EXERGY ANALYSIS OF THE CONVENTIONAL TEXTILE WASHING PROCESS

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ABSTRACT. In this paper the efficiency of the conventional textile washing process is examined. This is done by using the cumulative exergy consumption as developed by Szargut et al. [1]. Exergy is the quantity of work, that can be extracted from material or energy by reversible processes. Cumulative exergy consumption shows the exergy consumption in all production steps, from the extraction of natural resources to the final product.

In this paper the study on minimising the CExC of the washing process will be presented. In order to minimise the CExC some experiments have been performed to quantify the exergy consumption of the different process steps that occur during the washing process. These experiments show that the electrical heating process consumes the most exergy. Hence, different alternatives of this process are proposed.

Finally, the washing performance is related to the washing temperature and the detergent quantity, by performing a number of experiments. With this relation an optimum combination of washing temperature and detergent quantity can be found for the different heating systems, that results in an acceptable washing performance with a minimum quantity of CExC. It is shown that replacing the conventional electrical heating system by central heating or district heating will reduce the CExC by 35 or 57 percent, respectively.

INTRODUCTION

In the Netherlands washing machines account for 6.3 percent of the electricity consumption in households. Their market penetration is 97% [2]. It is, therefore, of interest to analyse the possibilities of more efficient washing machines.

In order to examine the textile washing process in a complete way, the process must be studied beginning with natural resources and ending with waste disposal or recycling. In this manner the total exergy necessary for the process is obtained. Exergy is the quantity of work, that can be extracted from material or energy by reversible processes. Hence, the cumulative exergy consumption (CExC) is used, which shows the exergy consumption in all production steps, from the extraction of natural resources to the final product. A picture of the process steps of the washing process is given in Figure 1.

The process steps within the marked area of this figure are examined and optimised to obtain the lowest CExC. Thus, the performance of the washing process and the inputs and outputs associated with it are studied. The CExC needed to produce the detergent has been determined by Zhao et al. [3]. The CExC needed by the water cleaning process has been obtained by Boom [4]. Their results are used, for calculating the CExC of the complete washing process.

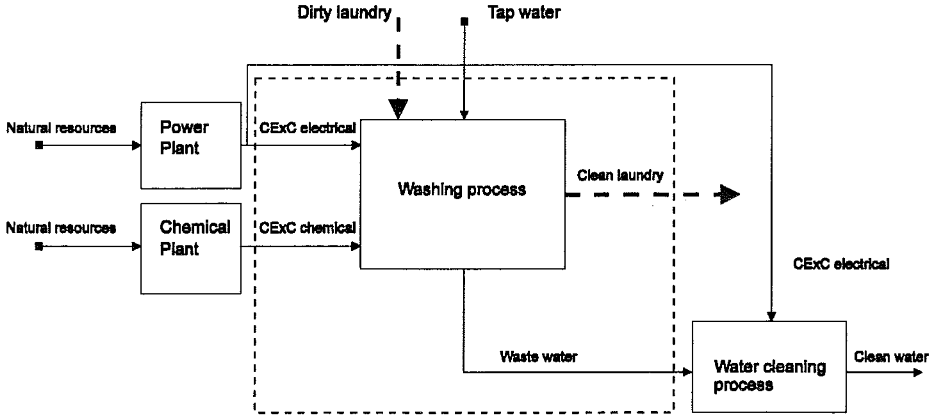


Figure 1. System diagram of the washing process

It is emphasised that the exergy rise due to soil removal from textiles is extremely low, due to the small quantity of soil to be removed. This exergy rise is, therefore, neglected in this study and no exergetic efficiencies of the washing process have been calculated. So instead, the CExC is minimised.

EXPERIMENTS

Set-up

Five variables can be distinguished that influence the washing performance. These are: temperature, detergent quantity, washing time, agitation and water input. From the viewpoint of minimising the CExC at a required washing performance only the temperature and detergent quantity are analysed. It can be argued that a lower water input is preferable for minimising the CExC, however, the water input is already quite low and the possibilities of reducing it are limited. Therefore, the water input has been kept constant. Higher agitation than used in the normal washing program is assumed not to have a large influence, because the mixing is already complete. From thermodynamic considerations a longer washing time is preferable, however, from the users viewpoint the washing time must not take longer than it already is. So this variable is also kept constant.

