Redefining the Teaching of Enthalpy and Entropy in Thermodynamics

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CONTEXT

This paper pertained to the teaching of Thermodynamics which is a subject focusing on the transformation of energy in engineering systems, common in Chemical or Mechanical Engineering. The concepts of enthalpy and entropy introduced are two of the toughest aspects in the subject, not easily understood by students. This could be due to the way in which these two concepts are introduced: enthalpy is introduced as a measure of energy level while entropy is introduced as a measure of disorder. A possible clearer approach, which is the motivation of this report, is to introduce these two concepts as mathematical conveniences of thermodynamics. This will redefine the way in teaching Thermodynamics.

PURPOSE

The purpose of this paper was to introduce the teaching of enthalpy and entropy as mathematical conveniences in Thermodynamics. This will provide an alternative to teaching these concepts from the phenomenal approach to help the students understand these concepts better.

APPROACH

The report was prepared based on the author's 5 years (10 semesters) experience teaching Thermodynamics. During the five years of teaching, there was a gradual change in from teaching the two concepts via a phenomenological approach to a mathematical convenience approach.

RESULTS

The new approach introduced allowed a better understanding on the purpose of the two concepts in Thermodynamics. Enthalpy is mainly a convenient approach to calculate two fluid properties simultaneously. The ambiguity of associating entropy as a measure of disorder in engineering application was also elucidated.

CONCLUSIONS

This new approach to teaching the concept of enthalpy and entropy in Thermodynamics allowed a clearer understanding of the concepts. Such an understanding will be particularly important when tying the concept back to practical engineering applications.

KEYWORDS

Thermodynamics, enthalpy, entropy.

Introduction

Thermodynamics is a study on the transformation and utilization of energy. As the name of the unit suggests, "thermo" delineates energy while "dynamics" refers movement, hence, it is a study on the movement of energy within engineering systems and the surroundings. This is a core unit of study in many branches of engineering, particularly Chemical Engineering and Mechanical Engineering. From the author's five years' experience teaching this unit, two concepts taught in thermodynamics which students find challenging are: enthalpy and entropy. Students are often confused on (1) what are these properties? (2) why do we need these properties? Without redefining the concept of enthalpy and entropy, this paper presents insights and strategies on how to teach this more effectively. In order to appreciate the ideas and best practice put forward in this paper, it will be important to firstly understand the historical context of this subject.

Historically, this branch of study was formally conceptualized in the pursuit to better understand the efficiency of steam cycles (engine). The father of thermodynamics leading this formal treatment is Sadi Carnot, an engineer in France. This led to further development on the concept of entropy by Rudolph Clausius and in developing the understanding of energy; from this came the concept of enthalpy. For these reasons, in most textbooks, these concepts are taught from the perspectives of steam engines, pistons, heat exchangers etc. This is sometimes referred to as classical thermodynamics (Cengel and Boles 2011).

The understanding developed, however, can be generalized to other non-classical engineering systems, as energy transformation is ubiquitous. William Gibbs adopted the concept of second law of thermodynamics and enthalpy to arrive at the famous concept of Gibbs free energy for chemistry application. Ludwig Boltzman studying the dispersion of gases, found that the degree of disorder in the energy levels of the gas particles could be described by the entropy of the gas (Ben-Naim 2010). Therefore, thermodynamics is also taught in Sciences particularly in Physics and Chemistry, albeit from different perspectives. Thermodynamics can also be examined from the statistical perspective; a more advanced learning typically beyond the scope of most undergraduate study.

Specific to Chemical Engineering, in view that thermodynamics is useful to describe the state of a chemical system, there is normally a second "chemical thermodynamics" course taught as part of the curriculum. Differentiating from classical thermodynamics, the concepts of entropy and enthalpy is then used or taught leaning towards the chemistry or physico-chemistry perspectives. Sometimes, classical and chemical thermodynamics are taught in a single unit, with emphasis on either one of the aspects. There may be curriculum in which only the chemical thermodynamics is taught. Such a combination of classical and chemical thermodynamics is also reflected in many thermodynamics textbooks particularly those pertaining to Chemical Engineering.

The strategies, which will be discussed in this paper, originated from the perspective of the classical thermodynamics. The author has 5 years' experience teaching classical thermodynamics in two units CHE2164 and MAE2402 in Monash University. CHE2164 is a unit in Chemical Engineering and typically comprises 60-70% Chemical Engineering and 40-30% Mechanical Engineering students. The class size is normally between 130-220. Chemical Thermodynamics is taught separately in another unit in the third year. MAE2402 is a unit in Mechanical Aerospace Engineering unit with a class size of about 60-90 students. In these two units, for each semester, there is small number of double degree students with the Faculty of Science; which contributed to the discussion of these two concepts from different perspectives.

