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Classification and evaluation of heat transformation processes

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Abstract — Energy transformation occurs if, in contrast to simple energy conversion, a part of the available energy is transformed into a higher quality. Heat transformation processes are cycles in which the temperature level of at least one heat is raised. They can be categorised as syn- and disproportionation processes and subdivided into several groups depending on the acting potential differences and interactions in the inner of the cycles. From the special viewpoint of transformation, a decomposition of transformation processes into a lift and a drive part is useful for the evaluation of these processes. The introduction of a Carnot lift, i.e. the difference of the Carnot-factors of the lift heat, allows a uniform treatment of all cycles. In addition, it permits a statement about the change of the exergy of the heat due to the transformation effect. Transformation ratio and coefficient of transformation are the ratios of the energy and the exergy of the lift (upvalued) heat as use respectively to the consumed amount in the drive part as expenditure. The three transformation characteristics Carnot-lift, transformation ratio and coefficient of transformation form a thermodynamically consistent model for the evaluation of transformation processes. In contrast to the conventionally used evaluation characteristics of cycles, they lead to unified qualitative and quantitative thermodynamic statements. © Elsevier, Paris.

energy transformation / heat transformation / absorption heat pump / absorption heat transformer / compression heat pump / refrigeration process / thermodynamic evaluation / exergetic evaluation

Résumé — Classification et évaluation des processus de transformation de chaleur. On définit une transformation d'énergie, par opposition à une conversion d'énergie, comme une opération dans laquelle on améliore la qualité de l'énergie. Ainsi, pour l'énergie thermique, une transformation thermique peut être réalisée à partir d'un cycle qui permet d'élever le niveau de température de la chaleur. Les cycles à trois sources présentés dans ce travail sont divisés en deux catégories : les cycles directs ou «synproportionnés» et les cycles indirects ou «disproportionnés». Tous les procédés de transformation de la chaleur comportent deux parties : l'une qui améliore la qualité de la chaleur, l'autre qui, au contraire, la dégrade. Afin de qualifier l'efficacité des différents procédés de transformation d'énergie, on introduit dans ce travail la notion de glissement des facteurs de Carnot, qui correspond à la différence des facteurs de Carnot calculée à partir des températures auxquelles se trouve la chaleur avant et après transformation. Ce paramètre rend compte directement de la variation du contenu exergétique de la chaleur. Le rapport de transformation et le coefficient de transformation sont aussi utilisés. Ils représentent respectivement, d'une part, le rapport de l'énergie à haute température à l'énergie consommée, d'autre part, le rapport de ces mêmes énergies multiplié par l'amélioration du facteur de Carnot. Les trois paramètres de la transformation (glissement du facteur de Carnot, rapport de transformation et coefficient de transformation) permettent une modélisation cohérente pour l'amélioration des procédés de transformation. Par rapport aux paramètres utilisés conventionnellement, ceux-ci conduisent à un traitement à la fois qualitatif et quantitatif. © Elsevier, Paris.

transformation d'énergie / transformation thermique / pompe à chaleur à absorption / transformateur de chaleur à absorption / pompe à chaleur à compression / procédés de réfrigération / évaluation thermodynamique / évaluation exergétique

Nomenclature

e	specific exergy	$\mathrm{J{\cdot}kg^{-1}}$
ΔE_{V}	exergy loss	J
K_{p}	equilibrium constant	
Q	Heat	J
s	Specific entropy	$\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$
T	Temperature	K

Greek symbols

ε	heat ratio. refrigeration ratio

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$\varepsilon_{\mathrm{tr}}$	transformation ratio
η	efficiency
η_{ex}	exergetic efficiency
η_{tr}	coefficient of transformation
τ	carnot-factor
$\Delta\tau$	difference of Carnot-factors

Subscripts

dis	disproportionation
syn	synproportionation
drive	drive part
ex	exergetic
H	high temperature level
hp	heat pump
in	input
lift	upvalued part
M	intermediate temperature level
out	output
rev	reversible
rm	refrigeration machine
th	thermal
Tr	transformation
U	surroundings
use	use, gain
0	low temperature level

1. HEAT TRANSFORMATION AS A SPECIAL CASE OF ENERGY TRANSFORMATION

Energy is found in nature in various forms, both without substance as heat, work, radiation or electrical energy and substance bound as enthalpy or chemical energy in fuels and other chemical compounds. All energy forms are completely or partially convertible into each other. Energy is characterised not only by its quantity but also by a quality. In technics the quality of energy can be defined by the specific exergy (that is the ratio between the exergy of an energy and it's energy) or with the help of the Carnot-factor formed with a thermodynamic middle temperature. For the discussion of energy transformation processes it is useful to describe also the quality of work and chemical energy with the help of thermodynamic temperatures. Work has a specific exergy equal to one so it is equivalent to heat of infinitely high temperature. The chemical energy of substances, e.g. fuels, can be characterised by the temperature of a corresponding reversible combustion reaction with defined equilibrium constant.

Due to the standardisation to the surroundings specific exergy and Carnot-factor have got the character of a potential. Potential differences serve as driving forces for processes and so can be lost owing to irreversibilities. Otherwise it is possible to transform potential differences, that means they can be used to increase a part of energy to a higher potential.

In this sense processes with the only destruction of potential differences are named simply energy conversion processes. Those processes are for instance throttling, heat transfer and mixing. Energy is here devalued from a higher to a lower potential only. Energy transformation occurs if, in contrast to simple energy conversion, a part of the available energy is transformed into a higher quality. Therefore, another part of the energy must be devalued to a correspondingly lower potential in agreement with the Second Law of Thermodynamics.

