EXERGY ANALYSIS

R. A. Chaplin
Department of Chemical Engineering, University of New Brunswick, Canada

Keywords: Available Energy, Unavailable Energy, Availability, Exergy, Effectiveness, Thermo-economic Analysis

Contents

Summary

In the Carnot cycle which is an ideal thermodynamic cycle, heat is received at a high temperature and rejected at a low temperature. For work to be produced some heat must be rejected and the amount is dictated by the temperature of heat rejection which in turn cannot be less than that of the surroundings. It follows that, since the temperature of heat rejection is fixed, the higher the temperature of heat acceptance by the cycle the better its thermal efficiency. Any reduction in this upper temperature by heat transmission through a heat exchanger reduces the thermal efficiency and useful work output of the cycle.

Energy may thus be classified as available and may produce useful work or unavailable and must be rejected. Energy entering or within a cycle may be degraded by various processes thus decreasing the portion of available energy and increasing the portion of unavailable energy. This leads to the concept of effectiveness of available energy transfer within a component such as a heat exchanger. The greater the effectiveness of available energy transfer the less the decrease in available energy and ultimately the smaller the loss in total work produced. Such an analysis of an individual component in a complex system allows the impact of deteriorating performance on power output to be immediately apparent.

A development of this concept is to assess the work producing potential of any fluid stream in the system by determining the amount of available energy or availability of the fluid under given conditions. Multiplying this by the mass flow rate gives the rate of available energy flow or exergy flow at all points. Hence an exergy flow or Grassman diagram shows immediately the main paths of useful energy flow and disregards unavailable or rejected energy. The visual impact of this is much stronger than that of an energy flow or Sankey diagram which shows a complete energy balance.

By putting a monetary value on available energy an exergy flow diagram can be converted into a monetary flow diagram. This shows dramatically where financial losses occur in the system due to irreversible thermodynamic processes. A complication arises however since the value of available energy increases through the system. This is due to the effect of thermal conversion efficiency on fuel cost and the capital investment to obtain the energy conversion or transfer. The resulting thermo-economic analysis can be used to assess the impact on overall costs of design modifications and equipment refurbishment but requires a detailed knowledge of equipment prices and financial arrangements.

1. Introduction

1.1. Theoretical Thermodynamic Cycle Concepts

In a thermodynamic cycle heat is received by the working fluid from a heat source. Part of this heat is converted into work while the remainder is rejected as waste heat. The working fluid circulates being alternately heated and cooled as heat is transferred to or from it by the hot source and cold sink respectively. Work is produced by the cycle but there is also a net rejection of heat from the cycle. The total amount of heat rejected Q_{rej} and work out W_{out} is equal to the amount of heat input Q_{in}

$$Q_{\text{in}} = W_{\text{out}} + Q_{\text{rej}} \tag{1}$$

Energy is conserved and this is consistent with the *First Law of Thermodynamics* which deals with the conservation of energy. The amount of work out W_{out} compared with the amount of heat rejected Q_{rej} is dictated by the temperatures of the heat source T_{hot} and the heat sink T_{cold} respectively. In the ideal case with no frictional nor thermal losses and all heat received and rejected at these temperatures, the cycle becomes the *Carnot Cycle* as shown in Figure 1. The total heat input Q_{in} is the area under the line 1-2. The waste heat rejected is the area under line 3-4. The work output is the area enclosed by the cycle 1-2-3-4.

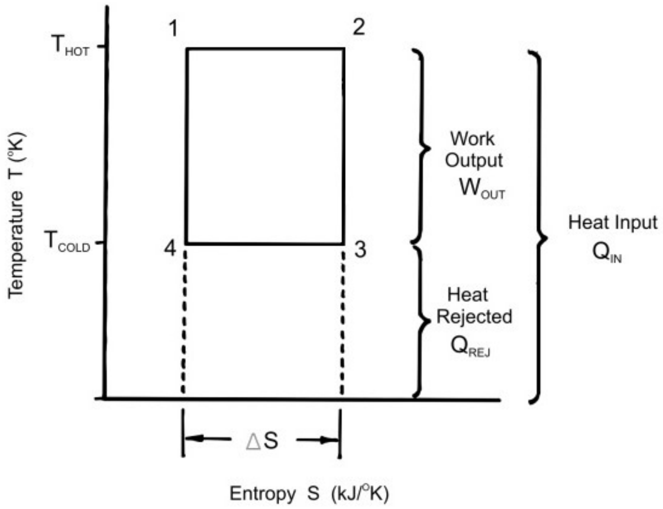

Figure 1: Carnot cycle

It is evident from this that, given a fixed upper temperature T_{hot}, the amount of work produced W_{out} compared with the amount of heat rejected Q_{rej} will be related to the temperature of waste heat rejection T_{cold}. Also the thermal efficiency of the cycle η_{thermal} may be defined as output over input or in terms of the upper and lower temperatures

