THERMODYNAMIC ASPECTS OF ENERGY CONSERVATION

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Abstract—Thermodynamics deals with processes in a time independent approach. Industrial productions and many other activities are bound to perform a certain production per unit of time. It will be demonstrated that the stationary process model is a useful tool in relating thermodynamic functions to the velocity of the process. Limitations on the use of functions such as Gibbs free energy and exergy are discussed with respect to the existing energy system. The quality of energy carriers is discussed using statistical mechanics. Energy losses due to an increasing process intensity (the velocity per unit of volume or surface) can be analyzed with either thermodynamics of irreversible processes or engineering data. Changing the conditions of a process, as in approximating the equilibrium situation, will lead to an increase of the size of the equipment when the production volume per unit of time is kept constant. A real energy minimum can be defined when the energy necessary to make equipment is taken into account. This minimum does not coincide with the thermodynamic limit. The importance of the energy embodied in the equipment for the development of conservation policy is explained.

1. INTRODUCTION

One of the interesting problems in energy conservation is to establish the minimum amount of energy necessary to run a certain process. The process might be a conversion of energy from one type into another, or the transport of energy, or a final utilization of energy in the form of heating, mechanic drive, or electric drive.

To solve the problem, the required production volume per unit of time has to be specified for a certain production line (as in ton/yr). By this approach, energy optimization of the production process is analyzed rather than the desirability of the produced materials, commodities, or energy carriers. It is not suggested that the analysis of the desirability is unimportant, but it requires studies different from those described in this paper.

It has been suggested that the lowest energy use can be derived from the application of the second law of thermodynamics. Quantities such as the available energy would describe the irreversibility of the process.[1] It is also suggested that their value is potentially available for conservation.[2,3] Using steady state processes, it will be demonstrated that these statements require many specifications to be true. A short description of statistical mechanics applied to energy conversion and energy application will be given in order to explain difficulties in the definition of the quality of energy carriers.

In Section 4, the possibilities for conservation are studied by modifying existing processes towards lower energy use. Taking into account the energy necessary to build the process equipment, it will be shown that a real energy minimum exists. The process energy used at this minimum is higher than the change of Gibbs free energy of the considered process.

The life cycle cost of energy embodied in the equipment and process energy can be compared to the life cycle cost in terms of money. Minimization of cost and minimization of energy lead to different situations. The conservation path leading from the cost minimum to the energy minimum shows the possibility of saving energy by higher investment in equipment. The net effect of a conservation program is obtained by correcting the gross savings with the corresponding amount of embodied energy. The importance of this embodied energy for the time dependent analysis is stressed in Section 4.

2. STEADY STATE MODEL

In this study, the interest is in processes rather than states. The reason for this is that energy is often used in society in processes which take place at high rates. Aluminium, steel, ammonia, monomers, polymers, and many other chemicals are produced in plants in large quantities per hour with high velocities in transport lines and in chemical reactors. Energy is converted at high rates, for example in the production of electricity. High velocities must be understood as a rate intensity per unit of length, surface, or volume of the equipment. This aspect will be discussed in more detail. A conservation theory is only useful when the high velocity of the process is taken into consideration.

It is necessary to distinguish between energy conversion and final use of energy, or energy service. This final use is also an energy conversion, such as the conversion of electric energy into chemical energy in the production of aluminum. The difference is that the energy input in the energy service is really the energy used by the process, whereas the energy input in energy conversions is not. The conversion process delivers energy, and this must be subtracted from the input to get the net energy use of the process.[4]

Another complication arises in energy conversions. It is not only the quantity, but also the quality of input and output that is relevant. The quality of the energy is a concept often used in discussions about energy problems. It is also relevant in the final use of energy, since some applications require a higher quality than others. Still, the total amount of energy involved might be equal if measured as the equivalent amount of low temperature heat.

In spite of its importance, the quality of energy is a poorly defined concept. We return to this problem in Section 3. In this section, however, the approach is outlined to deal with high-rate processes in the steady state mode, where all flows and gradients are time independent. Although the processes can be highly irreversible, this does not exclude them from certain thermodynamic relations.

