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Understanding entropy through a discussion of exergy

Jing Wu

School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China

E-mail: jingwu12@gmail.com

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Abstract

Entropy is an extremely important physical quantity in thermodynamics. However, students studying thermodynamics commonly find it difficult to understand entropy. In most thermodynamics textbooks, there is only a microscopic explanation of the physical meaning of entropy, with a lack of a macroscopic interpretation. This lack is far from sufficient for people who are more concerned about the macroscopic engineering applications of entropy. In this study, we comparatively analyse entropy and exergy to explain the macroscopic physical meaning of entropy based on the concept of exergy. That is, entropy is a measure of the unavailable energy of a system during reversible heat interaction with the environment. Based on this physical interpretation of entropy, we have answered three questions that students may raise when learning about the concept of entropy. In addition to theoretical derivation, we also try to use several examples from daily life to help readers better understand the macroscopic physical meaning of entropy. Finally, through a questionnaire survey, we learned about students' evaluations and their understanding of an engineering thermodynamics course. We have also learned whether the students prefer entropy or exergy and the reasons for their preference, as well as what aspects regarding the contents and methods the students would prefer the lecturer to improve upon when teaching entropy and exergy. The results of this work can make it easier for students to understand the physical quantity of entropy. Additionally, the results of the questionnaire analysis can be of a certain reference value for the instructions of an engineering thermodynamics course.

Keywords: entropy, exergy, unavailable energy, examples in daily life, questionnaire

(Some figures may appear in colour only in the online journal)

1. Introduction

Thermodynamics is a fundamental natural science that deals with all aspects of energy and energy transformation. Entropy is a central concept in thermodynamics. However, compared to energy and the first law of thermodynamics, which are readily understood and easily accepted by most people, entropy is perceived as abstract and is not even fully appreciated by people with technical backgrounds, although the concept of entropy is pervasive in many fields.

It is perhaps worth mentioning that many students who are learning engineering thermodynamics feel nervous and confused every time they encounter questions involving entropy (I and many of my fellow students felt this way). Even though students might derive the same values of entropy transfer, change, and generation as the standard answers, they still feel uncertain instead of feeling a sense of achievement as they might after solving other problems. It is no simple task to answer the following question about entropy: what exactly are 'transferred', 'changed', and 'generated'? (This question is referred to as Question 1 in section 2.3.) Furthermore, in our daily lives, the quantities of things usually decrease due to consumption; thus, the question of why entropy always increases (in an isolated system) is difficult to answer. (This question is referred to as Question 2 in section 2.3.) After learning about entropy, when students learn about exergy in the next chapter, they may be puzzled by another question: why is exergy transferred to or from a system by both heat transfer and work transfer, while entropy is transferred only by heat transfer (i.e. why is entropy not transferred by work transfer)? (This question is referred to as Question 3 in section 2.3.)

The microscopic interpretation of entropy, rather than its macroscopic interpretation, is presented in most thermodynamics textbooks. Although some interpretations of entropy on the microscopic level [1–3] can shed light on the concept of entropy, the analysis methods are almost solely macroscopic throughout the process of learning engineering thermodynamics. Thus, it is generally expected that Questions 1–3 mentioned above can be answered from a macroscopic perspective. Moreover, the microscopic interpretation of entropy, which involves concepts such as randomness [1], uncertainty or missing information [2], cannot easily be used to guide its macroscopic application for engineers and researchers in engineering fields, who are more interested in the macroscopic applications of entropy, such as in the efficiency of the heat-work conversion of a heat engine and the irreversibility of a thermal process when they analyse or design thermal systems.

In fact, many people, including some well-known scientists, have noted that it is difficult to understand entropy. For example, Cengel wrote in his thermodynamics textbook that 'Entropy is a somewhat abstract property, and it is difficult to give a physical description of it without considering the microscopic state of the system [1].' Nobel-Prize winner Prigogine once mentioned that '…entropy is a very strange concept without hoping to achieve a complete description…[4]'. In addition, there is an anecdote about the famous mathematician von Neumann, who has been quoted as saying that 'nobody knows what entropy really is' [5][1].

It can be seen that developing a better understanding of the aspects of the second law of thermodynamics, and especially the concept of entropy, is an important part of both engineering education and application. In light of this, previous researchers have made numerous

[1] In 1948, C. Shannon (who is renowned as the father of information theory) found a new physical quantity in the field of information but had no idea what to call it. In 1949, he happened to visit J. Neumann. To his surprise, Neumann told him, 'You should call it entropy'. The reason Neumann gave is that 'nobody knows what entropy really is, so in a debate, you will always have the advantage.'

attempts to provide adequate explanations of the concept. For example, the physical meaning of entropy has been explained from the perspectives of 'energy degradation [1, 6]', 'energy spreading [7, 8]', 'energy dispersal [9, 10]', 'heat reservoir/bath entropy [11–13]', 'freedom [14]' or 'thermal displacement [3]'.

Moreover, some lecturers of introductory physics or thermodynamics courses have performed questionnaire studies to analyse students' understanding of entropy and the second law of thermodynamics and designed tutorials/instructions to develop better teaching methods for this topic. For example, Cochran and Heron [15] found from a questionnaire study that most of the surveyed students failed to recognise the relevance of the second law and instead relied upon the first law of thermodynamics to determine whether given cyclic processes could occur, although the students had received correct and competent instruction in standard undergraduate physics or engineering thermodynamics courses. The authors then developed two separate tutorials on Carnot's theorem and entropy, each of which appeared to improve the students' understanding of these subjects. In the spirit of Cochran and Heron, Bucher [16] further suggested the incorporation of wedge diagrams in tutorials. Christensen *et al* [17] concluded from a different questionnaire study that a clear majority of students erroneously understood the total entropy to be a conserved quantity. These authors designed a 'two-blocks' tutorial on the entropy to address students' difficulties in understanding the non-conservative property of entropy. Haglund *et al* [18] investigated how students think and talk about entropy and the development in students' understanding of entropy. These authors designed four interview questions based on syntactic, semantic, and pragmatic perspectives. The results of interviews with three pairs of engineering students showed that the students did not consider entropy to be a substance-like entity, although entropy may be viewed as having some of the characteristics of a substance. For example, we can say 'generate more entropy [19]' or 'more entropy is contained in an object [20]'. Moreover, Haglund *et al* found strong positive correlations between student rankings of how closely concepts are related to entropy and the usefulness of these concepts in explaining entropy, whereas these rankings correlated strongly negatively with the students' perception of how scientific the concepts were seen to be. Haglund *et al* also found that the students had difficulties in seeing the connection between entropy and the second law of thermodynamics.

