Phase transitions in the frame of mechanical model

K. Susman, J. Pavlin, S. Ziherl, M. Pečar & M. Čepič

University of Ljubljana
Ljubljana, Slovenia

ABSTRACT: Phase transitions are present everywhere and we often do not even notice them. Students gain experience with phase transitions when water melts or freezes, when it evaporates or condenses. In the last decade, many different high technological devices that are based on liquid crystals have appeared. When describing their functions, one cannot avoid unfolding the properties of liquid crystals and *metaphases* that are typical for liquid crystalline substances. Since students are not familiar with these phases, and they often have problems explaining the behaviour in the vicinity of phase transitions, a mechanical model based on helical springs has been developed by the authors. The compression and tension springs show static and dynamic characteristics that are analogous to the behaviour of the systems close to the phase transitions in liquid crystals. Based on students' experiences with phase transitions in water, an experimental workshop was developed as well. It includes the mechanical model as accompanying teaching material to help students to develop new knowledge on intermediate phases and metaphases, such as super cooled water or super cooled liquid in heating pads.

INTRODUCTION

In general, phase transitions are of two kinds. First and second order phase transitions differ in a change of order parameter near a critical point (temperature). When the change in order parameter is discontinuous, the transition is of the first order, while the second order phase transitions have continuous change in order parameter close to the critical point (Figure 1).

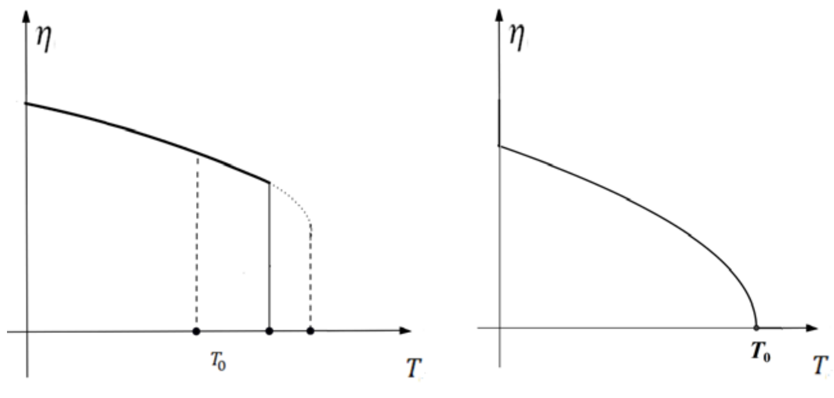


Figure 1: The order parameter η in dependence of the temperature T for the first order phase transition (left) and for the second order phase transition (right).

In the first order phase transitions, hysteresis can be observed. The term *hysteresis* is first introduced to students at the high school level, and it presents an abstract and pretentious concept. Hysteresis, and the characteristics of first and second order phase transitions, can be demonstrated by a simple mechanical model.

The mechanical model consists of simple material and a simple set-up. The model is based on tension and compression helical springs (Figure 2).

The springs are rigidly fixed into stands, or a rod can be used to support the spring as shown in Figure 3. The spring supported by the rod freely rotates around the vertical/long axis. The upright shape of the spring simulates one phase and the overturned spring simulates another phase. The analogy between phase transitions and mechanical model is, thus, in the change of the spring's shape.

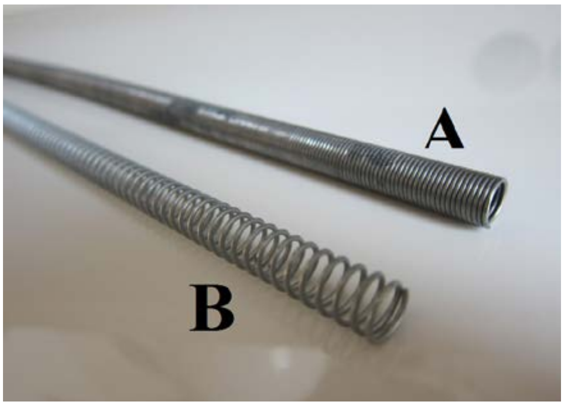


Figure 2: Tension spring (A) and compression spring (B).