A desiccation of a hygroscopic dry substance using concentrated sulphuric acid can be considered as a simple example for energy transformation involving chemical processes. In this case the specific exergy of the wet product is increased by the extraction of water and the specific exergy of the sulphuric acid is reduced. By contrast, the extraction of the surface moisture of the same wet product would be a simple energy conversion.

Unfortunately, Alefeld et al. [1] do not distinguish between simply energy conversion processes and energy transformation in his discussion about heat transformation. Both heat transfer—which is only a simple energy conversion—and mechanical transformation processes are titled as energy transformation between two temperature levels. This inaccuracy may be connected with the fact, that he doesn't give any definition of energy transformation.

Heat transformation processes exchange exclusively heat with the surroundings. The quality of all exchanged energies of the process is then characterised by the respective temperature of the heat fluxes. Both the increase and the decrease of potential are reflected in temperature differences between the corresponding two heat fluxes. The use of Carnot factors to characterise the quality of energy allows a clearly arranged system of evaluation. Of course, energy transformation processes with participation of work and chemical energy are at least as interesting as transformation processes with heat interactions only. That is why it is useful to understand heat in the above mentioned extended sense, including work and chemical energy. The wider range of energy transformation processes thus can be considered analogous to heat transformation processes with the only exchange of heat, Hebecker [2]. Heat transformation processes in this extended sense are the basis for the effective production and use of energy sources for the supply of heat, cooling and mechanical energy. Therefore, from a modern perspective, heat transformation is the most essential branch of energy transformation.

The paper aims to give a general definition of energy transformation including work and chemical energy. A classification of energy transformation will be carried out on the basis of different kinds of potential differences. A system of evaluation coefficients should be developed with special regard to the transformation effect.

2. SYN- AND DISPROPORTIONATION OF HEAT

Heat on at least three temperature levels is involved in every heat transformation process. The temperature levels can be characterised by constant or sliding temperatures of the heat sources and sinks. One temperature level can also embody several heat interactions at slightly different temperatures, e.g. absorber and condenser temperatures of an absorption heat pump.

All heat transformation processes can be divided into two general categories [3]:

synproportionation processes receive heat at high and at low temperatures and deliver it at an intermediate temperature;

– disproportionation processes receive heat at an intermediate temperature and deliver heat at higher and at lower temperatures (*figure 1*).

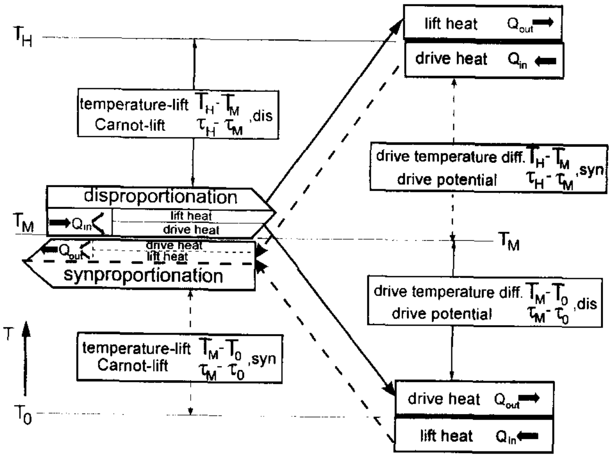

Figure 1. Synproportionation and disproportionation of heat.

In thermodynamics these cycles are often categorized as left-handed or right-handed cycles according to the sequence of the points in the T,s-diagram [4]. However, even a simple exchange of axis renders this definition invalid. In addition, it is only meaningful for processes where work is exchanged with the surroundings because the area inside the curve in the T,s-diagram represents this work. Cycles like absorption heat pumps or steam jet pumps are, in the sense of this classification, a combination of a power producing (right-handed) and a power consuming (left-handed) processes. Therefore it is impossible to assign them to exactly one of the two categories. A complete classification would require the distinction between processes with a left-handed cycle over a right-handed cycle (disproportionation) and processes with a right-handed cycle over a left-handed cycle (synproportionation). A combination of a variety of chemical reactions, as it occurs in thermochemical cycles, evades the classification completely. In contrast to this all thermodynamic cycles can be categorised according to the idea of syn- and disproportionation.

In practice, heat transformation processes are usually accomplished by cycles. Here both closed and open processes are used. In closed cycles only heat and work are exchanged with the external energy sources and sinks. One or more heat fluxes exchanged with the surroundings can have the form of substance bound energy in open cycles, e.g. a supplied fuel or a produced steam flow. The classification of a generic process as open cycle is based on the fact that the substance bound energy exchange in the process is also conceivable as substance free energy exchange in a closed cycle, in which the corresponding subprocess is included. In addition there are more complex, e.g. composite cycles that involve elements of both syn- and disproportionation. An example is the heat pump transformer suggested by Alefeld et al. [5].

Heat transformation processes can operate both continuously and discontinuously. Discontinuous processes are of interest if they have to produce a storage effect at the same time (solar energy), if there is a technological caused periodical heat demand, or in connection with special properties of the working fluid system (application of adsorbents).

3. CLASSIFICATION OF HEAT TRANSFORMING PROCESSES

Heat transformation processes are characterised by a temperature-lift which is the result of the nearly reversible effect of a driving potential—the drive temperature difference. The external behaviour permits a classification with regard to the kind of transformation (syn- or disproportionation).