The insights and suggestions described in this paper were not obtained via a formal research programme. Hence, there was no detailed student feedback or evaluation on these strategies. Rather, the ideas were obtained mainly from iterating the teaching method over the years, driven by questions (misunderstanding) raised by student during lecture and consultations on the concept of enthalpy and entropy.

Strategies on Teaching Enthalpy

The main challenge in teaching this concept is in giving a physical definition or meaning to enthalpy. Students are normally interested in this as part of the process of grasping this abstract idea. This state property is mathematically defined as,

$$H = U + PV \tag{1}$$

where H is enthalpy (J), U is internal energy (J), P is pressure (Pa) and V is volume (m^3). This form of the enthalpy is normally used in the closed system analysis of a system, such as the expansion or compression of a piston etc., where there is no transfer of mass and the analysis is on a fixed mass. For an open system, the derivative of the enthalpy is more applicable and the volume in the second term on the right is normally considered as the derivative,

$$\dot{H} = \dot{U} + P\dot{V} \tag{2}$$

where $\dot{H}$ is enthalpy (J/s), $\dot{U}$ is internal energy (J/s), P is pressure (Pa) and $\dot{V}$ is volume (m^3/s). Let us firstly start the discussion with a closed system. The confusion commonly encountered by student is due to the dimension of enthalpy, which is J. This creates a wrong impression, even amongst practicing engineers, that the enthalpy represents the total energy of the system. It is noteworthy that in the beginning of a classical thermodynamics course, students are typically taught that the total energy of a mass or fluid is the sum of the macroscopic and microscopic energy,

$$E = U + E_K + E_P \tag{3}$$

where E is the total energy (J), E_K is the macro kinetic energy (J) and E_P is the macro potential energy (J). Comparing Equation (2) and (3) which have the same unit, both having the internal energy term, students then becomes confused, as there seemed to be two apparent form of total energy due to the misconception mentioned above. It is then imperative to explain the difference by firstly explaining the meaning of the PV term.

It may be tempting to start by philosophically explaining that the PV term represents the expansion work required by the system to occupy a particular volume V at a pressure P, relative to a hypothetical situation of occupying zero volume. In the author's opinion, this may add more confusion to the students as it implies that the PV term actually represents another type of energy stored within the system in addition to the internal energy, which will be shown later that it is not.

An alternative approach is to examine this from the angle of the boundary work, which is normally covered in another section of the thermodynamic course; the work done to or by the system via expansion or compression. Take the example of an expanding piston from a small volume at high pressure (state 1) to a large volume, which inevitably reduces the pressure within the piston (state 2). The boundary work is computed by integrating the pressure of the piston at each increment,

$$W_B = \int_1^2 P\, dV \tag{4}$$

where W_B is the boundary work (J). This equation implies that work is only done if there is a change in the volume of the system or graphically represented by the area under the $P-V$ curve. Hence, even if the pressure is multiplied by the volume of the system (PV), at any single instance along the expansion process, giving a unit of (J), it does not refer to any transfer of energy. The PV term is simply the potential to expand. To further enforce this idea, the lecture can then explain (and possibly with some calculations) that the PV term of the piston after the expansion is always lower than that at the beginning of the expansion because expansion always go from a state of higher expanding potential to a state of lower expanding potential.

Examining the general open system equation below can further enforce this concept of the potential to expand,

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} + \dot{m}(P_1\hat{v}_1 - P_2\hat{v}_2) = \dot{m}[(\hat{u}_2 - \hat{u}_1) + 0.5({v_2}^2 - {v_1}^2) + g(Z_2 - Z_1)] \tag{5}$$

where the subscripts 1 denotes the inlet and 2 denotes the outlet of the system. $\dot{Q}$ is the rate of heat transfer (J/s), $\dot{W}$ is the rate of work done to or from the system (J/s), $\dot{m}$ is the mass flow rate (kg/s), P is the pressure (Pa), $\hat{v}$ is the specific volume (m^3/kg), v is the velocity (m/s), g is gravitational acceleration (m/s^2) and Z is the elevation (m). Comparing Equation (5) and (3), the right hand side of the equation represent the change in the rate of total energy flow between the inlet and the outlet. Mechanisms leading to these changes are given on the left hand side. The $(P_1\hat{v}_1 - P_2\hat{v}_2)$ term represents the difference in pushing potential between the inlet and the outlet driving the movement of the fluid.

