

**A GLOBAL SECOND LAW APPROACH TO THE
EVALUATION OF ENERGY CONVERSION SYSTEMS
TAKING INTO ACCOUNT ECONOMIC AND
ENVIRONMENTAL FACTORS**

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This paper outlines the basic foundations of a methodology for the optimum design and performance evaluation of energy conversion systems. Based on the Second Law of thermodynamics, it simultaneously takes into account not only the thermodynamics of the system being analyzed but also the economics of the capital equipment used and the impact which pollution and the use of natural resources (whether related to the capital equipment or the operation of the system) have on the environment. The resulting mathematical models incorporate the same types of assumptions used in more traditional approaches, assumptions based on good engineering practice. Specific features such as the introduction of penalty factors for pollution and the use of natural resources are discussed as well as a consistent Second Law basis (both from a manufacturing and recycling standpoint) for the value of the capital equipment used in such systems. A brief discussion of how these elements are incorporated into the optimization of an overall model of the system is presented.

mots-clés ● keywords

second law ● energy systems ● thermodynamics ● thermoeconomics ● environment ● pollution ● natural resources ● capital equipment

Nomenclature			
B	Boltzmann's constant	m	mass
C	concentration factor	N	Avogadro's number
\dot{C}	rate of thermodynamic costs	ORZ	ökologische Rückzahldaur
\dot{C}^s	rate of thermoeconomic costs	P	pollution factor
Ex	exergy	R	replacement factor
\dot{Ex}	rate of exergy	S	Entropy
ERZ	energetische Rückzahldauer	s	specific entropy
G	Gibbs free energy	t	component utilization time ($t = (\tau/\xi)$)
\dot{K}	rate of thermodynamique surcharges (a constant)	T	absolute temperature
\dot{K}^s	rate of thermoeconomic surcharges (a constant)	V	total volume of the environmentally effected region
L	exergy losses	\dot{V}	volumetric flow rate
\dot{L}	rate of exergy losses	x	concentration
Greek Letters			
β	thermodynamic performance parameter	ρ	density
η	exergy efficiency	τ	average lifetime of a component or part based on economic criteria
ν	frequency of replacing a component or part	ϕ	rate of the degree of pollution
ξ	utilization parameter for a component or part		
Subscripts			
ass	assembly	i	transformation process
i	pollutant	m	machining process
m	component	q	pollutant
n	component part	w	cooling water

INTRODUCTION

In the design and/or performance analysis of an energy conversion system, there are two factors other than the thermodynamic operation of the system which play an important role. They are the economics of the capital equipment used in the cycle and the past effects of the cycle (i.e., the construction of the capital equipment) and present and future effects of the cycle (i.e., its operation and the recycling of any used-up capital equipment) on the environment. All three factors - the thermodynamics, the economics and the environmental effects - are presently taken into account to some degree or another at different stages in the analysis of such a system. However, they are only considered separately or in some limited combination or not at all, since a consistent methodology which combines all of them into a single entity or tool is lacking. The purpose of our proposal is to develop such a methodology, providing a framework simple enough to be practical yet sufficiently consistent with good engineering practice and the complexities involved in this type of modelling. As a base, we will use some of the extensive work which has already been done in the literature by the authors themselves and others.

Of the work which has been done, it is that which comes from the field of thermoeconomics [1-18] which, along with some of the new ideas presented here, provide the basis for our methodology, for being able to simultaneously consider in a *single mathematical model* the factors listed above. It is with such a single model of all the above factors that an "optimum" design and/or system performance can be found.

This contrasts with the more traditional approach still used in industry today¹ (and to a large extent in

academics as well) that models the thermodynamic characteristics of a system and then considers the economic (and sometimes environmental) characteristics separately, iterating back and forth in order to find the "best" solution. In fact, the most that can be hoped for with this traditional approach is the best cycle among a limited number actually examined (in the case of Figure 1, three), a "best" which will more than likely not correspond to the "optimum" (again see Figure 1).

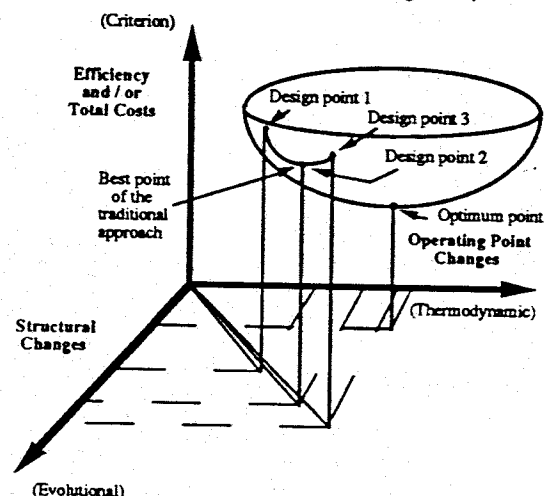


Fig.1 The design space of conceptual designs.

