CHAPTER III
CUMULATIVE EXERGY CONSUMPTION

3.1 Definition of Exergy

The exergy concept is based on both the First and the Second law of thermodynamics. Exergy is defined as the maximum obtainable work when some form of energy is converted reversibly to a predefined reference system, physically and chemically. An exergy analysis is performed to show where energy inefficiencies occur within processes. Exergy losses can directly be translated to an increase in primary fuel consumption.

The reference system, the environment, in an exergy analysis is defined as "an infinitely large body or medium in the state of perfect thermodynamic equilibrium". This means that there is no possibility of producing work from any form of interaction between parts of the environment. Any system besides the environment with different parameters has work-potential in relation to the environment.

The definition of the environment is important in exergy analysis as it is used as the Reference State. A state that is in full thermodynamic equilibrium with the environment has zero exergy. This state of thermal, mechanical and chemical equilibrium is called the dead state. Usually the reference state is chosen as defined by Szargut, which means T_o = 298.15 K and P_o = 101.325 kPa. Szargut defined the mean composition of the earth's environment as the Reference State for chemical equilibrium, for vapor, liquid and solid states, respectively. This means that for example the reference species for carbon is CO_2 in air, for sodium it is Na^+ in seawater, and for iron it is Fe_2O_3 in the earth's crust.

The total exergy of a flowing multicomponent material stream neglecting potential and kinetic exergy can be divided into three major contributions, the chemical exergy, the physical exergy and the exergy change due to mixing:

$$B_{tot} = B_{chem} + B_{phy} + \Delta_{mix}B \qquad (3.1)$$

which equals the more familiar formula:

$$B_{tot} = F*[(h - h_o) - T_o*(S - S_o) \qquad (3.2)$$

3.2 Chemical Exergy

The chemical exergy, B_{chem}, of a process component refers to that part of the total exergy that results from the chemical potential difference between the pure process components and the reference environment components in their environmental concentration evaluated at reference conditions T_o and P_o.

The standard chemical exergy of a gaseous species from the reference state is defined as follows:

$$B^o_{chem,ref\text{-}i} = RT_o*\ln(P_o/P_{ref\text{-}i}) \qquad (3.3)$$

in which $B^o_{chem,ref\text{-}i}$ denotes the standard chemical exergy of a reference species i and $P_{ref\text{-}i}$ denotes its partial pressure evaluated at the mean atmospheric pressure of 99.31 kPa according to Szargut. P_o is the defined reference total pressure (101.325 kPa).

The general expression by which the chemical exergy of a component can be calculated according to its formation reaction from its constituents elements, is given by

$$B^o_{chem,i} = \Delta_f G^o_i - \Sigma(n_j*B^o_{chem,ref\text{-}j}) \qquad (3.4)$$

where $B^o_{chem,i}$ denotes the Gibbs free energy of formation for the reaction for component i from reference species j, n_j denotes the stoichiometric number for the component in the reaction equation, and $B^o_{chem,ref\text{-}j}$ is the standard chemical exergy of a reference species.

3.3 Physical Exergy

The physical exergy of a material stream is the maximum obtainable work (or electrical energy) when this stream is brought from actual conditions (T_1, P_1) to thermomechanical equilibrium at ambient temperature and pressure(T_o, P_o) by reversible processes and heat being only exchanged reversibly with the environment at T_o.

The physical exergy is therefore equal to the amount of work arising when changing a stream, consisting of the unmixed components, reversibly from process condition(T_1, P_1) to reference conditions(T_o, P_o):

$$B_{phy} = [\Sigma(F_i{*}H_i) - \Sigma(F^o_i{*}H^o_i)] - T_o{*}[\Sigma(F_i{*}S_i) - \Sigma(F^o_i{*}S^o_i)] \quad (3.5)$$

Because the enthalpy and entropy of the pure (unmixed) components are used, the physical exergy includes the state of the stream but not mixing among the constituents.