In this paper the washing performance is only related to the washing temperature and detergent quantity. This relation is used to obtain the optimal combination of temperature and detergent with a minimum CExC at the required washing performance.

The experiments were carried out in a Philips Whirlpool 1200 Silent. This is a front loading drum type washing machine. Measurements were made of the electrical power input, the temperature of the washing fluid and the water input, during the entire washing process. A schematic picture of the experimental design is given in Figure 2.

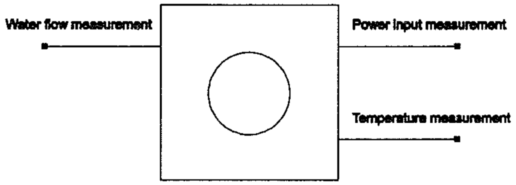


Figure 2. Measurements during the washing cycle

The exergy used by each process i.e. heating, agitation and pumping & centrifugation, were determined at the washing programs of 40, 60 and 80°C. The actual washing performance was tested in another set of experiments. These experiments were performed at 30, 40 and 60°C, with detergent quantities of 18, 36, 50, 72, 90 and 108 grams. The washing time was set at 35 minutes for each experiment. In this set of experiments six different test pieces were washed in duple, together with 3.4 kg of dummy towels. Sensitivity of the test pieces for the different components in the detergent are given in Table 1.

Table 1. Sensitivity data of the different test pieces

Test piece	Contains	Sensitive for
1	Particulate soil[1)]	Builder / actives
2	Same as 1+ casein, milk	Same as 1 + enzymes
3	Tea	Bleach
4	Olive oil + ink	Actives / enzymes
5	Sebum[2)] + ink	Actives / non-ionics
6	Pig blood	Enzymes

1) Iron oxide, silicate, cotton oil and some emulsifier
2) Sweat

Results

For all washing programs the water input for the washing cycle was equal to 17 litres. The results of the electrical power consumption of each separate process will be presented in the following figures and tables. The electrical power input for a washing program of 60°C is shown in Figure 3.

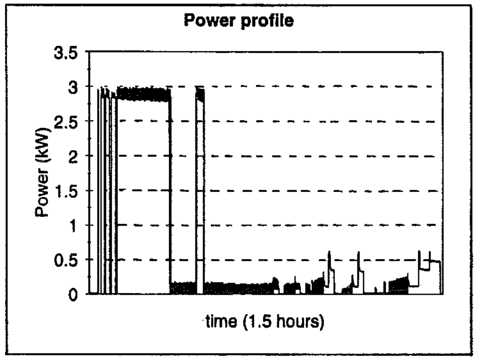


Figure 3. Power input profile at a 60°C washing program

The electrical power input used by the heating process can clearly be distinguished in this figure as large blocks. The power fluctuations during the entire washing process are caused by the agitation of the drum. The smaller blocks on the right hand side of Figure 3 are the electrical power used for pumping and centrifugation. By integrating the power over time, the electricity or exergy used by each process can be calculated. This is presented for each washing program in Table 2.

Table 2. Exergy consumption of the different processes for the washing programs

Washing program	**40°C** (kJ)	**60°C** (kJ)	**80°C** (kJ)
Heating	1450	3440	6400
Pumping + centrifugation	300	290	270
Agitation	100	100	140

Table 2 shows that the exergy consumption due to the heating process ranges from 78 to 94 percent of the total amount of exergy use for the different programs. The increase in exergy consumption of the agitation process at the 80°C program is explained by the longer rinsing program. From different experiments [5] including those presented in Table 2 a linear relation between the exergy use by the heating process and the washing temperature has been obtained, which is

$$Ex_{hp}(T) = -1.6 + 0.09 \cdot T \qquad (1)$$

where Ex_{hp} is expressed in MJ and T lies between 30 and 80°C.

To study the cleaning performance of the washing process, a reflection meter was used. This meter measures the reflection of a beam of light aimed on the test piece. Data of the reflection before and after the washing process can be converted into a dimensionless factor called detergency. This factor can be considered as the percentage of soil removal. By performing the experiments at the washing temperatures and detergent quantities as stated in the experimental set-up, a relation of the detergency for each test piece depending on washing temperature and detergent quantity could be found. The relations for the different test piece are shown in the appendix. The presented relations in the appendix are the best fittings that could be obtained. The standard deviation is given with the calculated parameters. The validity of the relations is restricted to the temperature range from 30 to 60°C and the detergent quantity ranges from 18 to 108 grams.