In a course of engineering thermodynamics, especially a course with many credit hours, a certain number of lecture hours are devoted to explaining the content of exergy. Apart from entropy, the concept of exergy has also been applied to the analysis of systems from a second law perspective [21]. The exergy of a system is defined as the maximum useful work that can be obtained as the system undergoes a reversible process from a specified initial state to the dead state (i.e. a state when the system is in equilibrium with the environment it is in). As far as I know, the lecturers of engineering thermodynamics in China all explain entropy first and then explain exergy. The order of chapters in some textbooks used in other countries [1, 22] is also arranged in a similar manner. As the two concepts are closely related to the second law of thermodynamics, entropy and exergy have certain similarities. For instance, entropy and exergy are both non-conserved quantities; entropy and exergy can both be transferred to or from a system; entropy generation and exergy destruction can both measure the irreversibility of a thermodynamic process quantitatively, etc. There are certainly differences between entropy and exergy, for instance, exergy is transferred by both heat and work transfer, whereas entropy is transferred only by heat transfer. The natural variation tendencies of the two quantities are also opposing; that is, the exergy of an isolated system always decreases, while its entropy always increases. Thus, after entropy and exergy have been successively introduced in an engineering thermodynamics course, is it possible to explain the macroscopic physical meaning of entropy based on the concept of exergy so as to offer a way of understanding entropy other than those presented elsewhere? This is what we intend to do in section 2. With this interpretation of entropy, the abovementioned Questions 1–3 can be easily answered, as detailed in section 2.3.

Entropy is a fundamental concept relevant to all sciences and engineering, whereas exergy is largely a concept that is relevant only to engineering. The concept of exergy is generally explained in relevant thermal engineering courses; the concept of exergy is not introduced in the introductory physics course. To help those that have learned about entropy but not exergy to understand the content of this paper, the concept of exergy will be explained in as much detail as possible when it is introduced in section 2.1. It is hoped that the interpretation of the macroscopic physical meaning of entropy by the interplay between entropy and exergy will be of significance as a reference to readers that are majoring in physics.

Moreover, the concepts of both entropy and exergy are 'universal' rather than specific only to 'technical' fields. The extension of thermodynamic principles or concepts to non-technical fields can be found in several papers or books [1, 23–27]. Inspired by these previous studies, in addition to theoretical derivations, we try to use some examples in daily life to help readers better understand the macroscopic physical meaning of entropy in section 2. Finally, in section 3, we present results from a questionnaire study on the perceptions of the concepts of entropy and exergy among undergraduate students from three universities.

This study is primarily intended for undergraduate or graduate students and practitioners with some knowledge of thermodynamics. However, it is hoped that even readers with nontechnical backgrounds appreciate the life-related part of this study to initiate their interest in having a basic understanding of the second-law aspects of thermodynamics. Additionally, the results of the questionnaire in section 3 may be useful for the lecturers teaching engineering thermodynamics.

2. Interpretation of the macroscopic physical meaning of entropy based on the concept of exergy

The pioneers of thermodynamics realised during its development that it is not sufficient to judge whether a thermodynamic process can be achieved by only relying on the conserved physical quantity, i.e. energy. What they did was look for a non-conserved physical quantity. This task was finally fulfilled in 1865 by Clausius, who found a physical quantity that was not conserved during thermodynamic processes and coined it entropy. Whether entropy generation of a process is greater than zero can determine whether the process can be achieved, and the size of entropy generation can measure the irreversibility of a process. In the 1950s, another non-conserved quantity, exergy (also called availability or available energy), with the physical essence of work potential of a system in a specified environment [1], was proposed [28] and now serves as a valuable tool for measuring the second-law performance of a thermodynamic process. We first revisit the expression of exergy and then explore the macroscopic physical meaning of entropy on the basis of exergy.

2.1. Revisiting the expression of exergy

The exergy of a closed system, $E_{x,U}$, is defined as the maximum useful work that can be obtained as the system undergoes a reversible process from a specified initial state to the dead state. It is given by the expression

$$E_{x,U} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0), \quad (1)$$

where U, V, and S denote the internal energy, volume, and entropy of the system at the specified initial state, respectively; U_0, V_0, and S_0 denote the internal energy, volume, and entropy of the system at the dead state, respectively; and p_0 and T_0 denote the environment pressure and environment temperature, respectively.

In general, a closed system may possess kinetic and potential energies, where the kinetic and potential energies themselves are forms of exergy. Thus, the exergy of a closed system should also include its kinetic and potential energies. However, the exergy in the forms of kinetic and potential energy is irrelevant to the interpretation of the macroscopic physical meaning of entropy using the concept of exergy. For the sake of convenience, exergy in the forms of kinetic and potential energy is not considered in the following discussion about the exergy of a closed system. In addition, it is noted that this study limits the discussion to thermo-mechanical exergy [1, 22] and thus disregards any mixing or chemical reactions. This notion means that a system at the 'dead state' is at the temperature and pressure of the environment, and it has no kinetic or potential energies relative to the environment. Although the system may have a different chemical composition than the environment, the contents of the system at the dead state are not permitted to enter into mixing or chemical reactions with environmental components and in so doing develop additional work. The thermo-mechanical exergy concept suffices for a wide range of thermodynamic evaluations [1, 22]. If chemical reactions are taken into consideration, it is necessary to consider the departure of the system state from the environment in terms of the temperature, pressure, and composition, for the composition now also plays a key role. In this case, there are two additive contributions to the exergy, thermo-mechanical and chemical. See the derivation in detail elsewhere [22].

It is noted that the Gibbs function (or Gibbs free energy) is also used in an analysis of a thermodynamic system. The Gibbs free energy is mostly used to analyse chemical reaction systems under constant-temperature–constant-pressure conditions. For example, as this kind of system undergoes a reversible process from a specified initial state to a final dead state, the maximum useful work that can be obtained is $G - G_0$, where G and G_0 are the Gibbs functions of the system at the initial state and final state, respectively [1]. The application of the concept of exergy does not require specific conditions (e.g. constant-temperature–constant-pressure conditions and constant-temperature–constant-volume conditions). The exergy represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws. Therefore, the difference between the exergy and the actual work delivered by a device represents the room that engineers have for improvement. The main purpose of an exergy analysis is to understand the exergy loss in each step of the heat-work conversion process, to determine effective measures for reducing the exergy loss, and to provide a reference for improving the thermal efficiency and energy-use efficiency of the process. However, it is easier to use the concept of free energy to analyse systems that involve chemical reactions, particularly chemical reaction processes under constant-temperature–constant-pressure conditions or constant-temperature–constant-volume conditions. For instance, the Gibbs function can be used to determine the direction of a process or to calculate the maximum work of a chemical reaction under constant-temperature–constant-pressure conditions.

