AC 2008-951: USING THE EXERGY CONCEPT IN AN INTUITIVE APPROACH TO THE SECOND LAW

Michael Swedish, Milwaukee School of Engineering

Using the Exergy Concept in an Intuitive Approach to the Second Law

Traditional Approaches to the Second Law

In the Mechanical Engineering Program at the Milwaukee School of Engineering all students take one full year of engineering thermodynamics. It is clear that most of the students in the classroom will not pursue a career focused on thermodynamic design specifically. The motivation for the alternative approach presented in this paper is a desire to explain the Second Law to the third-year engineering student in a way that can be easily recognized and understood. Further, it is considered important to communicate the importance of the Second Law in engineering design and policy decision-making, so that the mechanical engineer will see its relevance regardless of her (or his) career path.

Most engineering thermodynamics textbooks in use today begin the presentation of the Second Law with reference to the Clausius or Kelvin-Planck statements:

> Clausius statement: "It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body." [2]
>
> Kelvin-Planck statement: "It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of work to its surroundings while receiving energy by heat transfer from a single thermal reservoir." [2]

The principles embodied therein are applied to the behavior of processes and cycles. The concept of irreversibility is introduced, along with some discussion of the theoretical limits to processes and cycles. The Second Law is presented from an entropy perspective. At a later time, exergy analysis is presented as a way to make use of the Second Law in evaluating the "true" inefficiencies in a process or cycle.

Students find this to be an esoteric approach. They do not see how the Second Law will be relevant to them.

Exergy as Usefulness: An Alternative Approach

Exergy is commonly defined as the "useful work potential" of a system or the "maximum theoretical work obtainable" from a system, when compared to some reference system. As this paper will show, these definitions do not do justice to the power of the exergy concept. Also, these definitions, with their exclusive focus on "work", are misleading to the student of the Second Law.

The approach to the Second Law that is presented here is experiential.. How do we actually experience the universe? The dynamic aspect of the universe is "interaction": things happen. Lots of things are happening all the time. Many of these things happen without any specific intent on the part of humans. Some we cause to happen. We can say that we extract "usefulness" from the universe in the processes that we design. In fact, this is sometimes used as a definition of engineering: the manipulation of the processes of nature for useful purposes. This notion of usefulness is at the heart of the alternative approach presented here. We will give the name exergy to this usefulness. In developing the Second Law, we seek to model a particular aspect of the behavior of the universe; that associated with the usefulness of processes.

In this context, the Second Law is not really a Law at all, it is simply an attempt to model the operations of the universe. A model is valuable only to the extent that it accurately reflects, or predicts, the real world. We search, therefore, for a model that will stand up when applied to the widest possible variety of tests.

While some parts of this approach to the Second Law have been incorporated previously by the author, the pedagogy described below was presented in full for the first time to a class in the second course of the thermodynamics sequence in 2008. The students were asked to consider the universe as they experience it. They were presented with the hypothesis that the universe is infused with a characteristic that is called "usefulness", and that it is usefulness that is valued. This hypothesis was illustrated for them through a student exercise.

Student Exercise: Identifying Usefulness

The students were asked to take five minutes, and consider as a group what it is that they value. When they appeared confused by the question, they were asked to consider what sorts of things would be important enough that they would pay money for them. They were asked to make a list. The instructor left the room and returned a short time later. According to someone who was present, the discussion started slowly, but then became quite lively. The result of the exercise was the list presented below.

Time	Alcohol
Food	Technology
Religion	Sex
Protection (security)	Sleep
Shelter	Health
Family	Cars
Education	Transportation
Starbucks	A decent version of Word

Once the list was projected onto a screen so all could see it, the instructor went through each of the items, and showed in each case how what was listed was important because it was of use to the individual who suggested it. For example, Starbucks is useful because its product keeps the student awake for studying, or provides a pleasing venue for meeting with friends. The student who suggested religion said that it gave him peace of mind. The instructor asked if this peace of mind is worth paying for. The student said that he didn't think of it in that way, but it was clear that many people are willing to pay for peace of mind in general.

What is interesting about the list is its variety. Perhaps one-third of the list would be thought of as the traditional purview of the engineer. The other entries represent the wide variety of things of value to the college junior. The students might now have begun to think that it's just possible that thermodynamics is more widely applicable than they had realized. But they were also somewhat skeptical. At this point, the class returned to consideration of what might be thought of as more "typical" applications, with the promise to return to the list later.

The Freezer Example

This is a thought experiment that is used to show that the Second Law has an intuitive basis.

The students were asked to consider the freezer compartment of a standard household refrigerator. They had not yet been exposed to the refrigeration cycle, nor entropy, but this was not necessary to the exercise. They did have a basic understanding of how the freezer works. In the thought experiment, a container is taken down to the nearby pond (in the summertime) and water is scooped up. The container is brought back and placed into the freezer. For the system defined as the water, the students were asked if a process would occur. They agreed that it would. They were asked what would happen to the water, and they said that it would freeze, or "get cold". They were then asked to consider the answer that an ordinary person would give to the following question: Is it more reasonable to say in describing the process that the freezer cooled the water, or that the water heated the freezer?