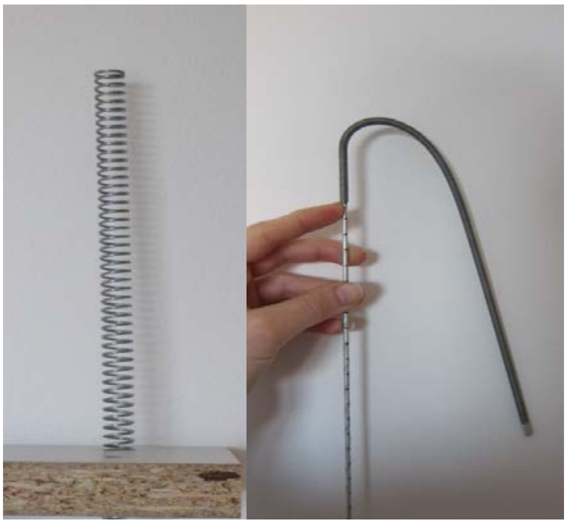


Figure 3: The compression spring fixed in a stand in upright shape (left). Overturned tension spring supported by a rod with the diameter that fits into the spring (right).

FIRST ORDER PHASE TRANSITIONS

To show a discontinuous phase transition using the spring model, the tension spring is used. The change in the shape of the spring is achieved by changing the length of the spring (change in supporting length) or by changing the mass attached at the free end of the spring. At the critical load/length, the spring suddenly overturns, i.e. the *phase transition* occurs (Figure 3). The measurements of the interdependence of unsupported length change (l-l_0) and inclination angle of the spring's free end θ produces results in the graph that are similar to the characteristics for the first order phase transition shown in Figure 1. The change in inclination dependent on the change in length by increasing the supporting length, differs from the change in inclination through the opposite procedure (when the supporting length is decreasing). With this experiment, hysteresis can be qualitatively described, and it enables the visualisation of this abstract concept (Figure 4).

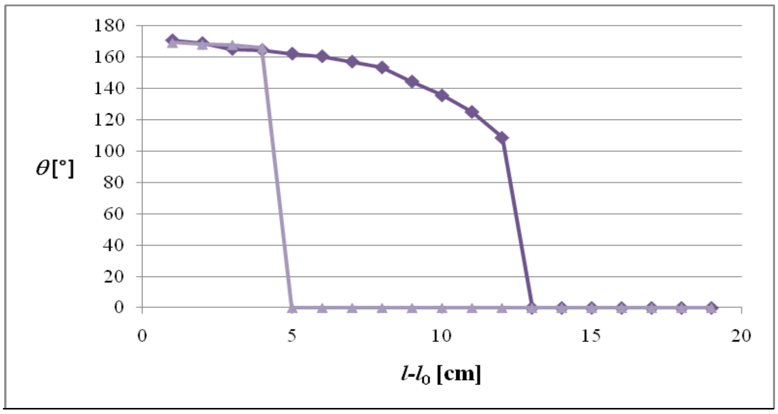


Figure 4: The interdependence of an inclination angle and a change in unsupported length for a tension spring. The graph is similar to the characteristic for first order phase transition.

SECOND ORDER PHASE TRANSITIONS

To show a continuous phase transition, a compression spring is used (Figure 2, B). If the rod is pulled out of the spring, the inclination of the spring increases continuously.

A similar situation can be observed when a load is attached to the free end of the spring (Figure 5). By changing the mass of the load, the inclination changes as shown on Figure 6.

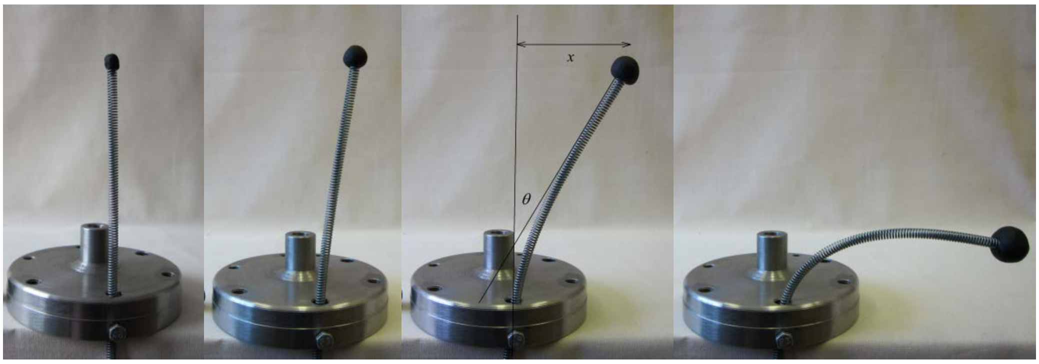


Figure 5: A load (plasticine ball) attached to the free end of a compression spring.