3.4 Exergy Due to Mixing

The mixing exergy is equal to the amount of work arising when a stream, consisting of the pure components, is mixed at process conditions(T_1, P_1) and calculated as follows:

$$B_{mix} = [F{*}H) - \Sigma(F_i{*}H_i)] - T_o{*}[F{*}S) - \Sigma(F_i{*}S_i)] \quad (3.6)$$

3.5 Cumulative Exergy Consumption

The Cumulative Exergy Consumption(CExC) analysis is essentially an accounting procedure in which the cumulative exergies associated with all input streams to a process section are distributed to the useful products. This implies that the exergy associated with a waste product discharged to the environment is zero, since such a stream is of no value.

CExC analysis provides a method of assessing different production methods for similar products. The specific CExC (Sp. CExC or c) of the process is a measurement factor in the economics and profitability of one process relative to another. Cumulative exergy values assigned to the product (s) of a process express the sum of the exergy of natural resources consumed in all steps of the process.

The cumulative exergy, C, of a process stream is the exergy sum of the natural resources associated with making that stream available for the process.

$$C = B_{tot,nr} \tag{3.7}$$

The summation will include the exergy consumption of any processing steps prior to introduction of the stream to the process under analysis. The term may include the chemical exergy of the materials comprising the stream. The exergy ratio η_i for stream i is defined by the expression.

$$\eta_i = B_{tot,i}/C_i \tag{3.8}$$

Clearly, $0 < \eta_i < 1.0$ and is a measure of the effectiveness of utilization of natural resources for the production of stream i.

For a process involving multiple products j, k, l from different plant sections and multiple recycle streams, the cumulative exergy balance equations are written for each section. The cumulative exergy input to section s, C_s, is apportioned to the useful products of the section in proportion to the mass or exergy of the useful products. However, for recycle streams, the cumulative exergy is set equal to the thermal exergy. This procedure is adopted to simplify calculations and substantially reduces computing time. For section s,

$$C_s = \Sigma C_{d,i} \tag{3.9}$$

For the useful product j,

The specific cumulative exergy consumption for product j, c_j, is defined as,

$$c_j = C_j/P_j \tag{3.10}$$

This is a measure of the exergy consumption of natural resources for the production of j.

3.6 Process Analysis

The analysis of a system by the Cumulative Exergy Consumption method is described in the following sections.

3.6.1 Definition on the System

In order to perform the Cumulative Exergy Consumption analysis, a system has to be defined. The system boundary is shown in Figure 3.1. It includes 2 sub-systems and a main system. This boundary shows that the exergy required to transport the raw materials to the site of the process is to be considered as part of the analysis.

The goal the exergy analysis may also influence the determination of the system's boundary. For instance, it may be necessary to include the exergy required to produce and deliver the raw materials and services to the system.

