Energy Education and Entropy Concept

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Abstract :

In order that students will become wise with energy not only in daily life but also in understanding scientifically human-environmental problems, the standard course of teaching energy should be reformed basically. We shall discuss the essential points for this purpose, including the treatment of the entropy aspect of the phenomena concerning the irreversibility of the arrow of time.

1. Introduction

The nuclear disaster at Chernobyl, U.S.S.R. in April 1986, strengthened strongly the anxiety all over the world against the usage of nuclear energy for electricity. This reminds us that everybody, as a responsible citizen in the democratic society, should be well informed and educated so as to be able to participate with confidence in the energy policy of the country. The necessity of energy education can also be seen in daily life both at home and work surrounded by full usage of modern technology.

In the school systems of modern countries, great efforts are paid to teach energy in the course of science education. Especially in physics, energy is often stressed as the core concept to understand the law of nature. It is even said that physics is the study of energy in many forms. In spite of this, the results have not been successful. The situation is similar in Japan and other countries.

The main reason for the failure of energy education can be seen in the crusial discrepancy of the energy concepts between the textbooks of physics and everyday life. Namely, the stress in physics education is laid on the conservation law, saying that the total amount of energy, which takes various forms, is strictly conserved. However, this law by itself is not much use in dealing with energy in daily life, where energies, understood as quantities contained in oil, food or batteries or something like that, tend to be exhausted and vanish. Physics teachers are apt to recommend the course of thermodynamics in university physics, where the second law, dealing with the entropy increase with time, is relevant to the subject. However, this again is not the solution, since the standard course of thermodynamics mainly treats limited calculable problems of equilibrium in unrealistic situations. Futhermore, it is often organized in such a way only as a prepara-

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tion to the statistical mechanics in higher grade for specialists.

In this situation, it is very urgent to reform the energy education up to the high school level on one hand, and thermodynamics part of physics course for non-specialists in the university level on the other. The purpose of this note is to clarify the fundamental points for this reformation. This problem is inevitably connected with the implication of the entropy law which is often quoted in the context of one-sided pessimism. We discuss in the last half of this paper that this law should be properly treated in clarifying the precondition of progress and development.

In section 2, we discuss the discrepancy of energy concepts in daily life and in physics in more detail. Basic properties of energy are listed in section 3, followed by the explanation of energy quality, degradation and exergy. In section 4, basis of evolution and development is discussed in connection with the basic properties of energy. Difficulties concerning the explicit use of entropy is mentioned in section 5. The final section is devoted to the conclusion.

2. Energy concepts in daily life and physics

In the research of physics education, the discrepancy of the energy concepts in and outside the classroom has been already noted and discussed.[1-6] As an everyday concept, energy is characterized by devaluation and consumption. It vanishes or disappears after its use. This way of thinking is common to children and adults.

In contrast, energy conservation is taught in physics as one of most fundamental laws of nature. A typical statement is seen in the very influential lecture notes by Feynman[7]: "There is a law governing all natural phenomena that are known to date. The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle ; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete;...".

Actually, at the introduction of the energy concept in mechanics, the careful teacher mentions about the role of friction, air resistance and other kinds of dissipative forces. However, such effects are treated usually as some nuisance to be disregarded. Then in teaching heat and electricity, various forms of energy and transformations among them are taught, both at junior and senior high schools in Japan.[8] The energy conservation is explicitly stressed in Rika I (first part of science, obligatory to all pupils at the first grade in Japanese high school), where the dissipative nature of heat and irreversibility in the transformation of energy are mentioned as afterthoughts in some textbooks very briefly at most. The logical structure in textbooks of general physics for university students is not much different from above.

Facing this discrepancy of energy concept in life world and science world, the attitudes of physics teachers seem to be divided into three. The first, which is the majority, regards the daily idea of energy in children's minds, such as quoted below,[9] just as unscientific, intuitive and undeveloped one:[10]

"Energy is a kind of fuel which gets used up. In discussing what happens to a wind-up toy after it is released, a 13 year-old girl acknowledges it has energy when it is moving but then it ' gets used up'."

The second attitude, which is opposite to the first and taken by minority of teachers, is to find out a wisdom in daily concept of energy, and go toward the re-examination of the standard presentation of the concept in physics. Namely, the energy concept in every-day life is characterized by devaluation and dissipation concerning its quality, which is beyond the conservation law, as explained in more detail in the next section. Therefore, in the course of energy education, these second law aspects should be taught from the beginning. This is the assertion adopted by Black and Solomon, Duit and others.[4-6] Strongly affirmative to this opinion, I will try to put forth this line of thought so that the energy concept will become a powerful tool for citizens not only in daily life but also in analyzing social and human-environment problems, together with a deeper understanding of the laws of nature.

