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Utilization of waste materials by means of thermal and materials conversion ☆

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Abstract — The extraordinary increase of waste quantities during the 1980s led to the development of numerous new technologies and principles which were aimed at a maximum possible reutilization of waste materials as valuable substances or as raw materials. As far as industrial waste management is concerned, more research was implemented concerning the principle of production-integrated environmental protection. For municipal waste management, new alternative technologies to thermal treatment of municipal waste were developed. The following contains an overview of the various methods for the treatment of solid, liquid and gaseous wastes as well as a presentation of the principles used to evaluate these methods in view of entropy aspects. © 2001 Éditions scientifiques et médicales Elsevier SAS

waste materials / thermal conversion / entropy

Nomenclature

E	energy, quantity of exergy	J
$\dot{E}$	exergy flow rate, energy flow rate	J
e	specific exergy	$\mathrm{J \cdot kg^{-1}}$
H_0	gross calorific value	$\mathrm{J \cdot kg^{-1}}$
H_u	net calorific value	$\mathrm{J \cdot kg^{-1}}$
$\dot{m}$	mass flow rate	$\mathrm{kg \cdot s^{-1}}$
P	mechanical energy flow rate	$\mathrm{J \cdot s^{-1}}$
p	pressure	$\mathrm{N \cdot m^{-2}}$
Q	quantity of heat	J
$\dot{Q}$	heat flow rate	$\mathrm{J \cdot s^{-1}}$
s	specific entropy	$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
$\dot{s}$	entropy flow rate	$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
T	temperature	K
$\Delta^\mathrm{R} s$	specific reaction entropy	$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
Δ	difference	
j	mass fraction	$\mathrm{kg \cdot kg^{-1}}$
ξ	exergy efficiency rate	
η	energy efficiency rate	
η_C	Carnot factor	
η_K	boiler thermal efficiency	
η_th	engine thermal efficiency	

Indices

B	fuel, waste material
L	air
V	flue gas, incinerator off-gas
u	values at ambient conditions
m	average value
v	loss to environment
Q	caloric energy by burning
DE	steam production
WE	heat production by burning
WKM	electrical or mechanical engine

1. INTRODUCTION

The development of new waste treatment processes is guided more and more by the concept of producing valuable substances from waste materials (materials conversion) instead of using the energy stored in waste materials as thermal energy (thermal conversion). The quality of the produced reusable substances depends on how much the applied process is adapted to the specific properties of the waste material.

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The waste materials are classified according to their composition, their origin and their physical parameters which are important for further treatment. The basic principles of production-integrated environmental protection give rise to the development of new production processes with diminished pollution potential. Process-technological solutions for materials conversion of wastes with the use of external energy are the recycling of plastics and the separation of reusable substances from exhaust air and waste water. The production of energy from waste materials, by thermal and biological processes, is also possible.

2. WASTE MATERIALS

2.1. Origin

The origin of waste materials is important for the selection of conversion treatment methods. At this point, we will differentiate between waste materials from production facilities (e.g., chemical industry) and waste materials from private households or business areas (municipal waste).

An industrial production facility is responsible for the treatment and disposal of the waste materials originating from it. Waste materials can either be reutilized as raw materials or substances within another production process or they must be eliminated. Industrial companies either operate their own treatment facilities (furnaces, special waste incinerators), or they use municipal facilities and pay the required fees. Since the fees for treatment and disposal of special wastes have increased enormously within recent years, the economic interests of any industrial company prescribe that as many waste materials as possible be put to further use or eliminated in their own facilities, thus avoiding an “export” of their wastes beyond property limits. The reutilization of waste materials within a production chain is the central idea behind the principle of “production-integrated environmental protection”.