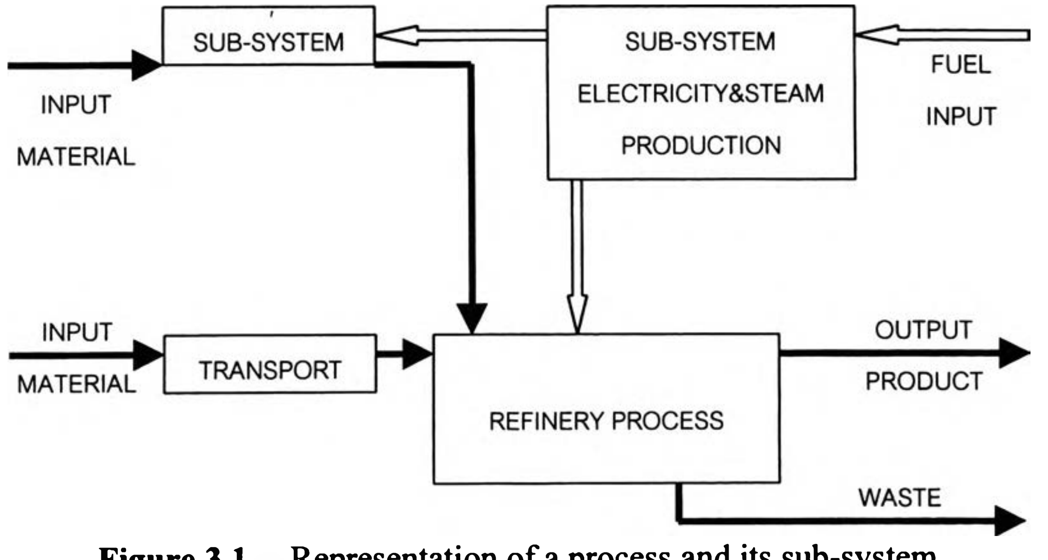

Figure 3.1 Representation of a process and its sub-system

3.6.2 Exergy Analysis

Once the boundary for the system under consideration has been determined the process' flowsheet must be divided into suitable sections so that they may be analyzed separately. It may also be necessary to divide the sub-systems that are contained within the system's boundary, into sections for individual analysis. Processes and sub-systems can be divided into as many sections as desired. However, sections usually represent a unit operation of the process that represents a specific function such as a set of washers or an entire bleach plant, as was done in this paper.

The first stage of the analysis of the sections comprising the process and sub-systems in question involves the construction of conventional material, energy and exergy balances. These balances are based on the Law of Conversation of Mass, on the First Law and the Second Law of thermodynamics, respectively. Upon completion of these balances, the Cumulative Energy Consumption balance and the Cumulative Exergy Consumption balance equations may be constructed.

3.6.3 Cumulative Exergy Consumption Balance Equations

A typical section of the system, which is under consideration, is depicted in Figure 3.2. Possible cumulative exergy inputs to this section are as follows:

3.6.3.1 Feed Streams

CExC values associated with the intermediate products coming from other sections in the system reflect the amount of exergy delivered to the system in all steps prior to this section. In the event that raw materials are fed directly to this section then the exergy associated with the processing and transportation of these materials will be reflected in the cumulative exergy values of these streams. In the following balance equations, the CExC values of feed species i entering a section will be represented as $C^F{}_i$.

3.6.3.2 Exergy Supply Streams

Exergy requirements of the section under consideration are supplied by electricity, steam (both injection and indirect heating) and exergy, usually in the form of heat, that is recovered from other sections of the process. The cumulative exergy values associated with the exergy supply streams of species i are represented and calculated by Equations 3.11 to 3.13.

$$C^E_{Elec,j} = \frac{B_{Elec,j}}{\eta_{ovelec}} \tag{3.11}$$

$$C^E_{Steam,j} = \frac{B_{Steam,j}}{\eta_{Steam}} \tag{3.12}$$

$$C^E_{Rec,j} = B_{Rec,j} \tag{3.13}$$

The efficiency of electricity and steam generation (η_{ovelec} and η_{steam} respectively) are determined by Equations 3.27 and 3.24. These efficiencies are calculated on a cumulative exergy basis, not on the conventional thermal exergy basis.

3.6.3.3 Recycle Streams

Materials output from one part of a production process that are fed back to some earlier part of the same sequence are known as recycle streams. These streams are recycled for a variety of reasons, however, the cumulative exergy values associated with these streams is set equal to their exergy values as shown in Equation 3.14.