Many aspects of steady states have been discussed in the literature. The total system can be split into subsystems, and there is a certain freedom to do so.[5] One can always apply the first law of thermodynamics to the subsystems and their interaction with other subsystems even when irreversible processes occur. The second law of thermodynamics can then be applied to the total system, in which case one distinguishes between reservoirs and devices. Reservoirs exchange only one type of energy with the remainder of the system. Furthermore, the intensive parameter descending the state of the reservoir is supposed to be unchanged when its extensive parameter is changed by the interaction with the surrounding system. Devices, on the other hand, are necessary for conversions and interactions between flows. Neither the intensive nor the extensive parameters describing the situation of the device change in the steady state. Steady state conditions can not always be established for any arbitrary combination of reservoirs, devices, or flows. When, for example, a certain amount of heat enters a heat exchanger, the exchange surface and the counter flow must be large enough to come to a steady state. We assume in this paper that steady state conditions have been established by taking into account physical, chemical and engineering laws.

A system using reservoirs, steady states and devices is an approximate model of energy use and industrial production, with the major advantage that the irreversibility of the processes is included in the set up.

The present energy supply is based mainly upon chemical energy in the form of oil, natural gas and coal reacting with atmospheric oxygen and giving off CO_2 and (often) H_2O. The fuels derive their value from the presence of oxygen, which necessitates treatment in terms of a chemical reaction system. We use freedom in selecting subsystems that single out the chemical process, albeit in a generalized form. Following Tykodi,[6] we distinguish the terminal parts (with reactants and the reaction products) and the gradient parts in which devices for conversion occur (see Fig. 1). We also specify the pressure-volume work reservoir accepting PV-work from the chemical system. In addition to a heat reservoir, another work reservoir is connected
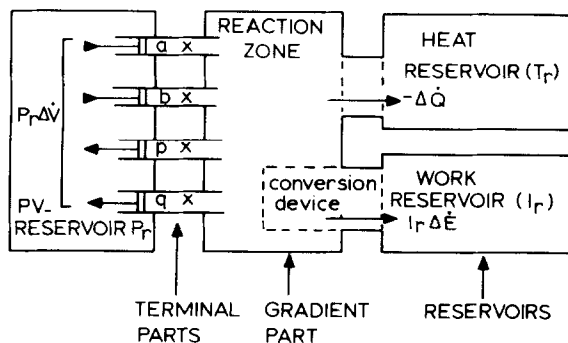

Fig. 1. Steady state model for chemical process.

to the device. This reservoir might accept electrical energy, chemical energy, or other forms of energy from the device when energy conversions are considered. We describe the reaction system as the subsystem including the chemical terminal parts and the gradient part as far as chemicals are flowing through it and/or reacting in it. The total system embraces the reaction system, the devices and the reservoirs.

The progress of the reaction is described by the parameter ξ, such that ξ has the value 1 when ν_a mole A and ν_b mole B have reacted

$$\nu_a A + \nu_b B \rightarrow \nu_p P + \nu_q Q. \tag{1}$$

We use $\Delta U = \nu_p U_p + \nu_q U_q - (\nu_a U_a + \nu_b U_b)$ to describe the change in internal energy of the chemical system. Corresponding notations are used for other quantities describing the reaction system, such as ΔH and ΔV.† We also use the notation

$$\Delta \dot{U} = \Delta U \cdot \frac{d\xi}{dt} = \Delta U \cdot \dot{\xi} \tag{2}$$

to indicate the rate at which the internal energy of the reaction system changes.