OPTIMISATION

To optimise the CExC of the heating process, the present electrical heating system and different alternatives are analysed. These are a central heating and a city heating system.

Heating systems

Electrical heating system

In order to obtain the CExC of the electrical heating system, the efficiency of electrical exergy production has to be determined. As an example the data of the 'Amercentrale' power plant are used, which has an electrical efficiency of 41.3 percent on the lower heating value (LHV) [6]. Taking into account the exergetic content of the used coal being 1.09 times higher than the lower heating value [1], the exergetic efficiency of this power plant is equal to 37.9 percent. This is approximately equal to the average exergetic efficiency of the Dutch power plants including transportation losses [7]. By dividing formula 1 by this exergetic efficiency, relation 2 is obtained, which expresses the cumulative exergy consumption in MJ as a function of the installed washing temperature,

$$CExC_{hp}^{eh}(T) = -4.3 + 0.24 \cdot T \qquad (2)$$

Central heating system

The energetic efficiency of the boiler on natural gas is assumed to be 85 percent on the lower heating value. Again the ratio between exergy content and lower heating value has to be known to obtain the CExC. For natural gas this value is equal to 1.04 [1]. Using this data in Equation 1 result in the following relation between the CExC (in MJ) and installed washing temperature for the central heating system.

$$CExC_{hp}^{ch}(T) = -2.0 + 0.11 \cdot T \qquad (3)$$

Equation 3 shows that the CExC of the central heating system is more than twice as low as the CExC of the electrical heating system. This is because in the central heating system the combustion heat is directly used to heat up the water.

District heating system

In order to obtain the CExC relation of the district heating system, we use the data of the before mentioned 'Amercentrale'. This power plant also provides heat to greenhouses and buildings in its surroundings. It is able to supply 350 MW of thermal power at 80 to 130°C at the cost of 50 MW electrical power [6]. The average heat loss due to the distribution is about 15 percent of the total heat supply [7]. So the CExC of 300 MW of heat supplied to the consumers is equal to 132 MW. By multiplying Equation 1 with the CExC of the supplied heat as stated above, Formula 4 is obtained

$$CExC_{hp}^{dh}(T) = -0.7 + 0.04 \cdot T \qquad (4)$$

This is six times better than the electrical heating system and three times better than the central heating system.

Determination of the total CExC

In order to determine the total CExC of the washing process two factors have yet to be determined i.e. the amount of CExC per unit mass of detergent and the CExC of water supply and water treatment per unit volume. The CExC per unit mass of detergent is taken from Zhao et al. [3]. This value is equal to 46.8 kJ/gr. The CExC of water supply ($V_{w,tot}$) and treatment of waste water ($V_{w,ws}$) is given in the following formula in kJ [4].

$$CExC_{wt}(V_{w,tot}, D) = 5.98 \cdot V_{w,tot} + 1.09 \cdot \frac{D}{V_{w,ws}} + 0.57 \qquad (5)$$

The first term on the right hand side of the equation is the CExC used for water treatment and water supply. The second and last terms are the CExC used to clean the waste water, produced by the washing process.

Experiments show a water consumption of 85 litres for the complete washing process. The water consumption of the washing cycle only, i.e. without rinsing, is equal to 17 litres. It is assumed that all detergent is removed after the washing cycle. Inserting these values in formula 5 results in the following relation for the CExC (in kJ) associated with water treatment.

$$CExC_{wt}(D) = 509 + 0.064 \cdot D \tag{6}$$

From formula 6 it can be seen that the CExC of waste water treatment is of a much lower order than that of the production of detergent, namely 0.064 kJ/g against 46.8 kJ/g. So the second term of formula 6 is neglected.

With the average value of Table 2 for agitation, pumping and centrifugation and the exergetic efficiency of electricity production, the CExC for these processes is calculated to be 1055 kJ per washing program. For the determination of the total CExC in the case of an electrical heating spiral, Equations 2 and 6 and the CExC for agitation, pumping and centrifugation must be added. This results in formula 7

$$CExC_{tot}^{eh}(T,D) = -2.8 + 0.24 \cdot T + 0.0468 \cdot D \tag{7}$$

where $CExC_{tot}^{eh}$ is expressed in MJ and T lies between 30 and 80°C.