When the states of a closed system and the environment are determined, the exergy of the closed system is determined. That is, in the derivation of the expression for the exergy of a closed system (equation (1)), we always obtain the same expression regardless of what reversible processes the closed system undergoes from a specified initial state to the dead state. Therefore, in the derivation of equation (1) for the exergy of a closed system, it can be

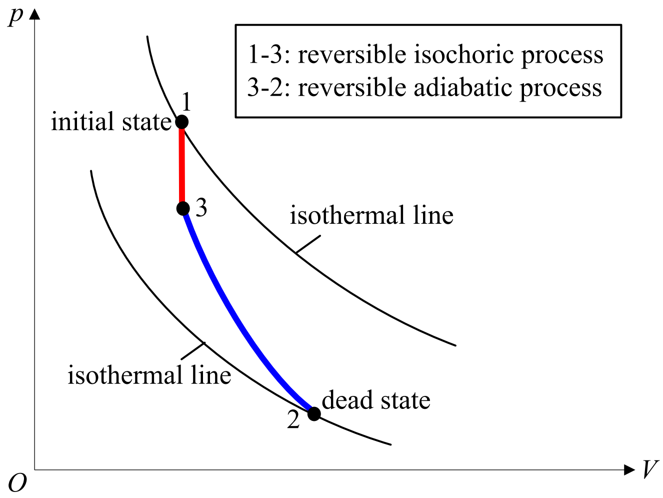

Figure 1. A thermodynamic system undergoes a reversible isochoric and reversible adiabatic processes from a specified initial state to a dead state.

assumed that the system first undergoes a reversible isochoric process 1–3 from the initial state 1 to the intermediate state 3 and then undergoes a reversible adiabatic process (i.e. an isentropic process) 3–2, arriving at the dead state 2, as shown in figure 1. In this way, the reversible heat interaction (process 1–3) and the reversible work interaction (process 3–2) between the system and the environment can be discussed separately.

In the reversible isochoric process 1–3, the volume of the closed system remains constant; there is only heat interaction but no work interaction between the closed system and the environment. A reversible process cannot involve any heat transfer across a finite temperature difference. Therefore, to ensure that process 1–3 is reversible and thereby can output the maximum useful work, in a heat interaction, any heat transfer between the system and the environment must occur through a reversible heat engine running between them. By infinite number of reversible heat engines, the total useful work delivered as the closed system undergoes process 1–3 is

$$W_{\text{heat interaction}} = \int_1^3 \left(\frac{T_0}{T} - 1\right)\delta Q > 0, \tag{2}$$

which is the contribution from the reversible heat interaction to the exergy of the closed system. Meanwhile, the heat released to the environment by the reversible heat engines is

$$Q_0 = -\int_1^3 T_0 \frac{\delta Q}{T}. \tag{3}$$

Substituting the definition of Clausius entropy, $\mathrm{d}S = (\delta Q/T)_{\text{int rev}}$ and the constant entropy relationship in the reversible adiabatic process 3–2, $S_3 = S_2 = S_0$, into the equation above, we obtain

$$Q_0 = -T_0 \int_1^3 \frac{\delta Q}{T} = -T_0(S_0 - S) = T_0(S - S_0). \tag{4}$$

Equation (4) shows that $T_0(S - S_0)$ in the exergy expression of a closed system (equation (1)) represents the heat exchanges during the reversible heat interaction between the closed system and the environment, Q_0, which is the unavailable energy in the reversible heat interaction between the system and the environment.

In the reversible adiabatic process 3–2 shown in figure 1, there is no heat interaction but only work interaction between the system and the environment. The work done by the closed system through reversible volume expansion is $W = \int_3^2 p\mathrm{d}V > 0$; at the same time, the non-useful work done by the closed system by compressing the surrounding medium in the expansion process is $W_0 = p_0(V_0 - V) > 0$. The contribution to the exergy of the closed system by the reversible work interaction is calculated by subtracting W_0 from W:

$$W_{\text{work interaction}} = \int_3^2 p\mathrm{d}V - p_0(V_0 - V). \tag{5}$$

Summing $W_{\text{heat interaction}}$ and $W_{\text{work interaction}}$, we obtain

$$\begin{aligned} W_{\text{heat interaction}} + W_{\text{work interaction}} &= \int_1^3 \left(\frac{T_0}{T} - 1\right)\delta Q + \int_3^2 p\mathrm{d}V - p_0(V_0 - V) \\ &= T_0 \int_1^3 \frac{\delta Q}{T} - \int_1^3 \delta Q + \int_3^2 \delta W - p_0(V_0 - V) \\ &= T_0(S_0 - S) - (U_3 - U_1) + (U_3 - U_2) + p_0(V - V_0) \\ &= U - U_0 - T_0(S - S_0) - p_0(V_0 - V) \\ &= E_{x,U}, \end{aligned}$$

which is the expression for the exergy of a closed system (equation (1)).

According to $Q_0 = T_0(S - S_0)$ and $W_0 = p_0(V_0 - V)$, the exergy of a closed system can be expressed as

$$E_{x,U} = \underbrace{U - U_0}_{-\Delta U} - \underbrace{T_0(S - S_0)}_{Q_0} - \underbrace{p_0(V_0 - V)}_{W_0}. \tag{6}$$

Equation (6) shows that when a closed system reaches the dead state from the initial state, the remaining energy, after the unavailable energy in the reversible heat and work interactions between the system and the environment is subtracted from the reduced internal energy of the system $U - U_0$, is the exergy of the closed system. It can be seen that under the constraints of the environment, the internal energy of a system cannot be completely used to do useful work. Q_0 and W_0 in equation (6) reflect the extent of the constraints during the reversible heat interaction and reversible work interaction, respectively.

The definition of exergy involves three aspects: a thermodynamic system, the environment, and the user (i.e. the output object of useful work). When a thermodynamic system is doing useful work to the user, the amount of useful work the user obtains is subject to environmental conditions. This is analogous to farming, in that the amount of harvest depends not only on how much effort the farmers put in but also on the environmental (weather) conditions, as shown in figure 2.

2.2. The macroscopic physical meaning of entropy

Equation (4) can be rewritten to express the property of entropy as

$$S = \frac{Q_0}{T_0} + S_0. \tag{7}$$

Generally, the dead-state pressure and temperature, p_0 and T_0, are taken as the typical environment conditions, such as 1 atm and 25 °C [1], and then, the entropy of a closed system