$$\eta_{\text{thermal}} = W_{\text{out}} / Q_{\text{in}} \tag{2}$$

$$\eta_{\text{thermal}} = \Delta S(T_{\text{hot}} - T_{\text{cold}}) / \Delta S T_{\text{hot}}$$

$$\eta_{\text{thermal}} = (T_{\text{hot}} - T_{\text{cold}}) / T_{\text{hot}} \tag{3}$$

Note that, in the latter equation, if all temperatures are multiplied by the change in entropy Δs, the terms all transform into work or heat as represented by areas on the diagram and this equation reverts to the previous equation.

Since the temperature of heat rejection cannot be lower than the lowest prevailing ambient temperature, T_{cold} is determined by local conditions which are always significantly higher than absolute zero. Thus, no matter how cold the heat sink is, there must always be a net rejection of heat and the thermal efficiency can never be 100 percent. This limitation of all thermodynamic cycles is given by the *Second Law of Thermodynamics* which deals with the conversion of heat to work. Mathematically this may be stated as follows:

$$Q_{\text{rej}} > 0 \tag{4}$$

$$W_{\text{out}} < Q_{\text{in}} \tag{5}$$

The concept may be illustrated graphically as shown in Figure 2. Here W_{out} is work that can theoretically be produced and is called *Available Energy* while Q_{rej} is heat that must be rejected and is known as *Unavailable Energy*. With the temperature of heat rejection fixed by the environment it is evident that unavailable energy is never able to be usefully recovered. Available energy on the other hand is available to produce work. Only in an ideal thermodynamic cycle with no losses of any kind can all available energy be converted into work. All practical thermodynamic cycles suffer losses of some kind or another and the work produced is less than the available energy. A comparison of the work produced with the available energy is however an excellent way of assessing the performance of a thermodynamic system and, since it is associated with the Second Law of Thermodynamics, it is commonly known as *Second Law Analysis*.

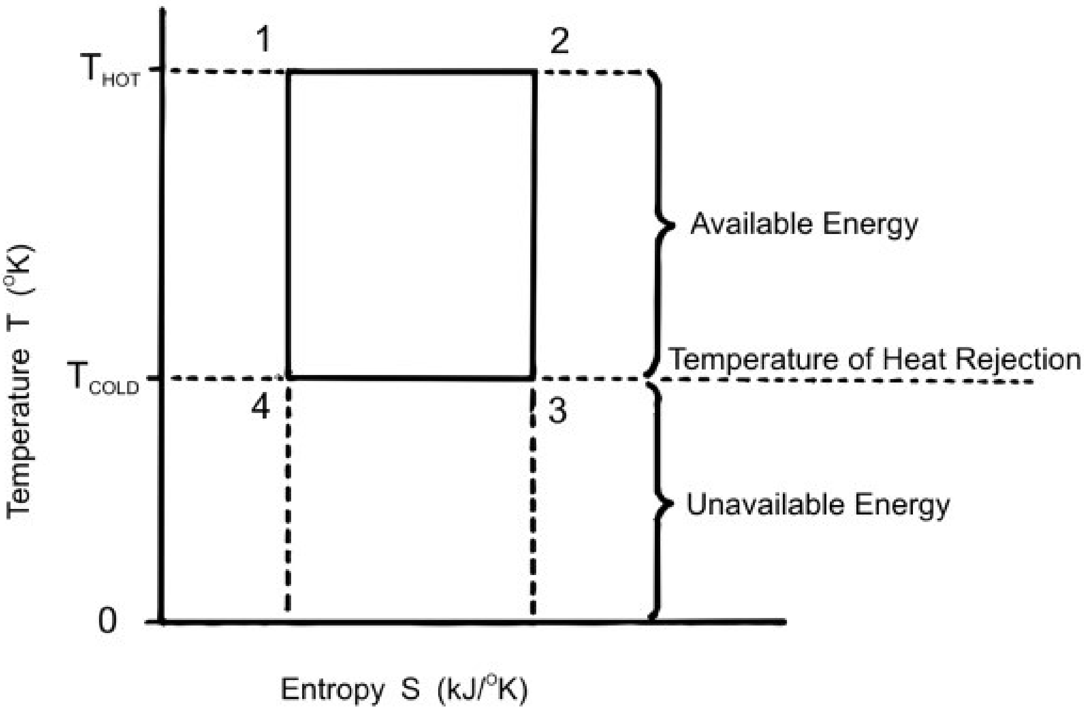

Figure 2: Available and unavailable energy

1.2. Practical Modifications to Cycle Concepts

The *Carnot Cycle* is not able to be adopted in practice for two reasons. Firstly heat must be received and rejected by the working fluid at a constant hot and a constant cold temperature.