Determination of the minimum CExC

Now that the relation for the total CExC is known and also the relations for washing performance depending on temperature and detergent quantity, a minimum quantity of CExC for the washing process can be found for each test piece separately at an acceptable detergency. This is considered to be 80 percent. A detergency of 80 percent could *not* be reached for the test pieces 3, 4 and 5, within the range of the used washing temperature and detergent quantities. These detergency's are therefore set to the maximum value of detergency that *could* be reached. The detergency's fixed for each test piece are given in Table 3.

Table 3. Fixed detergency for the different test pieces

Test Pieces	*Detergency*
1	80%
2	80%
3	58%
4	58%
5	75%
6	80%

Table 4. Optimum washing temperatures and detergent quantities for each test piece for a minimum quantity of CExC

Test pieces	T_{opt} (°C)	D_{opt} (gr)	CExC (MJ)
1	62 ±12	89 ±18	17.4 ±3.7
2	46 ±12	72 ±15	11.4 ±3.5
3	60	108	16.7
4	15	108	6.5
5	60	72	14.6
6	27 ±11	62 ±6	6.0±2.8

Substituting the detergency of each test piece into formula A1 to A6 of the Appendix, results in a relation between the washing temperature and detergent quantity. Substituting this relation into Equation 7, results in a relation of the total CExC and temperature or detergent quantity only. With this relation a minimum value of the total CExC can be found. The minimum value of CExC and the values of both variables are given in Table 4, for the case of the conventional electrical heating system. The variations in washing temperature, detergent quantity and total CExC are due to variations in the function parameters. To reach the maximum detergency of test piece 3, the highest temperature and detergent quantity are chosen. The same applies to test piece 5, with the exception that for greater amounts than 72 grams the detergency does not depend on the detergent quantity anymore. The detergency relation of test piece 4 does not depend on the washing temperature, hence the washing temperature has been set at the tap water temperature, which is about 15°C. Table 4 shows that a low optimum washing temperature immediately results in a low quantity of total CExC. This was already known, since the heating process is the largest cumulative exergy consumer of the washing process. A similar table can be drafted for the other heating systems that were mentioned, i.e. the central heating process and the district heating system. Instead of representing these data for each separate heating process, a table has been drafted that shows the average optimum temperature and detergent quantity for the different heating systems. For this comparison only test piece 1,2 and 6 are considered here, because the temperature and detergent quantities of the other test pieces are fixed to reach the maximum obtainable detergency, as can be seen in Table 3. The average detergency of these three test pieces is almost equal to 80 percent for each heating system within a range of 0.5 percent difference in detergency. However, the detergency of these separate test pieces deviates within a range of 10 percent in detergency. The average detergency of all test pieces is three percent lower for the central heating and three percent higher for the district heating compared to the electrical heating system

Tables 5,6 and 7 show that, as the heating system requires less cumulative exergy, the optimum washing temperature rises. This again results in a lower demand of detergent quantity and thus a lower optimum detergent quantity. More important, however, is that the total CExC decreases to a considerable extent; i.e. from 12.6 MJ in the case of the electrical heating spiral to 8.2 and 5.4 MJ in the case of the central heating system and the district heating system respectively, considering the three test pieces.