Generally, three relations are sufficient to answer thermodynamic questions. The first law of thermodynamics can be applied to the reaction system

$$\Delta \dot{U} = \Delta \dot{Q} + \Delta \dot{W} = \Delta \dot{Q} - P_r \Delta \dot{V} - I_r \Delta \dot{E}, \tag{3}$$

where I_r and E are used as intensive and extensive parameters of the work reservoir. The minus sign is used to indicate that the reaction system delivers work to the reservoir when $\Delta \dot{E}$ is positive. The second law of thermodynamics can be applied to the entropy production ($\Delta \dot{S}_{tot}$) of the total system

$$\Delta \dot{S}_{tot} \geq 0. \tag{4}$$

Here, entropy changes occur in the reaction system ($\Delta \dot{S}$) and in the heat reservoir ($-\Delta \dot{Q}/T_r$). We assume that the changes in the other reservoirs do not include entropy changes. This assumption is too simple to be applied to all energy conversions and energy services. For example, the energy accepting system might be a chemical system, in which case the chemical system would facilitate a higher energy content by splitting water into H_2 and O_2. In such a case, entropy changes would occur in the accepting work reservoir. Without changes in the work reservoirs, we get

$$\Delta \dot{S}_{tot} = \Delta \dot{S} - \frac{\Delta \dot{Q}}{T_r} \geq 0. \tag{5}$$

Other equations are obtained when a set of reservoir parameters is chosen such that equilibrium exists. Then

$$\Delta \dot{U} = \Delta \dot{Q} - P_e \Delta \dot{V} - I_e \Delta \dot{E} \tag{6}$$

and

$$\Delta \dot{S} - \frac{\Delta \dot{Q}}{T_e} = 0. \tag{7}$$

These basic equations can be used to get several results. For example, elimination of $\Delta \dot{Q}$ between Eq. (3) and Eq. (5) leads to

$$I_r \Delta \dot{E} \leq -(\Delta \dot{U} + P_r \Delta \dot{V} - T_r \Delta \dot{S}), \tag{8}$$

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†ΔU, ΔH, etc. refer to changes in the terminal parts. This means that either tabulated values can be used, or the values can be easily calculated when homogeneous mixtures are used or formed.

so that the maximum amount of converted work is related to the rate of change of the availability and the exergy of the chemical system.[7-9] Elimination of $\Delta \dot{Q}_e$ between Eq. (6) and Eq. (7), and using Eq. (5), then gives

$$T_r \Delta \dot{S}_{\text{tot}} = (T_r - T_e)\Delta \dot{S} - (P_r - P_e)\Delta \dot{V} - (I_r - I_e)\Delta \dot{E} > 0. \tag{9}$$

This has been used to define the essergy.[10] Furthermore, the system outlined above, with some modifications, can be used to describe other energy conversion processes or energy services. We do not continue this systematic description here. Instead, we point out some important conclusions.

It is frequently stated in the literature that energy considerations should not be based upon "first law" statistics (ΔU, ΔH) but on "second law" characterization (ΔG, exergy, essergy).[2] Such a statement requires careful specifications to be useful. For example, the use of Gibbs free energy (ΔG) for the energy donating system instead of ΔH often changes the numerical value for fuels less than 10%. Thus, it is not obvious why this change should be so important. Furthermore, Eq. (9) shows three sources for irreversibility. According to Eq. (8), the use of ΔG means that we have made the intensive parameters of the reaction system equal to the reservoir parameters P_r and T_r. We have also simplified the essergy function, which is certainly not acceptable in all situations. These objections are partly removed when we use exergy instead of Gibbs free energy, although the numerical differences with ΔH often remain relatively small. Again, the question arises as to why exergy considerations predict a large conservation potential in some energy applications, while enthalpy calculus shows room for only some improvement at best.

The problem is easily solved by recognizing that the exergy in efficiency often occurs in heating services, mainly heating of buildings and water at temperatures below 100°C. In these cases, the energy accepting system requires only small amounts of exergy when the formal definition is applied (see Fig. 2). From Fig. 2, it is obvious that the "process" in the accepting system is to leak heat from T_m to T_r when ($T_m > T_r$). Thus

$$\frac{d(\Delta \text{ exergy})}{dt} = -\{\Delta \dot{U} + P_r \Delta \dot{V} - T_r \Delta \dot{S}\} = -\left\{0 + 0 - T_r\left(-\frac{\Delta \dot{Q}}{T_m} + \frac{\Delta \dot{Q}}{T_r}\right)\right\} = \Delta \dot{Q}\left\{1 - \frac{T_r}{T_m}\right\}. \tag{10}$$

In terms of exergy, much less is required of the value ΔQ from the first law.