$$C^R_i = B_i \tag{3.14}$$

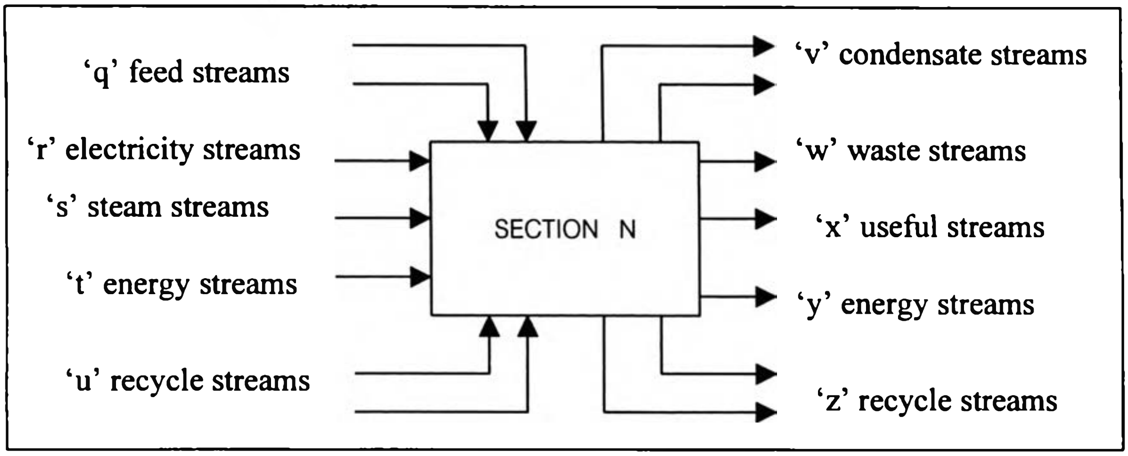

Figure 3.2 Diagram of Section N

The total cumulative exergy entering section N, C_N, is equal to the sum of the cumulative exergy delivered to the section with the feed, energy supply and recycle streams. Equation 3.15 represents the total cumulative exergy entering section N:

$$C_N = \sum_i C_i = \underbrace{\sum_{i=1}^{q} C_i^F}_{\text{Feed}} + \underbrace{\sum_{i=1}^{r} C_{Elec,i}^E + \sum_{i=1}^{s} C_{Steam,i}^E + \sum_{i=1}^{t} C_{Rec,i}^E}_{\text{Energy Supply}} + \underbrace{\sum_{i=1}^{u} C_i^R}_{\text{Recycle}} \tag{3.15}$$

The cumulative exergy input to Section N is distributed amongst the section's useful products. The useful streams leaving Section N are denoted by the letter j and they include:

3.6.3.4 Recycle and Recovered Streams

These stream are assigned cumulative exergy values equal to the physical energy of the streams, and shown in Equations 3.16 and 3.17.

$$C_j^R = B_j \tag{3.16}$$

$$C_{Rec,j}^E = B_{Rec,j} \tag{3.17}$$

If indirect heating steam is used in section N, the stream condensate is assigned a cumulative exergy value according to Equation 3.18.

$$C^{E}_{Cond,j} = \frac{B_{Cond,j}}{\eta_{steam}} \tag{3.18}$$

3.6.3.5 Product Streams

The remainder of the cumulative exergy input is apportioned to the useful products of the section in proportion to the exergy of the useful products. For each of the product streams, of Section N, equations similar to Equation 3.19a are constructed.

$$C_{u1} = \frac{B_{u1}}{B_{uN}} \times \left[C_n - \sum_{j=1}^{y} C^{E}_{Rec,j} - \sum_{j} C^{E}_{Cond,j} - \sum_{j=1}^{z} C^{R}_{j} \right] \tag{3.19a}$$

$$C_{u2} = \frac{B_{u2}}{B_{uN}} \times \left[C_n - \sum_{j=1}^{y} C^{E}_{Rec,j} - \sum_{j} C^{E}_{Cond,j} - \sum_{j=1}^{z} C^{R}_{j} \right] \tag{3.19b}$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$C_{uk} = \frac{B_{uk}}{B_{uN}} \times \left[C_n - \sum_{j=1}^{y} C^{E}_{Rec,j} - \sum_{j} C^{E}_{Cond,j} - \sum_{j=1}^{z} C^{R}_{j} \right] \tag{3.19k}$$

where;

$$B_{uN} = \sum_{j=1}^{k} B_{uj}$$

For a system involving multiple products from different plant sections as multiple recycle streams, cumulative exergy balance equations are written for each section.

The specific cumulative exergy consumption for product j, c_j is defined as;

$$c_j = C_j/P_j \tag{3.20}$$

3.6.4 CExC Balance Equations for an Energy Section

An energy section includes BoilerA&B, Generator1,2&3 and WHB. Figure 3.3 represents the energy section in block formation.

