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Educating Undergraduate Mechanical Engineering Students about Exergy Analysis

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Educating Undergraduate Mechanical Engineering Students about Exergy Analysis

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Abstract

The concept of availability and exergy analysis is one of the most abstract ideas in thermodynamics and undergraduate mechanical engineering students have a difficult time to understand it. Unfortunately usually existing textbooks cannot help students much when it comes to exergy. This paper presents the approach that the author has developed to teach the concept of exergy (and not just mathematical formulations).

The first law of thermodynamics deals with amount of energy transfer regardless of its form and conditions. This approach, however, is not appropriate for some applications. For instance, some forms of energy are more valuable than others. For example, work is more valuable than heat because the efficiency of generating work from heat is always lower than unity, with the maximum efficiency in the Carnot cycle. Similarly, the thermal energy at a high temperature is more valuable than the same amount of thermal energy at a low temperature because the thermal energy at the higher temperature can be converted to work at a higher efficiency in a thermal engine (e.g. a Carnot cycle) than that of the thermal energy at the lower temperature. Based on the first law of thermodynamics, 1 kJ of electricity, chemical energy of fuel, thermal energy at 500°C, and thermal energy at 50°C are basically equal. But in reality their economic values are not the same. Therefore, it is vital to find a methodology to evaluate thermal systems not only based on the amount of energy conversion but also the actual value of energy. This approach is called exergy.

Introduction

When the author took Thermodynamics I and II courses as an undergraduate student about 20 years ago, the topic of exergy analysis, also known as the availability analysis or the second law of thermodynamics analysis, was not a part of the syllabus. In fact, when the author asked many experienced engineers if they knew what the exergy analysis is, the majority of them did not know it and even did not hear the term at all. This is one of the rare occasions that a major new topic has been added to a classical mechanical engineering course, particularly thermodynamics, in the past few decades.

Review of teaching exergy analysis in the existing textbooks

When the author started to teach Thermodynamics, he was not satisfied with the way the textbook for the course handled the topic of the exergy analysis. So he started to look for other resources and teaching methods. He reviewed and evaluated 25 thermodynamics textbooks covering 1963 - 2013 [1-25]. Although the concept of exergy was first introduced by scientists in 1940s, this evaluation illustrated that the exergy analysis started to appear in the textbooks mainly since mid 1980. Furthermore, out of 25 evaluated textbooks, 16 presented the exergy analysis in a form of an independent chapter. Unfortunately, none of the sources was able to properly cover the topic.

The main question for us as educators is that what we are doing to teach and train our undergraduate students on exergy and how well we are doing it. A great majority of the existing textbooks provide a very brief, vague, and ambiguous discussion on the exergy analysis and then they directly jump to mathematical formulations of the exergy analysis. Using this approach, students may be able to solve some numerical problems, but they may not have a clear understanding of the fundamentals of the exergy analysis. Some of the questions that students need to answer about the exergy analysis are:

- Why the exergy analysis has recently become a major topic in thermodynamics? After all both the first and second laws of Thermodynamics, the building blocks of the exergy analysis, have been around for over a century.
- More importantly, why do we need the exergy analysis?
- How is the exergy analysis different from the energy analysis?
- What are the applications of the exergy analysis?
- When do we use each of the energy analysis and the exergy analysis?
- How do we interpret the results of the exergy analysis?

The objective of this paper is to present a conceptual approach to teach the exergy analysis so students can answer above questions as well as being able to solve numerical problems.

The concept of availability and exergy is one of the most abstract ideas in thermodynamics because it is difficult to find any physical parameters that represent exergy in the real world. As a result, undergraduate mechanical engineering students have a difficult time to understand the exergy analysis.

New approach for teaching exergy

This paper presents the approach that the author has developed to teach the concept of the exergy analysis (not just mathematical formulations). In order to start the discussion on the exergy analysis and how it differs from the first law of thermodynamics analysis, I initially start the topic with the following example from everyday life.

It should be noted that in this paper the italic text represents what the author presents in his lectures in the class.

Imagine that there are two professors, Dr. X and Dr. Y, teaching the same course, e.g. Applied Thermodynamics (!). At the end of the semester, both classes end up with the average grade B in the course. Which professor did a better job?

If we just look at the final results and consider them as the parameter to evaluate the performance of the professors, then both professors are doing equally good (or bad!) job. This approach resembles the first law of thermodynamics analysis or the energy analysis.