The technical devices used for the transformation are furthermore based on a multitude of processes and interactions in the interior of the cycles. A system of the extant great variety of those thermodynamic cycles derives from the use of the potential difference in the interior of the process as a basis for classification. The obtained classification is illustrated in *table I*.

It is remarkable that, for the category of sorption- and chemisorption-cycles that both the pressure and physical and chemical bound energy have an influence on the process. Chemical cycles are usually a combination of different chemical reactions for the sole purpose of generating heat at a definite temperature. However the use or the production of a chemical source of energy can be the main or a partial object of transformation processes. In this case it is an open cycle in the extended sense. The production or use of electrical energy or the action of a magnetic field is typical for

TABLE I
Classification of heat transformation processes and examples for syn- and disproportionation.

Inner potentials resulting flux	Kind of cycle	Working fluid peculiarities	Synproportionation			Disproportionation		
			Usable energy	Drive energy	Process example	Usable energy	Drive energy	Process example
Pressure and work mass flux	**Mechanical cycle**	Gas (no phase-change) Steam (phase-change) thermal compression by condensation	Usable heat cooling	Work	Gas/steam-compression-heat pump	Work heat	Heat (combustion or high temperature heat)	Gas-turbine steam-power process CHP station vortex tube
Concentration and pressure; substance flux	**Sorption-cycle**	Two and more component systems with phase-change ab-/adsorption	Usable heat	Heat (combustion or high temperature heat)	ab/ad-chemisorption heat pump and refrigeration machine	Work heat	Heat (combustion or high temperature heat)	ab/ad-chemisorption heat transformer and power process
Chemical potential and pressure; substance flux	**Chemisorption-cycle**	Dissociation–recombination reaction with phase change						
Chemical potentials; substance flux	**Chemical cycle**	Combination of reactions	Heat	Fuels or other chemical compounds	Reversible combustion	Heat or chemical compounds	Heat	Thermo-chemical hydrogen production
Voltage and chemical potential; electrical current	**Electrical cycle**		Cooling	Electrical energy	Peltier-element	Electrical energy	Heat	Photovoltaics thermocouple
Magnetic field strength and pressure; magnetic flux	**Magnetic cycle**							MHD-generator

the electrical and magnetic cycles. Some examples of syn- and disproportionation processes from the above categories of cycles are listed in *table I.*

In general, it is remarkable that refrigeration is provided by synproportionation, because there is practically no potential with lower than ambient temperature to which the heat can be devalued. As a more theoretical case the so-called cooling-increaser process proposed by Nesselmann [6] may be mentioned. It uses the enhancement of the cooling effect by disproportionation if a cold reservoir is available on a lower than required temperature.

In similar way, work can practically be only supplied by disproportionation because no higher potential than work exists. On closer examination this statement is only valid if the drive potential is really heat of a well-defined temperature. It is another matter if a combustion reaction is included in the balance. The exergy of some fuels is higher than its energy (caloric value) and so the production of work with use of synproportionation is possible. For the purpose of transforming fuel exergy completely into work a reversible combustion reaction that includes heat from the surroundings in the process must be realised. This is the process of reversible fuel cell. The practical realised fuel cells are irreversible and due to dissipation they cannot receive heat from the surroundings but have to reject heat to there. Because of this the reversible fuel cell is a synproportionation and the real fuel cell is a simple energy conversion.

4. EFFECT OF TRANSFORMATION: TEMPERATURE-LIFT AND CARNOT- LIFT

The effect of transformation for both the syn- and the disproportionation processes consists in the increase of the temperature level of a heat—the temperature-lift. In case of synproportionation this temperature-lift

TABLE II
Temperatures of usable heat and transformation effect for several transformation processes.

	Temperature of usable heat (T_{use})	Temperature-lift transformation effect	Carnot-lift $\Delta\tau_{\mathrm{lift}}$
Compression heat pump	350 K	10–50 K	0.07–0.14
Absorption heat pump	400 K	30–100 K	0.06–0.25
Adsorption heat pump	450 K	30–150 K	0.05–0.33
Vortex tube	350 K	10–20 K	0.025–0.1
Steam jet apparatus	350 K	50 K	0.14
Thermochemical hydrogen production	5 400 K	4 000 K	0.14
Steam power process		$\infty - T_{\mathrm{M}}\ T_{\mathrm{M}} = 600$ K	0.5
MHD-generator	∞ (work)	$\infty - T_{\mathrm{M}}\ T_{\mathrm{M}} = 2\,500$ K	0.25
Photovoltaics		$\infty - T_{\mathrm{M}}\ T_{\mathrm{M}} = 6\,000$ K	0.075

occurs from the lower to the intermediate temperature level, in the case of disproportionation, correspondingly, from intermediate to the upper temperature level.

Table II shows some temperatures of usable heat and temperature-lifts for selected transformation processes as examples. For chemical energy sources the temperature of a reversible reaction can be defined as equivalent temperature of usable heat. For this, the equilibrium constant must be fixed. Often the equilibrium constant $K(T) = 1$ is used because in this case the partial pressures of reactants and products are of the same order.