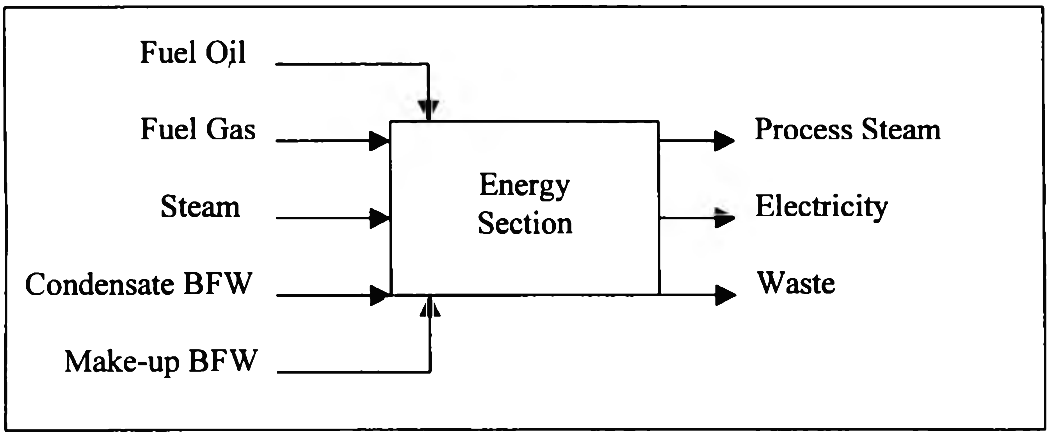

Figure 3.3 Diagram of the Energy Section

1. Fuel

Fuel used by the energy process includes fuel gas and fuel oil from the production process that is under consideration.

2. Make-up Boiler Feed Water

Losses of the working fluid (i.e., water/steam) from the energy process and steam supply system are replenished by make-up boiler feed water (BFW).

3. Steam

Saturated HP-steam produced from the Catalytic Reforming Unit was sent to a Waste Heat Boiler.

The total cumulative exergy entering the energy process, C_{Ener}, is distributed amongst the useful products, electricity and process-steam, of the energy process. Each system boundary, the cumulative exergy consumption is distributed in proportion to their exergy.

The total cumulative exergy entering the energy section, is represented by Equation 3.21 while the cumulative exergy is apportioned to the electricity and process-steam according to Equations3.22, 3.23.

$$C_{Ener} = \sum_i C_{di} = C_{Fuel\,Oil} + C_{Fuel\,gas} + C^{BFW}_{Make-up} + C^{F}_{Steam} \quad (3.21)$$

$$C^{Prod}_{Elec} = \frac{B^{Prod}_{Elec}}{\sum B_{Ener}} \times C_{Ener} \quad (3.22)$$

$$C^{Prod}_{Steam} = \frac{B^{Prod}_{Steam}}{\sum B_{Ener}} \times C_{Ener} \quad (3.23)$$

where;

$$\sum B_{Ener} = B^{Prod}_{Steam} + B^{Prod}_{Elec}$$

The efficiency of steam production is determined from Equation 3.24.

$$\eta_{Steam} = \frac{B^{Prod}_{Steam}}{C^{Prod}_{Steam}} \quad (3.24)$$

The overall efficiency of electricity generation is determined by considering an "electricity mixing" section as shown in Figure 3.4. This section mixes electricity that is produced in the energy section with electricity that is imported from EGAT. Equation 3.25 to 3.27 are the balance equation for the "electricity mixing" section.

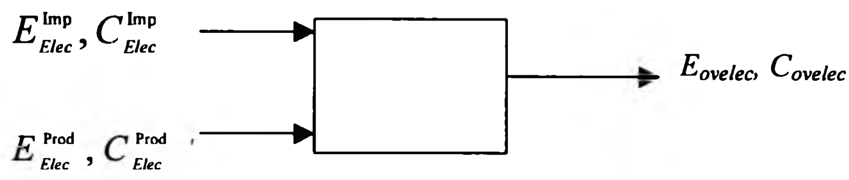

Figure 3.4 Representation of the "Electricity Mixing" Section

$$B_{ovelce} = B_{Elec}^{Prod} + B_{Elec}^{Imp} \tag{3.25}$$

$$C_{ovelec} = C_{Elce}^{Prod} + C_{Elec}^{Imp} \tag{3.26}$$

where;

$$C_{Elec}^{Imp} = \frac{B_{Elec}^{Imp}}{\eta_{Elec}^{Imp}}$$

The overall electricity generation efficiency is given as:

$$\eta_{ovelec} = \frac{B_{ovelec}}{C_{ovelec}} \tag{3.27}$$

Once all of the cumulative energy and exergy equations have been constructed for each plant section it should be found that there are equal numbers of unknowns and equations. A solution for these equations may be determined by a suitable method that will solve simultaneous linear equations.