The treatment and disposal of waste materials from private households is done by each municipality. The costs are charged to the originators as waste treatment fees. A differentiation is made between recyclable wastes (paper, glass, recyclable plastics) and nonrecyclable wastes. Waste materials should only be recycled, if there is a market for all materials that may result from recycling. This market is hardly ever identical with the originators of the wastes. Therefore, the costs for waste treatment paid as fees are hardly ever transparent for the originator. For the originator, the only possible manner to influence his costs is to separate waste into recyclable and nonrecyclable waste. He has no influence on treatment or disposal. Furthermore, only the direct treatment or disposal costs are taken into consideration. The costs resulting from damages to the environment caused by the treatment and disposal methods are neglected at this time. Thus, the selection of the treatment methods as well as the instruments for controlling waste quantities and types are by far more complicated for municipal waste than this is the case for industrial wastes.

2.2. Classification

Certain physical properties are important for the classification of waste materials in view of materials or thermal conversion with process-technological methods. In particular, these are the physical condition and the composition of the waste material. The different physical conditions are solid, liquid and gaseous.

Solid wastes include those substances usually called garbage. This is municipal waste from private households and business areas. However, solid waste may also originate from industrial production processes: combustion residues, reaction residues, biomass, particle-shaped emissions etc.

Liquid wastes mainly consist of sewage waters from residential and industrial areas. Normally, the pollutant concentration of waste water from residential areas is low. Waste water from industrial areas, however, usually contains various types of pollutants. Chemical production processes also apply a considerable quantity of solvents, which may be contained in the waste water in addition to the aqueous components.

Sludges are a combination of solid and liquid wastes. These are: sewage sludge, sludges from steel production processes which contain metals, or sludges with suspensions of microorganisms from biochemical plants.

Gaseous wastes are all types of exhaust air and exhaust gas which are released from production facilities, combustion engines etc. These exhaust gases may contain solid particles (dusts), liquid particles (aerosols) and gaseous particles (solvents).

The chemical and physical composition of waste materials from industrial production processes can be obtained very easily via the knowledge about the originating production process. Thus, the waste materials can be classified according to their contents of chemical compounds. From this information, the most suitable treatment or disposal method can be determined.

TABLE I
Typical pollutant contents in emissions.

HCl
HF
SO_2
NO_x
CO
Cd
Hg
heavy metals
PCDD/PCDF

Waste from households and business areas can be divided into various fractions. A separate evaluation of the avoidance and reutilization potential of each individual fraction can be implemented. For example, household and small business waste can be classified according to its contents of recyclable materials [1, 2]. Pollutant contents are also important to know. In general, pollutants are those substances that lead to an emission of the substances listed in *table I* during treatment. These emissions develop as a result of the chemical and physical decomposition of the substances contained in waste materials and are released to the environment as exhaust air or waste products.

An elements analysis can be used to classify household and business waste according to the contained elements. An exact determination of the contained chemical compounds however is not possible.

For waste materials from production processes which will be reutilized as substances, the exact chemical composition and the physical condition as well as temperature and pressure have to be known. Contaminations of the waste materials with traces of certain components may also be important to know for later treatment. A multitude of other physical parameters (density, viscosity, pH value etc.) determine, whether a waste material can be introduced directly as a substance into a subsequent process, or whether intermediate treatment is necessary.

It is important to know the calorific value of wastes subject to thermal treatment. The calorific value characterizes the energy released during complete thermal decomposition, related to the mass of the waste material. Typical calorific values are situated between 4.0 $MJ \cdot kg^{-1}$ (edible plants) and 35 $MJ \cdot kg^{-1}$ (plastics) [3]. According to the 17th BimSchV (federal emission control regulation), a minimum temperature of 850 °C must be maintained during waste incineration in order to guarantee a safe elimination of pollutants. Therefore, the calorific values of the waste materials are crucial factors in the decision about whether or not to introduce additional energy to the incineration process.

3. MATERIALS CONVERSION OF WASTE MATERIALS WITH EXTERNAL ENERGY FEED

Legal regulations concerning waste treatment and recycling economics give first priority to avoidance and reutilization of waste materials. Reutilization as stated in these regulations is the conversion of wastes into valuable substances (raw materials). The use of external energy is necessary for this process. This energy is required either for the physical transformation processes (shredding, grinding, melting) or for the chemical transformation processes. For materials conversion it is necessary that the waste materials are as pure and chemically well-defined as possible, since any required sorting or cleaning processes are highly energy-consuming. Reutilization as valuable substances is especially evident for industrial waste, however it is also applicable for recyclable municipal waste, if it has been collected separately.