In either case, finding the "best" or the "optimum" design is centered around a problem best illustrated by the classic example of a heat exchanger. In order to reduce its thermodynamic losses, the goal is to make it as efficient as possible. For a fixed heat transfer area and flow configuration, this requires balancing competing heat transfer and fluid flow irreversibilities in a way which minimizes them (see Figure 2 [21]). Further minimizing these losses by varying the heat

transfer area results in the optimum thermodynamic solution of an infinite heat transfer area. Such a result is, of course, not feasible; but even a large finite heat transfer area may for economic reasons not be practical. Thus, the thermodynamic balance of competing heat transfer and fluid flow irreversibilities is incomplete and must be altered to include the economic considerations represented by the heat exchanger's capital costs (used here in the broadest sense of the term to include investment costs, maintenance, replacement, etc.) in order to arrive at a realistic or feasible solution.

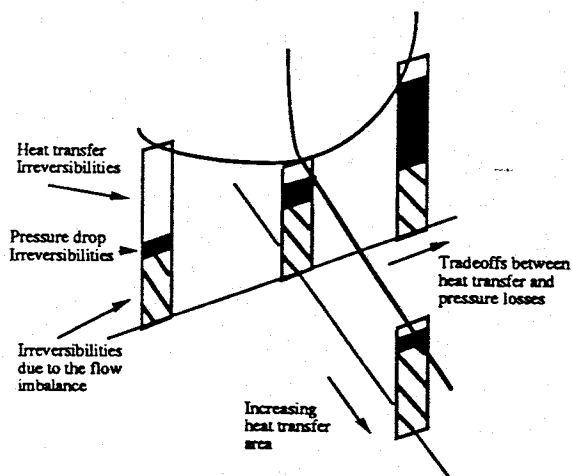


Fig. 2 Thermodynamic optimization structure of a heat exchanger [21].

However, even this balance is incomplete since it lacks the environmental considerations which may be pertinent not only to the use of the heat exchanger (or system) but to its construction and recycling as well. Including these environmental effects is justified on the basis that our present system of pricing energy (or more appropriately, exergy - see explanation below) results from an incomplete set of markets. These markets (as outlined by Faber, et al. [22]) are the *supply* and *demand* market (which includes the economic considerations associated with the capital equipment and fuel), a complete set of *future* markets (those markets which will exist or not exist depending on our present use of natural resources) and a complete set of markets dealing with the *impact of environmental pollution*. It is the nonexistence of this complete set of markets, which is the case when supply and demand are the sole market factors, that leads to prices on exergy being too low. Thus, environmental factors, i.e., future markets and markets dealing with environmental pollution, must also be considered. This can be done in two ways: by state intervention or by mathematically and thermodynamically accounting for the pollution of the environment and the effects on future markets of the extraction, regeneration, replacement and recycling of natural resources. State intervention is seldom a good approach since it is difficult to reflect true market conditions in this way. The second option, however, can lead to a more realistic pricing structure; and it is this option which is developed here as an integral part of our methodology.

GENERAL ASPECTS OF THE APPROACH

The economic factors used in the design and/or performance evaluation of energy conversion systems always have as a base the thermodynamic parameters which characterize the system and its components. Thus, when speaking of economic considerations, one speaks of the variations, for example, in component capacities or component heat transfer surfaces with the monetary cost of each component. As the costs increase, so do the capacities, surface areas, etc. Even though this variation is not on a one to one basis, the trends are the same. Thus, one can think in terms of actual monetary costs or in terms of the thermodynamic costs since the latter can always be converted to their monetary equivalent at any point in the analysis. This can be seen in Figure 3 [23] in which the diagram of Figure 2 has been modified to include the effects of the material (thermodynamic costs or material irreversibilities - see explanation below) on the heat exchanger design. As can be seen, an infinite heat transfer surface is no longer the optimum solution, a fact which reflects the economics of the design.

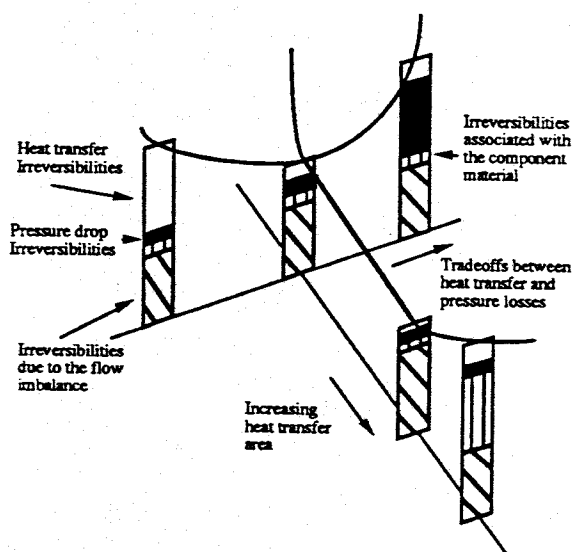


Fig. 3 Thermodynamic optimization structure of a heat exchanger when material considerations are included [23].