Table 5. Average optimum temperatures for the various heating systems

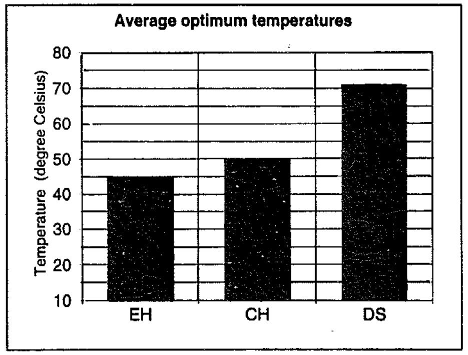


Table 6. Average optimum detergent quantities for the various heating systems

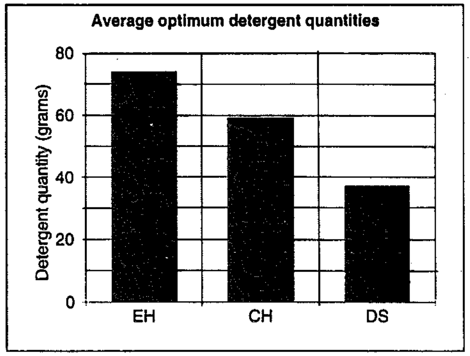
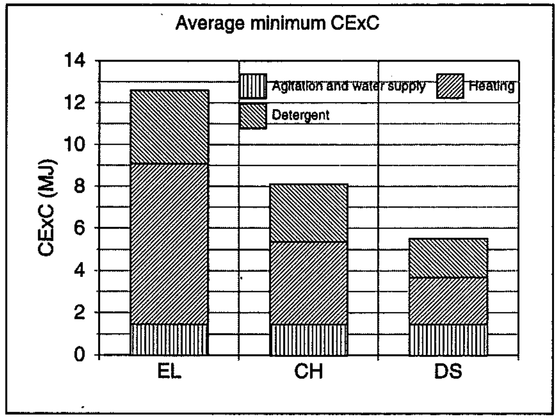


Table 7. Average minimum CExC for the various heating systems



DISCUSSION

In the conventional textile washing process large quantities of cumulative exergy are used to remove just a few grams of soil. Most of this exergy is consumed by the heating process, since it takes a large quantity of energy to heat up 17 litres of water. Although the CExC can be reduced to a considerable extent by using a district or a central heating system, the CExC remains relatively large, compared to the actual exergy needed for soil removal. Research should be carried out for alternative washing processes.

Since the heating and detergent quantity consume the larger parts of cumulative exergy, it seems reasonable to further exploit the other variables that influence the washing performance i.e. the washing time and the agitation input. These variables consume only a relative small part of the total quantity of exergy.

It is indeed possible to determine a minimum quantity of CExC that results in a certain detergency of the separate test pieces. The optimum values of the separate test pieces, however, differ to quite some extent. The average optimum temperature and detergent quantity lead to variation in the detergency of the different test pieces, despite the fact that the *average* detergency is nearly equal for the three test pieces in the comparison. This leads to the fact that in the comparison some test pieces are better and some test pieces are less cleaned. The average detergency for all test pieces deviates slightly more in the comparison.

The listed efficiency on the LHV of 85% can only be reached and even be higher, when special arrangements in or outside the washing machine are taken, for example a gas-fired boiler inside the washing machine. When the already existing tap water heating system is used the efficiency will be around 50% on the LHV, while in the case of a new high efficiency boiler for combined central and tap water heating the efficiency will be 60% on the LHV. A limit for the use of the district heating system can be the maximum obtainable temperature. It may not always be possible to obtain 80°C, so additional electrical heating may be necessary. This will lead to a higher CExC.

A washing machine with a hot fill, i.e. where hot water is directly inserted, may be disadvantageous to the removal of enzyme sensitive soil, because enzymes do not work at temperatures higher than 40°C.

CONCLUSIONS

It is shown that the CExC is a useful parameter to optimise washing cycles and compare different types of heating systems.

An optimum function is established for the CExC, which depends on the washing temperature and detergent quantity for three types of heating systems.

It has been found that the conventional electrical heating spiral is a very inefficient heating system in terms of CExC. It is, therefore, recommended to replace this system by a system based on gas heating or, if possible, on a district heating system. This will reduce the CExC by 35 and 57 percent, respectively.

NOMENCLATURE

CExC	MJ	Cumulative exergy consumption	V	m^3	Volume
CH		Central heating system	**Superscripts**		
C_P	J/kgK	Heat capacity	eh		Electrical heating system
D	gram	Detergent quantity	ch		Central heating system
Det	--	Detergency	dh		District heating system
de	J	Infinitesimal exergy			
quantity			**Subscripts**		
dq	J	Infinitesimal heat	det		Detergent
quantity			hp		Heating process
DS		District heating system	o		Reference
EH		Electrical heating system	opt		Optimum
Ex	MJ	Exergy	tot		Total
LHV	MJ	Lower heating value	w		Water
M	kg	Mass	ws		Washing
η	--	Efficiency	wt		Water treatment
T	°C	Temperature			

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APPENDIX

Relations of the detergency for the different test pieces.