The utilisation of the Carnot-factor is of special interest for the important class of transformation processes rejecting or consuming work. The Carnot-factor

$$\tau = \frac{T - T_{\mathrm{U}}}{T} = \frac{\Delta E}{Q} \qquad (1)$$

indicates the exergy of heat in relation to the heat itself. Accordingly, it depends exclusively on the temperature of the heat source or sink if the surroundings are fixed[1]. So the Carnot-factor is, just like the temperature, a definite characteristic of the quality of heat. However, it has, in contrast to the temperature, two essential advantages. Firstly, a linear relation exists between Carnot-factor and the quality of heat. Secondly work with $\tau = 1$ can be included in the considerations without the need to take a limit at $T \to \infty$. The Carnot-factor is a non-linear exergetic scale for the temperature and therefore, it is meaningful to introduce, in addition to the temperature-lift a Carnot-lift $\Delta\tau_{\mathrm{lift}}$ as characteristic for the evaluation of the transformation processes.

The Carnot-lift represents the change of quality of the lift heat, i.e., the increase of availability of work due to the transformation effect. So the information contained in the Carnot-lift goes beyond the one of the temperature-lift. The change of availability of work is caused not only by the temperature difference, the heat being lifted, but also by the relation to the ambient temperature. The evaluation with the Carnot-lift delivers a completely different impression than the comparison based on temperature-lift (*table II*). For instance, the temperature of the generated heat could be 4 000 K higher than the one of the consumed heat in a system of thermochemical reactions producing hydrogen. Due to the very high overall temperature level, however, the change of heat exergy is not higher than the one occurring in the case of the upvaluation of ambient heat in an ordinary compression heat pump. Similarly, this applies to the MHD-generator, where high temperature heat is upvalued to work. From the exergetic point of view that is reflected in the Carnot-factor scale, this is only a small upvaluation of this heat. This situation is typical for all transformation processes working far away from ambient temperature.

The drive potential of transformation processes which is required according to the Second Law can be described also as a difference of the Carnot-factors. With this difference of Carnot-factors, it is possible to quantify the drive potential of a compression heat pump although the drive temperature difference is infinite. For synproportionation processes the drive-potential follows from the difference between high and intermediate temperature. For disproportionation processes, it is the temperature difference between intermediate and low temperature. The use of the Carnot-factors and their differences allow a unified and quantitative description and evaluation of all transformation processes. The Carnot-factors characterise the concerned temperature levels and the differences between Carnot-factors (Carnot-lift $\Delta\tau_{\mathrm{lift}}$ and Carnot-drive $\Delta\tau_{\mathrm{drive}}$) are exergetic characteristics of the corresponding potential differences.

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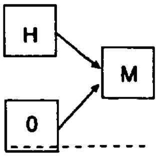
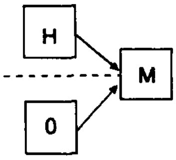
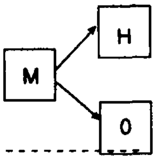
[1] Thus the Carnot-factor differs fundamentally from the Carnot-efficiency $\eta_{\mathrm{C}} = \dfrac{T_{\max} - T_{\min}}{T_{\max}}$ that describes a cycle and depends from the process temperatures $T_{\min}$ and $T_{\max}$.

TABLE III
Energetic and exergetic coefficients of evaluation of heat transformation processes.

	Synproportionation		Disproportionation
	Heat pump (hp)	Refrigeration machine (rm)	
			
Conventional energetic coefficients (with $\Delta E_V = 0$: $\varepsilon_{\dots,\mathrm{rev}}$)	heat ratio $\varepsilon_{\mathrm{hp}} = \frac{Q_M}{Q_H} = \frac{Q_{\mathrm{lift}} + Q_{\mathrm{drive}}}{Q_{\mathrm{drive}}}$ $= \left(\frac{\tau_H - \tau_0}{\tau_M - \tau_0}\right)$	refrigeration ratio $\varepsilon_{\mathrm{rm}} = \frac{Q_0}{Q_H} = \frac{Q_{\mathrm{lift}}}{Q_{\mathrm{drive}}}$ $= \left(\frac{\tau_H - \tau_M}{\tau_M - \tau_0}\right)$	coefficient of performance (COP) $\eta_{\mathrm{th}} = \varepsilon_{\mathrm{Dis}} = \frac{Q_H}{Q_M} = \frac{Q_{\mathrm{lift}}}{Q_{\mathrm{lift}} + Q_{\mathrm{drive}}}$ $= \left(\frac{\tau_M - \tau_0}{\tau_H - \tau_0}\right)$
Transformation ratio (with $\Delta E_V = 0$: $\varepsilon_{\mathrm{Tr,rev}}$)	$\varepsilon_{\mathrm{Tr}} = \frac{Q_{\mathrm{lift}}}{Q_{\mathrm{drive}}} = \left(\frac{\Delta\tau_{\mathrm{drive}}}{\Delta\tau_{\mathrm{lift}}}\right)$		
Relation between $\varepsilon_{\mathrm{Tr}}$ and ε	$\varepsilon_{\mathrm{Tr}} = \varepsilon_{\mathrm{hp}} - 1$	$\varepsilon_{\mathrm{Tr}} = \varepsilon_{\mathrm{rm}}$	$\varepsilon_{\mathrm{Tr}} = \frac{\varepsilon_{\mathrm{Dis}}}{1 - \varepsilon_{\mathrm{Dis}}}$
Exergetic efficiency	$\eta_{\mathrm{ex,hp}} = \frac{\tau_M Q_M}{\tau_H Q_H}$ $= \frac{\varepsilon_{\mathrm{hp}}}{\varepsilon_{\mathrm{hp,rev}}} \quad (\tau_0 = 0)$	$\eta_{\mathrm{ex,rm}} = \frac{\tau_0 Q_0}{\tau_H Q_H}$ $= \frac{\varepsilon_{\mathrm{rm}}}{\varepsilon_{\mathrm{rm,rev}}} \quad (\tau_M = 0)$	$\eta_{\mathrm{ex.Dis}} = \frac{\tau_H Q_H}{\tau_M Q_M}$ $= \frac{\varepsilon_{\mathrm{Dis}}}{\varepsilon_{\mathrm{Dis.rev}}} \quad (\tau_0 = 0)$
Coefficient of transformation	$\eta_{\mathrm{Tr}} = \frac{\Delta\tau_{\mathrm{lift}}\, Q_{\mathrm{lift}}}{\Delta\tau_{\mathrm{drive}}\, Q_{\mathrm{drive}}} = \frac{\varepsilon_{\mathrm{Tr}}}{\varepsilon_{\mathrm{Tr,rev}}}$		