However, we have now applied the concept of exergy to a situation it was not designed for. There is no "device" to produce work, and the situation represented in Fig. 2 can only be described by heat flows and first law relationships. Thus, it gives a wrong impression to suggest that the heating process as represented in Fig. 2 can be improved based upon exergy considerations. The only proper conclusion from exergy considerations is as follows: when we have a device that can convert the exergy available from the combustion process into high-value work, and when we have a second device that converts this work into exergy necessary to maintain the required temperature, then we can fulfill the energy service with much lower amounts of fuel than with normal heating equipment.

Of course, it is well known that practical solutions for this process are evaluated, as in the case of the gas fueled heat pump. In this paper, we are interested to know whether any type of energy can be completely converted into any other type of energy. This leads immediately to the problem of defining the quality of energy. We also realize that the devices necessary to use
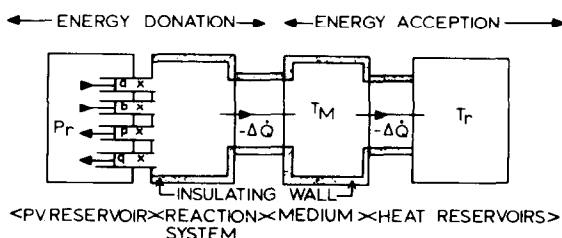

Fig. 2. Heating process.

the exergy fully require materials and energy to be constructed. Thus, it seems necessary to incorporate the energy embodied in the equipment in evaluations which determine the energy optimization.

Space does not permit an analysis of other conversions in detail. It is easy to see, however, that the quantity $\Delta \dot{U} + P_r \Delta \dot{V}$ is relevant when we need heat $\Delta \dot{Q}$ at high temperature. In addition, the pressure-volume work can be used effectively, as well as the heat production, with $\Delta \dot{U}$ as the characteristic quantity. These examples, and the aspects discussed earlier in this section, demonstrate that the second law characterization of an energy donating system is of limited applicability. One has to include the function of the energy service or the properties of the energy accepting system in any evaluation. In some cases, quantities other than second law characterizations are relevant, while in other cases this characterization does not apply to the existing situation. One can design a new structure for the fulfillment of energy needs, but this introduces other problems to be discussed in the following sections.

3. FUNDAMENTAL ASPECTS OF ENERGY CONVERSION

The power of thermodynamics is also its weakness. By not using detailed models, its applicability is quite general, but it also leaves many important specific questions of molecules, quantum states, relaxation times, etc. unanswered. Energy conversion, or the conversion of one type of energy into another by means of some device, conveniently illustrates this general remark.

In thermodynamics, there is neither any limitation to the conversion of one type of work into another nor is there any proof of the possibility of conversions. Only the conversion of heat into work is restricted by the Carnot factor, describing the maximum conversion possibility. Thermodynamics does not show whether this maximum is always attainable. It is of great importance to answer the fundamental questions about the possibility of energy conversions, even when the concept of "work" is used with greater diversity than in the original studies of thermodynamics.

Historically speaking, thermodynamics has heavily influenced ideas about energy conversion, and it is not uncommon to find the statement now that any form of energy can be converted into any other form of energy. When this proposition does not work, technological factors are held responsible. Large amounts of money were spent in the space program, for example, to find a catalyst which could convert the chemical energy of gasoline plus oxygen into electrical energy in a fuel cell. The idea was that this direct conversion was possible when the right technological conditions were found. This section will illustrate that very fundamental restrictions exist for energy conversions, especially when fundamental science other than thermodynamics is applied.