But as you may notice, this comparison is not really fair because the background of the *students at the beginning of the class is not taken into account. If we know that the GPA of the class Dr. X teaches in the past two years has been B and the GPA of the class Dr. Y teaches in the same period has been C, then the comparison will be totally different. If we take into account the background of the students in each class, we realize that Professor Y has been able to improve the grades of the students in his class from average C to B, whereas Professor X just maintained student grades at B. Thus, in this evaluation, where we take into account the quality of the students assigned to each professor as well as the final grades, Professor Y is doing much better job. This approach is the second law of thermodynamics, exergy, or availability analysis.*

After this preliminary introductory example, I ask some more technical questions that will be foundations for the further examples. These questions are related to some of the applications of the exergy analysis and are designed to give a tangible appearance to the abstract idea of the exergy analysis.

Example one

You are building your new house and you are trying to decide the source of heating for your house. Your options are:

- *Electricity,*
- *Natural gas (or any other fossil fuel),*
- *Steam at 500°C,*
- *Steam at 50°C.*

Which one is your choice? Based on purely economical considerations? Based on economical and environmental considerations?

Example two

There are two power plants A and B. The power plant A has an efficiency of 5% and the power plant B has an efficiency of 10%. Which one is better, both economically and environmentally?

Example three

In a steam power plant, for every 100 MW input of thermal energy to the boiler in the form of chemical energy of the fuel, 45 MW is converted to the electrical energy, 50 MW is lost in the form of heat transfer to the low temperature heat sink in the condenser and 3.5 MW is lost as heat losses in the boiler. You are asked to look at the ways to improve the performance of the power plant by reducing heat losses in the system. Which equipment will you focus on first?

In order to explain and understand the exergy analysis, we need to go into the core of thermodynamics. Since the exergy analysis usually is covered in the Applied Thermodynamics or Thermodynamics II course, the students' understanding of the concept of the first and second laws of thermodynamics might be a little rusty. So I provide them the following quick review of the thermodynamics laws.

Thermodynamics laws

Some subjects have a few core laws that everything else is based on them, for example the core *laws of Statics and Dynamics are the 1st, 2nd, and 3rd laws of Newton. In thermodynamics, these fundamental laws are the 0th, 1st, 2nd, and 3rd laws of thermodynamics.*

Historically, the second law of thermodynamics was discovered first by Carnot in 1823 for the maximum efficiency of a power generation engine, which later followed by the statement of the 2nd law of thermodynamics for refrigeration cycles. About a quarter of century later, the first law of thermodynamics was gradually formed as a result of over a century of experiments, and trials and errors. The turning point was when James Joule discovered that work and heat are two forms of energy in 1845. This led to the final statement of the first law of thermodynamics by Rankine and Clausius in about 1850. After the first and second laws of thermodynamics were properly stated, scientists realized that both of these laws are mainly about temperature but there was no official definition for temperature, so they developed a law to allow them to define and measure temperature. This law was a prerequisite for the other two laws; since the others were already called the 1st and 2nd laws of thermodynamics, this law was named the 0th law of thermodynamics. Finally, the 3rd law of thermodynamics was developed to define a reference point when the composition of the system is not fixed, for example during combustion or chemical reactions.

The first law of thermodynamics deals with the amount of energy transfer and energy conversion regardless of its form and conditions. This type of energy balance is also called the energy analysis. Some of the examples of this analysis are as follows:

1. When an object is released from a height, its potential energy is converted to the kinetic energy. According to the first law of thermodynamics, the decrease in the potential energy is equal to increase in the kinetic energy. Right before the object hits the ground, the potential energy is minimum and the kinetic energy is maximum. After the object hits the ground and stops, both the potential and kinetic energies are minimum and the whole kinetic energy is converted to the thermal energy. However, the first law of thermodynamics allows to heat the object sitting on the ground and as a result the object can raise to a higher elevation as long as the total energy is constant.

