A Companion to „Physics in the Enlightenment. Part 1”

The XVIIth century can be called „the century of scientific instruments” because of the numerous instruments devised and constructed for scientific research. A short list of new instruments in physical sciences is given in Slide 2. The use of these instruments greatly increased the accuracy of measurements, as shown in Slides 3-5. For example, the clocks used before introduction of the pendulum provided an accuracy of only about 10 minutes per day, whereas clocks at the end of the XVIIIth century were accurate to a fraction of the second per day (Slide 3).

The scientists of the XVIIIth century could therefore gather precise data needed for quantification of science. Measurements and calculations became common occupation of scientists (as nicely depicted by Peter Breugel the Elder)

The XVIIIth century was called by the French the *siècle des lumières*, the century of light, because of its emphasis on reason. In English it is called Enlightenment.

The *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers, par une sociéte de gens de lettres* (*Encyclopedia, or reasoned dictionary of the sciences, arts, and crafts, published by a society of men of letters*) in seventeen volumes of text and eleven volumes of plates with illustrations.

The first volume appeared in 1751. At once it met with very strong reaction from the conservative circles. The opponents claimed that the *Encyclopédie* intended to destroy religion, to propagate materialism and corruption of morals. The editorial process was interrupted by suspensions of the privilege of printing, and constant harassment. In spite of that the *Encyclopédie* was completed with publishing of the last volume in 1772.

The editors, Jean d'Alembert and Denis Diderot, invited many experts to write articles on their field of competence. The *Encyclopédie* was successful because of vast amount of information that it contained on philosophy, mathematics, chemistry, technology, agriculture, literature, law, and religion.

Physics in the Enlightenment is also called the physics of the weightless fluids because changes in the state of bodies were explained by presence of the subtle weightless fluids of heat, magnetism and electricity.

Slides 9-34. Mechanics from Newton to Laplace

Isaac Newton provided the solid fundament of mechanics and indicated proper direction of its development. It must be stressed, however, that almost the entire mechanics which we know now resulted from the works of famous mathematicians and physicists of the XVIIIth century. In Newton's time very little was known even on simple problems such as the mechanics of the collision of bodies (Slide 11). Descartes and Leibniz differed strongly in the definition of the „quantity of motion” (Slide 12) until Jean d'Alembert pointed out much later that it was simply a

„quarrel about words”, because there is no one but two important quantities: ***momentum*** defined as mass x speed, and ***quantity of motion*** equal to mass x speed squared. The latter quantity was then called *vis viva*, and one half of it became known as the kinetic energy.

A gallery of portraits of the great founders of mechanics is displayed in Slide 13. Swiss scholars are shown in the upper row, and the lower row presents the Frenchmen. The Bernoulli family played the leading role in the development of mechanics. They were driven out of the Netherlands to escape persecution by the ultracatholic Spanish rulers and settled in Basel in Switzerland. The members of that family all carried similar first names so that today they are distingushed by numbers (as kings or emperors). Jacob I excelled in the integral calculus (*calculus integralis*) and introduced the term *integral*. Earlier Gotfried Leibniz used the term summation calculus (*calculus summatorius*). Jacob I developed theory of probability and in his book *Ars conjectandi* (*The art of conjecturing*) gave the proof of the law of large numbers and studied binomial and multinomial distribution. He was also the pioneer of using the polar coordinates. His brother Johann I made important contributions to differential equations and presented the solution of the brachistochrone problem, that is to find the curve along which the particle will slide in the shortest time from one given point to a second lower given point not directly beneath the first point. The sons and grandsons of Johann I were working on many similar problems. The most famous of them was Daniel I, who excelled in hydrodynamics. In 1738 he published famous book *Hydrodynamica*, in which we find the Bernoulli theorem for fluid flow, and the first attempt to explain Boyle-Mariotte law as the result of collisions of gas molecules with the wall of the container (Slides 25-26).

Leonhard Euler wrote an immense number of books and papers on mechanical and mathematical subjects (Slide 16). He was the son of a clergyman who hoped that his son would also enter the ministry. However, Leonhard preferred mathematics and studied it under Johann Bernoulli. When Daniel Bernoulli went to St. Petersburg at the invitation of the empress Catherine the Great of Russia, he procured also the place for young Euler. Euler worked in Russia until 1741 when he accepted the invitation of king Frederick the Great of Prussia and joined the Academy of Sciences in Berlin. After spending twenty five years in Berlin Euler returned to Russia and died there in 1783.

Euler’s output was enormous. The list of works contains 886 entries. The French academician Arago said that „Euler could calculate without any apparent effort, just as men breathe, and birds sustain themselves in the air.”