3.1. Conversion of wastes from production facilities

Process-integrated waste treatment in terms of process-integrated elimination of wastes is not the objective of chemical industry [4]. Since an emission-free production process cannot exist, the objective is to reutilize wastes within the process chain and thus implement “production-integrated environmental protection”.

The reutilization of waste is achieved by

- recycling directly into the process,
- utilizing wastes as raw materials in the extended production chain, and
- utilizing wastes for the production of energy.

The last item includes thermal conversion such as incineration. The required plant must be integrated in the overall production concept.

If reutilization of avoidance are not possible or sufficient, a disposal of the remaining wastes becomes necessary, which means storage in a dump site. A chemo-physical treatment is necessary to make the waste materials inert, before they are transported to the dump site. This requires additional energy, which should come from thermal waste conversion.

Numerous publications [5–7] describe modifications of processes implemented in order to achieve the above

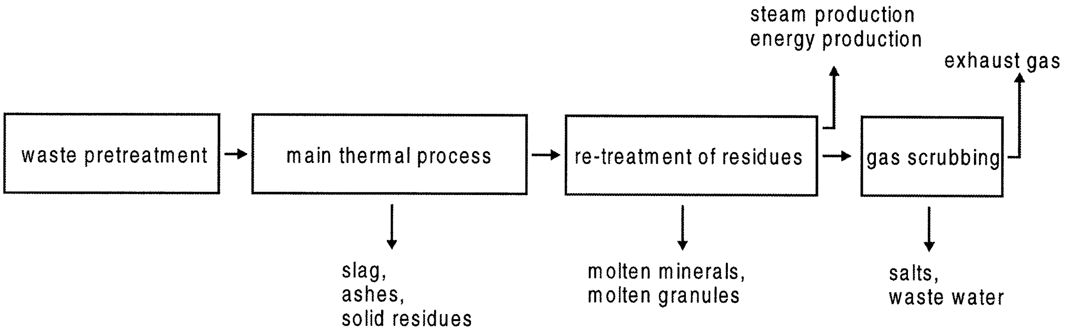


Figure 1. Schematic representation of thermal waste treatment plants.

described objectives. These are mainly modifications in view of materials conversion instead of thermal conversion or disposal.

The second priority of production-integrated environmental protection after avoidance of waste is materials conversion. For this purpose, the waste materials have to be cleaned and contaminations separated, before they can be used as raw materials in another production step. With the use of additional energy, the physical and chemical properties of the waste materials must be changed. This may include grinding and classifying processes in order to achieve a specific grain size and property. Cracking of chemical compounds by using energy is also possible. In general, materials conversion is possible with waste materials of all physical conditions. Many methods are described by examples in the literature [8, 9].

3.2. Thermal conversion of waste materials

If it is not possible to recover or recycle substances from waste materials, thermal conversion is the alternative to disposal. This means releasing the chemical energy contained in waste materials as thermal energy. For this purpose thermal waste treatment plants consist of a main thermal process as well as individual process steps such as waste gas scrubbing and production of steam or electric power. *Figure 1* lists schematically the process steps of a thermal waste treatment plant. It includes:

- waste pretreatment,
- main thermal process,
- waste retreatment,
- gas scrubbing.

Waste pretreatment is implemented to prepare the waste materials as much as possible for the subsequent process steps by means of shredding, sorting, homogenizing and preseparating of pollutants [10]. These preparations are necessary to keep conditions during the main process as constant as possible (e.g., constant incineration temperature). Also, the efficiency of the waste gas scrubbing process can be increased by keeping the variation of pollutants contained in the wastes as low as possible. This can be achieved only if the waste materials which normally consist of various components are homogenized with the described methods.