Why go through all this trouble to explain the PV term? These are mainly to show that the PV is not the 'actual' energy but only delineates a potential to 'push or expand' of the system. As this term is combined with the internal energy term in Equation (1) to form the definition of enthalpy, it also implies that enthalpy is also not the 'actual' energy of the system. Therefore one need not put a physical tangible meaning to enthalpy but can simply view it as a mathematically convenient parameter to lump the internal and its potential to push. Quoting a student from a lecture in 2015 "it is a double counting of energy". The lecturer can possibly explain this using the following approach,

"Consider a small piston which has 100J of internal energy. With this amount of energy within the system, the system may be hot and is occupying a volume of 0.01 m^3 with a pressure of 5000 Pa. Therefore, with this 100J, the system has the pushing potential of 50J. The enthalpy of the system is then 150J. Nevertheless, there is still only 100J of total energy within the system."

There are more reasons to support this view of treating enthalpy as a mathematical convenience. In practical applications of Equation (5), the pushing potential term is normally combined with the internal energy terms to arrive at the enthalpy difference form below,

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \dot{m}\left[(\hat{h}_2 - \hat{h}_1) + 0.5({v_2}^2 - {v_1}^2) + g(Z_2 - Z_1)\right] \quad (6)$$

Usage of specific enthalpy change then conveniently does not necessitate separate calculations of the internal energy change and the change in the pushing potential of the fluid at the inlet and outlet. Another case in point, consider the closed system equation below neglecting the change in kinetic energy and the change in potential energy,

$$Q_{in} - Q_{out} + W_{in} - W_{out} + W_{b,compression} - W_{b,expansion} = U_2 - U_1 \quad (7)$$

where the subscripts 1 and 2 denote the initial and the final state of the system respectively. It is not worthy that when simplifying Equation (7) for an analysis, only either compression or expansion is present. It can be seen that enthalpy or the change of enthalpy is not applicable in the analysis. However, in the case of a constant pressure process, let us consider a constant pressure expansion process, combining Equation (4) into Equation (7),

$$Q_{in} - Q_{out} + W_{in} - W_{out} - (P_2V_2 - P_1V_1) = U_2 - U_1 \quad (8)$$

By rearranging this equation,

$$Q_{in} - Q_{out} + W_{in} - W_{out} = H_2 - H_1 \quad (9)$$

Therefore, only in this scenario, enthalpy change can be conveniently used as a mathematical simplification to the analysis of a closed system. From these considerations, the author opines that it will be useful to introduce enthalpy as a mathematically convenient state property. As discussed earlier, to better explain this concept, it will be important to firstly elucidate the meaning of the PV term as the potential of a system to push prior to the introduction of enthalpy. Figure 1 summarizes this strategy proposed to teach the concept of enthalpy.

Strategies on Teaching Entropy

It is the author's opinion that the lack of a clear purpose on the application of this relatively abstract concept is one main cause on why student lose interest in the study of entropy. From the classical thermodynamics perspective and from a practical engineering viewpoint, the pinnacle application of entropy may be to study isentropic processes; processes which do not change in entropy. As an isentropic process, compression or expansion etc., is theoretically assumed to have no internal frictional losses and experiences no heat loss, it provides a most efficient theoretical benchmark to predict the outlet conditions from these processes (e.g. what is the outlet condition from a compressor). From such a prediction, a theoretical benchmark of the most efficient energy transfer from the process (e.g. how much energy can be extracted from the turbine) can then be made in a design of a system. It is the strategy of the author to start the lecture on entropy with the introduction of this 'endpoint' application of this state property before going into the details and rules of entropy transfer and generation.