2. If you leave your hot cup of coffee in the room temperature (I actually take my coffee to the class and point to it)*, the first law of thermodynamics states that the heat transfer to or from the cup is equal to the heat transfer from or to the room air. Thus, the first law of thermodynamics cannot predict the direction of the heat transfer or prevent the heat transfer in the wrong direction. So basically, according to the first law of thermodynamics, the hot cup of coffee can get either colder or hotter in the room temperature.*

3. When you drive your car uphill, the chemical energy of the gasoline consumed in the engine is first converted to the thermal energy through combustion. Then, the thermal energy is converted to the mechanical shaft work in the wheels which shows itself as the kinetic energy of the moving car. While the car is ascending the hill, this kinetic energy is converted to the gravitational potential energy. According to the first law of thermodynamics, during this process there would be no energy destruction and only energy is converted from one form to another. Now when your vehicle reaches to the top of the hill and then you drive downhill, according to the first law of thermodynamics, it is possible that the gravitational energy can be converted to the chemical energy of the fuel so at the bottom of the hill your car's tank can be full again.

4. According to the 1st law of thermodynamics, a power plant can convert the entire chemical energy of fuel to electricity, which means 100% efficiency.

5. According to the 1st law of thermodynamics, the refrigerator at your home can operate without any electricity as long as the amount of the cooling inside the refrigerator is equal to the amount of the heating of the room.

In all above examples, the energy conversion from one form to another is possible in both directions as long as the magnitude of the total energy is constant.

Obviously, the first law of thermodynamics is not sufficient to properly explain actual processes and cycles because:

1. It cannot predict the direction of energy conversion processes correctly (e.g. the hot coffee cannot get hotter in the room temperature).

2. The extent of which some processes or cycles of energy conversion can proceed is limited (e.g. the efficiency of a power plant cannot be 100%).

In summary, the first law of thermodynamics analysis only keeps track of energy. The concept of the energy analysis can also be very confusing. Imagine we have a power plant with the efficiency of 40%. This means for every 10 units of the energy input to the power plant, 4 units are converted to work and 6 units are lost. But we know that energy cannot be destroyed, so why we should concern ourselves about that 60% energy loss. After all, that 6-unit energy is not really lost but converted to other forms of energy and is somewhere else but not in our system.

That is why the energy analysis can be insufficient and ambiguous. Thus we need the second law of thermodynamics which has two main statements: the Kelvin-Planck statement for heat engines and the Clausius statement for refrigeration and heat pump cycles.

There are several ways for explaining the second law of thermodynamics some of which can help to determine the possible direction of energy conversions in the aforementioned examples one to three. But the explanation that is most useful for explaining the exergy analysis is the following one.

Exergy concept

Work is the most valuable form of energy with the highest quality and lowest entropy and its production is the most important objective of any thermodynamics power cycles, so it is used as the benchmark to evaluate the quality of any form of energy. Thus, the availability of a source of energy is defined based on the maximum theoretical work that can be produced from that energy source. In this definition, work is shaft mechanical work or a form of energy that is completely convertible to shaft work e.g. electricity. Unlike energy, availability can be destroyed. In any system that involves some sort of energy conversion (which basically means any possible system), the objective is to minimize the destruction of availability. So in the fourth aforementioned example, we can have the following facts that all are correct and equal based on the second law of thermodynamics:

1. $Q_L > 0$
2. $W < Q_H$

3. η < 100%

It should be noted that the above limits are for all cycles even for the ideal cycle with no losses of any kind.

The next logical question would be: Okay the efficiency cannot be 100%, but what is the maximum efficiency achievable for a system?

The answer is the Carnot cycle which has the highest possible efficiency for any cycle. The efficiency of the Carnot cycle that operates between the heat source at a temperature of T_H and the heat sink at a temperature of T_L can be calculated by the following equation:

$$\eta = 1 - \frac{T_L}{T_H}$$

This equation indicates that if we have a thermal energy of Q_H, the maximum amount of work that can be produced depends only on the temperatures of T_H and T_L. Usually T_L is not something that we can control and change significantly (which later we will see that it determines the dead state in the exergy analysis). Therefore, the value of any thermal energy source, which means how much work can be produced using that source, depends on its magnitude and temperature (Q_H and T_H, respectively). This is like a value of several coins that you have in your pocket, which depends on the number of coins you have and the value of each coin.

This leads us to the main concept of exergy: the value of an energy source depends on the maximum amount of work that can be produced using that energy source. The maximum potential to produce work from an energy source is what we call exergy.

Now we can define the exergy analysis and compare it with the energy analysis. In the energy analysis, we only take into account the amount of energy conversion. In exergy analysis, we study the balance of energy not just based of the magnitude of the energy but based on the comparison of how much work is actually produced and the maximum potential to produce work.