The actual thermal conversion of the waste materials takes place in the main thermal process following the pretreatment. It often consists of two steps [11]. During the first step, the waste is transformed into inert solids (slag, ashes) as well as liquid and gaseous substances by means of pyrolysis, gasification or incineration. Depending on the type of thermal process applied, the resulting products can be reused as substances — e.g., pyrolysis oil, pyrolysis gas, synthesis gas — or as energy — e.g., incineration exhaust gases.

The residual products of the first step are either utilized or transformed during the subsequent second process step. Incineration exhaust gases are cooled down to produce steam, which is then used as process steam or for the production of electric power. It is also possible to feed low-pressure steam into district heating networks (waste-operated heating power plants). Oxidizable gases are incinerated or gasified, and the obtained thermal energy is used to produce process steam or electric power. Solid and liquid wastes are treated in such a way that they can be used as raw materials for other processes or disposed as residues.

Waste retreatment is implemented to clean the obtained reusable substances again and to make all nonreusable substances inert. Type and quantity of these substances strongly depend on the type of waste and on the main thermal process applied. Sometimes the retreatment can be part of the main process — e.g., vitrification of slag during the Thermoselect process [11]. Some of the existing retreatment processes are [11–13]:

- further processing, e.g., to separate metals,
- solidification, e.g., to compact flying dust,
- melting, e.g., to vitrify and deenergize ashes and slags,
- scrubbing, e.g., to remove soluble salts and heavy metals.

Gas scrubbing is the last process step. It is implemented to separate, utilize or deenergize the pollutants remaining in the exhaust or process gas. This includes the separation of sulfur dioxide, hydrogen chloride, hydrofluoric acid, nitrous oxides, heavy metals as well as organic and toxic contaminations. Numerous other methods can be applied [11, 13].

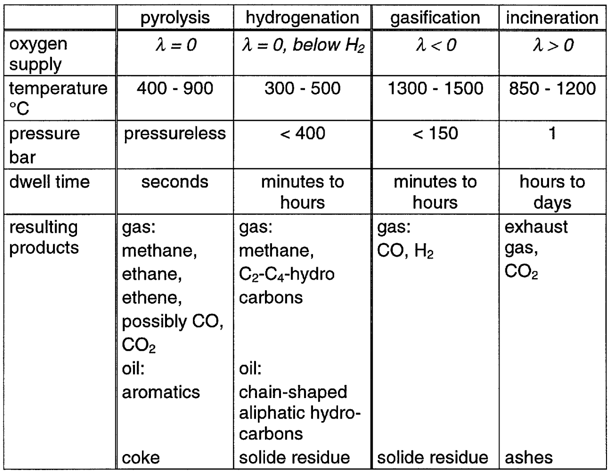
3.3. Methods for raw material recovery

In recent years, alternatives to classical waste incineration have been developed. The objective of these developments was to eliminate waste by applying methods with which as much reusable substances and raw materials as possible are obtained. Irreversible conversion — which is the result of incineration — was to be restricted. This was achieved by implementing the complex physical and chemical processes during incineration as separate process steps. Thus, a better control of the individual processes becomes possible, and they can be better adapted to the substances to be eliminated.

The physical processes that can be applied for this purpose are pyrolysis, hydrogenation and gasification. On the basis of their most important parameters, these methods are compared to each other and to incineration in *figure 2*. The extreme difference in parameters, regarding oxygen supply, temperature and pressure level, dwell time and obtained reusable substances is quite obvious [14].

Recently developed waste treatment processes usually apply a combination of the described physical processes instead of applying only one of them. *Table II* shows a comparison of the existing processes and their process-technological principles [14, 15].