Thus, it is the thermodynamic costs which we will be the focus of our methodology since it is only with a thermodynamic basis that our approach can be made generally applicable. The link to the monetary values is not made until the final step of our development.

Now, outside of the actual performance characteristics of the cycle being analyzed, these thermodynamic costs must reflect the existence or more appropriately the manufacture and recycling of the capital equipment being used in the cycle plus the effects that the operation of the cycle *has* on the environment and the effects that the manufacture of the equipment *had* and its recycling *will have* on the environment. One must, therefore, consider not only the present cycle or process being analyzed but the process of recycling and the entire chain of manufacturing processes (see Figure 4) leading up to the final one beginning from the extraction

of the raw material and continuing through its transformation, machining and assembly into capital equipment. Thus, decisions on design or operational changes in the final process will and more importantly should be based not only on the primary sources of energy used and produced in this process but also on the energy requirements, losses and products - the so-called "grey exergy"² (analogous to the term "grey energy" [25]) - of the recycling and manufacturing processes tied to this process. Decisions on the basis of such considerations may, in fact, be different from those which might be made on the basis of the final process itself.

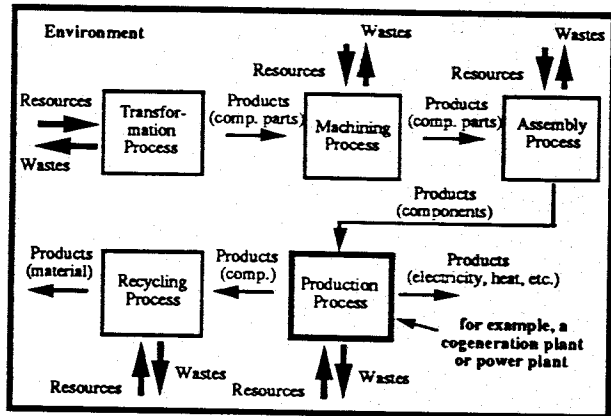


Fig. 4 Flow diagram of the processes involved from the point of extracting the required natural resources to the production of electricity and/or heat and the recycling of used-up components.

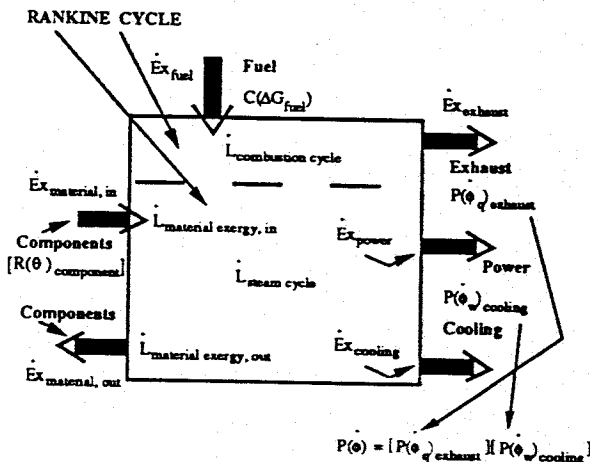


Fig. 5 Rankine cycle representation depicting losses and associated environmental factors.

Obviously, this requires extending the system boundaries of our final process to include these other processes as well as the environment, which from a practical standpoint makes the problem intractable. However, what can be done instead is to keep the original system boundary and to account for the external factors - environmental effects both past (previous processes), present and future (recycling process) and the

manufacture and recycling of the equipment - by thermodynamically assessing a value for each and then using these values, along with the actual thermodynamic performance losses or costs which occur in the final process or cycle, in a minimization of all the thermodynamic costs. As an example, equation (1) shows how the total system losses (the L with subscript "system total") of the Rankine cycle depicted in Figure 5 would be augmented by some of the external factors just mentioned (the L 's with subscript "material exergy" and the environmental functions P , C and R representing, respectively, the effects of pollution, the extraction of natural resources and the replacement of components or component parts).

$$\dot{L}_{system\ total} = \frac{\dot{L}_{system\ thermodynamic}}{[P(\phi)][C(\Delta G)_{fuel}]} + \dot{L}_{mat.\ exergy,\ in} + \dot{L}_{mat.\ exergy,\ out} \quad (1)$$

where

$$\dot{L}_{system\ thermodynamic} = \dot{L}_{combustion\ cycle} + \dot{L}_{steam\ cycle} \quad (2)$$

$$\dot{L}_{mat.\ exergy,\ in} = \frac{1}{t} \sum_{m=1}^{comp.} [f(\beta)]_m \left[\sum_{n=1}^{subgrps.} L_n + L_{ass} \right]_m \quad (3)$$