5. TRANSFORMATION RATIO. ENERGETIC EVALUATION

In the sense of a homogeneous evaluation of syn- and disproportionation processes from the viewpoint of transformation, it is suitable to use the categories drive and lift not only for the temperature differences but also for the thermodynamic evaluation. From this the subdivision in drive-heat and lift-heat indicated in *figure 1* follows. For synproportionation processes the delivered heat is the sum of drive and lift-heat and for disproportionation processes the consumed heat equals this sum.

The transformation ratio $\varepsilon_{\mathrm{Tr}}$ should be established as an energetic characteristic. It describes the analogue of the usual coefficient of performance (COP), the ratio between desired energetic output to the energetic input. In the special sense of transformation the transformation ratio defines the lift-heat as desired output and it defines the drive-heat only as input deviating from conventional COP. Therefore the reference temperature level is always the intermediate temperature. The conventional evaluation of right- and left-handed processes uses various evaluation bases and characteristics (*table III*).

Heat pumps

For heat pumps, one uses the ratio between supplied intermediate temperature heat and consumed high temperature heat, which is called coefficient of performance (COP) for compression heat pumps and, correspondingly, heat ratio for absorption heat pumps. So, the process use contains not only the lifted low temperature heat but also the consumed and then devalued high temperature drive-heat. The reference temperature is the low temperature that is often equated with the ambient temperature.

Refrigeration machines

For refrigeration machines, the ratio of cooling effect and the required work or high temperature heat input is used as coefficient of performance or heat ratio.

Due to the heat rejection to the surroundings, which is often assumed, the reference temperature is the intermediate temperature. This relation compares the upvalued and the devalued heat and thus equals the proposed transformation ratio.

Disproportionation processes

In the case of disproportionation processes, the thermal efficiency as an energetic characteristic for power processes and the heat ratio for heat transformers in a special sense is used. The supplied high temperature heat or work is set in relationship to the consumed heat of intermediate temperature. This evaluation also differs from the transformation ratio defined above, because not only the drive-heat, but also the complete intermediate temperature heat is counted as expenditure. So the fact that the latter use–the supplied work–is received already with a considerable amount of exergy is disregarded.

The energetic characteristics follow from the exergy balance, written down in [equation (2)] for a disproportionation process, under assumption of reversible behaviour, that means $\mathrm{D}\Delta E_\mathrm{V} = 0$.

$$\frac{T_\mathrm{M} - T_\mathrm{U}}{T_\mathrm{M}} Q_\mathrm{M} = \frac{T_\mathrm{H} - T_\mathrm{U}}{T_\mathrm{H}} Q_\mathrm{H} + \frac{T_0 - T_\mathrm{U}}{T_0} Q_0 + \Delta E_\mathrm{V} \quad (2)$$

At present, one heat interaction for each process is substituted with use of the energy balance and another reversible heat ratio is defined for each of the three different cycles. In contrast to this, the transformation ratio defined above is the same for both syn- and disproportionation and leads to

$$\varepsilon_\mathrm{Tr} = \frac{Q_\mathrm{lift}}{Q_\mathrm{drive}} \quad (3)$$

In case of reversible processes it can be expressed as a function of temperature differences

$$\varepsilon_\mathrm{Tr,rev} = \frac{Q_\mathrm{lift}}{Q_\mathrm{drive}} = \frac{\Delta\tau_\mathrm{drive}}{\Delta\tau_\mathrm{lift}} \quad (4)$$

In *table III* the expressions concerned are written in brackets. In contrast to the conventional energetic coefficients mentioned above, the transformation ratio delivers uniformly for all processes values between $0 < \varepsilon_\mathrm{Tr} < \infty$. $\varepsilon_\mathrm{Tr} = 0$ represents the case without drive potential and $\varepsilon_\mathrm{Tr} = \infty$ stands for a process without temperature-lift.

The numerical values of the transformation ratio and the conventional characteristics are different for a specific process. However, they can be easily transformed one into the other (*table III*). The comparison of the heat ratios for absorption heat pumps and transformers in the special sense offers a good example for the generalisation of evaluation by the use of the transformation ratio. For a rough estimation, the heat converted in each apparatus of these absorption devices is often assumed to be equal. In that case, the evaluation gives the value two for the heat ratio of heat-pumps and the value 1/2 for the heat ratio of heat-transformers. The transformation ratio is, however, equal to one for both processes due to the same heat being upvalued and devalued.

6. T,T AND τ,τ-DIAGRAM

The reversible heat ratio depends on the three characteristic temperature levels if the ambient temperature is constant. Transformation processes often transfer heat from or to the surroundings, so it is helpful to identify one temperature level with the ambient temperature for a reversible view of thermodynamic cycles. The whole of transformation processes can be plotted in a $T_\mathrm{in}, T_\mathrm{use}$-diagram ($T_\mathrm{in}$ denotes the temperature of the input-heat, T_use the temperature of the usable heat).