Due to intense research activities in the field of waste gas treatment in recent years, all existing processes meet the legal requirements for pollution control [11, 15, 16]. As far as the eluate behavior of solid residues resulting from thermal conversion (ashes, slag) is concerned, the described special processes are superior to incineration, since they produce vitrified slag. The eluate behavior becomes similar, if grate incineration is followed by vitrification of the ashes in a separate process step.



	pyrolysis	hydrogenation	gasification	incineration
oxygen supply	$\lambda = 0$	$\lambda = 0$, below H_2	$\lambda < 0$	$\lambda > 0$
temperature °C	400 - 900	300 - 500	1300 - 1500	850 - 1200
pressure bar	pressureless	< 400	< 150	1
dwell time	seconds	minutes to hours	minutes to hours	hours to days
resulting products	gas: methane, ethane, ethene, possibly CO, CO_2 oil: aromatics coke	gas: methane, C_2-C_4-hydro carbons oil: chain-shaped aliphatic hydro-carbons solide residue	gas: CO, H_2 solide residue	exhaust gas, CO_2 ashes

Figure 2. Variables of the most common conversion processes.

TABLE II
Thermal waste treatment processes [15].

Process/Supplier (company)	Main thermal processes
Grate incineration Fluidized bed incineration Rotary drum technology	incineration + re-incineration
Schwel-Brenn-Verfahren/ Siemens-KWU Duotherm process/von Roll Pyrocom process/BC	pyrolysis + incineration
Wikonex process/Lurgi	gasification + incineration
Noell conversion process VEBA conversion process Thermoselect process	pyrolysis + gasification, utilization of gas
Öko-Gas process/Lurgi	gasification, utilization of gas
NESA pyrolysis incineration	pyrolysis + incineration

For a comparison of the economical performance of the different processes, the investment and operating costs as well as the proceeds from the recovered reusable substances and the produced energy must be taken into consideration. A comparison based on investment and operating costs is difficult due to the fact that confirmed figures are available only for grate incineration at the present time. The operators of special processes compensate their high operating costs by offering extensive guarantees. A monetary evaluation of the produced substances and energies is possible only for electric power or steam, provided that they can be fed into a distribution system. An evaluation of the mass flows mainly depends on the question, whether customers can be found for the recovered substances and whether they will agree to long-term buying contracts.

3.4. Biological treatment of waste materials

Biological waste treatment by means of fermentation is applied for organic wastes with low pollutant concentrations. A comparison of the existing methods is given in [17]. Biological treatment consists of the following process steps:

- dry preparation,
- wet preparation,
- anaerobic fermentation,
- energy production,
- dehydration of the residue, and
- aerobic composting of the residue.

Undesired substances such as scrap and nondegradable matter are removed during dry preparation. Subsequently, the waste is shredded mechanically in order to increase its surface area.

During wet preparation, which can be an alternative to dry preparation as well as an additional treatment step, the water content required for fermentation is obtained by mixing process water into the waste material. Undesired substances are removed by gravitational separation. Subsequently, the waste mixture can be heated.

Hydrolysis, acidification and methanization take place in the subsequent anaerobic reaction process. The obtained products are a gas with a methane content of 50–70 %, waste water and fermentation residue. The process can be single-step or multiple-step. In the single-step process, hydrolysis, acidification and methanization take place in one reactor. In the double-step process, hydrolysis and acidification take place separate from methanization. The processes can be mesophile (operating temperature approximately 37 °C) or thermophile (operating temperature approximately 55 °C). Biogas can be burned to produce electric or thermal energy.

Combination processes consisting of biomechanical treatment and thermal treatment are investigated in addition to strictly biological processes [18, 19]. For this purpose, the waste material is divided into two fractions: one with low calorific value and high water concentration and another one with high calorific value and low water concentration. Both, parallel and serial operation of the two processes are possible. During parallel operation, the fraction with low calorific value is fermented and the fraction with high calorific value is treated thermally. During serial operation, the fraction with low calorific value is treated biologically at first. Then both fractions are treated thermally. A cost comparison between combination processes and strictly thermal treatment processes shows that the combination processes are more cost-efficient in special cases only [18, 19].