The first term on the right in equation (1) represents the losses in the current production process, i.e., the Rankine cycle, plus a penalty factor C associated with the extraction of the raw material used as fuel and a penalty factor P associated with the pollution due to the combustion process and any thermal pollution resulting from the condensing of steam. This term can actually be thought of as the sum of the system's thermodynamic losses and an environmental penalty function which is characterized by the penalty factors mentioned above and the losses which occur within the system itself, i.e.,

$$\dot{L}_{system's\ augmented\ losses} = \dot{L}_{sys.\ therm.} + \Phi_{environment}(P, C, \dot{L}_{sys.\ therm.}) \quad (4)$$

where

$$\dot{L}_{system's\ augmented\ losses} = \frac{\dot{L}_{system\ thermodynamic}}{[P(\phi)][C(\Delta G)_{fuel}]} \quad (5)$$

$$\Phi_{environment} = \left(\frac{1}{[P(\phi)][C(\Delta G)_{fuel}]} - 1 \right) \dot{L}_{sys.\ therm.} \quad (6)$$

Now, turning again to equation (1), the second term on the right represents the losses associated with the processes of transformation and machining (L_n) (see Ref. [26]) and of assembly (L_{ass}) (see Ref. [26]) of the capital equipment used in the Rankine cycle [26,23,27]. The relationship between these losses and the rate at which these losses are introduced into the operation of the Rankine cycle is given by the mean life time t of component/plant utilization and the function f which defines the relationship between the performance characteristics (β) of each component and the losses associated with their manufacture. Although not explicitly shown in equation (3), these loss terms already include (see Ref. [26]) the pollution extraction and replacement for

² It should be noted that "exergy" or potential work is more limited in scope than the more general concepts of "essergy" [6,10] and "coenergy" [24] since its definition is process dependent. "Essergy" and "coenergy", on the other hand, are process independent and, in fact, encompass

The third term on the right in equation (1) represents the losses associated with the recycling of capital equipment which no longer functions in the cycle. It is expressed in a fashion similar to that of the material exergy losses of the manufacturing processes given by equation (3).

This type of approach has been used in a similar fashion in the study of biological systems [28,29]. These systems (the human being in particular) maintain themselves at the expense of their environment. In effect, the entropy of a healthy adult is constant during the course of years because the irreversibilities or losses which occur in the interior of the body are compensated by the fact that the entropy of the food that the body absorbs is less than the entropy of the wastes that it rejects. In other words, the human being would be the site of an increase in entropy if it were not able to reject wastes to its environment. Thus, as with biological systems, a like approach for energy systems is proposed so that the increase in entropy due to external elements (the degradation of the environment, etc.) is taken into account (as described above) by artificially increasing the exergetic losses of the system while maintaining a boundary which includes the cycle itself but not its surroundings or any additional processes.

Now, as should be apparent from the terminology such as exergy, thermodynamic losses and irreversibilities which have been used here, a Second Law approach is envisioned. There are at least two primary reasons for this although several others exist. The first is that even the thermoeconomic approaches in the literature based on energy as opposed to exergy constrain their search for an optimum subject to the thermodynamic functions of state such as pressure, temperature, etc. Furthermore, in a heat exchanger, for example, the exergy losses due to friction are directly linked to the pressure losses of the flows. Thus, regardless of the approach, the Second Law is implicitly or explicitly present. As a consequence, the extended thermoeconomic approach proposed here is based on the First and Second Laws of Thermodynamics and in particular on exergy.

The second reason which is also tied to the first is that a great number of industrial processes involve heat directly (the melting and tempering of metals, the production and distribution of heat, drying, etc.) for which the value of energy (the First Law) is not sufficient since this value provides information solely on the quantity of heat and not on its quality (e.g., its level of temperature). In contrast, the heat's exergy value (Second and First Laws) does both. Certain parameters which have been introduced into the literature recently such as the *ERZ* (energetische Rückzahldauer) and *ORZ* (ökologische Rückzahldauer) coefficients [30] are interesting but are based solely on the First Law and, thus, lack the completeness which comes with the Second. Of course, for processes and products which deal exclusively with "noble" forms of energy (electricity, mechanical work, etc.) or forms which approximate these (combustibles, etc.), an energy based approach may be sufficient (from a global but not a detailed level) since globally it gives the same or almost the same results as

that of an approach based on exergy. However, the difference becomes important if, for example, the exergetic levels between the different products or between the grey energy and the products is significant. It seems rather inappropriate to compare on equivalent terms the grey energy needed to produce a solar collector frame (e.g., of aluminum) and the energy at low temperature received from the collector throughout its lifetime. Thus, for this reason and the others stated above, it is preferable to work with the two Laws of thermodynamics combined (e.g., in the form of exergy) since the majority of industrial processes deal with many different kinds of energy.