As it was stressed in Section 2, we have to deal in energy conversions with an energy donating and an energy accepting system. Statistically speaking, the change in either system during energy conversion can be described by the change of the frequency distribution $f(\epsilon)$ from the "particles" occupying the available density of states $D(\epsilon)$. Figure 3 shows a donating system in which the product function $n(\epsilon) = f(\epsilon) \cdot D(\epsilon)$ gives the distribution before and after transition, while $\Delta n(\epsilon)$ gives the change of the distribution for each value of the energy. In case the donating system is based upon heat transfer, it is easy to calculate the fraction of energy that cannot be converted into other forms of energy. The result is $1 - (T_1 - T_2)/T_1$. This illustrates in a simple way why only a fraction of the heat qualifies for conversion in other work.

The question of whether this fraction is really converted depends upon details in the energy donating system, the conversion device and the accepting system. It is impossible to obtain the frequency distribution $n(\epsilon)$ vs $\Delta\epsilon$ without these specifications, since the distribution reports the frequency of jumps $\Delta\epsilon$ when the donating system transforms from its initial to its final state. A corresponding situation occurs in the accepting system, where the jump distribution $m(\epsilon)$ cannot be determined without details of the total system.

It is now possible to discuss some aspects of the quality of energy, or more precisely the quality of the energy donating system. By quality of energy, we describe the possibility to deliver quantum jumps of the size $\Delta\epsilon_b$ or larger. Just as with the Carnot efficiency, we can calculate the quality of the donating system for the boundary $\Delta\epsilon_b$, or $Q_d(\Delta\epsilon_b)$, and we keep in
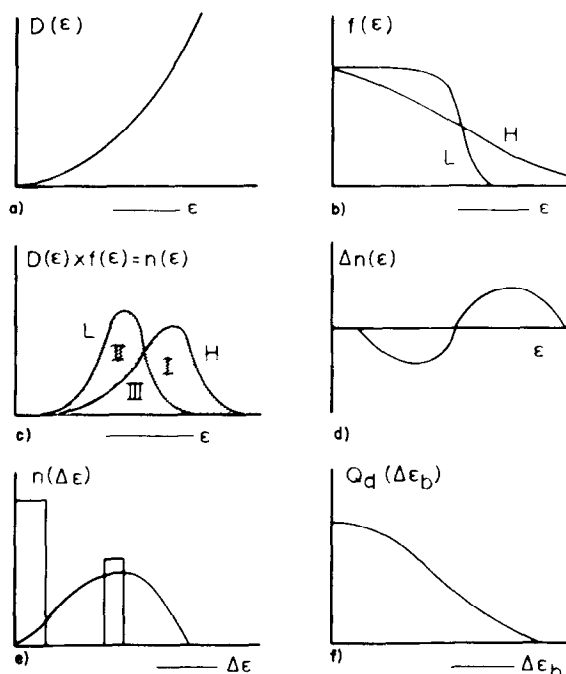
Fig. 3. Schematic characterization of energy donating (or energy accepting) system: (a) density of states; (b) Fermi-type occupation for high and low energy states; (c) number of particles (in the transition, particles in I change to II, delivering energy; particles in III do not delivery energy); (d) change in number of particles; (e) frequency distributions for quantum jumps $\Delta\epsilon$; (f) quality factor for quantum jumps $\Delta\epsilon$.

mind that the possibility for real conversion must still be demonstrated. The quality of the energy accepting system $Q_a(\Delta\epsilon_b)$ can then be defined as 1 minus the unavailability fraction, although this definition requires some amplification. We use non-acceptability to indicate that one energy jump in the energy donating system will correspond to one jump in the accepting system. If the accepting system is able to integrate the energy of many jumps of the energy donating system, we define the fitting factor $Q_f(\Delta\epsilon_b)$ to represent the specific properties of the conversion device. This leads to the definition of the overall quality factor $Q(\Delta\epsilon_b)$ for energy conversion, such that

$$Q(\Delta\epsilon_b) = Q_d(\Delta\epsilon_b) \cdot Q_a(\Delta\epsilon_b) \cdot Q_f(\Delta\epsilon_b). \tag{11}$$