In between the first and second attitudes, the third one respects the standard view of physicists as it is, but keeps some distance from it, as it is far from real life. There the task is to build more practical or human-oriented courses such as domestic physics, energy in society, or history of physics.[11,12] Although such efforts cannot make a breakthrough by themselves against the strong influence of physics to impose the standard course to everybody, they are surely important as teaching materials.

3. Renovation of energy concept

In this and following sections, we discuss the whole aspects of energy concept in physics and science, without closing eyes at the second law, and consider the interrelation to daily one.

In the scientific view of energy, the following points should be taken as its basic properties :

a. There are various forms of energy with different qualities, and transformation among them occurs.

b. Total amount of energy is conserved, taking into account all forms including leaked ones.

c. The quality of energy degrades in the transformation, as the net account.

d. Concentration and separation of energy with higher quality is possible, and seen in various phases of nature.

e. Matter evolution such as the purification and development of higher structure is possible in the expense of energy degradation.

As we have noted, the first two points are widely regarded as the core concept of energy in physics education, but without enough notice on the grade of quality. On the other hand, the importance of the third point about energy degradation is stressed in 4-6), so as to take into account the second law aspect of the energy concept. Fully admitting this, I would like to assert that the last two points are indispensable as the implication of the second law on energy. Now we discuss the above points in some detail, starting from the grade of energy quality.

The degradation of energy in irreversible transformations was noted by Lord Kelvin already in 1852, in a way of formulating the second law.[13] There, he classified various forms of energy into three categories ; high, intermediate and low. Mechanical and electric energies are of high quality, while chemical and heat energies belong to intermediate and low ones, respectively. Although this classification is simple and useful, it attracted not much attention of physicists, as they were too busy in dealing with entropy rigorously.

For quantitative treatment of energy degradation, there is a very useful physical quantity called *exergy*, or *available energy*, introduced by Rant in 1956.[14] Exergy is the part of energy defined as the theoretical maximum amount transformable to the mechanical work, or electricity. The grade of energy quality can be measured by the percentage of exergy in energy.

For examples, mechanical energy in macroscopic forms such as kinetic energy in motion, gravitational potential energy at higher position, and one of elasticity stored in a spring are 100% exergy, as well as the one of electricity. These are 100% transformable among themselves as taught in physics, disregarding friction and other losses. On the other hand, not all of chemical energy in an amount of fuel or food is exergy, as the emission of exhausted heat of some amount is unavoidable.

The rate of maximum work available from heat energy at absolute temperature T_H is given by

$$\text{maximum efficiency} = 1 - T_L / T_H,$$

where T_L is the absolute temperature of the surroundings. The above formula of maximum efficiency, found by Carnot concerning heat energies,[15] shows that the higher the T_H of heat energy is, the higher its quality, indicating why the steam locomotives have faded away. As the energy of light is characterized by thousands degree of T_H, its quality is rather high.

Fortunately, the energy concept in everyday life, subject to devaluation and consumption in its use, is very close to the implication of exergy which decreases or vanishes in irreversible and dissipative processes.[16] In practice, there are no serious discrepancies in identifying the both. However, the word exergy is quite unfamiliar yet except for the domain of energy engineering. We may find two reasons. First, the physicists and physics teachers are not quite ready to accept new ideas from outside pure physics. Second, it is usually explained only after the study of entropy in sophisticated ways, as well as the free energies a la Helmholtz and Gibbs for chemists.

At the present stage, it may be appropriate to give the following answer to the language problem :

"Energy conservation in physics refers to the all kinds of energy including useless ones. The total amount of energy can be divided into available energy (exergy) and unavailable one (*anergy*). In real processes, available energy decreases irreversibly."

In the conventional course of physics in science, energy is first introduced in mechanics as the quantity of ability to do mechanical work defined by displacement length times force along the displacement, or convertible to it. This is exactly equivalent to exergy! Then, however, energy concept is extended to include useless energy stressing the conservation, i.e., invariance amidst the changes and variation. Still, the concept of useful energy is kept in pupils mind in spite of no support from textbooks.

4. Basis of evolution and development

Now let us come to the last two points, *d* and *e*, concerning the basic properties of energy. Energy degradation by itself concerns the net available energy. However, if we only stress it simply saying that energy degrades in an irreversible process, it leads to a one-sided understanding of its implications. Therefore, the possibility of evolution and development stated as points *d* and *e* should be noticed.[17]

Namely, simple degradation processes are such as heating of water by electricity, and cooling down of hot water emitting its heat to the surroundings. Besides them, there are plenty of processes where energy of higher quality comes out from lower ones. Typical examples are heat engines generating mechanical energy or electricity, where concentration and extraction of purely available energy is done from heat energy which is of lower grade. Also, dynamical activities of an animal are achieved through chemical processes in the body to generate physical work from organic substance, as in heat engines. The processes of energy quality increase are not limited to human-controlled or biological processes, but are also seen in the inorganic world. For examples, heat causes convection currents such as wind, and the solar energy causes the circulation of water through air, rain, river and sea.