SPECIFIC ASPECTS OF THE PROPOSED APPROACH

At this point, some of the specifics of the initial ideas which will be used in the development of our methodology are in order. The purpose of the factors and the losses which were briefly discussed above is to include them in the mathematical model of some energy conversion process (e.g., the cycle of Figure 5) in order to optimize that process or system. Such a model can be purely thermodynamic in nature and as such represent solely the thermodynamic costs of the system's operation, its subsequent impact on the environment and the use of its capital equipment. If it is thermoeconomic in nature, the model represents the actual monetary costs associated with the thermodynamic ones. Figure 6 depicts a breakdown of these different types of costs (purely thermodynamic or monetary) and the balance which must be struck between the equipment costs and the operation of a cycle in order to arrive at some optimum.

The model itself consists of an objective function (either thermodynamic or thermoeconomic) and a set of constraints which describe the operation of that system. The optimization of the thermodynamic model is useful for guiding the design or operational decisions of a single system or in making comparisons on a purely thermodynamic cost basis between varying technologies which are meant to accomplish the same task. The optimization of the thermoeconomic model is useful for actually refining the comparisons and specific design or operational changes of the thermodynamic model's optimization.

Returning again to Figure 5 and equation (1), the total losses L (or the rate of these losses) of the system can be included for the purposes of optimization in an overall thermodynamic objective function for the cycle which takes into account external factors effecting the environment and the manufacture and recycling of the capital equipment. Letting :

$$\dot{E}x_{\text{system's augmented boundary losses}} = \frac{\dot{E}x_{\text{exhaust}} + \dot{E}x_{\text{cooling}}}{[P(\phi)][C(\Delta G)_{\text{fuel}}]} \quad (7)$$

represent the losses due to a transfer of heat and mass across the system boundary, the thermodynamic objective function can be written as

$$\text{minimize } \dot{C}_{\text{total}} = \dot{E}x_{\text{material}} + \dot{L}_{\text{system total}}$$

where \dot{K} is a constant representing any thermodynamic surcharges and \dot{C}_{total} (the total thermodynamic costs) is minimized at constant system load (e.g., for the cycle of Figure 5, a power output which remains constant) subject to a set of constraints representing the thermodynamic interactions within the cycle and where

$$\dot{E}x_{material} = \dot{E}x_{material,in} - \dot{E}x_{material,out} \quad (9)$$

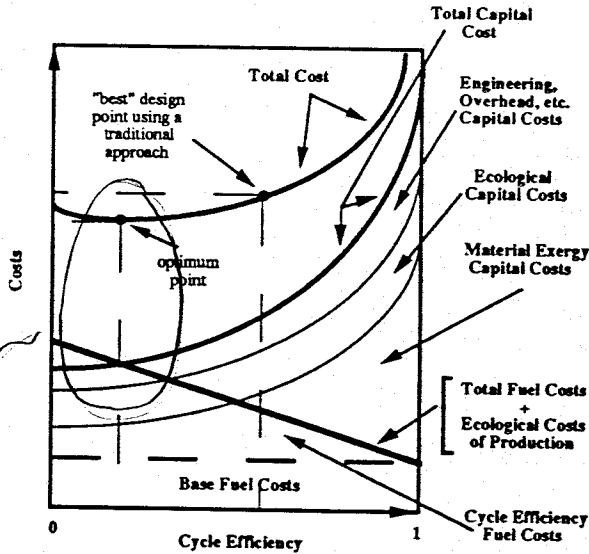


Fig. 6 Balance and breakdown of costs (thermodynamic or monetary).

An equivalent expression for equation (8) can be found based on a classical exergy balance for the system (equation (13)) and equations (1), (11) and (12) such that the objective function is

$$\text{minimize } \dot{C}_{total} = \dot{E}x_{material} + \dot{L}_{material\ exergy} + \dot{E}x_{system's\ augmented\ resources} + \dot{K} \quad (10)$$

where

$$\dot{L}_{material\ exergy} = \dot{L}_{material\ exergy,in} + \dot{L}_{material\ exergy,out} \quad (11)$$

$$\dot{E}x_{system's\ augmented\ resources} = \frac{\dot{E}x_{fuel}}{[P(\phi)][C(\Delta G)_{fuel}]} \quad (12)$$

and the balance is

$$\dot{E}x_{fuel} = \dot{L}_{system\ thermodynamic} + \dot{E}x_{exhaust} + \dot{E}x_{cooling} + \dot{E}x_{power} \quad (13)$$

Note that since the optimization of equation (10) or (8) occurs at constant $\dot{E}x_{power}$, this power term is excluded from both equations. Furthermore, this alternate form (equation (10)) of the objective function (equation (8)) aids in defining the transition from purely thermodynamic costs to the monetary costs represented by the thermoeconomic objective function

$$\text{minimize } \dot{C}_{total}^S = \dot{C}_{capital\ equipment}^S + \dot{C}_{fuel}^S + \dot{K}^S \quad (14)$$

Now, returning to the objective function of equation (8), the total system losses (equation (1)) consist of both thermodynamic and material losses. The former is augmented in the example of Figure 5 by two pollution factors P which account, respectively, for the pollutants due to the exhaust gases from the combustion process in

these factors take is based on ideas initially presented by Kümmel [31] and further developed by Faber, et al. [22] in which the effects of the pollution are measured by a function which varies continuously between one (no significant pollution) and some small value greater than zero (the worse case). This is shown in Figure 7.