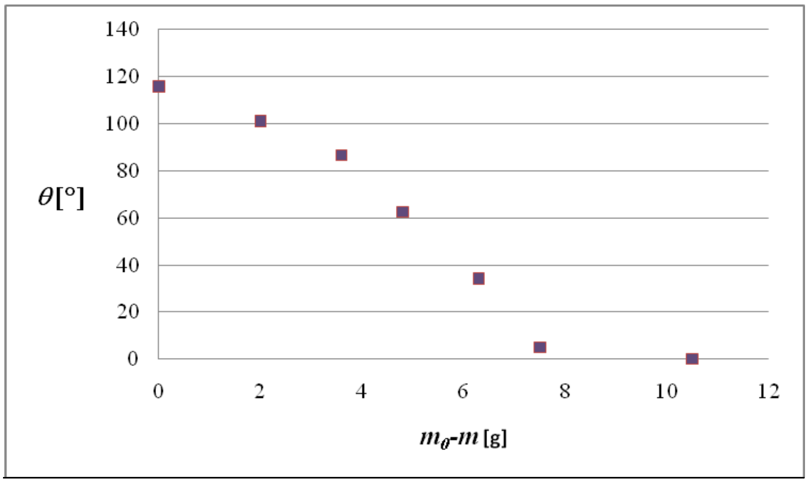


Figure 6: Inclination of the spring depends on the change of mass attached to the free end of a compression spring.

DYNAMICS NEAR THE SECOND ORDER PHASE TRANSITION

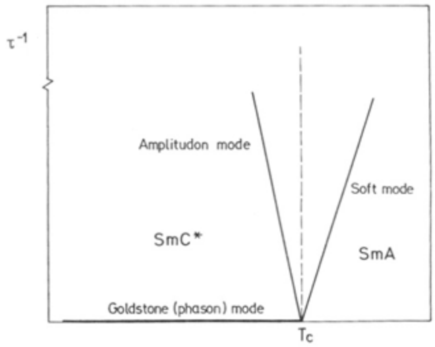
The mechanical model of second order phase transition shows the dynamics near the critical point as well. When the free end of the spring is displaced from the equilibrium position, it oscillates. The measurements of the oscillation time shown in the graph are analogous to the characteristics of the dynamics near the second order phase transition (see Figure 7). Some phase transitions in liquid crystals are also phase transitions of the second order.

An example is the transition between the smectic A and smectic C phases. Smectic phases are phases in which the molecules are arranged in layers. The long axes of the molecules in a specific layer have the same direction in space, on average.

The model was developed with an objective to provide visualisation, and to present phase transition in liquid crystals, where the molecules are oblong rod like shape. The shape of the spring is similar to the shape of the liquid crystalline molecule. SmA and SmC phases differ also in the inclination (tilt) of the molecules regarding the smectic layer.

In the SmA phase, the molecules are perpendicular, while in the SmC phase, the molecules are tilted with respect to the layer normal. Parallels with the model are evident, since it is easy to implement the situation where the springs are upright in one *phase* and tilted in the other *phase*.

The dynamics close to the phase transition between SmA-SmC phases reveal three modes (soft mode, amplitude mode and Goldstone mode) [1]. The dynamics measured on the model show similar behaviour close to the critical load (Figure 7). The decreasing of the oscillation frequency is observed when approaching the critical load from above and from below [1][2].



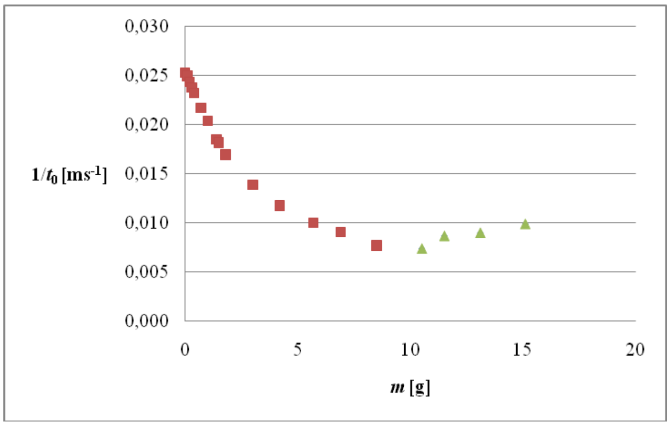


Figure 7: The splitting of modes at phase transitions between SmA and SmC phase in ferroelectic liquid crstals (left) [3]. Measurements of the oscillation frequency dependent on the mass of the load attached on the free end of a compression spring (right).

WORKSHOP ON PHASE TRANSITION FOR FIRST YEAR STUDENTS OF PHYSICS EDUCATION

Phase transitions are included in the curricula at all levels of science education in Slovenia, from the kindergarten to the secondary school. Through the overview of curricula, and through the analysis of semi-structured interviews among physics students from the Faculty of Education and the Faculty of Mathematics and Physics at the University of Ljubljana, one can observe a paucity of topics connected with the metastable states of matter.