The consensus among the students was that it was "more reasonable" to say that the freezer cooled the water. Why? This made the students think. Most would say that it is the "point" of the freezer to cool the water. In fact, of course, both statements are correct; it depends on the point of view. Even so, the First Law shows that energy flows from the water to the freezer. What is it about the process that leads one to say that the freezer cooled the water?

The answer is developed from the notion of equilibrium. Initially, the water was in its natural state, in equilibrium with the "environment". It was "free" in fact; that is, no payment was necessary to acquire the water. However, the freezer (in this case, the refrigerant in the tubes in the freezer) was not in its natural state, it was not in equilibrium with the environment, it was not "free". It was cold, and it was necessary to pay the electric company for the electricity to run the compressor of the freezer. Because the refrigerant was out of equilibrium with the environment, it had the potential to influence the water; the refrigerant was useful. As a result of the process, the water was taken out of equilibrium, and so was made useful. For example, the ice cube could be used to cool a drink, taking the drink out of equilibrium with the environment, making the drink useful.

It was argued that it is "potential to influence", or "usefulness", that is transported from the freezer to the water. This is what we were going to call by the strange name "exergy".

Is Usefulness Conserved?

It was easy to show that something that is useful can be rendered useless. We can burn the contents of a can of gasoline on the ground (in the summer, when its "warmth" is not of use to us), and we have "wasted" it. The usefulness that it had is gone. Nothing else has increased in usefulness, therefore this usefulness has been destroyed in fact. Or, the ice cube can be left to melt on the table. It has not cooled a drink; its usefulness has been destroyed. That usefulness can be added to the water again by placing it back into the freezer, but only at the cost of additional electricity. Perhaps we need to be careful about our stewardship of usefulness.

Next, the students were asked to consider the premise that some "usefulness" is destroyed in every process. Here, examples were drawn from the mechanical engineer's world. Friction is easy for the students to grasp. All of the work transport in pushing a piston in to compress a gas cannot be returned when the gas is allowed to expand, due to friction between the piston and the cylinder wall. It was then pointed out that all of the work transport cannot be returned even if the piston is frictionless, unless the process happens infinitely slowly. This is true of any process; a "price is paid" for conducting processes in real time.

What happened to the usefulness imparted to the gas in the previous example? Some of it was destroyed in the process. The conventional approach would say that entropy was generated. If usefulness is destroyed in any real process, then this is why some hypothetical processes will happen, and others not. Only those processes that destroy usefulness can happen.

The Role of Entropy in the Alternative Approach

At this point, it was necessary to introduce the students to the property called entropy. It is disorder, or randomness. It can be illustrated on either a macroscopic level (chairs in a room, for example) or a microscopic level (disorder at the molecular level, what was once known as "heat"). In the alternative approach, there is no attempt to give a theoretical underpinning to entropy (not because such an underpinning is not valid, but because entropy is not the primary concept in this approach). It is simply a characteristic that is exhibited by a system. The property entropy is of interest to us because its value can be established independent of the environment (thus, it appears in property tables).

The Exergy Balance:

The exergy balance was developed in the standard way, through a combination of energy and entropy balances. Two examples were used; one involves only a work transport to some other system, and the other involves only a heat transport to another system. Out of these examples flow the expressions for exergy of a system, work transport of exergy, heat transport of exergy, and destruction of exergy.

In the standard approach to exergy, where exergy is seen as the useful part of the system energy, it is apparent that exergy must have the same unit as energy, Joule or BTU. This is confusing for the students, who are trying to get used to thinking of exergy as something different from energy. Therefore, in the classroom units of exergy are given as kJx or BTUx. In the wider view of exergy as usefulness, however, coming up with the proper unit is problematic. Is there a single unit that can quantify the usefulness contained in each of the items in the student-generated list? This will be explored further below.

Exergy transport can be in the form of a work transport or a heat transport. This is why it is confusing to the students to refer to exergy as "useful work potential". The freezer example illustrates this point clearly, as it is a case where the useful output to the water (ice) is a heat transport of exergy. Once the exergy concept had been thoroughly developed for the students, the freezer example was reexamined. Here is a case where the water has been taken out of equilibrium with the environment by lowering its temperature, not raising it. The students were shown that a calculation of the heat transport of exergy showed that exergy was transported from the freezer to the water; that is, in the opposite direction to the energy transport (see Figure 1). But this was precisely what intuition suggested about the process. The Second Law is a powerful model indeed.

