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A Study of Thermodynamic Heat Transfer and System Efficiency

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ABSTRACT

In this paper, we try to provide an overview of thermodynamics first and second laws, which mainly deal with the transfer of heat. We mainly focus on heat transfer devices and the efficiency of energy conversion. We discuss and construct different cycles, taking into consideration the conversion of any forms of energy under consideration, in particular heat, to work on a continuous basis, which is the fundamental objective of nuclear power plant owners. One needs to have a better understanding of cycles and the way they operate. An energy conversion device converts one form of energy into another, and it is a crucial component of societal evolution. In reality, significant developments in energy conversion technology can be used to analyze the development of civilization.

Keywords: Thermodynamics, first law, second law, heat, efficiency, entropy

AMS Mathematics Subject Classification (2010): 80A20

1. Introduction

Thermodynamics is a branch of physics which mainly deals with the transformation of heat into mechanical work. The first law specifies that energy can be transferred between physical systems as heat, as work, and with the transfer of matter [1-4]. The second law defines the existence of a quantity called entropy, which describes the direction, thermodynamically, that a system can evolve and quantify the state of order of a system and that can be used to quantify the useful work that can be extracted from the system[4]. Almost exclusively on those physical properties of everyday materials that are associated with the motions such as power plants. Higher energy efficiency translates directly into lower energy costs [5]. We shall illustrate this statement in the work. Power plants are intricate systems that transform various sources of energy into electricity. thermodynamics influences their behaviour and performance in order to operate and maintain them effectively and safely [6-8]. Every part and process of a power plant must adhere to the laws of thermodynamics, which is the science of heat, work, and energy in the types of motion that we normally call "heat" [7-8]

1.1. Efficiency of energy conversion devices

A device is a kind of equipment that serves a specific objective. An energy conversion device converts one form of energy into another. It is a crucial component of societal evolution. In reality, significant developments in energy conversion technology can be used to analyze the development of civilization.

In Figure 1.1 an energy conversion device is illustrated schematically. It may be simple device or a very complex device which converts energy from one form to another. We won't focus too much on how they function; instead, we'll pay attention to what they achieve. In other words, at this micro scale, our attention will be on the supply (output) and demand (input) of energy. Figure 1.1 is an illustration of this.

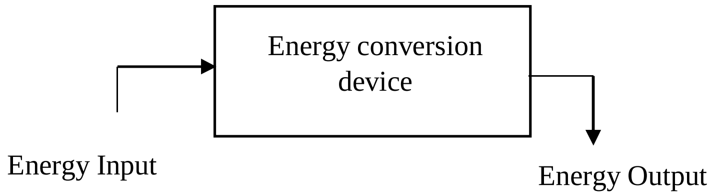

Figure 1.1: Schematic representation of an energy conversion device.

From 1st law: Energy Output = Energy Input

From 2nd law: Useful Energy Output = Energy Input

This balance between energy input and energy output is expressed quantitatively by an energy conversion device's efficiency. It is defined as below:

$$\text{Device efficiency} = \frac{\text{Useful energy output}}{\text{Energy input}}$$

Input energy is the total amount of energy supplied to a device, whereas useful output energy is the usable energy that is delivered by the device (for example, thermal energy by a heater). According to the First Law of Thermodynamics, energy is conserved throughout all of its transformations. Therefore, the energy output to energy input ratio is always one, or 100 percent. Depending on the device's intended application, the word "useful" has different meanings.

An energy conversion device's efficiency can be expressed quantitatively as a value between 0 and 1 (or between 0 and 100%). The efficiency of the gadget will undoubtedly increase as this number rises, but a value higher than one would be in violation of the First Law of Thermodynamics. The two laws of thermodynamics are thus combined in the idea of efficiency. It displays the qualitative and quantitative equivalence of the various energy forms. Its comprehension necessitates some familiarity with thermodynamics; once understood, simply this idea from the subject of thermodynamics is required for comprehending the main energy problems facing humanity.