This is only feasible during evaporation and condensation respectively of a two phase fluid. Secondly during the work producing process there is some fluid friction leading to generation of heat in the fluid and loss of work output by the cycle. The first of these constraints is partially satisfied by the Rankine Cycle.

In the Rankine Cycle as shown in Figure 3 the thermodynamic processes are confined by the saturation line of the working fluid which in power generation is water-steam. Heat addition occurs from point 2 to point 4 and heat rejection from point 5 to point 1. Some heat is added at temperatures lower than T_{hot} and thus it deviates from the Carnot Cycle.

Nevertheless the Rankine Cycle is useful as a measure of the best efficiency that can be obtained when using a simple steam cycle between given temperature limits. This is always less than that of the Carnot Cycle.

$$\eta_{\text{thermal (Rankine Cycle)}} < \eta_{\text{thermal (Carnot Cycle)}} \quad (6)$$

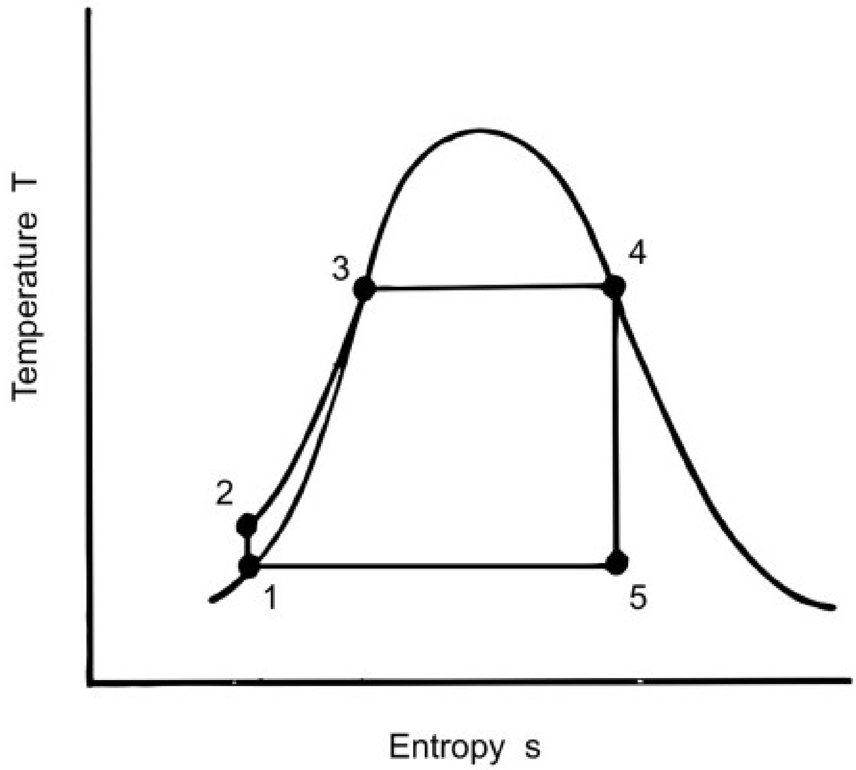

Figure 3: Rankine cycle

In both the Carnot Cycle and the Rankine Cycle heat is assumed to be transferred from the heat source to the working fluid and from the working fluid to the cold sink without a temperature difference.

Heat requires a temperature difference to flow so all practical cycles operate with the working fluid upper and lower temperatures T_{hot} and T_{cold} inside the range between the temperature of the heat source T_{source} and the temperature of heat rejection T_o.

Figure 4 shows this applied to a Carnot cycle and it is evident that the actual work output from the cycle is less than the available energy dictated by T_{source} and T_o. The same reasoning can be applied to the Rankine cycle.