In the scope of the first year university study of physics in the Faculty of Education at Ljubljana, two workshops on phase transitions and metastable states of matter in connection with the mechanical model have been prepared. In the first workshop, experiments with super cooled water, heating pads and basic measurements of water heating were carried out in an active learning approach [4].

Students worked in pairs, discussing with each other and writing a report including their conclusions. The reports were collected at the end of the workshop, and were subsequently analysed. In the second workshop, students discussed the parallels between phase transition in water and the static properties of the springs. They were faced with the problem of searching for analogies and describing the properties of the two parallel systems. They compared the system of spring and the system of concrete example of water boiling. As an example of metastable states, they were confronted with the heating pads in comparison with the properties of springs.

Analysis of Students' Reports

Most of the students understood and found the parallels between the shape of the spring and the state of matter. Students had difficulties considering the two parallel systems and elimination of variables in each of them. When they attributed one of the variables in one system to another variable in the other system, they often used the same variable for another comparison, which was not accurate.

One of the examples is in the inclination of the spring. They used it for the analogy of the state of matter and, at the same time, for the analogy of temperature. Those students, who correctly described the analogy between the heating pads and springs realised that the tension spring is appropriate for the demonstration. Tension springs can occupy the vertical position without support of the rod. When the mechanical interruption of the spring occurs, the spring overturns. This is the analogy of the metastable state of liquid in heating pads. The interruption of the system by bending the metal discus causes a change in the phase transition to stable (solid) phase (Figure 8).

In primary and secondary schools, students are not introduced to the classification of phase transitions of the first and second orders. It is believed that this is the reason why they understood the difference in properties between the springs, but they seldom used it in a proper way, with regard to the experiments (boiling of water). Some of the students found good analogies between the continuous change in inclination of the compression spring and spreading of the phase transition front.

CONCLUSIONS

The awareness of phases in chemical substances is often compared to the properties of water. Since the liquid crystalline phase has no analogy in the phases of water, students are lacking in imagination. There is a l ack of awareness of metastable states of matter after the secondary school level, as well. When describing the liquid crystalline phase and phase transitions, it is worth putting some effort into the demonstration of such phenomena. The advantage of the mechanical model is its universality. Although the model was developed for liquid crystals, it can be also be used as an instrument in a teaching process in the secondary and undergraduate school level.

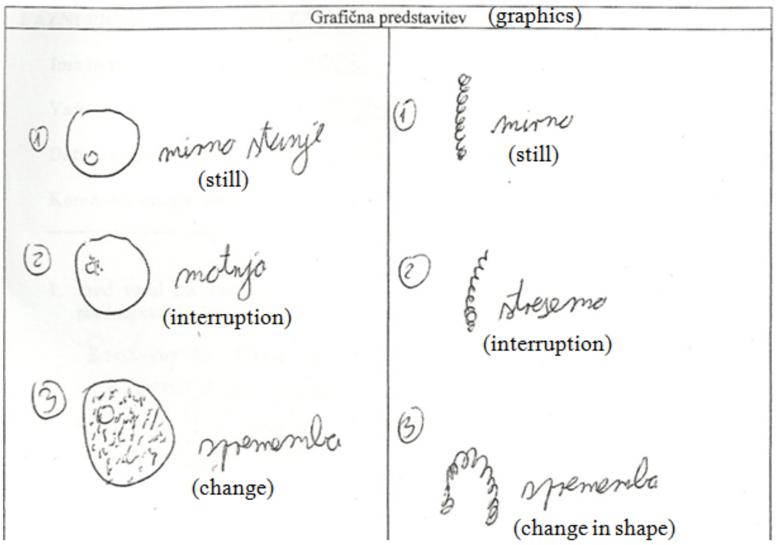


Figure 8: A graphic representation of a student who correctly described analogies between heating pads and properties of springs.

REFERENCES

1. Susman, K., Pavlin, J., Ziherl, S. and Čepič, M., A mechanical model for phase transitions in Smectics C. *Molecular Crystals & Liquid Crystals*, **547**, 233-240 (2011).
2. Bobnar, J., Susman, K., Parsegian, V.A., Rand, P.R., Čepič, M. and Podgornik, R., Euler strut: a mechanical analogy for dynamics in the vicinity of a critical point. *European J. of Physics*, **32**, 1007-1018 (2011).
3. Muševič, I., Blinc, R. and Žekš, B., *The Physics of Ferroelectric and Antiferroelectric Liquid Crystals*. Singapore: World Scientific, Cop. (2000).
4. Sandnes, B., The physics and the chemistry of the heat pad, *American J. of Physics,* 76, **6**, 546-550 (2008).