2. Electric power plant

A power plant is an industrial facility used to generate electric power with the help of one or more generators which converts different energy sources into electric power. The electric power plant is one of the most significant energy conversion technologies in modern society. Figures 2.1 and 2.2 represent it schematically. Chemical energy is first transformed into thermal energy in the boiler, followed by mechanical and electrical energy transformations in the turbine and generator.

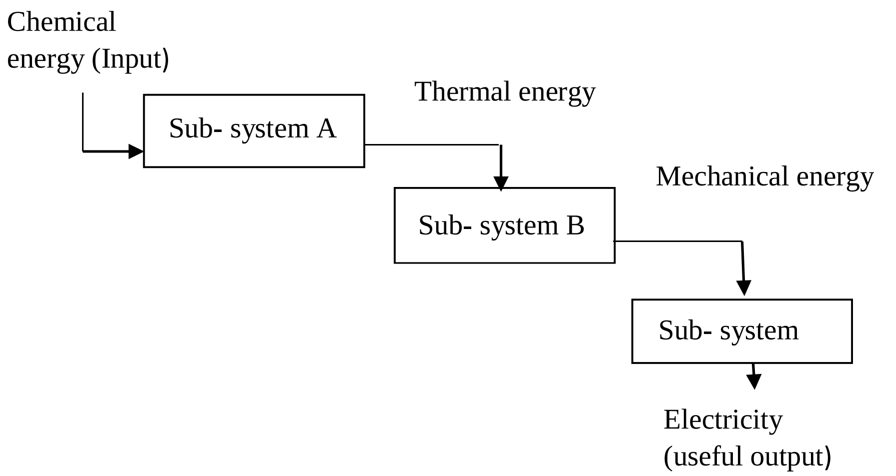

Figure 2.1: Energy conversion in an electric power plant.

System efficiency is, therefore,

$$E_{\text{power plant}} = [E_{\text{boiler}}]\,[E_{\text{turbine}}]\,[E_{\text{generator}}]$$

$$= \left[\frac{\text{Thermal energy}}{\text{Chemical energy}}\right] \left[\frac{\text{Mechanical energy}}{\text{Thermal energy}}\right]\left[\frac{\text{Electricl energy}}{\text{Mechanical energy}}\right]$$

$$= \frac{\text{Electric energy}}{\text{Chemical energy}}$$

The boiler is the main theme of the electric power plant. This is depicted in Figure 2.1. A fuel is burned in the boiler, and heat is transmitted to the water flowing through the tubes around the combustion chamber by the hot combustion products. When the water boils, it turns into steam. The steam achieves a high pressure and temperature, at 1000 pounds per square inch and about 1000 °F respectively (roughly sixty times greater than atmospheric pressure). It is rich in thermal energy. The turbine, which consists of a wheel with blades mounted on a shaft, receives this steam. The shaft rotates as a result of the turbine blades of the turbine rotating due to the impulse of the high-velocity steam. As a result of this process, the steam "exhausts," losing energy and cooling down in temperature. In the condenser, it is converted back to water and then circulated back into the boiler to complete the cycle. According to the electromagnetic induction theory, electricity is generated by the turbine's shaft rotating within the electric generator's magnetic field.

Consider the generator to be a "black box" that transforms mechanical energy into electricity; we don't need to explain this further.

