switch the illumination of isolines and binodals in every 2D-projection

[11]. All important lines got labeled by an erasable chalk pen. The axis labeling was printed as well with a shift of 45 °, so it is possible to read it easily from every angle of view.

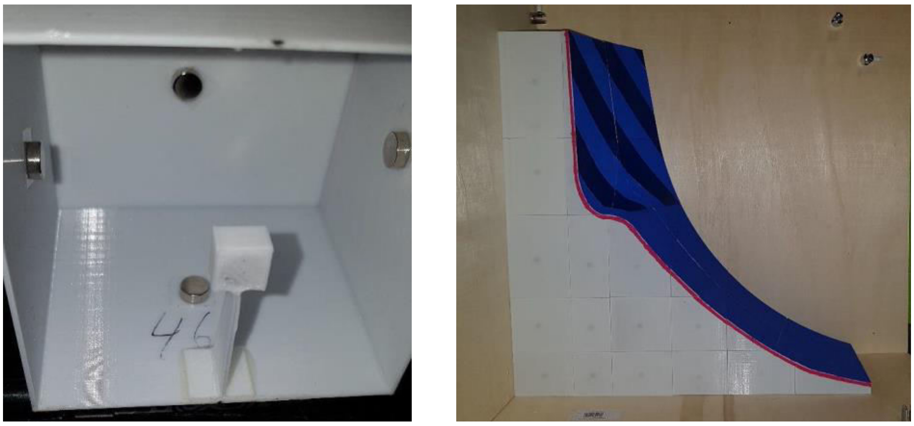

Fig.2: Inner side of a 3D printed hollow body of a single segment with round magnets for detachable cohension (left); Critical isotherm on the opened model (pink line) (right) [1].

6. Innovative functions of the developed model and use in teaching sessions

After the manufacturing process the developed model was tested in thermodynamic teaching sessions and showed many advantages: The division of the model into 94 segments with detachable cohension between them lead to several possibilities of depiction of phase areas, isolines, binodals and the three different 2D projections of the 3D phase diagram. In case the projection areas would be removed the tree-dimensional phase diagram with its different phase regions and binodals was visible directly. The model could easily be cut open in several levels or certain areas could be taken out for presentation. In the opened model the isolines could be seen as well. The different binodals in each projection can be illuminated independently, in different colors.
Students easily understood the derivation and meaning of the three-dimensional phase diagram and its 2D-projections. Especially turning the 3D-diagram led to an illustrative understanding of the 2D-projections. Light effects helped to highlight certain lines in the diagram in lectures.
In general teaching sessions became more interactive because students were able to puzzle themselves with the model. Also exercises could be straightforwardly replicated with this model to underline the explanation of the steps towards the solution. Students were more motivated to acquire knowledge of complex issues like thermodynamics in comparison with usual courses.
The designed model resulted in a significantly better understanding of thermodynamic lectures and also turned out to be very useful in a selfmade educational film for students homeschooling during the Corona pandemic in 2020.

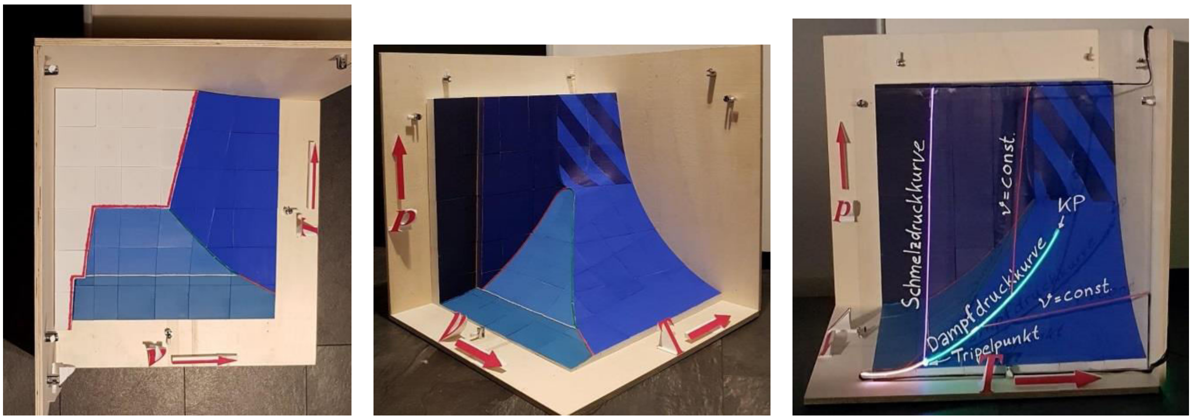

Fig.3: Opened phase diagram showing an isobar (pink line) in v, T projection (left); Three-dimensional p, v, T phase diagram with colored binodals and phase areas (middle); Illuminated and labeled lines of projection on acrylic glass for two-dimensional p, T diagram (right) [1].

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