Paper

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A new perspective of how to understand entropy in thermodynamics

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Abstract
Using the analogy between thermodynamics and electricity, two new concepts of thermal charge and quantity of thermal charge are introduced. A simple yet explicit definition of entropy is then derived—entropy is the quantity of thermal charge. As a result, quantity of thermal charge (entropy) and quantity of heat (energy) are now clearly distinguishable from each other. The former is an energy carrier while the latter is energy itself. This largely eliminates the difficulties in learning and applying thermodynamics, and therefore will be of considerable assistance to those who work, teach and study in the fields associated with thermodynamics. This also leads us to re-examine the validity of caloric theory and make a brief comment on it.

1. Introduction

Being a branch of physics, thermodynamics is one of the most important fundamental theories in modern science and technology. When it comes to explaining phenomena in nature, conducting scientific experiments and theoretical research, developing new technology, designing and manufacturing new products, etc., thermodynamics does have a wide application as the other branches of physics do. However, in comparison to the others, thermodynamics is commonly viewed as a difficult subject to study. A number of abstract concepts such as entropy, enthalpy, free energy, state function, reversibility and cycles, etc. make it even more obscure. Among the concepts, entropy is no doubt one of the most difficult physical quantities to understand in conventional thermodynamics.

The history of science tells us the development of thermodynamics at its early stage was fairly independent and a bit arbitrary. It shared little commonalities with the better-developed branches at that time: mechanics and electricity. Therefore, it was challenging to clarify the concepts in thermodynamics by analogizing to similar concepts in other subjects. As a result, thermodynamics developed much slower than other branches and experienced more twists and turns. Since the misconceptions or misinterpretations were not corrected or clarified over time, it resulted in this subject becoming even more complex and difficult to study.

Scottish chemist Black [1] (1728–1799) made a significant contribution to the theory of heat. He was one of the first to state that two physical quantities—*intensity of heat* and *quantity of heat*, were required to describe thermal phenomena. The former was already known as *temperature* at that time, the latter, however, was not given a specific name or term. In 1865, the concept of entropy with its mathematical definition was put forwarded by the German physicist Clausius. As Truesdell [2] pointed out, the term 'entropy' means nothing to ordinary persons and only intense headaches to those who have studied thermodynamics. Or, let us quote Callendar's words [3], '…Clausius gave it the name of 'entropy' and defined it as the integral of dQ/T. Such a definition appeals to the mathematicians only'. As a matter of fact, the majority of today's physics teachers still believe that entropy is quite difficult to teach [4], and many engineers and technologists confess that although they have been working in the fields related to thermodynamics for many years, they never feel they have fully grasped the concept of entropy. This reality obviously has a negative impact on teaching and applying thermodynamics in various areas. Therefore, in order to update its concepts and structure to make it easier to study and apply, a reform in thermodynamics is urgently needed.

2. Attempts to reform thermodynamics

Several attempts have been made to reform the traditional thermodynamics since 1911 when Callendar, the president of the British Physical Society at that time pointed out that entropy was basically what had already been introduced by Carnot and had been called caloric. It was defined directly by his equation $W = AQ\ (T - T_0)$, where W is the work done by a quantity of caloric Q falling from a temperature T to T_0; A is a conversion factor for units. This means entropy could be introduced in a way 'which any schoolboy could understand' [3]. In 1972, Job [5] proposed to base the teaching of thermodynamics on the concept of entropy and pointed out that our everyday usage of the word 'heat' which was explained as a physical quantity could be equated to entropy in conventional thermodynamics.

About one decade later, Falk *et al* [6] introduced a concept of teaching physics based on 'substance-like' quantities that can be treated as a 'fluid', such as mass, electric charge, momentum, amount of substance, etc. as the carriers of energy in physical processes. Entropy was just the energy carrier in thermal phenomena. This idea was really helpful in visualizing the relationships between abstract physical quantities and making analogies between them. Falk also wrote [7], 'The entropy introduced into physics by Clausius was, contrary to general belief, not a new physical quantity but the reconstruction of the 'quantity of heat' conceived about one hundred years earlier by Scottish chemist Black'. In his opinion, Black's concept of 'quantity of heat' coincided perfectly with what was called entropy [4, 7]. To use Callendar's words [3], 'In justice to Carnot, it (entropy) should be called caloric'. In addition to the previous attempts, Der Karlsruher Physikkurs [8] (the Karlsruhe Physics Course, or KPC for short), based on Job's idea, suggested at the very beginning that entropy is what in everyday language we call 'quantity of heat' or simply 'heat' with the symbol S and its unit of measurement Carnot, abbreviated Ct.