Already in 1735 Euler lost sight in his right eye, and in 1766 started to lose sight by cataract in the remaining eye. It did not slow down his activity, and for the last seventeen years he dictated his calculations to the assistants. Euler’s contributions to mechanics are listed in Slide 17. He introduced algebraic methods to mechanics in his influential book *Mechanica sive motus scientia analytice exposita* (*Mechanics, or science of motion, explained in an analytic form*), published in 1736 (Slides 22-24). He also introduced modern units for speed and acceleration (Slide 24).

Euler took part in the controversy concerning the shape of the Earth (Slides 18-20). According to Newton the Earth was flattened at the poles, whereas Descartes' theory of rotating vortices predicted it to be elongated. The French Academy of Sciences organized expedition to Lapland and to Peru in order to measure there the length of one degree by astronomical methods. The results obtained by the expeditions tended to confirm the opinion of Newton, but the followers of Descartes did not give up.

In 1748 the French Academy of Sciences announced competition for a treatise on the motion of the Moon. Three papers were sent in by d'Alembert, Clairaut, and Euler. All three of them found disagreement of their calculations with astronomical observations. They suspected that perhaps Newton's law of gravitation was not exact and had to be completed by adding an extra term. Euler and d'Alembert thought that the disagreement with observations was perhaps caused by additional forces of magnetic type. However, after repeating the calculations all the three authors found small mistakes in their approximations and when these had been corrected the agreement with observations was obtained.

Jean Rond d'Alembert derived his first name from the Paris church of Saint Jean-le-Rond on the steps of which he was found abandoned as an infant. He was illegitimate son of high rank people. His foster parents were workers. D'Alembert displayed marked gift for mathematical sciences. He became member of the French Academy of Sciences. At the age of only twenty six he published *Traité de la dynamique* (*Treatise of dynamics*) which contained the famous d'Alembert principle, one of the fundamental principles of mechanics (Slide 27). It is interesting to note that d'Alembert expressed the first law of Newton's dynamics as two separate laws (Slide 28).

Joseph Louis de Lagrange (Giuseppe Lodovico Lagrangia) was born in Turin, Italy, but both his parents were of French origin. He is usually regarded as being French scholar, but the Italians claim him as their own. In 1766 he accepted invitation of king Frederick II of Prussia and came to Berlin where he spent twenty years after which he settled in Paris. Lagrange's *Méchanique analitique* is a modern textbook which could be used even nowadays, except for the fact that it does not yet contain vector calculus, introduced only at the end of the XIX$^{\text{th}}$ century. It marks the end of the use of Newtonian geometric methods in mechanics. Lagrange proudly announced that „no diagrams will be found in this work" (Slides 29-31).

Great French scholar Pierre Simon Laplace is known for his *Traité de méchanique céleste* published in five volumes in the years 1792-1825. In this impressive work he summarized all discoveries of earlier mechanicians and added his own results. Laplace was also proponent of the classical determinism (Slides 33-34).

It is worth to know that throughout the XVIII$^{\text{th}}$ century the branches of physics which could be treated with the use of mathematics were called „mixed" mathematics and usually included in mathematical texbooks. An example is presented in Slide 34.

The discovery of the aberration of starlight by James Bradley (published in 1729) provided the proof of Earth's motion around the Sun, confirmed Roemer's discovery that the velocity of light is finite, and also set a lower limit for the distances of the stars. It became evident that the universe is very many times bigger than thought in Newton’s times (Slides 35-37).

Great progress in astronomy was due to William Herschel who built himself the largest telescope of that time, discovered a new planet Uranus, and for the first time published an estimate of the shape and dimensions of our Galaxy (Slide 38).

Another important contribution to our knowledge was the measurement of the density of the Earth performed by Henry Cavendish in the laboratory which he built inside his own house. He succeeded to measure very small gravitational attraction between two metal balls by applying the dynamic method, the measurement of the period of oscillations of the torsion balance (Slides 39-40).

Slides 41-76. Physics of the phenomena of heat.

The knowledge of heat at the turn of the XVIIIth century was still in its infancy. Heat and cold have been long regarded as separate entities, i.e. cold was not conceived as a low degree of heat. Moreover, some scientists discussed particles of heat and also particles of cold (frigorific particles).

A few dozen different thermometric scales have been proposed, most of them used only by their authors. It was thought that thermometers measure „heat” which was said to be proportional to mass or volume.

The crucial step was taken around 1760 by Joseph Black who discovered the difference between temperature - measured with thermometeters, and the amount of heat - measured with calorimeters which he first devised and used. Black also discovered the latent heat which reveals itself during the changes of state (e.g. melting of ice). The road to these discoveries is told in Black’s own words in Slides 48-53. The term „specific heat” was proposed by the Swede Johann Wilcke who independently made similar discoveries as Black.