It is not entirely possible to discuss this approach in detail, but some special situations can be used for illustration. It is obvious, for instance, that high quality work (mechanical, electrical) can be fully converted into low quality heat when a heat reservoir of sufficient size is available. Such a reservoir might contain solids or liquids. The Debye–Einstein theory of specific heat for solids shows that large numbers of states are available for small ϵ values (here Bose–Einstein statistics are used). This means that $\Delta\epsilon_b$ can be small, and that all Q factors approach the value of 1.

Other examples are also important, since the device integrates a large number of small energy contributions, which means $Q_a(\Delta\epsilon_b) \cdot Q_f(\Delta\epsilon_b) \approx 1$. This happens in a frictionless piston, when gas expands adiabatically while performing pressure-volume work.

Interesting situations occur when the donating or the accepting process is a chemical process. When both processes are chemical, we have the situation of coupled chemical reactions. This type of energy conversion is one of the basic processes in biochemistry. The energy delivering system is food plus oxygen, and the intermediate-accepting system is the change of adenosinediphosphate (ADP) into the corresponding triphosphate (ATP). In another energy conversion, mechanical energy is obtained, while ATP is converted back into ADP.

There is no room here to discuss the conversion of chemical energy in any detail. Basically, however, we find in many chemical processes some step or steps with a large energy change,
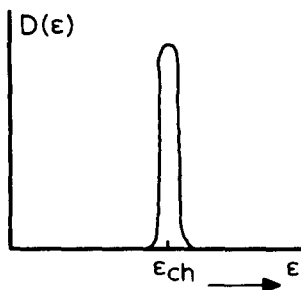
Fig. 4. Density of available states for a chemical process with an energy change ϵ_{ch}.

generally without integration possibility. Thus, when the system acts as an acceptor system, large quantum jumps of the donor system are required.

When this situation occurs, as in Fig. 4, the conversion quality of the total system is influenced considerably. It can be expected, for example, that the conversion of heat into chemical energy will proceed with an efficiency lower than the Carnot factor. This limitation of the Carnot-efficiency does not follow from thermodynamics, but its foundation is just as fundamental. Conversions of this type are now being studied.[11,12]

When the chemical process is the energy donating system, and the production of heat is the accepting system, there might be a problem when the essential step in the chemical process is a two particle encounter. Some medium might be required to convert the chemical energy quantums into a large number of smaller heat quantums, otherwise the process cannot take place. A wall, an inert gas, or the solid catalyst might act as quantum convertors.

Until now, we have used a static description for processes which are essentially dynamic. The general dynamic treatment would require more knowledge about relaxation of non-equilibrium quantum distributions than is available at this moment. It is possible, however, to deal with specific situations by using empirical or special laws. We illustrate this with one simple example.

An energy donating system is assumed to deliver heat by the adiabatic burning of natural gas by oxygen. This is done with an inert gas and a catalyst present, so that a gas mixture of 1480°K is obtained. The accepting system is a water reservoir which is heated from 280 to 360°K. The conversion device contains just a pipe of length L, and a pump which circulates water of the reservoir in a countercurrent flow along the pipe. The system might be representative of a gas water heater, for example. Engineering data next permits us to calculate all relevant quantities of this conversion process. For the present approach, it is sufficient to recognize that gas flows in the pipe with a temperature of 1480°K and that the gas is cooled throught he pipe wall. Thus, a temperature distribution is obtained which depends upon the distance L_x along the pipe and the radius measured from the middle of the pipe (see Fig. 5, a and b). When the conditions are chosen properly, and when some approximations are made
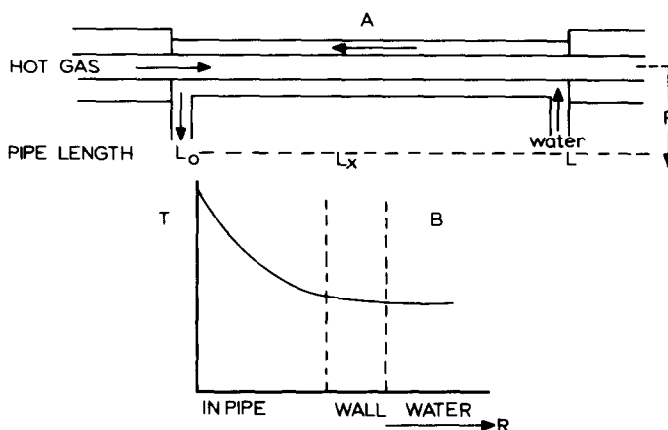