It should be mentioned that the German Physical Society (DPG) published a report[3] in 2013, in which KPC's approach was questioned and its definition of entropy as 'colloquially called heat' was rejected. Herrmann and Pohlig from KPC responded[4] about two weeks later.

The above-mentioned attempts all have certain things in common. They try to provide tangible explanations to Clausius' mathematical definition of entropy in order to make it easier to understand by employing such terms like 'quantity of heat' or simply 'heat', 'caloric' and 'calory' [2]; they use temperature and the redefined entropy as the two core physical quantities in thermodynamics. To conventional thermodynamics, redefining entropy and reorganizing the structure of the subject was no doubt very innovative. The new concepts of entropy directly related to 'heat' or 'caloric' are more intuitive and could therefore be regarded as a great improvement over Clausius' abstract concept. However, the new ideas must be convincing and scientifically correct, as indicated in DPG's report.

It is worth of notice that what is called 'heat' by Black is fundamentally different from the interpretation of heat in conventional thermodynamics, where the word 'heat' denotes a specific form of energy. It is unambiguous that Black's 'heat' is an extensive quantity of a substance-like nature, a state variable with no possibility of being a form of energy. Thus we have a conflict.

[3] www.dpg-physik.de/veroeffentlichungen/publikationen/stellungnahmen-der-dpg/bildung-wissenschaftlicher-nachwuchs/kpk/stellungnahme_kpk.pdf.
[4] www1.unipa.it/girep2014/accepted-papers-proceedings/16_Herrmann.pdf.

That is, the new concept of entropy and the traditional concept of energy are both called 'quantity of heat' or simply 'heat'. In other words, the same term 'heat' is used to express two different concepts and/or interpreted in two different ways. This results in confusion. As pointed out in DPG's report, '…entropy is by far not the same as heat, and cannot be referred to as such, not even 'colloquially'. For the sake of further discussion, let the new interpretation of heat be called Falk's interpretation and the other one conventional interpretation.

3. A few thoughts on entropy

Is it possible to resolve the conflict or eliminate the confusion? G. Job suggested that the word 'heat' and its combinations be denoted with an asterisk (∗) when Falk's interpretation is used, and with a dot (·) when the conventional interpretation is used [5]. However, this only provides a temporary solution. It seems to us that the problem has to be solved literally and conceptually rather than symbolically. This was our first thought.

To clearly differentiate these two concepts, it is necessary to make changes to one of the 'heat' or 'quantity of heat'. But, which one? Our second thought was the term 'quantity of heat', i.e. entropy in Falk's interpretation has to be redefined while the same term or energy in conventional interpretation remains unchanged. The reasons are as follows:

(1) In the eyes of physicists, teachers and engineers, heat is nothing but a 'form of energy'. The principle of 'heat equivalent of work' or 'mechanical equivalent of heat' in various textbooks and professional publications strengthens the direct correlation between 'quantity of heat' and energy.
(2) To the laypersons, the age-old view that heat is energy is deeply rooted in their minds that it would be too difficult to change or eradicate, particularly in the Chinese language, including Mandarin, Cantonese and almost all the other dialects. For example, most people know that food can produce energy and the labels on food packages indicate calories (amount of energy) the food contains. And quite a few of them know that calorie is a unit of energy and one small calorie equals about 4.2 joules.
(3) Majority rules. We agree with DPG's viewpoint: Heat is energy. Hence, it is much easier to change the concept of entropy in KPC thermodynamics as opposed to changing the concept of energy in conventional thermodynamics. As a matter of fact, this change will cause no harm to KPC itself, rather will make it easier to study and master.

Our next thought was how to find a new term to change the concept of entropy. On the one hand, it seems to us that the word 'thermal' would be the best substitute for 'heat'. But we need an answer to the question 'thermal what?' On the other hand, the word 'caloric' does not seem suitable because it was not only banished from physics as an invalid concept for many years, but also has the meaning 'thermal substance' or 'heat substance' in English with its Chinese translation '热质', in which the first character means 'heat' or 'thermal' and the second one means 'substance'. It is 'substance', however, that got caloric theory into serious trouble in the first place.

The fourth thought was how to answer the above question. By using Callendar's, Job's and Falk's ideas, H. Fuchs [9] once wrote, '… we have to search for a thermal quantity, a 'fluid', a 'substance' [5] which is analogous to electrical charge. The properties of this 'fluid' have to be extracted from experience, and its relationship to temperature and energy have to be worked out'. His idea is actually quite close to ours. As previously mentioned, thermodynamics missed the opportunity to borrow ideas from electricity and mechanics at its early stage. As an old saying goes: 'It is never too late to mend'. So, why don't we do it right now? It is known that analogy has been considered as an effective tool utilized to teach students physics as it is conducive to activating their associative and creative thinking. Thus far, the analogy between thermodynamics and electricity has been used in the curriculum quite successfully. However, can we make the analogy closer or stronger by applying it at the fundamental level of the two subjects, i.e. compare the substance-like quantity entropy with quantity of electric charge by introducing the terms 'thermal charge' and 'quantity of thermal charge'? The former is actually the answer to the previous question 'thermal what?' and the latter is analogous to quantity of electric charge. In

Table 1. Analogy between electricity and thermodynamics.