4. THERMODYNAMIC EVALUATION METHODS

The thermodynamic evaluation of a certain waste conversion method requires investigations of the irreversible processes taking place. Exergy is stored in every waste material as chemical energy. This chemical energy can be transformed into other types of energy. During materials conversion of waste materials, the chemical energy of the waste is transformed into the chemical energy of the recovered raw material. During the incineration of waste materials, the chemical energy is transformed into thermal energy (heat). From a thermodynamic point of view, the different energy types are not equivalent. Thermal energy can only partially be transformed into chemical, mechanical or electrical energy.

4.1. Exergy balance

The exergy loss due to chemical reactions is of essential importance during waste conversion. The specific exergy of the waste material must be known to predict the exergy loss and the exergetic efficiency rate during waste conversion. According to the following equation, it is calculated on the basis of complete, reversible oxidation of the waste material [20, 21]:

$$e_{\mathrm{B}}(T_{\mathrm{u}}, p_{\mathrm{u}}) = H_0(T_{\mathrm{u}}, p_{\mathrm{u}}) + T_{\mathrm{u}}\Delta^{\mathrm{R}}s(T_{\mathrm{u}}, p_{\mathrm{u}}) + \Delta e(T_{\mathrm{u}}, p_{\mathrm{u}}). \tag{1}$$

In this equation, e_{B} is the specific exergy of the waste material related to the mass of the fuel, H_0 is the gross calorific value of the waste material, $\Delta^{\mathrm{R}}s$ is the specific reaction entropy during oxidation of the waste material, and Δe is the exergy difference between the oxygen feed and the discharged gaseous oxidation products (in first approximation these are the following gases: carbon dioxide, water, sulfur dioxide and nitrogen).

Table III shows an analysis of the elements of several fuels as well as an analysis of the elements of waste material of typical composition [23, 24]. The high concentration of inert substances is the only essential difference between waste material and fuels. On the basis of

TABLE III
Composition and net calorific value of waste material compared to primary energy carriers [22, 23].

Mass portion	Pit coal (from the Ruhr area)	Brown coal (from the Rhein area)	Gasoline	Waste
γ_{C}	0.813	0.280	0.837	0.278
γ_{H_2}	0.045	0.020	0.143	0.036
γ_{S}	0.007	0.003	–	0.002
γ_{O_2}	0.040	0.101	0.020	0.171
γ_{N_2}	0.015	0.003	–	0.008
γ_{Cl}	–	–	–	0.005
γ_{water}	0.035	0.555	–	0.25
γ_{ash}	0.045	0.038	–	0.25
H_u in MJ·kg^{-1}	32.1	8.06	42.6	10.3

the rest of its composition, waste material can be situated anywhere between brown coal and pit coal. *Table IV* lists the calculated molar gross and net calorific values, specific exergies as well as the ratios of the exergy to the gross and net calorific values for the same substances. The exergy of liquid fuels is about 2 % lower than the gross calorific value. The exergy of solid fuels is about 1–2 % higher than the gross calorific value. The small deviation between exergy and calorific value is due to the fact that the calorific value has the by far largest portion on the right-hand side of equation (1), compared to the other two terms. Sulfuric compounds make an exception, because their exergy is up to twice as high as the gross or net calorific value. Thus, the thermal energy described by the calorific value, which is released during complete oxidation of the compounds listed in the table, is almost identical to the chemical energy stored in the compounds.

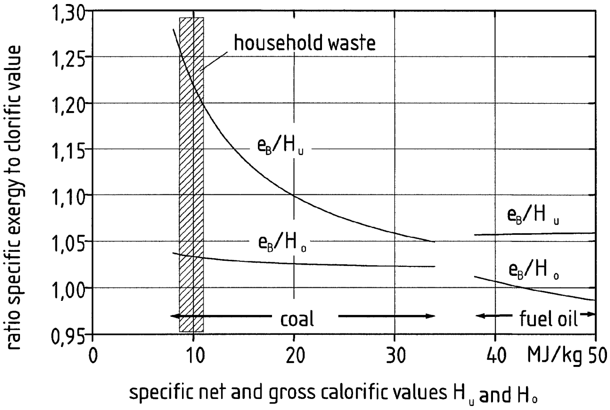


Figure 3. Ratio of the specific exergy to the calorific value for various fuels [22].