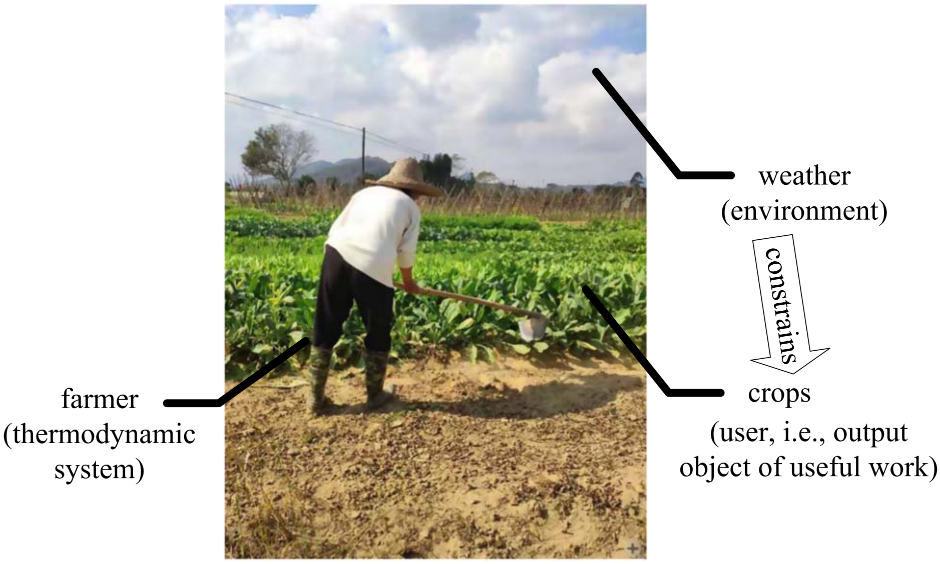

Figure 2. Illustration of the three aspects of the exergy definition using farming as an analogy.

with the designated compositions at dead state, S_0, is a fixed value. In this way, equation (7) shows the positive proportional relationship between S and Q_0, that is

$$S \propto Q_0. \tag{8}$$

As shown in equation (8), the macroscopic physical meaning of entropy can be expressed as follows: the property of entropy is a measure of the unavailable energy of a system in a reversible heat interaction with the environment or entropy represents the unavailable energy at a unit ambient temperature during a reversible heat interaction between a system and the environment. The greater the entropy of a system is, the more unavailable energy there is during the reversible heat interaction between the system and the environment. Here, we emphasise the specific condition of 'reversible heat interaction', because in a reversible work interaction (i.e. process 3–2 in figure 1), the system undergoes a reversible adiabatic process, and the entropy of a system remains constant. In other words, reversible work interaction has no effect on the entropy of a system.

As mentioned in the introduction part, the usage of 'generate more entropy [19]' and 'more entropy is contained in an object [20]' in the literature endow entropy with the characteristics of a substance. Moreover, the substance metaphor is helpful to model how the quantity of entropy are stored in, and flow into or out of systems [18] (which is also referred to as entropy transfer). By doing so, the entropy balance equation can be derived (see equation (11) in section 2.3). Thus, the substance metaphor may provide another possible way to understand the concept of entropy. However, Haglund *et al* [18] found from a questionnaire study that students did not consider entropy to be a substance-like entity. By contrast, students considered energy to be a substance-like entity. The physical interpretation of the aforementioned presentation of entropy as 'entropy is a measure of the unavailable energy of a system in a reversible heat interaction with the environment', or alternatively, 'entropy represents the unavailable energy at a unit ambient temperature during a reversible heat interaction between a system and the environment' shows that entropy is a certain kind of

Table 1. A comparison between the two expressions of entropy to demonstrate the role of T_0.

Expression of entropy	$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}}$ or $\Delta S = \int \left(\frac{\delta Q}{T}\right)_{\text{int rev}}$	$S = \frac{Q_0}{T_0} + S_0$
Characteristics	1. Differential or integral expression	1. Direct expression
	2. Unrelated to ambient temperature	2. With the aid of the concept of exergy, which is related to both the system and the environment, the ambient temperature T_0 appears
	3. Difficult to give a macroscopic physical meaning of entropy by this definition in a direct way	3. The macroscopic physical meaning of entropy is obtainable

energy. This interpretation of entropy that relates entropy to energy may help students understand the characteristics of a substance of entropy.

It is worth noting that in the derivation of equation (6), the reversible heat interaction (process 1–3) and the reversible work interaction (process 3–2) between the system and the environment are discussed separately. Therefore, during the reversible heat interaction, no work input/output occurs, while during the reversible work interaction, there is no heat transfer into/out of the system (i.e. adiabatic process). Under this circumstance, the conclusion that 'a reversible work interaction has no effect on the entropy of a system' is drawn. However, if a system, instead of remaining adiabatic, exchanges heat with its environment while exchanging work with the environment in a certain reversible process, the entropy of the system will change in this process (for an ideal gas, its entropy change can be calculated by the relation $\Delta S = C_V \ln(T_f/T_i) + n\, R \ln\,(V_f/V_i)$), where the subscripts 'f' and 'i' denote the final and initial states, respectively.

Next, let us discuss the role of the ambient temperature T_0 in understanding the physical meaning of entropy based on the concept of exergy. We know that in geometric proofs, especially some difficult ones, it is sometimes necessary to add one or several line segments to the original graph to help us complete the proof. This additional line segment is called auxiliary line. The addition of auxiliary lines often helps us reveal information that is not directly visible in the graph. For example, an auxiliary line can build logical relationships between two or more seemingly unrelated objects through a transformation to simplify the proofs. Table 1 gives two expressions of entropy and summarises the characteristics of the two expressions. It can be seen that, before the introduction of the parameter T_0, a macroscopic physical meaning of entropy cannot be intuitively derived by only the Clausius definition of entropy. With the aid of T_0, the physical quantity S (instead of its differential form dS) appears explicitly in the expression of the exergy so that the physical meaning of S is directly apparent. Thus, the ambient temperature T_0, in understanding the physical meaning of entropy using the concept of exergy, plays a similar role as auxiliary lines in geometric proofs.

In the above analysis, with the help of $T_0(S - S_0)$, we can better understand the physical meaning of the entropy S. Similarly, according to equation (6) we can also express the property of volume V as

$$V = -\frac{W_0}{p_0} + V_0. \tag{9}$$

With constant environmental parameters T_0 and p_0, for a closed system with a designated composition, V_0 (the volume of the system at the dead state) is a fixed value. Therefore, the physical meaning of the volume V can also be understood as follows: the property of volume is a measure of the unavailable energy during the reversible work interaction between a system and the environment. The larger the volume of a system is, the less unavailable energy there is during the reversible work interaction between the system and the environment. Similarly, we emphasise the specific condition of the 'reversible work interaction', because in a reversible heat interaction (i.e. process 1–3 in figure 1), the system undergoes an isochoric process and the volume of the system remains constant. In other words, the reversible heat interaction has no effect on the volume of a system.

Of course, the volume is a property that can be directly measured, and it is usually not necessary to use equation (9) to help us understand its physical meaning, but the above analysis provides us another way of understanding the volume.

2.3. Answers to the three questions raised in the Introduction

After analysing the macroscopic physical meaning of entropy based on the concept of exergy (available energy), we can answer the three questions raised in the introduction as follows.

Question 1. I have derived the value of entropy transfer, entropy change, or entropy generation, but what exactly are 'transferred', 'changed', and 'generated'?