Branch	Extensive Quantity	Intensive Quantity	Strength of current	Energy flow
Electricity	Quantity of electric charge Q	Electric potential φ	Electric current $I = \mathrm{d}Q/\mathrm{d}t$	$P = \varphi I$
Thermodynamics	Quantity of thermal charge (entropy) S	Temperature T	Entropy current $I_S = \mathrm{d}S/\mathrm{d}t$	$P = T I_S$

other words, our goal has been reached. It might be worth mentioning that the Chinese translation for thermal charge is 热荷, in which the second character means 'attaching to' or 'residing in'. As an aside, the term 'thermal charge' was once mentioned in some literature [5, 10], although no follow-ups or further discussions were found.

4. Thermal charge and quantity of thermal charge (entropy)

Thermal charge is analogous to electrical charge. And being the substitute for 'heat', its concept is highly intuitive. Thermal charge is something that can flow from hotter bodies to colder bodies, and can be generated in an oven, contained or stored in a thermos flask.

Table 1 shows the analogy between electricity and thermodynamics. It can be seen that the table contains not only physical quantities, but also relations between these quantities. Let us first draw an analogy between electrical charge and thermal charge. As is well known, electric charge is the physical property of matter that causes it to experience a force when placed in an electromagnetic field. Objects carrying electric charge are called charged or electrified objects. The more electric charge an object carries, the higher its electric potential; conversely, the less electric charge an object carries, the lower its electric potential. Electric charge is not a substance, but a type of charge that is attached to the substance. In nature, no electric charge can independently exist apart from substance. For convenience, however, electrified particles are sometimes called electric charge. But electric charge itself is in fact not a 'particle'. In addition, electric charge can be quantified. The amount of electric charge is called quantity of electric charge, a substance-like quantity and also an energy carrier. In international system of units (SI), the symbol for quantity of electric charge is Q with its unit Coulomb (C).

Similarly, thermal charge is the physical property of matter that causes it to become hotter or colder when the amount of charge increases or decreases. The more thermal charge an object contains, the higher its temperature; conversely, the less thermal charge an object contains, the lower its temperature. Thermal charge is not a substance, but a type of charge that is contained in the substance. In nature, no thermal charge can independently exist apart from substance (here light is viewed as a type of substance). In addition, thermal charge can be quantified. The amount of thermal charge is called quantity of thermal charge or entropy, a substance-like quantity and also an energy carrier. In international system of units (SI), the symbol for quantity of thermal charge (entropy) is S and its unit is J K^{-1}.

It is clear that once we introduce the concepts of thermal charge and quantity of thermal charge, the analogy between thermodynamics and electricity can be made broader and deeper. More importantly, the two entirely different concepts 'entropy (quantity of thermal charge)' and 'energy (quantity of heat)' in thermodynamics can now be distinguished very easily. The corresponding Chinese translations are 热荷量 and 热量, respectively, in which the last character means 'quantity'. Therefore, the confusion or conflict has been eliminated. The previous description 'entropy is what in everyday language we call 'quantity of heat' or simply 'heat' can now be changed to '**entropy is the quantity of thermal charge**', a simpler and clearer definition. As a consequence, thermodynamics will become a subject much easier to understand and study than ever before.

We believe that the concepts of thermal charge and its quantity can easily be understood and accepted by the masses including students in secondary schools. To a certain extent, they are easier to understand than electric charge and its quantity since the latter has two types of charge: positive and negative. Moreover, anyone can generate thermal charge or entropy simply by rubbing hands together, burning a piece of paper or turning on a heater. In other words, thermal charge is easier for people to experience in everyday life as opposed to electric charge.

It is worth mentioning that even though quantity of electric charge (electric charge for short) and quantity of thermal charge (entropy for short) are both extensive quantities and energy carriers that share some similarities, however, they are indeed two very different quantities each possesses its own unique characteristics. One of the significant differences is that electric charge is a conserved quantity, but entropy is not. Instead, entropy is just a so-called half conserved quantity as it can be created, but cannot be destroyed. To use the words in DPG's report, '… also entropy flows, it is of crucial importance in thermodynamics that entropy is additionally created, …' Entropy is conserved only in reversible processes which are very limited in practice. In general, however, entropy is not conserved since most processes in the universe are irreversible. For example, electrical current is the same everywhere in a series circuit because electrical charge is conserved. But entropy current moving in a metal rod (assuming insulated from its surroundings) from the hotter end to the colder end increases because entropy is created everywhere during the process [8].

