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ENERGY ANALYSIS AND OPTIMIZATION OF ENERGY SYSTEMS

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ABSTRACT

Exergy analysis and exergy optimization are used to study industrial energy use. One methodology is developed which is used on three different aggregation levels: national energy use, regional studies, and the process level. The optimization is applied to a demand pattern of cold flows by offering to the system heat exchangers, cogeneration, and heat pumps. A considerable conservation potential is established on the national level. Detailed studies of production processes gives the possibility to point out where exergy is lost. A process improvement index (PI-Index) is developed which permits a ranking of processes with respect to the potential of increasing energy productivity.

INTRODUCTION

A great deal of research in the field of energy conservation was performed in the period 1974 to 1985. Besides implementing simple improvements and enacting energy management procedures in industrial processes, it is also possible to save energy by heat recovery (heat cascading), cogeneration and other more involved techniques, such as heat pumps. Even larger savings might be possible when new technology is used, for example membranes in stead of distillation for the separation of liquid mixtures. In the sequence mentioned, these options require larger investments, longer lead times, and larger uncertainties about the return on investment.

With the fall of the oil prices after 1985, the public and political interest in the energy conservation are waning and many government programs to stimulate energy conservation were reduced or cancelled. For industry the risk of long payback times for large investments in energy conservation became obvious.

The lack of stability in oil prices and -related to this- the lack of stability in energy policy in many countries, is detrimental to the long term realization of major options for a low energy society, while maintaining the desired production of goods and commodities.

Energy analysts have stressed that the real limitation to the energy system is not to be sought in the energy resource situation, but in the environmental burden due to the use of the resources. After neglecting this message for many years, the time has now come that the media and the politicians are making up for cleaning the environmental dirt and for creating an environmentally beautiful future.

The environmental pollution has many sides, but in this paper the analysis will be restricted to one aspect: what does the risk of a possible warming of the atmosphere due to the carbon dioxide product means for the survival of industrial productions on a long term? Can this lead to a compulsory curtailment of industrial production?

Obviously, the best industry can do on this moment is to analyze the long term possibilities to improve its energy productivity. This paper is limited to the methodology of this analysis. Other options to decrease the threat of the carbon dioxide emission, such as a shift in primary fuels from coal to natural gas and nuclear energy and the reuse of carbon dioxide, will be discussed elsewhere [1].

With these restrictions the analysis fits quite well in the developments in the last decade in the methodology to analyze steady state processes for energy losses. The exergy concept is useful in this analysis. Since there is some reluctance to use exergy in stead of enthalpy, a short discussion of the exergy concept is given, together with a warning for some pitfalls and some applications. The exergy concept makes possible to derive a process improvement index for comparing unit operations or processes with respect to their potential of being improved. Industrial processes can be described in terms of hot and cold streams. There are many methods to optimize such a system

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by means of heat exchangers. Linnhoff and coworkers have developed the pinch technology [2,3]. The pinch technology becomes difficult to use quantitatively when other heat handling technolo&gies, such as cogeneration and heat pumps, are applied to the system. Especially the simultaneous application of these options leads to problems when using the pinch concept.

In recent years we developed another methodology. While starting with the hot and cold stream pattern, all required heat handling equipment is offered simultaneously to the system, after which the total system is optimized. The pinch concept is not required in this method, but when there is a pinch we can see it from the result of the optimization. The exergy optimization is discussed in this paper, and some preliminary results of the analysis of a sugar plant are summarized.

EXERGY ANALYSIS

The exergy concept is nearly as old as the basic formulation of thermodynamics by Gibbs: Szargut [4], in a historical survey, mentions publications in 1889 (G. Gouy) and 1898 (A. Stodola). What has changed in this long period are the name of the concept, the processes to which it is applied, and the way it is used in the interpretation of processes. The name exergy originates from Rant (1951) and is used extensively in Europe. American authors use availability. There is enough modern literature available explaining the exergy concept [5,6,7]. In this paper some basic aspects are summarized, especially those related to the application to steady state industrial processes.