Answer. Let us first look at the meaning of entropy transfer. According to the second law of thermodynamics, it is impossible for heat to be completely converted into work continuously, and the portion that cannot be converted is called the unavailable energy of heat. A differential amount of heat transfer, δQ, can be written as the sum of the available part and the unavailable part, that is

$$\delta Q = \underbrace{\left(1 - \frac{T_0}{T}\right)\delta Q}_{\text{available part}} + \underbrace{\frac{T_0}{T}\delta Q}_{\text{unavailable part}}. \tag{10}$$

The second term on the right-hand side of the above equation divided by the ambient temperature T_0 is the entropy transfer by heat transfer $\frac{\delta Q}{T}$. It can be seen that entropy transfer by heat transfer actually represents the transfer of the unavailable energy of heat. Next, let us look at the meaning of entropy change and entropy generation. As shown in section 2.2, entropy is a measure of the unavailable energy of a system in a reversible heat interaction with the environment. Therefore, entropy 'change' and entropy 'generation' are actually the 'change' and 'generation' of the unavailable energy that are measured by entropy.

Considering that, as shown in Christensen *et al*'s questionnaire study [17], some students may hold the erroneous view that the total entropy is conserved in a process, it must be emphasised that the engineering use of the term 'entropy transfer' does not negate the non-conservation property of entropy. The term 'entropy transfer', together with the terms 'entropy change' and 'entropy generation', constitutes an entropy balance equation, that is [20]

$$\begin{bmatrix}\text{change in the amount of}\\\text{entropy contained within}\\\text{the system during some}\\\text{time interval}\end{bmatrix}=\begin{bmatrix}\text{net amount of}\\\text{entropy transferred in}\\\text{across the system}\\\text{boundary during the}\\\text{time interval}\end{bmatrix}+\begin{bmatrix}\text{amount of entropy produced}\\\text{within the system}\\\text{during the time interval}\end{bmatrix}. \tag{11}$$

The non-conservation property of entropy is reflected by the second term (i.e. entropy production or entropy generation) on the right hand side of the above equation.

Question 2. In our daily lives, the quantities of things usually decrease due to consumption; why is there a principle of entropy increase?

Answer. By observing the things around us, it is not difficult to determine that the amounts of things that are precious and useful are continuing to decrease, while the amounts of things that are discarded and useless are continuing to increase. For example, the amount of printing paper in a tray will decrease, while the amount of wastepaper in a trash bin will increase over time. Based on the interpretation of the macroscopic physical meaning of entropy in section 2.2, entropy is a measure of unavailable energy. This unavailable energy is discarded and useless energy, and thus, the entropy of an isolated system always increases. In contrast, exergy is a precious and useful energy and will be consumed and naturally decrease.

Question 3. Exergy is transferred to or from a system by both heat transfer and work transfer, but why entropy is transferred only by heat transfer (i.e. why is entropy not transferred by work transfer)?

Answer. As mentioned in section 2.2, entropy is a measure of the unavailable energy of a system during a reversible heat interaction with its environment. Therefore, entropy transfer represents the transfer of this unavailable energy. This means that the entropy transfer during a work interaction is zero, regardless of the form of work. Thus, no entropy is transferred by work transfer. In contrast, it is known from the second law of thermodynamics that heat cannot be completely converted into work continuously, and thus heat transfer is always accompanied by a transfer of unavailable energy. Based on the relationship between entropy transfer and the transfer of unavailable energy during heat interaction, we know that entropy is always transferred by heat transfer.

3. Which one do you prefer, exergy or entropy?

We conducted a questionnaire survey on this question to undergraduate students from three universities. The questionnaire was issued in Chinese but is translated into English and presented in appendix A. These undergraduate students are from Peking University (PKU), Huazhong University of Science and Technology (HUST), and Nanjing University of Aeronautics and Astronautics (NUAA). Among the universities in China, PKU ranks in the top 2, HUST ranks around 10th, and NUAA ranks around 50th. In PKU, the engineering thermodynamics course is offered in the third year, so the questionnaire was conducted for Juniors. In the other two universities, the engineering thermodynamics course is offered in the

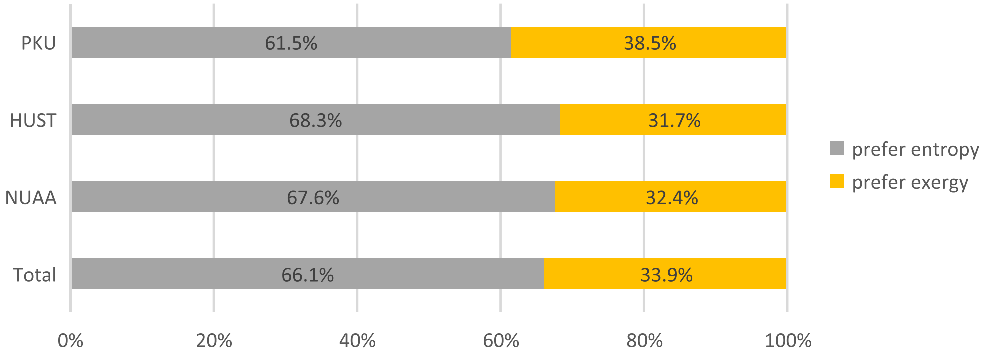

Figure 3. Statistical results of the question 'Which one do you prefer, exergy or entropy?'.

Table 2. Statistical results of the reasons for preferring entropy.

Option	Reason	Percentage of those who selected the choice
A	The expression of entropy is simple, while the expression of exergy contains many environment-related parameters that are difficult to remember.	57.2%
B	The entropy of a system is only related to the state of the system and is unrelated to the environment; in contrast, the exergy of a system is not only related to the state of the system but also related to the state of the environment, making it too complicated.	56.5%
C	The entropy balance equation contains fewer terms, while the exergy balance equation contains more terms.	27.1%
D	Other.	13.4%

second year, so the questionnaire was conducted for Sophomores. After the lecturer introduced the concepts of entropy and exergy in class, the copies of questionnaire were distributed to the students and were collected in class after the students completed the questionnaire. A total of 442 copies were collected, including 130, 164, and 148 copies from PKU, HUST, and NUAA, respectively.

Regarding the question 'Which one do you prefer, exergy or entropy?' (i.e. Question 3 in the questionnaire), the statistical results shown in figure 3 indicate that the students from the three universities prefer entropy. Overall, more participants (66.1%, approximately 2/3) prefer entropy.

The statistical results of the reasons for preferring entropy (i.e. Question 5 in the questionnaire) are shown in table 2. Compared with options A and B, the number of students who chose option C is smaller. One possible reason is that after learning entropy and exergy, the students have a certain understanding of the definition and expression of the two physical quantities. Options A and B explain and compare the definitions and expressions of entropy and exergy. Therefore, it is easier for students to choose A or B, while option C involves a balance equation of entropy and exergy. Many students have certain difficulties in understanding the definition of entropy and exergy. It may be more difficult for them to understand the balance equations that are derived based on the definitions of entropy and exergy. Many

Table 3. Statistical results of the reasons for preferring exergy.