Fig. 5. Heat transfer from gas to water through a pipe.

(such as no PV work for the gas, energy use of the pump neglected, good heat conduction of the pipe material, and thin tube walls), it can be shown that the major part of the radial temperature drop occurs in the gas phase of the pipe. This temperature decrease is determined by the heat transmission in the gas phase.

This is an important observation. We are interested in the minimum length of the pipe needed to transfer an important fraction (say 90%) of the heat obtained in the water reservoir by burning the natural gas. We find that this transfer is largely determined by the relaxation time of the non-equilibrium energy distribution in the gas mixture. The conclusion is that a certain minimum length is required to use 90% of the heat input. This length is largely controlled by the relaxation phenomena in the gas mixture. Since it requires energy to make the pipe, it is also obvious that the total energy of the system—including the energy embodied in the construction of the pipe—cannot be arbitrarily decreased whenever we want to use all or even 90% of the input heat.

In this section, some fundamental aspects of energy conversion have been discussed. Using the statistical mechanics of equilibrium distributions, it becomes obvious that conversion possibilities might be limited when a chemical process is the energy accepting system. Consequently, it is useful to define the quality of the energy for a conversion process rather than for the donating system alone. In other conversions, the converting device, together with the accepting system, can integrate contributions of different size, as in heat production. Then, non-equilibrium energy distributions have to be used to analyze the constraints on energy conversion. Transport rates are fundamentally limited, but high conversion efficiencies can be obtained by adapting the size of the equipment. However, energy is required to produce the equipment, and the question arises when we ask what size of equipment leads to the energy minimum when conversion efficiency and embodied energy are both taken into account.

4. ENERGY MINIMUM

Where the length of the heat exchanger has been increased to recover a larger fraction of the available heat, the energy efficiency has been improved. This follows from the thermodynamics of irreversible processes. The irreversible entropy production is proportional to the product of fluxes and forces, and the flux is proportional to the forces in the scope of linear relationships. For many industrial processes, the linear relationships cannot be used, but the applicable engineering laws also demonstrate higher energy losses when the fluxes are increased. Fluxes are measured either as currents or flows per unit of surface, or as converted amounts per unit of reactor volume. Thus, in many cases, energy losses can be decreased when the size of the equipment is increased at a constant total production volume.[13] The fact that some equipment might decrease in size when the process is moved in the direction of thermodynamic equilibrium[14] does not change this general observation.

Energy is required to make the materials and equipment used for unit operations. Since these installations have a limited lifetime, it might be interesting to evaluate the total amount of energy required for producing a certain volume of material per year or converting a certain amount of energy per year. This total amount of energy would include the direct (or process) energy and the indirect (or embodied) energy. Note that the embodied energy is not really recoverable from the equipment, because a large fraction of the energy used to make a material or commodity is lost as irreversible heat to the atmosphere during production.

The trade off between process energy and embodied energy becomes obvious when one wants to approach the thermodynamic equilibrium for the process under discussion. Generally, the specific rates go to 0, and the equipment becomes infinitely large when the total annual production volume is kept constant. The minimum energy used is then determined in principle from the strength of different materials for the pipe, and from its lifetime based on first principles. This procedure seems highly impractical, but it does demonstrate that energy embodied in the equipment is a fundamental and necessary part of the energy required to make some material in order to convert energy or to render a service at a fixed annual rate.