The basic idea is that even highly irreversible processes can be analyzed for energy losses. Two conditions must be fulfilled: The processes must be in a steady state and the irreversible sections are connected by material flows that can be described thermodynamically. Under these conditions thermodynamic analysis can be applied, the combination of first and second law being essential. See fig.1.

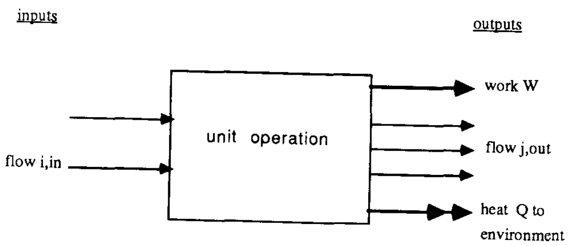

Fig.1 Inputs and outputs for a unit operation

$H_{i,in}$ is an input flow i into the unit operation to be analyzed, whereas $H_{j,out}$ is the enthalpy of an outflow. Q is 2 heat lost to the surrounding and W is high-quality work (mechanical work or electricity) obtained from the unit operation. Since the process is in a steady state, there is no change of enthalpy within the unit operation, and the first law applied to in- and outgoing flows becomes:

$$\Sigma h_{i,in} = \Sigma h_{j,out} + Q + W \quad (1)$$

It is very important for the application of the first law to practical situations that the enthalpy efficiency of a unit operation must be 100%, when all in- and outputs are taken into account. This also means that one can not learn anything from the enthalpy efficiency of the operation.

The second law states that the entropy increases for any irreversible process in a closed system. Thus, the irreversible entropy production is:

$$\Delta S_{irr} = S_{out} - S_{in} = \Sigma s_{j,out} + Q/T_0 - \Sigma s_{i,in} \geqq 0 \quad (2)$$

Note that the environment is considered as a heat reservoir with temperature T_0. The heat Q entering the reservoir leads to an entropy production Q / T_0. The reservoir concept is used both for heat and for compounds and mixtures The intrinsic properties of the reservoir do not change when heat or chemicals are entering or leaving the reservoir. W is considered as highly ordered energy and has a zero entropy value.

First and second law are combined by multiplying eq. 2 by T_0 and eliminating Q from eqs.1 and 2:

$$T_0 \Delta S_{irr} = \Sigma(h_{i,in} - T_0 \cdot s_{i,in}) - \Sigma(h_{j,out} - T_0 \cdot s_{j,out}) - W \geqq 0 \quad (3)$$

The exergy B of the flows is defined by:

$$b_{i,j} = h_{i,j} - T_0 \cdot s_{i,j} \quad (4)$$

With $B_{in} = \Sigma b_i$ and $B_{out} = \Sigma b_j$ (5)

eq.(3) becomes:

$$T_0 \Delta S_{irr} = B_{in} - B_{out} - W \geqq 0 \quad (6)$$

Given the in- and output exergy flows, the maximum value of high quality work is equal to the difference. This actual amount of work is lower due to irreversibility of the processes. For that reason one speaks about the lost work W_{lost}:

$$W_{lost} = T_0 \Delta S_{irr} \quad (7)$$

and thus:

$$W = B_{in} - B_{out} - W_{lost} \quad (8)$$

For practical applications eq.4 is used to calculate the exergy from the enthalpy and entropy of all in- and outgoing flows. Based upon eq.7 one can conclude that entropy calculations suffice to find the exergy loss of a unit operation. The question whether to use just entropy or to to take the exergy loss of a the flows has been discussed in the literature [8]. In practice the answer to this question is simple. It is obvious from eq.6 that exergy calculations are impossible when no entropy data are available. However, when they are available it is still necessary to check the enthalpy data. Although the enthalpy balance sums up to zero, this will often not be true when using plant data. Unregistered heat losses and measuring errors might occur. When the enthalpy balance is not fulfilled exactly, large errors might occur in the calculated exergy loss. Therefore, the enthalpy balance is first compensated by introducing an imaginary stream LOST to the output. Note that this stream might be negative under certain conditions. Related to this stream is an entropy flow LOST/T_0 . This leads to a zero exergy contribution for the lost flow, but a sometimes important contribution to the entropy calculation. Since the enthalpy values are necessary anyway to calculate the lost correction, no real difference exists between the the two ways of calculating the exergy loss.