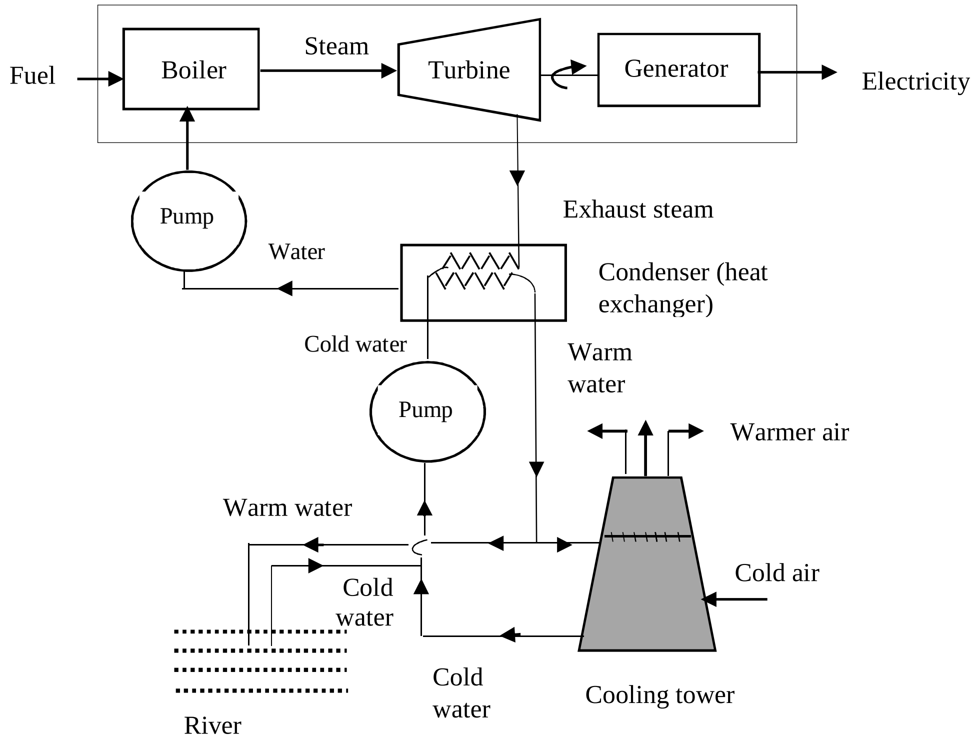

Figure 2.2: Schematic representation of an electric power plant

The structure water cooling system, which is shown in Figure 2.1, is an essential part of the power plant. In reality, the most noticeable aspect of the plant is a cooling tower when it is used for this purpose, as seen in Figure 2.1. It defines that not all of the light energy is absorbed by plant. Some energy is reflected and some is lost as heat. The loss of energy to the surrounding environment result in an increase of disorder or entropy. It resembles the second law of thermodynamics. Within the power plant's system restrictions, the entropy falls. As a result, it must also increase in its surrounds, which in this example are the river and the environment, as shown in Figure 2.1.

The energy for the conversion of heat to work in the turbine is provided by the drop in temperature between the water in the condenser and the steam in the boiler. Although it is not quite accurate, the following analogy is useful for understanding how this occurs.

From thermodynamic analysis, which we do not need to go into, it is possible to define the maximum (or ideal) heat engine efficiency.

$$E_{\max} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}.$$

Illustration: At a temperature of 700 °C, steam from the boiler of a power plant enters the turbine. 100 °C wasted steam exits the turbine. Figure out the turbine's maximum efficiency. Compare it to the typical value.

Solution: From the above expression, $700^{\circ}C = 973K$ and $100^{\circ}C = 373K$, we have:

$$E_{\max} = \frac{973k - 373k}{973k} = 1 - \frac{373}{973} = 0.62(62\%)$$

This is greater than the normal efficiency of around 45%, as expected.

Temperatures are expressed in absolute units in this place. It is necessary to highlight two implications of this definition: (1) the maximum efficiency rises as T_L decreases, but it doesn't reach 100% until $T_L = 0K$; (2) the difference $T_H - T_L$ is in the numerator and the larger it is, the higher the efficiency will be.

3. Comparison of efficiency

Now that we have provided all the thermodynamics that we need, we can prove its usefulness in comparing energy choices. Consider the use of various major energy sources for electric home heating as an example. We are assessing the most significant energy input alternatives (coal, petroleum, and natural gas), and we have a shared useful energy output (electric home heating). These fundamental sources can only be used to generate electricity economically by converting their chemical energy to heat, work, and subsequently electricity (see Figure 1.2). These main sources must first be taken from the soil, processed, and delivered before we can use them in a power plant. Figure 3.1 provides an illustration of this. If the power plant is built to burn that specific fuel, the efficiency of converting the chemical energy of various fuels to electricity once they are there is roughly the same.