Figure 2, for example, represents on the right half of the diagram the reversible (i.e. maximally attainable) heat ratios for cycles operating above the ambient temperature. Point ① corresponds to a absorption heat pump that lifts heat from 300 to 360 K and point ② corresponds to a heat transformer lifting half of waste heat from 360 K to a usable temperature of 450 K. The actually attainable heat ratios differ from these ones shown in the diagram represented by the exergetic efficiency $\varepsilon_\mathrm{real} = \varepsilon\eta_\mathrm{ex}$. A compression heat pump (③) and a power-process (④)are also shown.

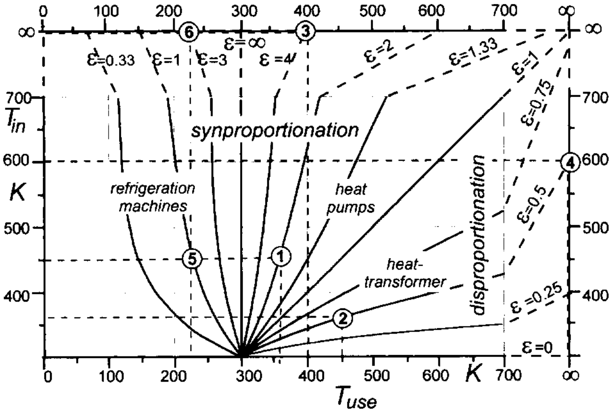


Figure 2. $T_\mathrm{in}, T_\mathrm{use}$-diagram for syn- and disproportionation processes. ① absorption heat pump, ② absorption heat transformer, ③ compression heat pump, ④ power process, ⑤ absorption refrigeration process, ⑥ vapour compression-refrigeration process.

The maximally attainable COP's of reversible refrigeration processes (e.g. absorption refrigeration machine ⑤ and vapour compression refrigeration process ⑥) are given in the left side of *figure 2*. T_{use} is the refrigeration temperature in this case. Those processes reject the heat at intermediate temperature which is assumed to be equal to the ambient temperature for the reversible view. The curves show a non-linear dependence of exergy of heat on the temperature which is even stronger than for processes above ambient temperature. The compact and clear presentation in the T_{in}, T_{use}-diagram has the disadvantage that both axes go to infinity and that interpolations for the heat ratio are difficult due to the non-linear relation between the temperatures and the heat ratio.

Using the Carnot-factors instead of the temperatures, i.e., using a non-linear temperature scale, both disadvantages are removed without significantly reducing the clearness of representation (*figure 3*). The Carnot-factor becomes negative below ambient temperature and the abscissa goes to infinity if the refrigeration temperature approaches absolute zero. The chosen limit at $\tau_0 = -1$ corresponds to a temperature of 150 K, for an ambient temperature $T_U = 300$ K. This temperature range contains a large part of technically interesting refrigeration processes, in other cases the coordinate can be prolonged arbitrarily.

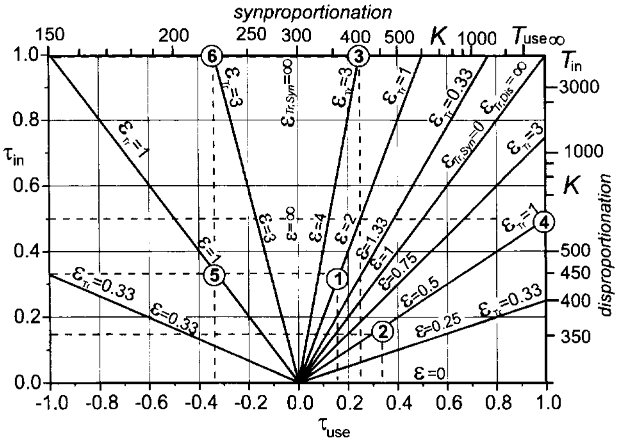


Figure 3. τ_{in}, τ_{use}-diagram for syn- and disproportionation processes.

A comparison of the heat and refrigeration ratio in the τ_{in}, τ_{use}-diagram shows equal ε- values at equal absolute τ-values. This surprise is due to the different definition of heat and refrigeration ratio. This is connected with the fact that for processes above and under ambient temperature another temperature level is equal to ambient temperature, and therefore, several reference states are used. The use of intermediate temperature as reference temperature, as is usual for refrigeration processes, corresponds to the idea of transformation due to the subdivision in drive and lift potential (see § 5). Therefore, the coordinates used may be interpreted as Carnot-lift or Carnot-drive by adding or subtracting τ_M which equals to zero in this case.

$$\tau_{use} = -\tau_0 = \tau_M - \tau_0 = \Delta\tau_{lift}$$
$$\tau_{in} = \tau_H = \tau_H - \tau_M = \Delta\tau_{drive} \qquad (5)$$

This fact is of special importance for the following generalised consideration.

7. $\Delta\tau_{drive}$-$\Delta\tau_{lift}$-DIAGRAM

In the above shown diagrams, only included are those processes in which one temperature level is equal to the ambient temperature. However a variety of interesting transformation processes exist for which this is not the case, e.g. the cogeneration of heat and power or the coupling of heat and refrigeration processes with absorption or compression devices. For such processes, it is meaningful to find a comparative graphic representation in which all temperatures can be varied. The reference axes of such a diagram are drive potential and temperature-lift (*figure 4*). This representation is connected with the change from the process orientated τ_{in} and τ_{use} to the potential orientated τ_M and τ_H.