The exergy efficiency is usually defined by the ratio B_{out} / B_{in}. However, depending upon the purpose of the analysis, other definitions might be relevant. Comparing, for example, the evaporation of water in the salt and in the sugar industry, one finds with the given definition a much higher efficiency in the sugar than in the salt production for a comparable process. The reason is the high exergy value of the sugar flow compared to the low exergy value of the salt flow, which makes the energy losses relatively low in the sugar production. It is relevant for this analysis to consider the reference system used to calculate the exergy values. In the reference system an approximation to the dead state is used, which means that stable compounds are used as reference for the elements. The choice of an appropriate reference system is not yet standardized [9,10].

In the process analysis many different types of flows can be distinguished. Inputs to some unit operation might have been generated internally in the process or might be fed in externally. Output flows of a unit operation might be used internally or they might leave the process. In the latter situation the flows might constitute the required product or a useful byproduct, but it is also possible that the flow is worthless. To calculate the efficiency of the process, only the useful products are included in the efficiency. Note that in this situation the first law efficiency can also be lower than one. It is impossible to give here the details of the analysis, but an example of some results might illustrate the use of the analysis.

AN EXAMPLE: THE AMMONIA PRODUCTION

Exergy analyses according to the principles outlined above have been reported in the literature [7]. Recently we analyzed the ammonia process by means of literature data [11,12]. Since these data refer to plants as they were used in the seventies, our analysis should show which unit operations qualify for improvement.

The potential to improve the efficiency of a

Table 1. Exergy data of unit operations in the ammonia production (per kg NH_3)

UNIT OPERATION	EXERGY IN (kJ)	USEFUL EXERGY OUT (kJ)	EXERGY EFFICIENCY	EXTERNAL EXERGY INPUT (kJ)	TOTAL EXERGY LOSS (kJ)	PI-INDEX
1. Primary Reformer	39033.1	31916.0	0.818	13355.1	7117.1	100
2. Secondary Reformer	31916.0	30280.2	0.949	0	1635.8	6.5
3. Shift Convertor	26871.8	26789.4	0.997	0	73.4	0
4. CO_2 Absorption	27103.9	24450.8	0.902	309.6	2653.1	20
5. Methanation	24179.5	23894.8	0.988	0	284.6	0.3
6. Compressor	25383.4	24661.4	0.972	1488.6	722	1.6
7. Synthesis Convertor	91491.1	89321.3	0.976	161.6	2169.9	4
8. Condensing Cooling	89781.1	86774.4	0.967	0	3006.7	7.8
9. Methane Preheat	25349.7	24105.6	0.951	25349.7	1244.1	4.7
10. Air Compression	2891.9	2551.1	0.882	561.3	340.8	3.1
11. Chiller	814	459.8	0.565	814.0	354.2	11.9
12. Waste Heat Boiler	30570.9	29212.9	0.956	0	1358	4.6
SUM OF ALL OPERATIONS				42040	20960	

unit operation depends upon two factors: the total exergy loss in that operation and its exergy efficiency. Obviously, when the exergy loss is low or the efficiency is high, improvement potential will be low. We use the index

index = exergy loss * (1 - exergy efficiency) (9)

Comparing a number of unit operations is possible by setting the value of the operation with the largest improvement potential Indexmax equal to 100 and expressing the operations by their Process Improvement Index (PI-Index):

PI-Index(j) = Index(j) * 100/ Indexmax (10)

The result is summarized in table 1.