Baehr provides the following equations to estimate the exergy of coal with calorific values of less than 34 MJ·kg^{-1}:

$$\frac{e_B}{H_u} = 0.9775 + 2.410\frac{\text{MJ·kg}^{-1}}{H_u} \tag{2}$$

and

$$\frac{e_B}{H_0} = 1.018 + 0.152\frac{\text{MJ·kg}^{-1}}{H_0} \tag{3}$$

Since the ash content is neglected here, it can be assumed that equations (2) and (3) can be applied for waste material as well. *Figure 3* shows a graphic representation of equations (2) and (3). The graphs for liquid fuel (fuel oil) have also been entered. A significant increase of e_B/H_u can be observed for decreasing net calorific values. This means that a growing portion of the chemical energy cannot be totally transformed into thermal energy any longer. Municipal waste with a net calorific value

TABLE IV
Molar calorific values, reversible reaction energy and exergy of solid and gaseous fuels [22].

Fuel	Net calorific value H_{um} in kJ·mol^{-1}	Gross calorific value H_{om} in kJ·mol^{-1}	Exergy E_B in kJ·mol^{-1}	Exergy, net calorific value	Exergy, gross calorific value
C (graphite)	393.51	393.51	410.43	1.04	1.04
S	296.83	296.83	602.69	2.03	2.03
H_2	241.82	241.83	235.15	0.97	0.97
H_2S	518.02	562.03	804.30	1.55	1.43
CO	282.98	282.98	275.24	0.97	0.97
CH_4	802.34	890.36	830.03	1.03	0.93
C_2H_2	1 255.6	1 299.6	1 265.2	1.01	0.97
C_2H_4	1 322.9	1 410.9	1 359.3	1.03	0.96
C_2H_6	1 427.8	1 559.8	1 495.5	1.05	0.96
C_3H_8	2 043.9	2 219.9	2 148.5	1.05	0.97
n-C_4H_{10}	2 658.4	2 878.5	2 802.0	1.05	0.97

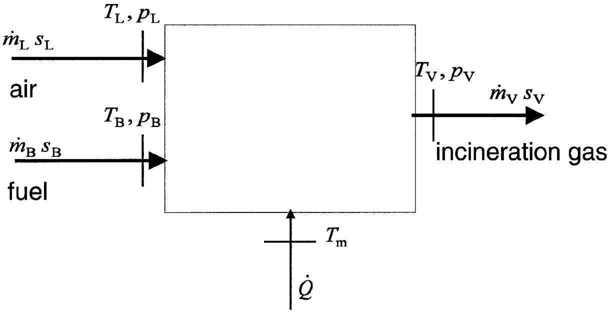


Figure 4. Balancing chamber for incineration.

between 9 and 11 MJ·kg^{-1} is thus situated at around $e_B/H_u \approx 1.2$.

The exergy loss during waste incineration according to *figure 4* is calculated with the following equation:

$$\begin{aligned}\dot{E}_V &= \dot{m}_B e_V = T_u \dot{S}_{irr} \\ &= T_u \Big[\dot{m}_V s_V(T_V, p_V) - \dot{m}_B s_B(T_B, p_B) \\ &\qquad - \dot{m}_L s_L(T_L, p_L) - \frac{\dot{Q}}{T_m} \Big]\end{aligned} \tag{4}$$

$\dot{m}$ is the mass flow, index B is the waste material, index V is the incineration gas, index L is the air and the last term on the right-hand side of equation (4) is the heat flow rate $\dot{Q}$ absorbed at the mean temperature T_m. If the incineration is adiabatic, the temperature T_V is identical to the adiabatic incineration temperature and the heat flow rate equals zero. If the conversion is replaced by a process other than incineration (e.g., gasification or pyrolysis), the corresponding inlet and outlet entropy flow rate must be balanced.