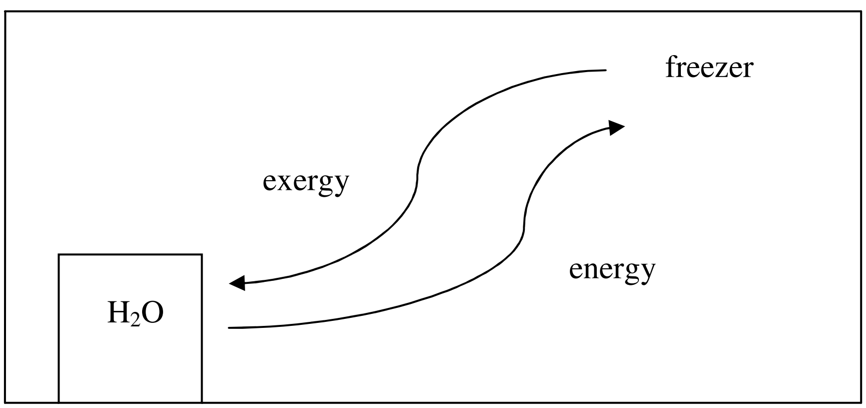

Figure 1

A Return to Exergy as Usefulness

If the water in the freezer was made useful as a result of the interaction with the freezer, then it is reasonable to say that exergy is that usefulness. This idea was explored further with the students in a number of ways. Conventional numerical examples were used to demonstrate the quantitative determination of exergy for processes (commonly referred to as exergy analysis, or Second Law analysis). The class then returned to the list that was generated previously. The students were invited to expand what they had learned about exergy to encompass all of the "things of value" that appeared on the list. In what way was each item useful? And how might this usefulness be quantified?

Dollars as a Unit of Exergy

The students were asked if they could imagine a single unit for "usefulness" that would cover all of the examples generated by the students. One possibility presented to them was to use dollars (or "currency" more broadly). After all, currency represents the value of goods and services. Then "what one would be willing to pay" does in fact represent the value attached to it. Examples of assigning a dollar value to the various items on the list were given to the class. For example, it is easy to see how a dollar value can be placed on an Ipod (a piece of technology), or even onto a commodity like alcohol. But consider the family. How does one assign a dollar value to the usefulness of family? In one instance, it might be done in a courtroom in a wrongful death lawsuit. An award is often made for "lost wages", but often times an additional award is made for "loss of companionship". Is this not a monetary award to compensate for the usefulness of the family member? Or, one can think about how much some might be willing to pay for adopting a child. This is another example of putting a dollar value on the usefulness of family.

Finally, the students were asked to consider how this approach might influence decision-making. In a system where oil, for example, was priced based on what an individual, or collection of individuals, was willing to pay for it (rather than on its supply), great care might be taken in using oil, since it effectively cannot be replaced.

Assessment

To assess the analytical abilities of the students, all sections of the second thermodynamics course are given a partially common final exam. This exam was administered to a total of 80 students, 39 of whom were exposed to the approach presented in this paper. The results show that there was no statistically significant difference in the level at which the students perform Second Law analysis of engineering systems, based on a rubric that identified number and types of errors.

36 students completed the course evaluation. There were nine comments specifically about the approach to the Second Law. All of these were positive. Some examples:

> "I did enjoy learning about exergy first rather than entropy as I understand when something is destroyed and can't be recovered because it always raises questions about how much we have left."
>
> "The Second Law project with usefulness was helpful in understanding exergy. The notion that exergy must be referenced to a surrounding environment became much more clear afterwards."

> "I feel as if I have a deeper understanding of thermodynamics because of [the author's] style of teaching Second Law concepts."

It should be noted that the students were able to compare the alternative approach to the textbook's traditional presentation. A common criticism in the evaluations was likely related to the use of the alternative approach: the perceived lack of a sufficient number of example problems. The alternative approach takes time, and this must be balanced against other needs in the class.

Anecdotal information also supports the approach presented here. The author had little difficulty in keeping the entire class engaged in the conversation about usefulness. In addition, the students were not shy about comparing and contrasting their experience to those of their friends in other sections.

Conclusion

Much of what has been presented here goes far beyond the traditional approach to the Second Law. The goal has been to present the Second Law to the students in a way that grabs their attention, causes them to think, and leaves them with a lens through which they can see their everyday lives in a different way, while still providing them with the analytical tools to solve thermodynamic problems. Out of this approach flows the idea of stewardship of resources. Hopefully, the students are better prepared to face the resource challenges that will confront them in the future.

Acknowledgment

The author is indebted to Professor Richard Gaggioli who, in 1973, introduced the author to what was then called availability. He and his colleagues developed the basic principles of an alternative formulation of the Second Law. Specifically, the freezer example presented in this paper is his.

References

1. Thermodynamics, by Gaggioli and Obert, unpublished, 1972.

2. Fundamentals of Engineering Thermodynamics, 5th Edition, by Moran and Shapiro, Wiley, 2006.

3. Thermodynamics, An Engineering Approach, 6th Edition, by Cengel and Boles, McGraw-Hill, 2007.

4. The Upside of Down, by Homer-Dixon, Island Press, 2006.