Recent developments to improve the efficiency of the ammonia production were indeed directed to the improvement of the CO_2 absorption, the synthesis convertor and the chiller. In conclusion it is relevant to perform an exergy analysis of energy consuming processes and of the design of new processes. Once the operations with the largest PI-Index have been established, the question arises how to improve the situation. This is discussed in the next section.

EXERGY OPTIMIZATION

The optimization of heat exchange networks has attracted the attention for a long time already [13]. Some methods use the exergy explicitly, whereas others use enthalpy in the description, taking care of the second law in an implicit way. The problem then is that the temperature level on which heat is lost is not important. Other problems arise when other heat handling options, such as heat pumps and cogeneration, are possible. The problems are quite complex when the analysis procedure is performed on a very detailed level with respect to the technical options.

Recently we developed procedures which are applicable on different levels of aggregation. In this analysis all options are offered to the system of hot and cold flows at once.

The first applications were performed on the energy demand pattern on a national level for several countries [14]. It is assumed that a considerable fraction of the energy used on a certain temperature level, will be available on lower temperature levels, where they are used again.

The analysis is strictly based upon the exergy description [15]. For each energy flow, but also for all chemical flows, the quality is defined according to

$$\text{Quality} = \text{exergy of flow/enthalpy of flow} = B/H = (H - T_0 * S)/H = 1 - T_0 * S/H \quad (11)$$

H and B are expressed in the environmental reference system. Since the sign of S can be negative, the quality can be larger than one, which means that more high-quality energy can be obtained than corresponds to the enthalpy. For most fuels the quality is roughly one. Since the quality is also used to describe the exergy equivalent of chemicals, it should not be applied in situations where H is zero.

The use of quality permits to put enthalpy and exergy in one diagram, together with the supply and (or) the demand. Fig.2 shows the HQD-diagram and the original temperature diagram for West Germany [16]. Level indicates ten times the quality.

The optimization calculations lead to the results given in table 2.

Although the conservation options look impressive, one has to take into account the simplifications that must be made when using data on a national level. Heat transport and time dependency are not considered. A semi quantitative cost estimate was made for some of the situations [17,18]. Heat

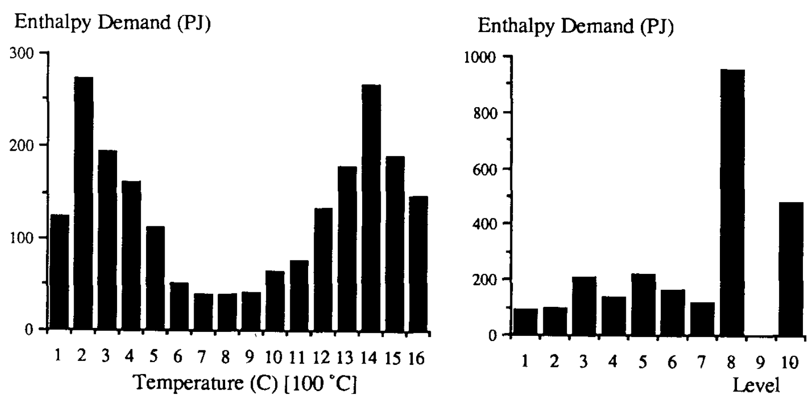

Fig. 2 Temperature and quality pattern of West-Germany energy demand.

Table 2. Exergy optimization for some national energy demand pattern. Industrial energy demand in PJ (Ex=heat exchange, P=heat pump and C=cogeneration)

	Netherlands		West Germany		Japan		USA	
No Saving	976	100%	3544	100%	8765	100%	18976	100%
Ex	483	50%	1816	51%	3381	39%	12904	68%
Ex+P	353	36%	1754	50%	2926	33%	15524	66%
Ex+C	393	40%	1816	51%	3381	39%	12904	68%
Ex+C+P	351	36%	1755	50%	2926	33%	15524	66%

exchange occurs as a favorable option, but heat pumps and cogeneration -when applicable- are financially about neutral, although they may lead to energy conservation. The possibility to apply this options is very sensitive to the specific exergy pattern of the demand. The cost analysis has been extended recently to show the trade-off between the conservation potential versus cost [17,18]. This type of information is relevant for the formulation of long term energy and environmental policy.