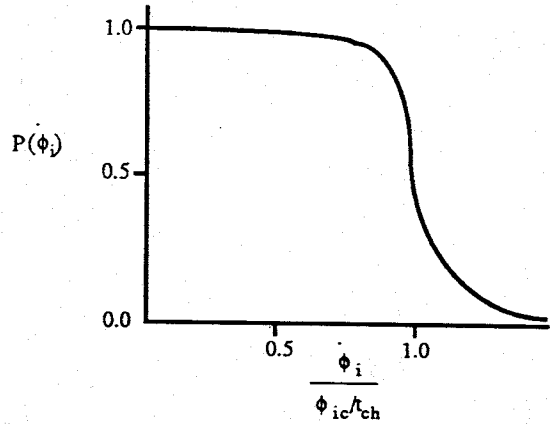


Fig. 7 The pollution factor.

In equation form, the pollution factor is written as

$$P(\phi_i) = \left[\exp\left(\frac{\phi_i - \phi_{ic}/t_{ch}}{\phi_{oi}}\right) + 1 \right]^{-1} \quad (15)$$

where

$$P(\phi_i) = P(\phi_k)_{m,n} \text{ or } P(\phi_q)_{exhaust} \text{ or } P(\phi_w)_{cooling} \quad (16)$$

$$\dot{\phi}_i = \left(\frac{1}{V}\right) \frac{dS_i}{dt} = \left(\frac{1}{V}\right) \rho_i s_i \dot{V}_i \quad (17)$$

$$\dot{\phi}_{ic} = \left(\frac{1}{V}\right) S_{ic} = \left(\frac{1}{V}\right) \rho_{ic} s_{ic} V \quad (18)$$

$$t_{ch} = \frac{V}{\dot{V}_i} \quad (19)$$

Note that the denominator in equation (19) is the volumetric flow rate of pollutant i while the numerator is the total volume of the environmentally effected region.

The pollution factor itself is based on the rate of change of entropy associated with each type of pollutant whether it is one of the common pollutants due to combustion or a fluid at a temperature high enough that when it comes into contact with the environment (a river or a lake, for example) it results in thermal pollution. The rate of change of entropy of each pollutant per unit volume (that volume associated with the environmentally effected region) is defined as the total degree of environmental pollution, ϕ_i . It is the rapidity and spatial concentration of this increase which endangers the ecological balance [31]. The value ϕ_{ic} is called the critical upper limit for each pollutant, a value which society sets and which reflects the limit above which the pollution effects become very costly and no longer acceptable. The parameter ϕ_{oi} (or the rate of) is the natural purification rate of pollutant i by the environment and is typically some fraction of ϕ_{ic} . It in fact, acts as a

and, thus, the costs or penalties incurred. This parameter can also be used to parametrically reflect things such as the height and position of the pollutants entry into the environmentally effected region since both may effect how the pollutants actually impact the environment.

The term, t_{ch} , is a characteristic time which relates the volumetric flow rate of pollutant i with the total volume of the environmentally effected region. Such a region represents the volume which is typically chosen in an environmental impact study as a function of the geographic and meteorological conditions at a given site. Of course, for certain types of pollutants such as CO_2 , this volume may, in fact, become quite large. This does not pose a problem, however, since the limiting value of the pollution factor P as this volume approaches infinity can be used.

Now, again turning to Figure 5 and equation (1), the rate of the thermodynamic losses of the system can be further increased by the concentration (or extraction) factor C of the fuel used. It represents an additional cost or penalty which might be incurred due to the lack of the abundance of a particular type of fuel (locally and/or globally) and/or the difficulty of extracting it. Figure 8 shows the behavior of this function which as with the pollution factor varies continuously between one (no penalty) and some very small number greater than zero (large penalty). Even if this type of effect is already taken into account in terms of the economics or market price of the fuel, this factor provides a thermodynamic basis for these costs, so that even in a purely thermodynamic analysis this effect can be taken into account. In equation form, the concentration / extraction factor is written as

$$C(\Delta G_i) = \left[\exp\left(\frac{\Delta G_i - \Delta G_{ic}}{\Delta G_{oi}}\right) + 1 \right]^{-1} \quad (20)$$

where

$$C(\Delta G_i) = C(\Delta G_i)_{m,n} \text{ or } C(\Delta G_{fuel}) \quad (21)$$

ΔG_i is the change in the Gibbs free energy of the extracted raw material (i.e., the minimum energy (exergy) requirement) which is a function of the entropy change of this material and the temperature at which the extraction takes place. As can be seen in Figure 9, this change in entropy depends on the concentration x of the raw material [22]. The lower the concentration and the higher the temperature, the greater are the energy (exergy) requirements for extracting one mole of this material.