At this point, I revisit the example of Professors X and Y and explain that the background of the students can resemble the maximum theoretical work.

Now let's go back to the three initial examples (at this point I change the headings from examples to applications, because these are three most important applications of the exergy analysis):

Application (example) one

Based on the first law of thermodynamics, 1 kJ of electricity, 1 kJ of chemical energy of fuel, 1 kJ of thermal energy at 500°C, and 1 kJ of thermal energy at 50°C are basically equal. But in reality, their economic values are not the same.

Some forms of energy are more valuable than others. Work is the most valuable one. Electricity is considered as a form of work with the same value. The same amount of thermal energy at a higher temperature is more valuable than thermal energy at a lower temperature because the thermal energy at the higher temperature can be converted to work at a higher efficiency in a thermal engine (e.g. the Carnot cycle) than that of the thermal energy at the lower temperature.

One way to compare the value of various energy sources is to check how efficient they can be converted to each other. Work is more valuable than heat because work can be completely converted to heat but the efficiency of generating work from heat is always lower than unity, with the maximum efficiency in the Carnot cycle. Similarly, electricity can be converted to mechanical work with a very high efficiency (theoretically 100%). Also, fuel can be used to produce work at a relatively high efficiency (up to 60% in modern power plants). However, for thermal energy at 500°C and 50°C, potential to generate work is limited and is bounded by the efficiency of the Carnot cycle (for a heat sink temperature of 25°C, this maximum theoretical efficiency is equal to 61.4% and 7.7%, respectively).

So the energy sources to heat your house can be ranked as follows, starting from the least valuable source (increasing value):

- *Steam at 50°C,*
- *Steam at 500°C,*
- *Natural gas (or any other fossil fuels),*
- *Electricity.*

Your choice of energy source will be in the same order, because the least valuable source will be the most inexpensive one. Most likely this will be also the one with the least environmental effects.

It should be noted that natural gas is more valuable than steam at 500°C because by combusting it you can produce steam at a much higher temperature. Moreover, the chemical energy of natural gas can be converted to thermal energy but thermal energy cannot be easily converted to the chemical energy of natural gas.

Application (example) two

If we have two thermal engines with the efficiencies of 10% and 5%, which one is better?

When comparing energy systems or equipment, it is not fair to just consider the amount of energy. In this comparison, the quality of energy should also be taken into account.

From the first law of thermodynamics prospective, the first engine is more efficient. But from the exergy analysis point of view, we cannot compare two systems until we know what the temperature of the heat sources are for each engine.

At this point, I remind my students about the GPA of students in Professors X and Y classes and how this GPA resembles the temperature of the heat sources in the engines.

If we have two thermal engines with heat sources at the temperatures of 500°C and 50°C and the engines have the efficiencies of 10% and 5%, respectively, is it fair to say the former is more efficient than the latter?

Now we can compare the efficiencies of the actual engines with the maximum possible efficiency at the Carnot cycle operating at the same temperature difference. From this point of view, the feeling about more efficient engine will be different. The maximum theoretical efficiencies for the engines with these heat sources are (for an ambient temperature of 25°C):

$$\eta_1 = 1 - \frac{25 + 273}{50 + 273} = 7.7\%$$

$$\eta_2 = 1 - \frac{25 + 273}{500 + 273} = 61.4\%$$

When we compare 10% out of the maximum of 61% for the first engine with 5% out of the maximum of 8% for the second engine, the second engine is doing much better job than the first one. That is why the second law of thermodynamics efficiency will be defined to take into account this effect.

Application (example) three

When we want to optimize a thermal system (a power plant for example) and increase its efficiency, we first need to identify the sources of inefficiency and then try to avoid them. Using the first law of thermodynamics for identifying these inefficiencies can be misleading. In this example, which one of these two components, the boiler or the condenser, should we try to optimize first? From the first law of thermodynamics prospective, the answer is the condenser. But this may not be true from the second law of thermodynamics point of view. Although the amount of thermal energy loss in the condenser is much higher than the amount of energy loss in the boiler, the temperature that these thermal energies are lost is much higher in the boiler compared to the condenser. Thus, the value of the energy loss in the boiler might be higher than that of the condenser, so this equipment might be the more appropriate place to consider first for optimization purpose.