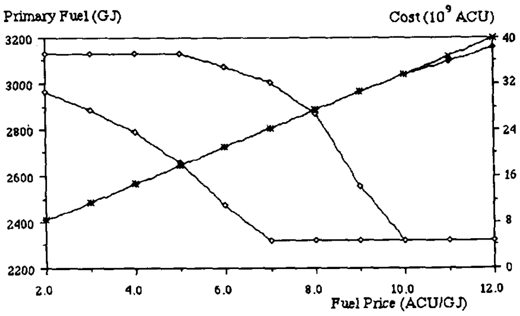

Fig.3 Total energy use N(F) and total cost (C) as function of the oil price b(F) dus to the use of energy saving options. The drawn line represents the situation when the cost of the system including the options is kept equal to the cost without applying these options. The dashed line gives the situation when a 10% increase of the total cost is permitted. Note: 4 ACU/GJ = 24 $ 1986/barrel.

The guidelines obtained from these analyses are in agreement with other studies. The perspectives of energy conservation and the need to get a feeling of the limits of industrial energy use are such that a further evaluation makes sense. This means that the analysis has to be applied on lower aggregation levels in order to use more detailed information. Two lines are followed.

One study deals with the energy supply in a region. From the analysis made thus far it is obvious that a diverse demand pattern gives the best conditions for heat integration. This study requires heat transport as a unit operation and the introduction of time dependency in the models.

In the other study the model is applied on the lowest aggregation level, viz. the analysis of production processes and their unit operations. Once all process flows are introduced, one needs a detailed division of the quality scale in order to match the temperatures of the process flows. The adapted model was used in the analysis of a sugar plant [19]. The demand pattern and the fulfilling of the demand with heat exchange, cogeneration, and heat pumps is shown in fig.4.

The result is interesting, since it is known that this plant was optimized already with respect to the energy use. The analysis shows that a few percent can be saved by heat exchange (which is unfavorable due to the lay-out of the plant) and perhaps 10 % by applying a recompression heat pump in the evaporization process (which will not be done for economic reasons).

Presently, research continues to integrate the exergy analysis (as described for the ammonia production) with the optimization procedures. In all processes energy is donated by one subprocess and energy is accepted by another subprocess. The condition for energy optimization is the exergy matching of donor and acceptor processes [20]. Theories based upon heat exchange networks take the inputs and outputs of the unit operations as given, which means that the energy losses in the unit operations are accepted. However, quite im-

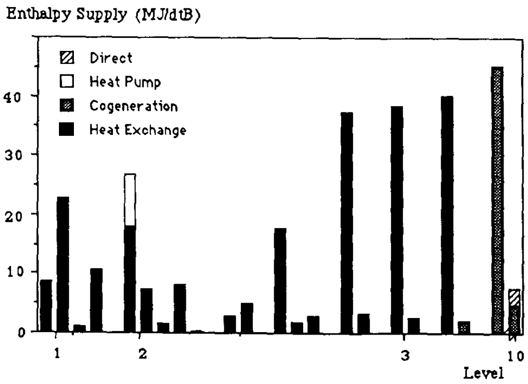

Fig.4 Demand and optimized supply of a beet sugar plant.

portant losses occur in these unit operations as is illustrated with the primary reformer in the ammonia process (see table 1). Studies are continued by taking these unit operations apart and translate them in a set of hot and cold streams. This gives problems when chemical reactions occur in large temperature trajects, but there are ways to specify minimum requirements [21].

CONCLUSIONS

The analysis of industrial processes to establish exactly were energy losses occur and their size should be done using the exergy description of energy and material flows. The potential to improve the exergy efficiency of unit operations follows from the product of the exergy loss and one minus the exergy efficiency. The process improvement index (PI-Index) follows directly from this product. The PI-Index makes it possible to rank the unit operations with respect to the improvement potential.