Option	Reason	Percentage of those who selected the choice
A	Exergy has a clear macroscopic physical meaning, while entropy does not.	63.3%
B	Exergy has units of energy, Joules (J), making it more sensible; in contrast, the unit of entropy is $\mathrm{J\,K^{-1}}$, and students do not understand what $1\ \mathrm{J\,K^{-1}}$ means.	42.7%
C	Other.	13.3%

students may be unfamiliar with these balance equations and therefore would not choose option C.

The statistical results of the reasons for preferring exergy (i.e. Question 4 in the questionnaire) are shown in table 3. Note that because Questions 4 and 5 are both multiple-choice questions (e.g. some people may have selected both A and B), the sum of the percentages of the various choices is greater than 100% in tables 2 and 3.

For Questions 4 and 5 of the questionnaire, we also set an open option (option C for Question 4 and D for Question 5), hoping to learn more reasons for the preference for exergy or entropy. According to the results of the survey, 39 of the 292 students who prefer entropy chose option 'D. Other' in Question 5. The reasons given by the students are diverse, and the two most frequent reasons are as follows: (1) They have learned entropy in other lectures either in high school or in the first year of college, making entropy more familiar/intimate (14 out of 39 student expressed such an opinion, accounting for 35.9%); (2) Entropy is a more essential physical quantity of a system, and it is also used in fields other than thermodynamics (such as social science), but exergy is generally only used when analysing an engineering system (12 out of 39 students expressed such an opinion, accounting for 30.8%). Among the 150 students who prefer exergy, 20 students chose the option 'C. Other' in Question 4. The three most frequent reasons are as follows: (1) Exergy is more suitable for analysing engineering problems and can reflect economic efficiency (7 out of 20 students expressed such an opinion, accounting for 35%); (2) It is easier to understand exergy (6 out of 20 expressed such an opinion, accounting for 30%); (3) Exergy is a type of energy in a higher class/can be infinitely converted, which is great (4 out of 20 expressed such an opinion, accounting for 20%).

Before asking the students whether they prefer exergy or entropy, we investigated the students' evaluation and understanding of the engineering thermodynamics course (by considering the responses to Question 2 in the questionnaire). Different numbers of students chose each of the four options A–D. In addition, different proportions were chosen for each option by the students among the three universities, which may be related to the overall study performance of the students at the three universities. (Detailed data and further discussion are presented in appendix B.)

To further understand the preference for entropy or exergy among students with different degrees of understanding engineering thermodynamics, we made cross-tabulation on the feedback of Questions 2 and 3 in the questionnaire. The results are shown in figure 4. We found that, although the number of students that chose each of the four options A to D in Question 2 is different, the proportions of students preferring entropy and exergy for each option are approximately 2/3 and 1/3, respectively. This proportion is consistent with the overall proportion of preference for entropy and exergy, indicating that the students'

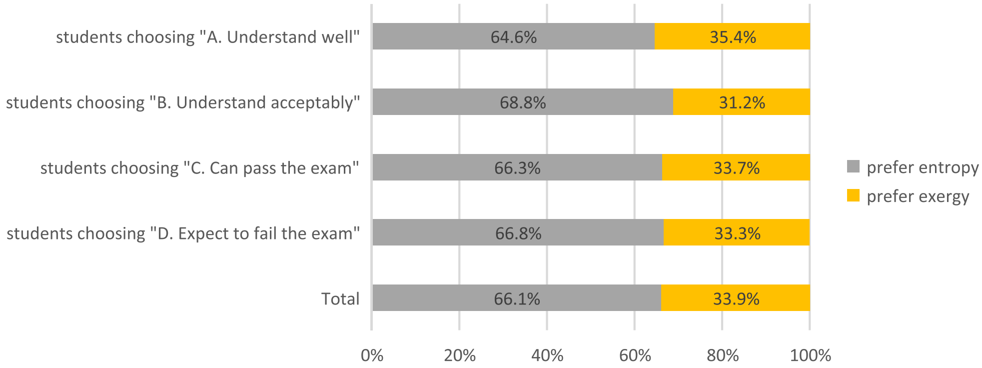

Figure 4. Cross-tabulation results of the preference for entropy or exergy among students with different degrees of understanding engineering thermodynamics.

understanding of thermodynamics is not quite related to their preference for entropy or exergy.

At the end of the questionnaire, we invited students to write down their expectations about improvements in the content or methods of the lectures regarding entropy and exergy (i.e. Question 6 of the questionnaire). Of the 442 copies collected, 145 were empty, and the remaining 297 (approximately 70% of the total survey) were filled with suggestions. After analysis, we found the following suggestions appeared most frequently: (1) Give more application examples of entropy and exergy/enhance practical application (121 of 297 students expressed such opinions, accounting for 40.7%); (2) Use more vivid and straightforward methods to explain entropy and exergy (45 of 297 students expressed such opinions, accounting for 15.2%); (3) Spend more time explaining entropy and exergy in more detail (38 of 297 students expressed similar opinions, accounting for 12.8%); (4) Clarify the connection and difference between entropy and exergy in detail to avoid confusion/provide a more detailed comparison to determine the characteristics of each quantity (20 of 297 students expressed such opinions, accounting for 6.7%); (5) Help students understand the physical essence of entropy and exergy (17 of 297 students expressed such opinions, accounting for 5.7%). The remaining small number of suggestions included, for instance, 'hope to have better textbooks', 'hope that the teacher is more passionate' (the number of each type of suggestion is smaller than 3) and are not listed here.

I am delighted to see that the method of both distinguishing between entropy and exergy and relating entropy to exergy, as well as the method of using examples from daily life to explain entropy and exergy, are consistent with the students' suggestions in (2) and (4) above. The exploration of the macroscopic physical nature of entropy in this study is also in line with suggestion (5) above. This result also motivates me to make more attempts at teaching entropy and exergy in these three aspects in the future.

In the past several years of teaching the course of engineering thermodynamics, I always spend approximately 25 min explaining the content of section 2 of this study after lecturing on entropy and exergy. Afterwards, I always listen to the students' feedback. Students generally report that this part of the content is very helpful for them in terms of understanding the concept of entropy. The method of explaining the macroscopic physical meaning of entropy using the concept of exergy, which is based on rigorous mathematical derivation, makes the students convinced of the results. At the same time, these mathematical derivations are not too complicated, and the concept of exergy is also familiar to students, making it less difficult for the students to understand the content of this part. The contents that are associated with examples in daily life are also very vivid and greatly engage the students. Some students even proposed to put this part into textbooks. Two students later emailed me short essays based on their own observations and experiences about the connection between entropy and examples in daily life (I did not give the assignment to them).