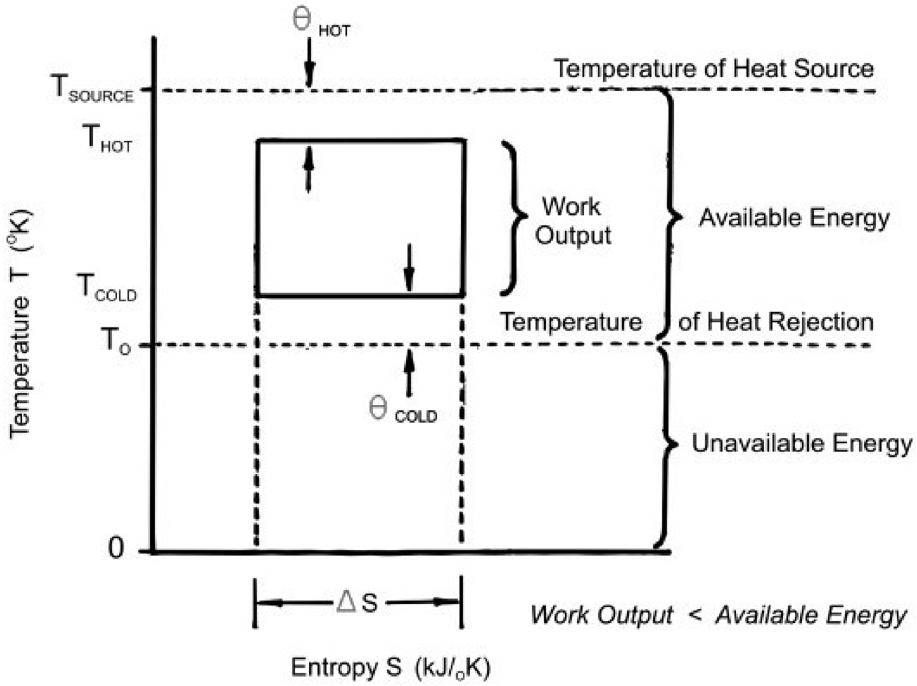

Figure 4: Available energy and work output

The two temperature differences have obviously created a situation where the work output has been diminished even though the energy available for conversion to work has remained the same.

The work output could be increased by reducing the temperature differences. This could only be achieved by increasing the surface area of the heat transfer surfaces since the heat flow rate Q is given by the following equation where U is the overall heat transfer coefficient, A the surface area and θ the temperature difference:

$$Q = U\,A\,\theta \tag{7}$$

Hence it follows that the heat received and rejected by the cycle are given respectively as follows:

$$Q_{\text{in}} = U\;A\,\theta_{\text{hot}}$$

$$Q_{\text{rej}} = U\;A\,\theta_{\text{cold}}$$

To reduce the temperature difference to zero would require an infinite surface area which is impossible. From Figure 4 and Eq. (7) it is evident that reducing the temperature difference increases the work output and hence the efficiency but requires an increase in surface area and hence capital cost. Due to the nature of the mathematical function, progressive increases in surface area and cost will not be recouped by corresponding decreases in temperature difference and efficiency. It is this sort of insight that leads to the strength of Second Law Analysis.

1.3. Reversible and Irreversible Processes

In Thermodynamics it is convenient to make a distinction between reversible and irreversible processes. *Reversible Processes* are processes where the fluid conditions can be returned to their original state without loss or expenditure of energy. *Irreversible Processes* are ones which cannot be returned to their original state without energy input. It follows that reversible processes are ideal processes involving no thermodynamic loss. This is useful in the analysis of the distinct and ideal processes making up a thermodynamic cycle as it allows simple calculations to be executed and efficiencies calculated. There are however some processes which are irreversible. These are usually related to certain practicalities and in fact permeate all ideal processes to some degree. Typical irreversible thermodynamic processes are:

-
-
-

Bibliography

Cengel Y.A. & Boles M.A. (2002). *Thermodynamics - An Engineering Approach*, McGraw Hill. [Provides good introduction to available energy concepts and exergy analysis. Gives examples of exergy transfer in different components]

Kotas T. J. (1985). *The Exergy Method of Thermal Plant Analysis*, Butterworths. [Provides a complete approach to exergy analysis with examples of industrial plants. Includes thermoeconomic applications]

Moore D.F. (1981). *Thermodynamic Principles of Energy Degrading*, MacMillan. [General text on available energy and second law analysis].

Szargut J., Morris D.R. & Steward F.R. (1988) *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, Hemisphere. [Provides examples of the application of exergy analysis to various industries].

Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear

Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.