Now we come to the last point, i.e., the role of energy in matter evolution. It is too simple to say such as "the deep structure of change is decay", "time depreciates the value of the world," or "the universe is continuously losing its order". This is the second law pessimism.[18]

On the contrary, in fact, there are plenty phenomena of matter evolution in nature, such as concentration, purification and separation of matter into different components from mixed states, and development of specific structures. Crystalization from a hot solution of various substances by cooling down is a simple example. Furthermore, there are growth and evolution of living things. Such processes are inevitably accompanied by some kind of energy degradation and consumption. In other words, the flow of energy from higher to lower grade is the driving force of matter evolution.

Before closing this section, we discuss practical aspects of energy in everyday life, which are not suffieciently covered by the principles of science.

There exist two aspects of utility of energy, i.e., energy for energy and for final consumption. The first is to get a specific form of energy from other forms. For this purpose, one of higher grade such as electricity is valuable, because it can be almost fully transformed into any other form of lower quality as one knows from energy degradation. In order to get flexible form of energy with highest quality, the extraction process from energy resources such as fuels and an apparatus for it such as heat engine or power plant are necessary.

For final consumption, very specific forms of energy and matter are required. We eat foods, but we cannot eat electricity which is of higher quality. The use of various forms of energy adequate to the purpose of final consumption was widely discussed by Lovins with some overemphasis on natural energy resources.[19] In the system analysis by Odum and Odum, the role of energy flow is extensively discussed with proper attention to the degradation and increase of energy quality, and its role on recycling materials.[20]

For the practical use of energy, its quality in the sense of physics is not the only measure. We should also take into account properties concerning storage, translation, safety, separation, size in use, handiness, and so on. The first two points for energy education are stressed by Duit.[6] The other points are also important in practice.

Finally, we note a close interrelation between information carriers and energy forms, such as sound, light, electro-magnetic wave for broadcasting, and so on. It is to be stressed that we should not reduce physics education concerning information into energy education, because the former requires its own logics not covered by rigorous treatment of energy and exergy. For example, the main theme of optics should not be limited to the energy flow but should include visual information.[21]

5. How about entropy ?

Up to now, we have not explicitly discussed entropy, though we mentioned energy degradation as a manifestation of the entropy law, i.e., the second law of thermodynamics. This is because pollution and environmental problems can be analyzed without explicit use of entropy.

From the conservation of total energy and the degradation of its quality, it follows that used energy with lower quality should be expelled from the system. This is very important for heat engines as cooling mechanism. Usually, energy takes the form of heat and increases the temperature of the surroundings, and finally leaves the earth into the space as infra-red radiation. Space has enough capacity for it, but heat pollution may happen locally by too much concentrated use of energy, or globally the overrun of the greenhouse effect through the accumulation of CO_2 in the air.

The pollution by harmful matter happens, since the production of useful materials is accompanied by the rest rubbish containing unwanted materials. According to the mass conservation law, the total mass does not change in any process (except for a slight change in nuclear reactions which can be disregarded in everyday phenomena on the earth). Various atoms circulate on the surface of the earth changing their combinations as chemical substances, but unchanged by themselves. Whether the rubbish is harmful to the environment depends on specific properties of its substances, and cannot be simply measured by entropy. What can be generally said is that its disposal into harmless form requires the consumption of available energy.

We should note that the entropy law has received high reputation for conceptual difficulty. In fact, entropy as a physical quantity has the following difficulties for daily use :

1. It has a negative implication as a measure of disorder, in contrast to exergy.
2. There are no handy devices to measure it, except for Gedanken experiments.
3. Its physical dimension, which is the fraction energy／temperature, is far from intuition.
4. It increases unlimitedly without upper bound.

There are excellent analyses and criticism on the oil-consuming nature of modern civilized society, where the entropy concept served as a strong motivation.[22] As we have discussed, essential implication of the entropy law concerning energy and matter can be understood with plain words of daily use. Therefore, the bulk of their discussions may be performed without recourse to sophisticated arguments.

As for the course of thermodynamics in university physics, standard teaching of entropy may be allowed, if there is enough time. It should be supplemented with the theory of exergy, and the study of the properties of energy as discussed in this note, so that rigorous knowledge of thermodynamics will become a powerful tool in analyzing the real world. For this purpose, considerations of non-equilibrium states and open systems concerning energy and／or matter are indispensable.

For non-specialist courses in university physics, systematic studies of energy problems is possible based on wisdom in daily concepts, without recourse to mathematical handling of physical quantities. An excellent example may be the textbook by Odum and Odum, who started from biology.[20] For the students belonging to the science course in the faculty of education, I have developed a curriculum consisting of three parts ; Ⅰ. heat phenomena and states of matter, Ⅱ. thermodynamics, Ⅲ. social and environmental implications, where conventional thermodynamics is compressed into a part of Ⅱ. The attitude and understanding of students are remarkably improved in contrast to traditional approach.