As mentioned in the introduction, Cochran and Heron [15] and Christensen *et al* [17] developed tutorials with an increased number of examples on cyclic devices and thermodynamic processes, respectively. This effort is consistent with the students' suggestions in (1). Moreover, the typical use of tutorials for supplementary instruction in standard undergraduate courses and the frequent step-by-step guidance provided to students by a tutorial instructor [15, 17] are reasonably synchronous with suggestion (3) above. In addition, some metaphors have been developed to articulate the concept of entropy, such as 'energy degradation [1, 6]', 'energy spreading [7, 8]', 'energy dispersal [9, 10]', and 'freedom [14]'. Although some of these metaphors have specific limitations, and the study of the usefulness of metaphors for entropy in student education is still in progress, Haglund *et al* [18] have suggested a shift in focus to providing students with a broad range of complementary descriptions and explanations of the concept of entropy. These authors also concluded, in light of the questionnaire findings, that lecturers should strive to develop semiotic resources with high pedagogical affordance to help students understand what entropy is. I agree with the authors' recommendations, which are also in line with the students' suggestion (2) above.

Over 40% of the students suggested that more examples of entropy and exergy should be provided. In fact, students do not perform well on exergy/entropy-related exercises. Evidence for this claim comes from the final test of the engineering thermodynamics course Spring 2019, where 73.3% of the students correctly answered the problem-solving question that was related only to energy, compared to only 38.7% of the students that correctly answered the problem-solving question on entropy. The data are obtained based on a statistics from the 315 final test papers of all of the students in the engineering thermodynamics course this semester. This feedback also prompts me to develop more methods to enhance the teaching of practical applications of entropy/exergy (e.g. re-distributing the semester hours to allot more time for explaning examples involving entropy and exergy, or designing projects on applications of entropy and exergy, which would count towards the course grade and thus not jeopardise the lecture time).

4. Concluding remarks

Entropy is a central concept in thermodynamics that students find abstract and do not fully appreciate. Previous researchers have made numerous attempts to provide adequate explanations of entropy by using concepts such as 'energy degradation', 'energy spreading', 'energy dispersal', and 'freedom'. Some lecturers have performed questionnaire studies and designed tutorials/instructions to develop better methods for teaching entropy and the second law of thermodynamics. In this study, another explanation of entropy is offered that is based on the concept of exergy/available energy. A macroscopic interpretation of entropy is as a measure of the unavailable energy of a system in a reversible heat interaction with the environment or the unavailable energy at a unit ambient temperature during a reversible heat interaction between a system and the environment. This interpretation of entropy that relates entropy to energy may help students understand the characteristics of a substance of entropy because students regard energy to be a substance-like entity.

The results of the questionnaire show that approximately two-thirds of the students expressed a preference for entropy over exergy, and a student's grasp of a thermodynamics course is unrelated to a preference for the concept of entropy. This finding is somewhat surprising because the concept of entropy has been recognised as being much more abstract and difficult to understand than the concept of exergy, which with a clear macroscopic physical meaning and units of energy would be the more rational preference. Thus, there appears to be little correlation between the students' preference for a concept and the difficulty of understanding the same concept. This finding should encourage lecturers to develop more approaches to help students better understand entropy because of their preference for the concept. Note that although the students overwhelmingly (2/3) prefer entropy, from an engineering perspective, the concept of exergy (as related to the maximum work available) is still important and thus should be treated as an important concept in the teaching of engineering thermodynamics.

From the students' suggestions of which aspects of the course they would like the lecturer to improve when teaching entropy/exergy, we found that the method of both distinguishing between entropy and exergy and relating entropy to exergy, as well as the method of using examples in daily life, as shown in section 2, are both consistent with the suggestions that the students frequently mentioned in the questionnaire. The development of tutorials by some lecturers and the use of various metaphors for entropy are also in line with the most frequent suggestions made by students.

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Appendix A. Questionnaire: exergy and entropy of engineering thermodynamics. Which one do you prefer?

Hello, I am a lecturer for the course 'Engineering Thermodynamics' at the School of Energy and Power Engineering, Huazhong University of Science and Technology. I am conducting a survey on students' preferences for some basic thermodynamic concepts. I would like to invite you to take a few minutes to help fill out the questionnaire. This questionnaire is anonymous. All data are only used for statistical analysis. Please feel free to fill it out. **There are no right or wrong answers, and I hope you can express yourself freely** and fill in the questionnaire according to your actual situation. Thank you very much for your help!

1: Which year of college are you in?

A. First year B. Second year C. Third year D. I am a graduate student.

2: Which of the followings best matches your evaluation and understanding of 'Engineering Thermodynamics' (single choice)?

A. I like this lecture, I understand it well.

B. Just okay, I understand it acceptably.

C. This is too hard for me, I do not understand it well, but should be able to pass the exam.

D. I have no clue, I may fail the exam.

E. Other____________________(I sincerely hope that you write down your evaluation and understanding of this lecture.)

3: Frankly speaking, the concepts of entropy and exergy (also known as available energy or availability) involved in the second law of thermodynamics are difficult to understand. Comparing the two concepts, do you feel that:

A. You prefer exergy (if you choose this option, please continue with Question 4 and skip Question 5).

B. You prefer entropy (if you choose this option, please skip Question 4 and continue with Question 5).

4: The reasons for your preference for exergy (multiple answers allowed):

A. Exergy has a clear macroscopic physical meaning (the potential of a system to do work), while entropy does not, and I do not know what entropy is.

B. Exergy has the units of energy in Joule (J), which is sensible, while the unit of entropy is J K^{-1}, and I do not know what 1 J K^{-1} represents.

C. Other____________________(I sincerely hope that you write down your reasons for your preference for exergy).

5: The reasons for your preference for entropy (multiple choice allowed):

A. The expression of entropy is simple; the expression of exergy contains many parameters that are related to the environment (p_0, V_0, T_0, S_0), which is difficult to remember.

B. Entropy of a system is only related to the state of the system and unrelated to the environment; the exergy of a system is not only related to the state of the system but also related to the state of the environment, which is too complicated.

C. The balance equation of entropy contains fewer terms, while the balance equation of exergy contains more terms.

D. Other____________________(I sincerely hope that you write down your reasons for your preference for entropy).

6:Which aspects regarding the teaching content or methods of the lectures about entropy and exergy do you expect improvements in?

I expect that____________________

****

This is the end of the questionnaire.

Thank you very much for your participation and valuable suggestions!

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Appendix B. Questionnaire survey results for Question 2

The questionnaire survey results for Question 2 are shown in figure A1. Different numbers of students chose each of the four options A–D. In addition, different proportions were chosen for each option by the students among the three universities. Option A (understand well) was chosen by most (52.3%) of the students at PKU, by slightly fewer (40.2%) students at HUST and by the lowest number (16.2%) of students at NUAA, where a larger percentage (37.2%) of students chose option B (understand acceptably). The number of students at NUAA who chose option D (expect to fail the exam) was significantly higher (21.6%) than at the other universities. Only 1.5% and 3.0% of the students at PKU and HUST chose option D. This result may be related to the overall study performance of students at the three universities.