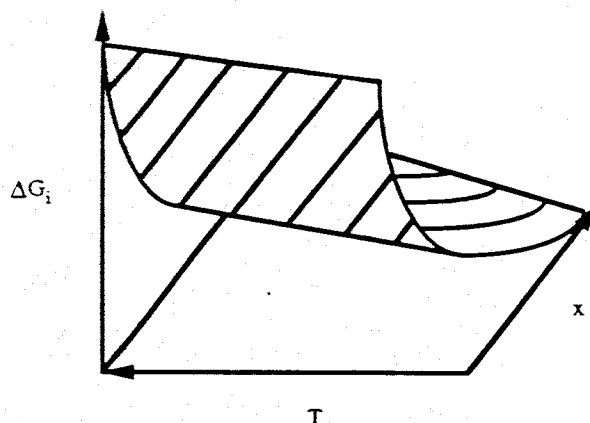
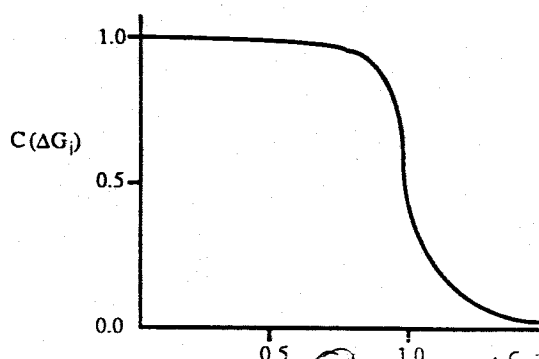


Fig. 9 Concentration as a function of the Gibbs free energy and temperature.

In equation form, this is given by

$$\Delta G_i = -T\Delta S_i = -(T)(N)(B) \times \left[\log(x) + \frac{1-x}{x} \log(1-x) \right] \quad (22)$$

where N is Avogadro's number, B Boltzmann's constant and ΔS_i the entropy change per mole of extracted raw material i . Of the remaining terms in equation (20), ΔG_{ic} is the critical upper limit for ΔG_i corresponding to the concentration below which it becomes economically unattractive to extract any more of the raw material. ΔG_{oi} , on the other hand, is a sensitivity parameter which may, for example, correspond to the concentration below which the extraction is still economically viable from an energy standpoint but is not from an abundance standpoint. In other words, the local and/or global scarcity of this material and, thus its effect on future markets is taken into account by an increased penalty in the concentration factor.

It should be noted here that the pollution and concentration factors are not all inclusive in that other external effects to the system may need to be taken into account as well. One of these is the replacement factor ($R_f(\theta)$ in Figure 5) and it is discussed in some detail in Ref. [26]. The identification of other factors is a part of our future work.

MATERIAL EXERGY AND ASSOCIATED LOSSES

The following discussion specifically centers on the losses and material exergies of the manufacturing processes ($L_{material\ exergy, in}$ and $Ex_{material\ exergy, in}$). A similar type of approach applies for the recycling process ($L_{material\ exergy, out}$ and $Ex_{material\ exergy, out}$).

As shown in Figure 4, the processes of manufacturing a component can be broken down into three basic processes. For a heat exchanger, these can be described as the transformation of minerals into the primary forms of material (Figure 10), the machining of the primary forms of material (e.g., cube, tube, sheet, etc. - Figure 11) and the assembly of the various machined parts. Figure 11 is based on a division of the heat exchanger into six parts which form the basis for evaluating the exergy losses (equations (3), (23) and (24) and

manufacture (see Ref.[26] for more details). As seen from this figure, these six parts are the tube bundle, the tube plates, supports, shell and header.

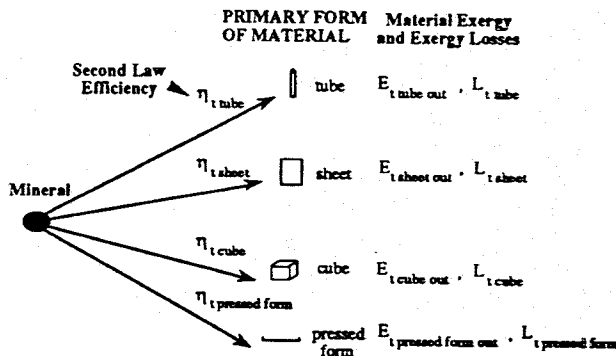


Fig. 10 Transformation processes.