It is more practical, therefore, to use the methods developed in energy analysis on this particular problem. For the major contributions to the involved energy, one might have to use the process analysis, whereas minor contributions could be evaluated by applying input–output analysis to economic data.[15] The major result of the analysis is that the total energy goes
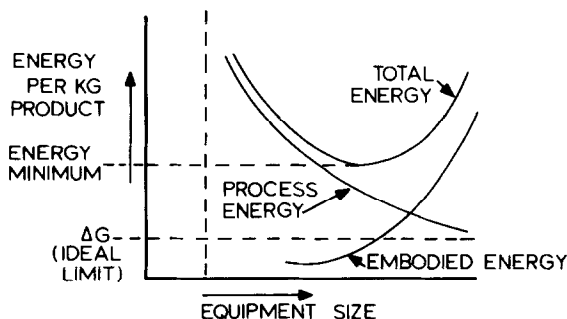
Fig. 6. Process energy and embodied energy as a function of equipment sizes.

through a minimum when a unit operation is changed, such as to approach the thermodynamic minimum while maintaining the production volume. When lifecycle considerations are relevant, it makes no sense to decrease the process energy below the value corresponding to the minimum of the total, although this is technically possible. It is, of course, quite feasible that another process or production method might lead to a lower energy minimum (see Fig. 6).

In earlier sections, it was already shown that the use of Gibbs free energy values to measure the conservation potential of existing processes is not always acceptable. Now it has also been shown that there are fundamental objections in using only the process energy for such an evaluation.

There is no space to discuss the importance of the developed theory for conservation policy. Some results have been (or will be) published,[13,16,17] and a more detailed analysis is currently in progress.[18]

The only other question is whether the embodied energy is of any importance at all. For many processes, embodied energy is less than 10% of the total energy required for production. There is a problem, however, since the embodied energy has to be invested before the process starts, and one cannot borrow this energy from the future. Take, for example, a production process that uses 100 MJ per kg product, from which 95 MJ is process energy and 5 MJ is embodied energy. Assume that the lifetime of the equipment is estimated to be 15 years. Under these conditions, one would have to invest $5 \times 15 = 75$ MJ for each kg production capacity. When such a process were installed to replace another process, using 120 MJ per kg, one could recover a savings of 20 MJ per kg, or 17%. By installing 75 MJ, it would take nearly four years of production in order to save the embodied energy.

The dynamic analysis of the net effect of a conservation program is important for any national energy policy. Large savings in process energy, and fast introduction of appropriate conservation measures, will require large investments in materials and energy that would decrease the net results of the policy at the beginning of the program. It has been demonstrated that the relationship between the increase of the size of equipment and the decrease of the process energy for a constant production volume is based upon fundamental physical laws.

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DISCUSSION

Thomas Brzustowski, University of Waterloo, Canada. Realizing that rate processers and activation energies may limit the extent of improvement possible in unit operations may direct attention to seeking to new processes that have lower activation energies. These same limitations occur in industrial burners that attempt to burn "low Btu" gases.

Author's response. The optimization used in the paper deals with certain unit operations, such as steam making or evaporation. One can decide not to make steam anymore or not to evaporate, but to use another technology. Obviously, the other technology must be characterized differently. One can represent different technologies in cost vs energy plots, for example. Then, the envelope compassing the different technologies gives the optimum path.

Francis Huang, San Jose State University, U.S.A. In your model of a steady state chemical process, you included the pressure reservoir, the work reservoir, and the heat reservoir. When you summarized entropy production according to the second law, why did you exclude the entropy change associated with the work and pressure reservoir?

Author's reply. The reservoirs used in the theory are artifacts. By definition, the only change of the reservoir is the one corresponding to the extensive parameter and no entropy change is involved. For a real situation, one has to check whether or not that model can be applied. When the "work" is a chemical process—such as charging a battery—then an entropy change is involved and this must be included in the entropy production.