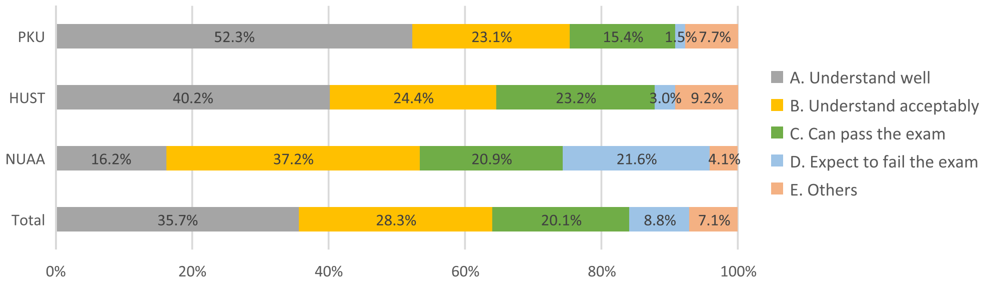

Figure A1. Statistical results for students' evaluation and understanding of an engineering thermodynamics course.

Note that we also designed an open option (i.e. option E) in Question 2 to allow students to freely evaluate and express their understanding of the engineering thermodynamics course. As this is an open question, the answers were very diverse. However, as many as 71% of the students who chose option E expressed the opinions that they 'like this lecture/find the lecture very interesting/hope to learn it well, but at the same time feel the lecture difficult/understand it poorly/understand it only acceptably'. We know that, in taking a survey, many people (including myself) are more willing to choose an option that can be directly checked rather than an open option that requires the expression of opinions. These students voluntarily chose option E and expressed opinions indicating an intense willingness to express that they 'like thermodynamics/find thermodynamics very interesting/hope to learn it well'.

As a lecturer of this course, I am very happy to find that so many students like this course. At the same time, I perceive distress from the students' responses that thermodynamics is a difficult subject, which they understand poorly or only acceptably. Therefore, I especially hope that more methods can be used to minimise the difficulties students have in learning thermodynamics, such as introducing some of the excellent textbooks on thermodynamics that are available in English from Europe and the United States into teaching or improving teaching methods of theories or concepts. This study is precisely an attempt to provide a method of understanding entropy via the interplay between entropy and exergy, in the hope that this method will make entropy/exergy, and therefore thermodynamics, easier to learn.

ORCID iDs

Jing Wu https://orcid.org/0000-0003-0873-3092

References

[1] Cengel Y A and Boles A M 2015 *Thermodynamics: An Engineering Approach* 8th edn (Boston, MA: McGraw-Hill) pp 329, 343-347, 421-422, 433, 463-466, 784
[2] Leff H S 2012 Removing the mystery of entropy and thermodynamics: V *Phys. Teach.* **50** 274–6
[3] Kostic M M 2014 The elusive nature of entropy and its physical meaning *Entropy* **16** 953–67
[4] Prigogine I 1989 What is entropy? *Naturwissenschaften* **76** 1–8
[5] Tribus M and Mclrvine E C 1971 Energy and information *Sci. Am.* **225** 179–84
[6] Kostic M M 2011 Revisiting the second law of energy degradation and entropy generation: from Sadi Carnot's ingenious reasoning to holistic generalization *AIP Conf. Proc.* **1411** 327–50
[7] Leff H S 2012 Removing the mystery of entropy and thermodynamics: II *Phys. Teach.* **50** 87–90

[8] Leff H S 1996 Thermodynamic entropy: the spreading and sharing of energy *Am. J. Phys.* **64** 1261–71
[9] Lambert F L 2002 Entropy is simple, qualitatively *J. Chem. Educ.* **79** 1241–6
[10] Wei R, Reed W, Hu J and Xu C 2014 Energy spreading or disorder? Understanding entropy from the perspective of energy *Teaching and Learning of Energy in K-12 Education* ed R F Chen *et al* (Cham: Springer) pp 317–35
[11] Langbeheim E, Safran S A and Yerushalmi E 2014 Visualizing the entropy change of a thermal reservoir *J. Chem. Educ.* **91** 380–5
[12] Gyftopoulos E P and Beretta G P 2005 *Thermodynamics: Foundations and Applications* (New York: Dover) pp 102–3 108
[13] Gyftopoulos E P 2011 Thermodynamics: generalized available energy and availability or exergy *Thermodynamics and the Destruction of Resources* ed B R Bakshi *et al* (New York: Cambridge University Press) pp 15–44
[14] Styer D F 2000 Insight into entropy *Am. J. Phys.* **68** 1090–6
[15] Cochran M J and Heron P R 2006 Development and assessment of research based tutorials on heat engines and the second law of thermodynamics *Am. J. Phys.* **74** 734–41
[16] Bucher M 2007 Comment on 'development and assessment of research-based tutorials on heat engines and the second law of thermodynamics', by Matthew J Cochran and Paula R L Heron [Am. J. Phys. 74 (8), 734–741 (2006)] *Am. J. Phys.* **75** 377
[17] Christensen W M, Meltzer D E and Ogilvie C A 2009 Student ideas regarding entropy and the second law of thermodynamics in an introductory physics course *Am. J. Phys.* **77** 907–17
[18] Haglund J, Andersson S and Elmgren M 2016 Language aspects of engineering students' view of entropy *Chem. Educ. Res. Pract.* **17** 489–508
[19] Atkins P W 1998 *Physical Chemistry* 6th edn (Oxford: Oxford University Press) pp 102
[20] Herrmann F 2000 The karlsruhe physics course *Eur. J. Phys.* **21** 49–58
[21] Sciubba E and Wall G 2007 A brief commented history of exergy from the beginnings to 2004 *Int. J. Thermodynamics* **10** 1–26
[22] Moran J M, Shapiro N H, Boettner D D and Bailey B M 2011 *Fundamentals of Engineering Thermodynamics* 7th edn (New York: Wiley) pp 281, 295, 359, 365, 817-821
[23] Wu J 2015 Three factors causing the thermal efficiency of a heat engine to be less than unity and their relevance to daily life *Eur. J. Phys.* **36** 015008
[24] Cápek V and Sheehan D P 2005 *Challenges to the Second Law of Thermodynamics: Theory and Experiment* (Dordrecht: Springer) pp 11–2
[25] Saslow W M 1999 An economic analogy to thermodynamics *Am. J. Phys.* **67** 1239–47
[26] Emden R 1938 Why do we have winter heating? *Nature* **141** 908–9
[27] Volkenstein M V 2009 *Entropy and Information* (Basel: Birkhäuser Verlag AG) pp 59–61
[28] Rant Z 1955 Energy value and pricing *Strojniški Vestnik* **1** 4–8