The assembly process is also broken into several intermediate stages and a final stage which assembles the results of the intermediate ones. The former can be broken down into testing for air and water tightness, mounting the headers, welding of the shell to the tube plates, mounting and expanding the tubes on the tube plates, welding the supports to the tube plates and baffles and the intermediate assembly required to realize the six parts depicted in Figure 11.

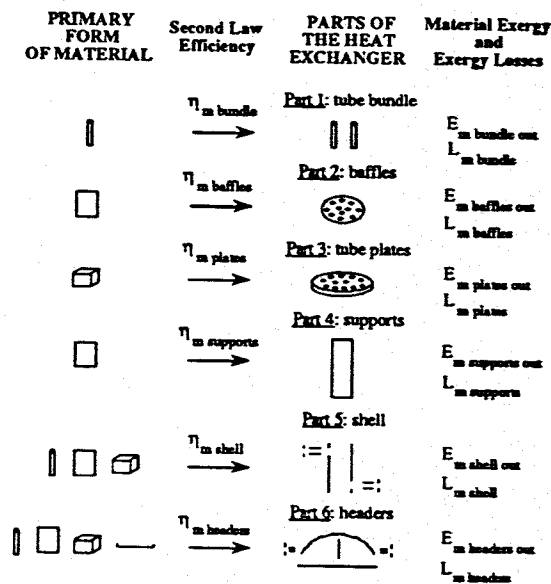


Fig. 11 Machining processes.

The material exergy which results from all of these processes is the exergy content of the final product (in this case the heat exchanger). This value will depend on the inputs and efficiencies of the various manufacturing processes involved. The material losses, on the other hand, will be a sum of all the losses which occur in these processes, a result given by the following relations :

$$L_{material\ exergy,\ in} = \sum_{n=1}^6 L_n + L_{ass} \quad (23)$$

where each L_n represents some combination of the exergy loss terms shown in Figures 10 and 11.

$$L_{ass} = \frac{\left(\sum_{n=1}^6 (E_{m\ out\ n}) + E_{ass\ in} \right) (1 - \eta_{ass})}{(PCR)_{ass}} \quad (24)$$

where the n refer to the various parts of the heat exchanger. This term accounts for both the intermediate and final assemblies.

Many of the values required for these equations and the material exergies can be found directly in the literature [32-35,24] since many of the manufacturing processes described above have already been analyzed. Values for those which have not must be established in order that the database required for the approach presented here gradually becomes more complete. For a more detailed discussion, the reader is referred to Ref. [26].

Also, as was discussed earlier, the loss term, $L_{material\ exergy,\ in}$ is introduced as a rate term (equation (3)) into the thermodynamic objective function by using the mean lifetime t of component utilization and a performance function f . For the heat exchanger, this performance function turns out to be the well-known number of transfer units (NTU).

One final thing which should be mentioned is that the summation of the losses which occur in the various processes just discussed introduces a certain amount of error since the reference environment used for each process may not be exactly the same. However, two points can be made concerning this. The first is that these processes primarily involve chemical and mechanical types of exergies. With the latter, no reference state or environment is required. With the former, variations from that of the dead state or reference environment of the standard temperature and pressure associated with the chemical exergy are small and have little effect on the chemical exergy. In addition, as long as a suitable common reference level for the chemical exergy is chosen, then no problem arises in the calculation of the chemical exergies and the internal and external losses associated with them. As suggested by Szargut, et al. [32], such a reference level must be consistent with a separate reference level for each chemical element taking part in a chemical reaction (internal exergy losses) and a convention which allows for the correct calculation of any associated external exergy losses (e.g., those associated with the interactions of the wastes with the environment). A reference environment satisfying these criteria is given in Ref. [32].

As to the second point mentioned above, most of the processes which have been described occur at fairly high temperatures (e.g., welding, molding, etc.) so that slight changes in the reference environment or dead state have negligible effects on the physical exergies (temperature and pressure effects) calculated. If such differences do become significant, corrections can be made using weighting factors such as those suggested by Evans and von Spakovsky [6] which account for the existence of multiple dead state environments.

CONCLUSIONS

systems has been presented. This methodology incorporates into a single entity the thermodynamic, economic and environmental (pollution, utilization of natural resources, etc.) effects which presently are only taken into account separately or in some limited combination or not at all. It also establishes a thermodynamic foundation based on the Second Law for the costs associated with the capital equipment used. The optimization of the thermodynamic models which result from this methodology can be used in guiding the design or operational decisions of a single system or in making comparisons on a purely thermodynamic cost basis between varying technologies which are meant to accomplish the same task. The optimization of the resulting thermoeconomic model can be used to actually refine the comparisons and the specific design or operational changes resulting from the thermodynamic model's optimization.

Application of this methodology is presently being pursued for various energy technologies (heat pumps, cogeneration, etc.). The problems to be solved are complex. However, the essential idea of preserving a classic system boundary and accounting for the past, present and future environmental and process oriented effects which this system has can make an intractable problem tractable.

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