To sum up this part:

- *The first law of thermodynamics deals with the magnitude of energy during any energy conversion process.*
- *The second law of thermodynamics deals with direction of energy transfer and the extend that one form of energy can be converted to another form.*
- *The energy analysis focuses on the amount of energy conversion not its value.*
- *The exergy analysis focuses on the amount of energy conversion compared to the maximum theoretical possible in an ideal cycle.*

Exergy is a thermodynamics property of the system because it does not depends on the process but just the state of the system.

Recently exergy analysis has become very popular because of recent concerns about the non-renewable nature of fossil fuels and an efficient use of these limited resources as well as their environmental impacts.

Definition of environment

Thus far, we talked about temperature difference as a driving force for work production. This can be extended to other properties beyond just temperature. Whenever two systems are at different states, there is potential to produce work. This can be accomplished by letting two systems to communicate and to come to equilibrium. For exergy analysis, one of the two systems are fixed and idealized as an environment. The environment is part of the surrounding that its intensive properties are uniform and fixed with no irreversibilities. As stated, the exergy is the maximum theoretical work that a system can produce when it interacts with the environment. Thus, the exergy depends on the states of the system and the environment. So the exergy is a quality that measures the departure of the system from environment. As the system and the environment interact, their states get closer and the exergy of the system reduces. When they are *at equilibrium, there is no potential to produce work, so the exergy is zero. This means the minimum value of exergy is zero and it cannot be negative. For exergy analysis, the environment is fixed. When the system is at equilibrium with the environment, the system is at the dead state. The minimum exergy destruction is in an ideal process where there is no irreversibility and the maximum exergy destruction is in a spontaneous process where no useful work is generated.*

At this point, I ask students to study the flow across a half-closed valve with no heat transfer (throttling process) from the first and the second law of thermodynamics point of view as their homework.

To determine and fix an environment, the following characteristics should be determined:

1. *Intensive properties (commonly T_0 and P_0): If the atmosphere air is considered as the environment, usually the temperature of 25°C (77°F) and the pressure of 1 atm are considered for the environment. In some systems, the temperature of water interacting with the system is considered as the temperature of the environment.*
2. *Composition of the environment: The common substances of the Earth's atmosphere, curst, or ocean are considered for the environment.*
3. *Kinetic and potential energies: Both these energies in the environment are considered zero, which means the relative elevation and velocity of the environment are zero.*

So, there is work production potential if there is a system that its temperature, pressure, composition, velocity, or elevation differs from these properties for the environment.

At this point I start to explain and derive the mathematical formulations of the exergy analysis. Usually, this part of the topic is properly covered in the available textbooks.

Based on the students' feedbacks, this approach to teach the concept of the exergy has been effective and has improved the students' understanding of the concept.

Conclusion

At the end of this part of the lecture, I give the following handout to students to summarize what we covered in the class.

Exergy can be defined when two systems that are in different states are brought into communication, and there is an opportunity to develop work. In this case, if one of the systems is idealized as an environment, the maximum theoretical work that can be obtained when two systems come to equilibrium is called exergy. Therefore, the exergy is a property that indicates the departure of the state of a system from the state of the environment. The following statements are true about exergy:

1- Exergy is not conserved (unlike energy) but it can be destroyed by irreversibilities.
2- It can be transferred to or from a system accompanying heat.
3- The exergy of a system of interest depends on both the state of the system and the state of the environment.
4- The environment used in the definition of exergy is different from the definition of the surrounding in the energy analysis. The surrounding of the energy analysis is everything outside of the system of interest but the environment in the exergy analysis is part of the

surrounding that its intensive properties are not affected by interaction with the system. Based on this definition of the environment, the immediate surrounding of a system is not considered as a part of the environment.

5- The environment is usually modeled as a large simple compressible system with uniform temperature (T_0) and pressure (P_0) and free of irreversibilities.

6- When the desired system and the environment are in equilibrium, there is no opportunity to generate work. In this state, the system is in the dead state, and the temperature and pressure of the system and the environment are equal. The system is at rest relative to the environment, and there is no flow mass. In other words, the system is in thermal and mechanical equilibrium with the environment. This does not mean the system and environment do not posses energy but the potential to generate work does not exist. In other words, exergy is zero.

7- The unit of exergy and energy are the same.

8- Exergy is a property of the system but exergy destruction is not.

9- The value of exergy cannot be negative.

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