The exergy description is also used to optimize a process with hot and cold streams when heat exchangers, heat pumps, and cogeneration are available for application to the process.

A considerable saving potential is found when the optimization procedure is applied to the national industrial energy use in Japan, West Germany, and The Netherlands. How much of this potential can be realized can be established by studies on aggregation levels lower than the national level.

Studies dealing with a region need heat transport as an additional unit operation. Cost estimates are made using average values for investments and varying oil prices.

On a still lower aggregation level production processes and their unit operations are studied. The results of the optimization study of a beet sugar plant are reported.

The important aspect of the methodology is that one theoretical framework is used for all aggregation levels.

REFERENCES

[1] F. Diepstraten and W. Van Gool, "Prospects for Carbon Dioxide Emission Reduction", to be published.

[2] A.R.Eastwood and B.Linnhoff," CHP and Process Integration", paper presented at the seminar, The Efficient Use of Energy, 51st Autumn meeting 12th Nov 1985.

[3] B.Linnhoff et.al., "User Guide on Process Integration for the Efficient Use of Energy", The Institution of Chemical Engineers, Rugby (1982).

[4] J. Szargut, "International Progress in Second Law Analysis", Energy, Vol. 5, No. 8-9 (1980).

[5] H. D. Baehr, "Thermodynamik", Springer-Verlag, Berlin (1988).

[6] T. J. Kotas, "The exergy method of thermal plant analysis", Butterworths, New York (1985).

[7] W.F. Kenney, "Energy Conservation in the Process Industries", Academic Press, Orlando (Florida) (1984).

[8] "Thermodynamics: Second Law Analysis", ACS Symposium Series 122, R.A. Gaggioli (Ed.) (1980).

[9] J. Szargut, "Die Exergiebilanz der Wärmeprozesse in der Hüttenindustrie", Freiberger Forschunghefte Nr. B68, pp.81-103 (1962).

[10] H. D. Baehr, "Die Exergie der Brennstoffe", Brennstoff-Wärme-Kraft 31, nr.7, July 1979.

[11] H.Cremer, "Thermodynamic Balance and Analysis of a synthetic Gas and Ammonia Plant", ACS Symposium Series 122, pp. 111-127 (1980).

[12] Department of Energy, Energy Analysis of 108 Industrial Processes, Drexel University, Philadelphia, sept. 1985, no. 2873:Nitrogenous Fertilizers, 3rd revised edition (1980).

[13] N.Nishida et. al., "A Review of Process Synthesis", AICHE Journal, Vol 27, No. 3 pp 321-351 (1981).

[14] W. Van Gool and R. Kümmel, "Limits for Cost and Energy Optimization in Macrosystems", in: Energy Decisions for the Future, Vol. I, (Miyate, Matsui Eds.), Tokyo, pp. 90-106 (1986).

[15] W. Van Gool, " The Value of Energy Carriers", Energy, 12, 509 (1987).

[16] R. Kümmel, H.M. Groscurth and W. Van Gool, "Thermodynamic Limits to Energy Optimization", in M. Ire and K. Yajima (eds), Proceedings of the 13th IFIP-Conference on System Modelling and Optimization, Springer, Tokyo (1987).

[17] H.M. Groscurth, R. Kümmel and W. Van Gool, "Cost Aspects of Energy Optimization", in Proceedings of the International Conference on Computing and Information (ICCI'89), Toronto, Canada, 23-27 (May, 1989).

[18] H.M. Groscurth, R. Kümmel and W. Van Gool, Energy, 14, 241 (1989).

[19] A.J. Hoogendoorn and W. Van Gool, "Exergy Optimization of Industrial Processes", to be published.

[20] W. Van Gool, "Thermodynamic Aspects of Energy Conservation", Energy, Vol. 5, No.8-9, pp. 783-792 (1980).

[21] J. Gaasbeek, A.J. Hoogendoorn and W. Van Gool, to be published.