Analogy is merely a cognitive process, a comparison of two things to show the similarities between them. The things being compared could be quite similar in certain respects, but very different in other respects. It is therefore very important for us to keep in mind that when the similarities are discussed, the differences should also be reviewed and studied.

5. Look back in history—re-examine caloric theory

To further recognize the significance of introducing the concepts of thermal charge and quantity of thermal charge, it is necessary to briefly look back in history. There was a widely accepted theory called caloric theory throughout the 18th century and almost half of the 19th century. It was used to explain phenomena of heat in terms of the flow of an imaginary weightless fluid known as 'caloric'. In this theory, heat (caloric) was a substance, a fluid that flows from hotter bodies to colder ones and also a kind of gas that could pass in and out of pores in solids and liquids; in other words, it could penetrate any substance. The more caloric an object contains, the higher its temperature; conversely, the less caloric an object contains, the lower its temperature. Therefore, the temperature of an object depends on the amount of caloric it contains. As a 'fluid', it could neither be created nor destroyed, i.e. obeying the law of conservation of matter.

Caloric theory was once popular and influential. In fact it played a positive role in science development in history, although it contained a major mistake. We believe the main reason caloric theory sustained itself for such a long period of time is because it could be used to explain numerous heat phenomena in a simple and compelling way at that time. Also, scientists were trying to use this theory to solve their problems in theoretical research and engineering practice, and had attained a number of achievements. For example, Fourier established his famous heat transfer theory, Carnot developed the principle of the Carnot cycle, which today still forms the basis of heat engine theory, and Laplace improved Newton's calculation of the speed of sound, etc. These successes made people firmly believe in the validity and correctness of the theory.

At the end of the 18th century caloric theory was beginning to be challenged as it could not explain all aspects of heat phenomena, in particular, the results of some well known experiments in which limitless amounts of heat (caloric) were generated by doing work, indicating that caloric was not really a substance obeying the conservation law, or, its quantity was not conserved. In 1860, the law of conservation of energy was successfully established. Joule's mechanical equivalent of heat confirmed that heat is a form of energy created by motion of particles. Caloric theory began to decline, but still remained in part of the scientific literature until the end of the 19th century.

So what exactly caused caloric theory to experience such a dramatic change? Logic tells us that caloric theory should not be completely repudiated because it must contain some valid ideas and concepts. How else could we explain the achievements made by a number of outstanding scientists in their scientific research and/or experimental investigations on the basis of this theory? We then ask ourselves what led to the rise and fall of caloric theory. Our answer might be surprising to many. The reasons are the same: regarding heat or caloric literally as a substance. How could this be? Now that we have the definitions of thermal charge and its quantity (entropy), as well as the concept of substance-like quantities, we can easily identify it.

By sheer fluke, regarding caloric as a hypothetical fluid that could travel through space and any objects resulted in the quantity of caloric being treated as a physical quantity, in today's term what we call an extensive quantity or a substance-like quantity. This is what led the theory to its glory. On the other hand, its fatal mistake was to regard caloric as a real substance that obeyed the law of conservation of matter. This is what finally led the theory to its fall.

In our view, the correct understanding should be: quantity of thermal charge (entropy) is a substance-like quantity, not a substance; it is an energy carrier, not energy itself. If we replace 'caloric' or 'quantity of caloric' with the new definition of entropy and eliminate any portions that are related to real substance, the theory makes perfect sense. Entropy does not conform to the conservation law since it is merely a substance-like quantity and an energy carrier. To avoid confusion, we can give the theory a new name: 'theory of thermal charge and entropy' or simply 'thermal charge theory'.

6. Conclusion

In the history of thermodynamics, there was a very long period during which the concepts of the terms 'temperature' and 'heat' were not correctly understood and distinguished, despite the fact that they had been used for many years. In 1757, Scottish scientist Black cleared the confusion and called 'temperature' and 'heat' the 'intensity of heat' and 'quantity of heat', respectively. Einstein [11] once said, 'The most fundamental concepts in the description of heat phenomena are temperature and heat. It took an unbelievably long time in history of science for these two to be distinguished, but once this distinction was made rapid progress resulted'. It is our hope that a clear distinction between the two concepts of entropy (quantity of thermal charge) and energy (quantity of heat) would be conducive to the teaching of thermodynamics and also beneficial for professionals to master and apply thermodynamics.

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