An attempt by Daniel Bernoulli to explain the Boyle-Mariotte law by introducing molecular picture of gases was not taken seriously because at that time the molecules were regarded as purely hypothetical entities (Slide 55). Instead, the material theory of heat was developed, as explained by Black (Slides 56-57). The basic assumptions concerning the nature of caloric are summarized in Slide 58. The attempts to measure the specific weight of caloric by using ordinary balance (Slide 59) gave conflicting results because of many disturbing effects (e.g. convection currents and thermal expansion of balance’s arms). In 1799 count Rumford decided after very many careful studies that caloric was probably weightless.

In 1790 Marc-Auguste Pictet in Geneva published the account of his experiments with the radiation of heat and cold. He used metallic mirrors placed opposite one another (Slide 60). A sensitive thermometer was placed at the focus of one of the mirrors. When a glass bulb filled with hot water was placed at the focus of the second mirror, the thermometer began to show the increase of temperature. If instead of hot object a vessel with pounded ice was placed in the first mirror, the thermometer in the focus of the second mirror showed decrase of temperature. Pictet thought that his experiment showed radiation and reflection of the rays of heat as well as of the rays of cold.

In the following year Pierre Prevost provided an explanation which did not involve the rays of cold. He understood the notion of the „dynamic equilibrium" between absorbed and radiated heat by every object. Under normal conditions each body radiates as much energy as it absorbs from the environment and its temperature remains constant. In Pictet's experiments the thermometer received from the side of its mirror either more or less energy than before a hot or a cold object were placed in the focus of the second mirror, so that the dynamic equilibrium was destroyed and the thermometer showed higher of lower temperature (Slide 61).

The German chemist Georg Stahl proposed explanation of heat phenomena and of chemical changes by assuming the existence of *phlogiston* (Slides 61-65).

The great French chemist Antoine Lavoisier banished phlogiston from chemistry but he nobilitated caloric by including it in his list of chemical elements (Slides 66-69). The theory of caloric provided explanation of many phenomena (Slide 71).

If the gravitational attraction were the only existing force, every particle of matter would be attracted toward each other, so they would make a single homogenous mass. Thus, the existence of gases was explained by extensive repulsive atmospheres of caloric which surrounded every gas particles and kept them in some distance of each other (Slides 72-73).

The caloric theory provided an obvious explanation of the thermal expansion of matter. The process of heating a body consisted of adding more caloric to the body and it expanded. The gravitational force was known to be inversely proportional to the square of the distance from the centre of the body whereas the atmosphere of caloric which caused the repulsion was assumed to obey an exponential law by analogy to the Earth's atmosphere. In the figure shown in Slide 74 the gravitational attraction due to the atom m is represented as a solid line, and the caloric repulsion as dotted line. At the point P where they are equal another similar particle would be at equilibrium.

As the temperature of the body of which m is an atom was increased, the caloric atmosphere around each atom was assumed to increase and the caloric curve was thought of as rising, hence the point P receded from the centre of m and the body expanded.

The opinions opposing the caloric theory were easily dismissed (Slides 75-76).

Slides 77-84. Remarks on the state of chemistry. One has to remember that according to alchemists the number of possible combinations of the four elements (air, water, fire, and earth) could be infinite. The first modern approach to the notion of chemical element was due to great Robert Boyle, who expressed it in the very influential book *The sceptical chymist.* Lavoisier gave his definition of the element in his *Traité élémentaire de chimie* (1789). Lavoisier's list of elements is shown in Slide 83. It was in sharp contrast with the previous views (Slide 84).

Slides 85-99. Modern atomic theory.

Slide 86 presents a summary of important steps which led to the discovery of gas laws. The construction and use of the first baloons was a by-product of investigations of the properties of matter. In the second half of the XVIII$^{\text{th}}$ century atoms were not treated seriously by the physicists

(Slide 89). It was changed by John Dalton who is regarded to be the father of the modern atomic theory. He assumed that molecules of chemical compounds are composed of atoms in the simplest proportions - see Slides 92 and 93. This assumption led to correct classification of most known compounds, except for a few, such as water and ammonia (Slide 94). Dalton invented nice graphic symbols of atoms and molecules (Slides 90 and 91). The present symbols of elements were introduced by the Swedish chemist Berzelius in 1814.

At that time several regularities have been discovered in proportions of atoms in molecules. It was, however, impossible to reconcile some of the established regularities. The solution was proposed in 1811 by Amedeo Avogadro, the Italian lawyer who was interested in physics and chemistry. Avogadro’s law (Slide 98) had to wait several decades for the acceptance by the chemists.

It is important to know the difference between the atomic theories of Dalton (who relied on the caloric theory) and Avogadro, whose theory is accepted nowadays (Slide 99).