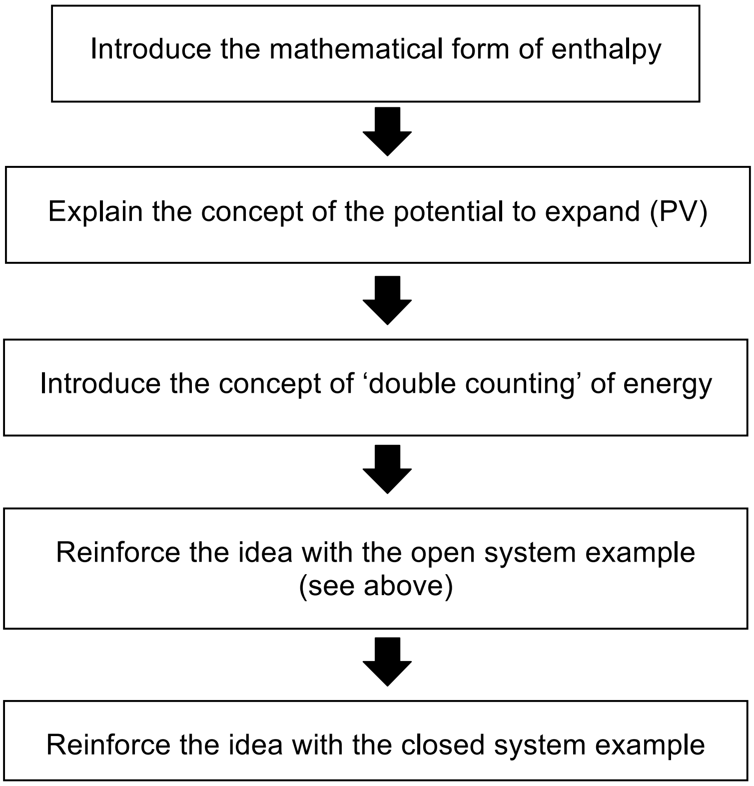

Figure 1: Proposed strategy for teaching enthalpy

Naturally, with such important applications in mind, students may then question on what is really entropy? It may be tempting to describe entropy as a measure of disorder. This definition was introduced by Ludwig Boltzman examining dispersion of gas particles at the statistical microscopic level of a system.

$$S = k \log(w) \tag{10}$$

It is noteworthy, however, the mathematical form of entropy was firstly discovered by Rudolph Clausius for a macro system, the steam cycle; before Ludwig Boltzman. At that point in time, entropy was mainly developed as a parameter given by the form below, which behaves like a state property,

$$S = \frac{Q}{T} \tag{11}$$

In other words, the initial concept of entropy (from a macro perspective) and its associated theories such as the entropy balance of a system (not given in detail here for brevity), does not evolve from the concept of disorder of a system. In fact, understanding those concepts within the context of classical thermodynamics may not require associating entropy as a measure of disorder. For example, the increase in entropy theory and the rule on how entropy is affected by heat transfer and not by the work done to or by the internally reversible system can be derived mathematically from the basic expression in Equation (11) without the need to view entropy as a measure of disorder.

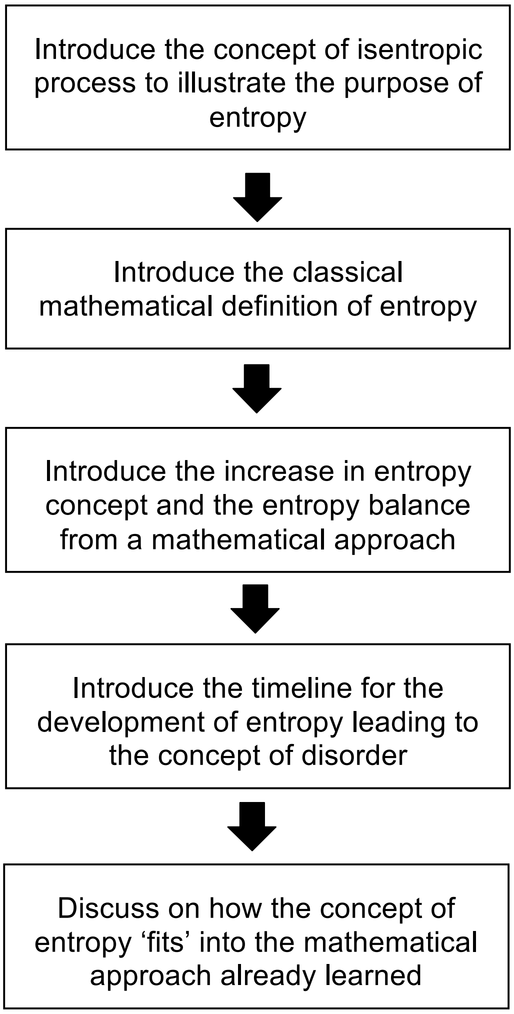

Figure 2: Proposed strategy for teaching entropy

Therefore, beyond the introduction of the isentropic process, the author would normally proceed by teaching these basic concepts of entropy by treating entropy strictly as a mathematical parameter (or property), which is convenient for engineering application. The rationale behind the rules associated with entropy change or balance is then approached from a mathematical viewpoint. How is then the concept of a measure of disorder introduced? Once the class is familiar with the basic rules of entropy, the author will then firstly introduce the historical timeline of entropy development as described above. The final few sessions on the topics will then focus on how the concept of disorder 'fits' into the mathematical rules taught earlier. This will then provide an additional view on entropy in terms of the physical basis of this concept. The author opines that this mathematics followed by the physical approach is less confusing for students; rather than using the physical basis to teach the fundamental rules of entropy. Figure 2 summarizes this strategy proposed to teach the concept of entropy.

Conclusion

The strategies proposed here is certainly an alternative to teaching enthalpy and entropy. If these strategies are inspected as a whole, it does provide a logical framework, which ties up some of the common questions or ambiguities faced by students. This is especially if the students are learning the subject matter or following references from the perspective of the classical thermodynamics. It is hoped that these strategies will be adopted and be evaluated by other academics teaching this unit. In addition, it will be interesting to evaluate these strategies to see if it is logical or not from perspectives differing from classical thermodynamics from which these concepts were derived.

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