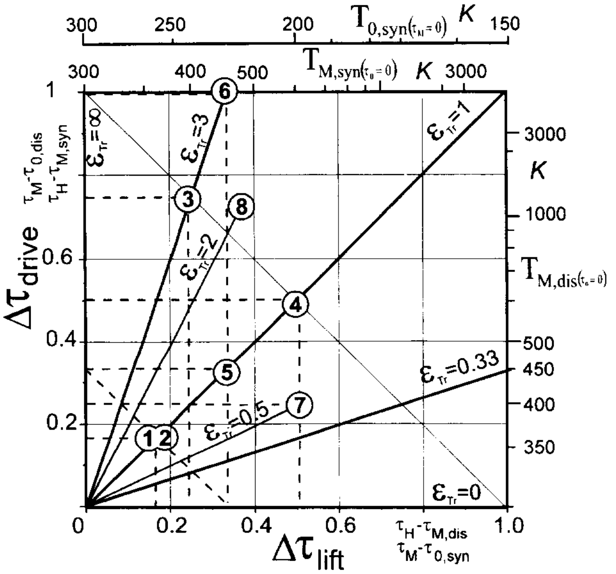


Figure 4. $\Delta\tau_{drive}$, $\Delta\tau_{lift}$-diagram for syn and disproportionation processes, points see *figure 2*; ⑦ combined heat and power process; ⑧ coupling of heating and refrigeration.

In this diagram the gradient represents the transformation ratio defined above. The drive potential, i.e. the difference of the Carnot-factors between intermediate and low temperature level $\tau_{\mathrm{M}} - \tau_0$ for disproportionation processes and the difference between high and intermediate temperature level $\tau_{\mathrm{H}} - \tau_{\mathrm{M}}$ for synproportionation processes is shown on the ordinate axis. Analogously the temperature-lift ($\tau_{\mathrm{H}} - \tau_{\mathrm{M}}$ for dis- and $\tau_{\mathrm{M}} - \tau_0$ for synproportionation) on the abscissa is used. Such a representation illustrates that the cycles are the same if the temperatures are the same, and their heat ratios are reciprocal due to the different definition of use and expenditure.

Using this definition the lines of constant gradient characterise equal transformation ratios and permit a comparison of energetic efficiency of syn- and disproportionation processes at the same evaluation scale. In *figure 4*, the cogeneration of heat and power (⑦) and a coupling of heating and refrigeration (⑧) are indicated as examples for a disproportionation and a synproportionation respectively. From the figure, one can see that the Carnot-lift of refrigeration processes is bigger than the Carnot-factor of intermediate temperature level due to the negative Carnot-factors below ambient temperature. The diagram is suitable to show the expected reversible transformation ratio if the temperatures of drive and lift heat are known. The transformation ratio is easy to determine due to the agreement with the gradient. Moreover, the necessary drive potential or the possible temperature-lift can be determined with help of the diagram for a given transformation ratio.

The diagonal between $\Delta\tau_{\mathrm{lift}} = 1$ and $\Delta\tau_{\mathrm{drive}} = 1$ forms the boundary for possible processes with consumption or production of work for all processes with a low temperature level above ambient temperature. In all these cases is $\tau_{\mathrm{H}} = 1$ and the diagonal then represents just the function $1 - \tau_{\mathrm{M}}$ for the assumed case $\tau_0 = 0$. Points above this diagonal are only meaningful for processes with participation of heat below ambient temperature. The vapour compression refrigeration machines lie on the line $\Delta\tau_{\mathrm{drive}} = 1$, provided that the temperature of heat rejection again agrees to $\tau_{\mathrm{M}} = 0$. All transformation processes can be represented in the $\Delta\tau_{\mathrm{drive}} - \Delta\tau_{\mathrm{lift}}$-diagram.

8. COEFFICIENT OF TRANSFORMATION AND EXERGETIC EVALUATION

A characteristic for exergetic efficiency which considers the peculiarities of transformation processes can be specified, analogue to the transformation ratio. The coefficient of transformation η_{Tr} shall be defined as the counterpart to the exergetic efficiency η_{ex} used conventionally for exergetic evaluation of cycles. The coefficient of transformation indicates the ratio of exergetic gain of the transformation (the exergy change of the lift heat) and exergetic expenditure (the exergy change of the drive heat).

$$\eta_{\mathrm{Tr}} = \frac{\Delta\tau_{\mathrm{lift}}}{\Delta\tau_{\mathrm{drive}}}\,\frac{Q_{\mathrm{lift}}}{Q_{\mathrm{drive}}} = \frac{\varepsilon_{\mathrm{Tr}}}{\varepsilon_{\mathrm{Tr,\,rev}}} \qquad (6)$$

This ratio goes to zero for processes in which no transformation is realised because heat is not lifted to a higher temperature level. Therefore, it reflects the qualitative and quantitative aspects of the process. In the above case a transformation process degenerates into a simple energy conversion process. The exergetic efficiency η_{ex} in the conventional sense treats the exergy of devalued drive energy as use. Therefore the efficiency differs from zero even for processes where no transformation occurs. With the coefficient of transformation, a scale is introduced which allows the distinction of transformation processes and simple energy conversions or heat transfer processes.

The coefficient of transformation can be attributed to the transformation ratio without additional restrictions, i.e., without the identification of any temperature level with the surroundings. For the exergetic efficiency this simple coherence is lost in this case.