Electricity needs to be transferred to our houses after being generated at the power plant. This operation has a high efficiency, let's say around 90%. Electricity is changed from low to high entropy energy when it enters our dwellings, resulting in a 100% efficiency conversion to heat. Therefore, the following formula is used to calculate the overall (system) efficiencies for the three instances taken into account.

$$E_{coal} = [E_{extraction}][E_{processing}][E_{transport}][E_{powerplant}][E_{transmission}][E_{electricheater}]$$

= (0.66) (0.92) (0.98) (0.35) (0.90) (1.00)

= 0.19 (19%)

$$E_{oil} = [E_{extraction}][E_{processing}][E_{transport}][E_{powerplant}][E_{transmission}][E_{electricheater}]$$

= (0.35) (0.88) (0.95) (0.35) (0.90) (1.00)

= 0.09 (9%)

$$E_{gas} = [E_{extraction}][E_{processing}][E_{transport}][E_{powerplant}][E_{transmission}][E_{electricheater}]$$

= (0.73) (0.97) (0.95) (0.35) (0.90) (1.00)

= 0.21 (21%)

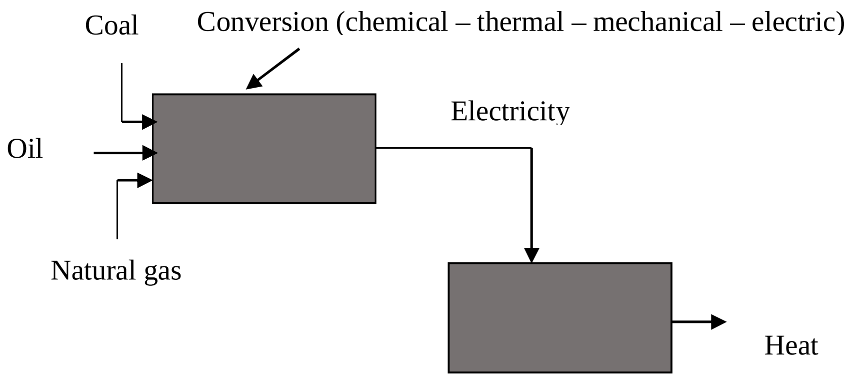

Figure 3.1: Electric home heating analysis by using different primary sources.

These results imply that we only have the use of 21, 19, and 9%, respectively, of the chemical energy of natural gas, coal, and petroleum in our homes. The rest is wasted. If the efficiencies shown in Figure 3.1 are accurate, we can draw a significant conclusion about the usage of coal, oil, and natural gas in power plants from this straightforward analysis. It makes more (technically) sense to use coal or natural gas than oil, mostly due to the low thermodynamic efficiency of oil extraction (35%, compared to 66 and 73% for extraction of coal and natural gas, respectively) This is the conclusion that a utility executive would arrive at if they were worried about the best way to distribute fossil fuels.

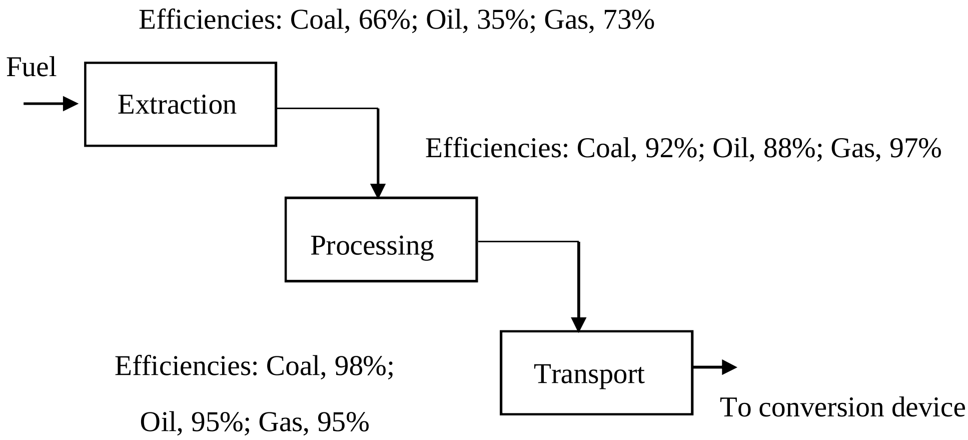

Figure 3.2: Schematic (thermodynamic) representation of fuel preparation for use in an energy conversion device. Typical efficiencies are also included.