Test piece 1 :

$$Det_1(T,D) = (a_1 + b_1 \cdot T) \cdot (1 - f_1 \cdot e^{-g_1 \cdot D}) \qquad \text{(A1)}$$

a_1	49.3 ± 6%	[--]
b_1	0.551 ± 11%	[1/°C]
f_1	0.845 ± 12%	[--]
g_1	$3.4 \cdot 10^{-2}$ ± 19%	[1/gr]

Test piece 2 :

$$Det(T,D) = (a_2 + b_2 \cdot T) \cdot (1 - f_2 \cdot e^{-g_2 \cdot D}) \qquad \text{(A2)}$$

a_2	54.9 ± 6%	[--]
b_2	0.551 ± 13%	[1/°C]
f_2	1.25 ± 18%	[--]
g_2	$5.23 \cdot 10^{-2}$ ± 18%	[1/gr]

Test piece 3 :

$$Det(T,D) = a_3 + b_3 \cdot T \cdot D \qquad \text{(A3)}$$

a_3	13.2 ± 16%	[--]
b_3	$6.9 \cdot 10^{-3}$ ± 28%	[1/°C·gr]

Test piece 4 :

$$Det(D) = a_4 + b_4 \cdot D \qquad \text{(A4)}$$

a_4	30.2 ± 7%	[--]
b_4	0.256 ± 13%	[1/gr]

Test piece 5 :

$$Det(D) = a_5 + b_5 \cdot D \quad \{15<T<30\} \quad \text{(A5)}$$
$$Det(T,D) = f_5 \cdot T + g_5 \cdot D \quad \{T>30 \wedge D<72\}$$
$$Det(T) = h_5 \cdot T \quad \{T>30 \wedge D\geq 72\}$$

a_5	23.2 ± 13%	[--]
b_5	0.154 ± 27%	[1/gr]
f_5	0.461 ± 14%	[1/°C·gr]
g_5	0.342 ± 25%	[1/gr]
h_5	1.251 ± 18%	[1/°C·gr]

Test piece 6 :

$$Det(T,D) = b_6 \cdot T + f_6 \cdot (1 - e^{-g_6 \cdot D}) \quad \text{(A6)}$$

b_6	0.295 ± 14%	[1/°C·gr]
f_6	72.9 ± 2%	[--]
g_6	$7.25 \cdot 10^{-2}$ ± 6%	[1/gr]

THERMODYNAMICS AND CHEMICAL REFERENCES FOR EXERGY ANALYSIS

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ABSTRACT. Exergy references for chemical elements have long been discussed in literature, but up till now the data are not included in thermodynamic standard tables. One reason is that assumptions and procedures used in the derivation of an environmental reference system are quite unusual from a thermodynamic point of view. Examples are the application of often very low concentrations of elements in the atmosphere and ocean as standard states and the abundance of elements in the earth's crust (the Clarke number) to indicate the economic value of elements. The main objective of this paper is to describe a methodology to obtain a chemical reference system based upon the use of standard thermodynamics. In stead of using the exact composition of air to determine exergy values of the first few key elements a generalised well-defined gas mixture is selected. For all other elements data of pure compounds from standard thermodynamic tables are applied to develop the reference system. Linear optimisation technique is essential to minimise exergy values of the elements and to allocate unambiguously reference compounds to elements. Exergy values and reference compounds are reported for 89 elements. The generalised composition of air is the only aspect that reminds of the original reference system set-up. Otherwise just standard thermodynamics has been used.

INTRODUCTION

In the last few decades the use of exergy in the determination of efficiencies of industrial processes and other energy requiring operations increased considerably. Presently in several countries exergy analysis starts to play a role in developing energy policy as there is a close connection between energy policy and exergy losses. Exergy is the maximum amount of work that can be obtained if a material or a form of energy is converted into its inert reference state. Also, exergy is the minimum amount of work to be supplied if a material or form of energy has to be produced from the inert reference system. The reference system includes, in addition to physical parameters such as temperature and pressure, references for chemical elements. The lost exergy in a steady state process is independent of the chemical reference system if the chemical contents of input and output are equal. Chemical content refers to the chemical inventory in terms of number of atoms of each element. An important application of exergy analysis is the determination of exergy efficiency. This is the ratio between exergy output to exergy input and for this ratio references for elements are required. Exergy values of input and output of a process must be non-negative to determine the exergy efficiency.