During adiabatic incineration, the major portion of the exergy loss is caused by the difference between the entropy flow rates of discharging hot incineration gas and entering cold air. The entropy of the waste materials is about one magnitude less than this difference (examples: air at 79 °C: 38.9 kJ·kg^{-1}·K^{-1}; waste at 25 °C: 1.8 kJ·kg^{-1}·K^{-1}; flue gas at 1 300 °C: 55.9 kJ·kg^{-1}·K^{-1}).

4.2. Efficiency rates of conversion

An exergetic efficiency rate is defined in order to express nonreversibilities during the conversion process

$$\zeta \equiv 1 - \frac{\dot{E}_V}{\dot{E}_Q}, \tag{5}$$

or

$$\zeta \equiv 1 - \frac{e_{v12}}{e}. \tag{6}$$

The maximum possible value is one, if the exergy loss equals zero, which means that the process takes place in a completely reversible manner. With exergetic analysis, efficiency rates are introduced for the various process steps of waste incineration, which are shown in *figure 5*.

Exergetic efficiency rate of the heat production (incineration):

$$\zeta_{WE} \equiv \eta_C\left(\frac{T_u}{T_m^*}\right)\eta_K \frac{H_u}{e_B}, \tag{7}$$

$\eta_C(T_u/T_m^*)$ means the Carnot factor derived with the mean gas temperature of combustion and η_K as the boiler efficiency rate.

Exergetic efficiency rate of the steam production:

$$\zeta_{DE} \equiv \frac{\eta_C(T_u/T_m)}{\eta_C(T_u/T_m^*)} \tag{8}$$

with $\eta_C(T_u/T_m)$ as the Carnot factor derived with the mean steam temperature of the boiler.

Exergetic efficiency rate of the thermal engine:

$$\zeta_{WKM} \equiv \frac{\eta_{th}}{\eta_C(T_u/T_m^*)} \tag{9}$$

with η_{th} as the thermal efficiency rate of the thermal engine.

The overall exergetic efficiency rate ξ is linked with the partial efficiency rates as follows:

$$\zeta = \zeta_{WE}\zeta_{DE}\zeta_{WKM} = \frac{-P}{\dot{m}_B e_B} \tag{10}$$

with $-P$ as the released electrical or mechanical energy.

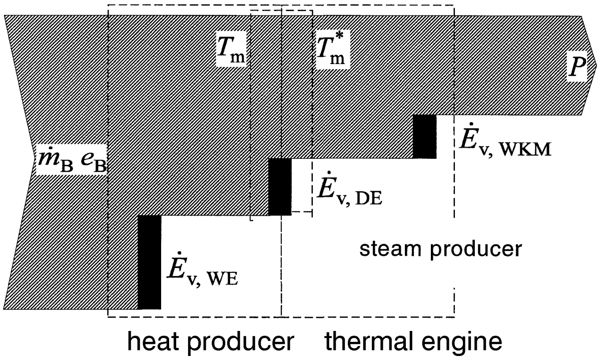


Figure 5. Energy losses during incineration, production of steam and production of electric power [22].

The energetic efficiency rate η is linked to the exergetic efficiency rate via the ratio $e_{\mathrm{B}}/H_{\mathrm{u}}$ described above

$$\eta = \zeta \frac{e_{\mathrm{B}}}{H_{\mathrm{u}}} \tag{11}$$

5. SUMMARY

All basic process-technological operations are suitable for materials conversion and thermal conversion of waste materials of industrial origin.

Recent developments of new processes were concentrated on the specific recovery of certain valuable substances from waste materials by keeping the required energy consumption as low as possible. These processes are preferred to thermal conversion in situations where the obtained substances can be reused in highly pure form as raw materials in the production chain. Treatment processes (thermal and materials conversion) for municipal waste must be evaluated on the basis of environmental and process safety, reusability of the obtained substances and disposal safety of waste residue.

For a thermodynamic based evaluation of treatment processes, exergetic efficiency rates can be defined for various process steps. Municipal waste of typical composition contains about 20 % more chemical energy than can be transformed into thermal energy. This surplus of chemical energy can be recovered only by applying materials conversion instead of thermal conversion.

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