Also, keep in mind that all of the efficiencies are quite low. Although using electric heating in our houses is convenient, we can observe that it is thermodynamically inefficient. We'll see in the future that it's also extremely expensive. It actually makes sense that it should be ineffective if we take a moment to consider it. In order to get the heat we need, the fuels must first be burned. Next, the heat is converted into electricity, and ultimately the electricity is converted back into heat. The scenario is different if we eliminate this useful but ineffective limitation. Figure 3.2 shows how this is done. Thus, the following is how the system efficiencies were determined:

$$E_{coal} = [E_{extraction}][E_{processing}][E_{transport}][E_{furnae}]$$

$$= (0.66)\ (0.92)\ (0.98)\ (0.55)$$

$$= 0.33\ (33\%)$$

$$E_{oil} = [E_{extraction}][E_{processing}][E_{transport}][E_{furnae}]$$

$$= (0.35)\ (0.88)\ (0.95)\ (0.65)$$

$$= 0.19\ (19\%)$$

$$E_{gas} = [E_{extraction}][E_{processing}][E_{transport}][E_{furnae}]$$

$$= (0.73)\ (0.97)\ (0.95)\ (0.85)$$

$$= 0.57\ (57\%)$$

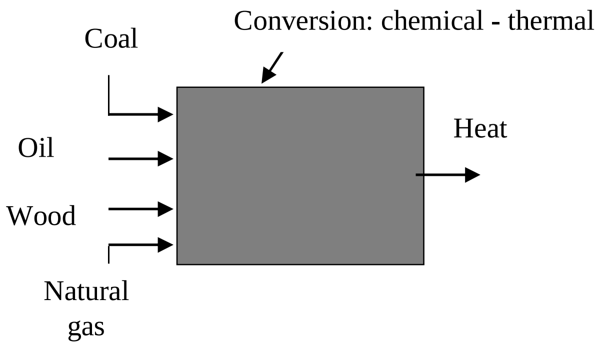

Figure 3.3: Analysis of home heating using different primary energy sources. (Additionally, wood is used, mostly as an aesthetic supplementary fuel, but it is not a significant source of energy in modern society).

With by far the highest efficiency, natural gas emerges as the (thermodynamic) winner in this situation. The computations that are displayed above are intended to achieve two goals. They first serve to show a crucial fact: natural gas is the most desirable fossil fuel for residential heating. Second, they provide as an example of the value and influence of the efficiency principle. We don't need to be experts in the specifics of the technology used to supply energy to our homes; by understanding the different efficiencies, we may evaluate the relative technical benefits of the numerous approaches that are available. More importantly, as we'll see in a moment, we can also evaluate their comparative economic qualities. The theoretical development that we finally complete here was not an academic exercise, the reader may claim. We are now prepared to apply this straightforward thermodynamic instrument in practice.

4. Result and discussion

In this paper, it is shown that a heat engine converts heat to usable energy, particularly mechanical energy, which can then be used to do mechanical work. The efficiency of a heat engine is always less than 100%, and it is made up of two or more energy conversion technologies. In an electric power plant, not all of the light energy is absorbed by the plant; some energy is reflected, and some is lost as heat. The loss of energy to the surrounding environment results in an increase in disorder, or entropy. It resembles the second law of thermodynamics. Among the most significant energy input alternatives (coal, petroleum, and natural gas) in electric home heating, natural gas emerges as the (thermodynamic) winner for its highest efficiency.

5. Conclusion

In this work, we first discussed some energy conversion devices and heat transfer devices; we then used the concept of energy efficiency; and finally, we quantified greater efficiency, which is improved by reducing the amount of energy consumed while achieving the same level of energy service. Our goal is greater efficiency, and greater efficiency has several benefits, including lower consumer energy costs, improved environmental quality, preservation and improvement of our standard of living, more freedom and energy security, and support for a robust economy.

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