The quantitative difference between exergetic efficiency and coefficient of transformation is illustrated in *figure 5*. Here, the characteristics of compression heat pump cycles with equal reversible heat ratios or transformation ratios at various temperatures of usable heat are shown. The deviations of the results amount to up to 40 % in the real working range of compression heat pumps. From the viewpoint of transformation the exergetic efficiency gives too high values because a part of the expenditure, namely the required drive heat (work), is included in the gain.

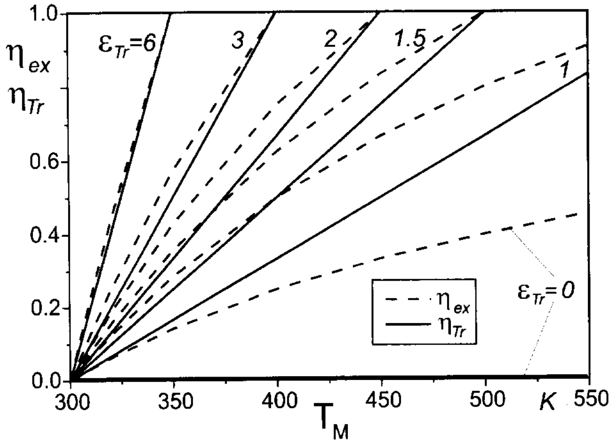


Figure 5. Coefficient of transformation and exergetic efficiency of compression heat pump cycles as a function of transformation ratio.

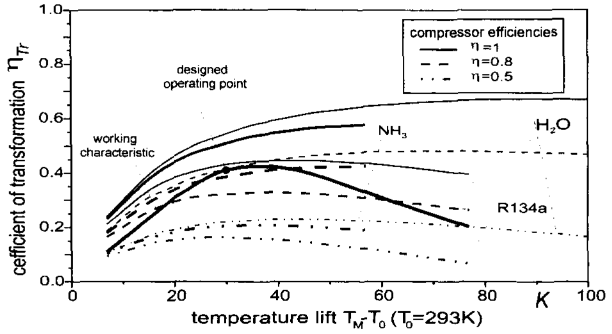


Figure 6. Coefficient of transformation of compression heat pump cycles with different working fluids as a function of temperature lift and influence of compressor working characteristic ($\Delta T_{\min} = 10$ K in condenser and evaporator).

The coefficient of transformation of real compression heat pump cycles depends, besides the temperature-lift, also on the used working fluid, the temperature differences necessary for heat transfer and the efficiency of the compressor. In *figure 6*, the coefficients of transformation of real compression heat pump cycles are represented for three different working fluids with extreme values of evaporation enthalpies. The evaporation enthalpy is the property which has the largest influence on the transformation process. The minimal temperature differences for heat transfer were assumed to be 10 K in both vaporiser and condenser. The efficiency of the compressor that was taken into account is mainly determined by the type of machine. The bandwidth of the efficiency extends from 0.9 for high-quality screw compressor till to approximately 0.35 for liquid ring compressors. As expected, large evaporation enthalpies and high efficiency of compressors affect the coefficient of transformation favourably.

Besides of the construction, the efficiency of the compressor is mainly influenced by its operating point. Therefore, a variation of waste heat temperature, which is the same as a change of temperature-lift, has a significant influence on the process efficiency. *Figure 6* shows this influence for a compression heat pump cycle with water as working fluid and a maximal compressor efficiency of 0.8. A decrease of the heat source temperature causes an encase of temperature-lift, an increase of necessary compression ratio and therefore causes the increase of power consumption of the compressor. Finally, if the heat ratio decreases, the efficiency of the compressor decreases simultaneously, leading to a further deterioration of the process. As a result of the falling compression ratio, i.e. increasing waste heat temperature, the coefficient of transformation decreases in spite of a slight improvement in the heat ratio due to the steep fall of the compressor characteristic. This means that every deviation from the design data leads to a reduction of the effectiveness of the compression heat pump process.

9. CONCLUSION

Energy transformation occurs if, in contrast to simple energy conversion, a part of the available energy is transformed into a higher quality. For the discussion of energy transformation processes it is useful to describe also the quality of work and chemical energy with the help of thermodynamic temperatures. Work is equivalent to heat of infinitely high temperature. The chemical energy of substances can be characterised by the temperature of a corresponding combustion reaction. Heat transformation processes can be categorised as syn- and disproportionation processes. Synproportionation processes receive heat at high and at low temperatures and deliver it at an intermediate temperature. Disproportionation processes receive heat at an intermediate temperature and deliver heat at higher and at lower temperatures. According to the idea of syn- and disproportionation all thermodynamic cycles can be categorised, regardless of the variety of interactions and potential differences in the inner of the cycles.

From the viewpoint of evaluation it is meaningful to use special transformation characteristics for transformation processes. The three transformation characteristics introduced here, Carnot-lift, transformation ratio and coefficient of transformation permit a comparison of energetic and exergetic efficiency of syn- and disproportionation processes at the same evaluation scale.

The Carnot lift, i.e. the difference of the Carnot-factors of the lift heat, allows a statement about the change of the exergy of the heat due to the transformation effect. Transformation ratio and coefficient of transformation are the ratios of the energy and the exergy of the lift heat as used respectively, to the consumed amount in the drive part as expenditure.

In contrast to the conventionally used evaluation characteristics of cycles, the used evaluation characteristics lead to unified qualitative and quantitative thermodynamic statements.

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