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EXERGY IN TECHNOLOGICAL HEAT EXCHANGE PROCESSES

EXERGIE V TECHNOLOGICKÝCH PROCESECH VÝMĚNY TEPLA

**Abstract**

The exergy concept applied to technological heat exchange processes has been presented and discussed in detail. The special behavior of the thermal parts of the exergy flows could be stated once more and applied to formulate the thermodynamic transition formula and hence the generalized exergy rating quotient, then thermodynamic effectivity. All possible exergy rating quotients have been tested to prove their advantages and disadvantages. The appropriate discussion led to the statement that just the proposed thermodynamic effectivity quotient is a very promising way of solving the problem of complex system thermodynamic analysis. The considerations presented are the base for generalized analysis and rating of substance change processes.

**Abstrakt**

V článku je exaktně popsána exergetická koncepce v technologických procesech výměny tepla. Zvláštní chování tepelné části toku exergie by mohlo být uvedeno ještě jednou a použito na formulaci termodynamické rovnice pro přenos, zobecněný exergetický kvocient a pak pro určení termodynamické efektivity. Všechny možné zhodnocovací exergetické kvocienty byly testovány za účelem prokázání jejich výhod a nevýhod. Vhodná diskuse vedla k tvrzení, že navrhovaný kvocient termodynamické efektivity je velmi slibný způsob řešení problému termodynamické analýzy komplexního systému. Předložené úvahy jsou základem pro všeobecné analýzy a hodnocení procesů změny látky.

**1 INTRODUCTION**

In power engineering and especially in process & chemical engineering systems the very important processes are the so-called technological exchange unit operations. They are the heat and substance (mass) transfer phenomena applied to achieve certain temperatures and/or chosen specie concentrations. Thus, the technological exchange processes can be parted into three main groups due to their goal in the engineering practice. They are: heat exchange, heating up (or cooling down), drying (wetting) and absorption. The first group is the most important in every engineering branch and hitherto very good described and analyzed from the thermodynamics point of view. Drying and absorption, however, are not that widely known and applied in thermodynamic analyzes, especially using the *Second Law* and the exergy method. The goal of investigations (the presented contribution is a part of them) led within the project is the universal (or generalized) method of modeling and exergy analysis of main processes that can be used for building whole complex systems modeled, analyzed and rated in the same way. The homogeneity of the proposed approach is its main advantage and the right use of the exergy method, which allows analyzes taking into account not only *First Law* (balancing), but also *Second Law* (process run possibility) and the natural environment with constant intensities during the time of analysis. The following discussion is dedicated to the generalized exergy analysis and rating of technological heat exchange processes with the so-called thermodynamic effectivity quotient.

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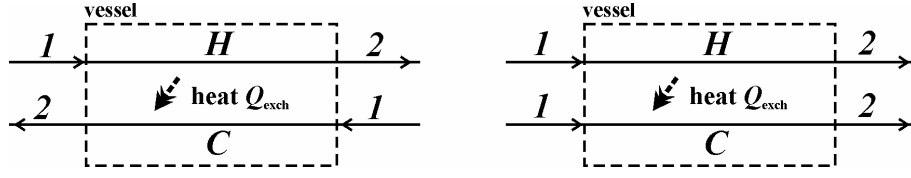
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## 2 TECHNOLOGICAL HEAT EXCHANGE PROCESSES

The technological heat exchange processes run in counter-current and concurrent vessels. For the following analyzes evaporation and thermal thickening as in fact separation processes will be excluded. The heat exchange two main cases are presented in Figure 1. The subscript  $H$  points to the hot medium and the subscript  $C$  to the cold one. The exchanged heat  $Q$  is presented as  $Q_{\text{exch}}$ . The energy (heat) balance of processes presented schematically in Figure 1 for an adiabatic-isobaric (phase changes excluded) vessel is

$$n_H \bar{c}_{p,H} (T_{H,2} - T_{H,1}) + n_C \bar{c}_{p,C} (T_{C,2} - T_{C,1}) = 0$$



**Fig. 1** Technological heat exchange in a vessel (apparatus): case counter-current (*to the left*) and concurrent (*to the right*) flow

### 2.1 Process Irreversibilities via Exergy Concept

The technological heat exchange between the hot (subscript  $H$ ) and the cold (subscript  $C$ ) medium takes place in an adiabatic apparatus (no heat losses to the surroundings) and their start (subscript  $1$ ) and end (subscript  $2$ ) temperatures are  $T_{1H}$ ,  $T_{2H}$ ,  $T_{1C}$ ,  $T_{2C}$ , respectively. The heat exchanging media are perfect gases for simplicity. For the process the exergy balance can be written down as

$$E_{1,H} + E_{1,C} = E_{2,H} + E_{2,C} + T_0 \Delta S_{\text{irr}} \quad \text{or} \quad -\Delta E_{1,H} - \Delta E_{1,C} = T_0 \Delta S_{\text{irr}} \quad (01)$$

where

$$\Delta E_{1,H} = \Delta I_H - T_0 \Delta S_H \quad \text{and} \quad \Delta E_{1,C} = \Delta I_C - T_0 \Delta S_C$$

From the known thermodynamic equations for the perfect gas in an isobaric process it becomes

$$\Delta E_{1,H} = n_H \bar{c}_{p,H} (T_{1H} - T_{2H}) - n_H \bar{c}_{p,H} T_0 \ln \frac{T_{1H}}{T_{2H}}$$

and

$$\Delta E_{1,C} = n_C \bar{c}_{p,H} (T_{1C} - T_{2C}) - n_C \bar{c}_{p,H} T_0 \ln \frac{T_{1C}}{T_{2C}}$$

or setting for simplicity  $n_H = n_C$  and  $\bar{c}_{p,H} = \bar{c}_{p,C}$

$$\Delta E_{1,H} = n \bar{c}_p (T_{1H} - T_{2H}) - n \bar{c}_p T_0 \ln \frac{T_{1H}}{T_{2H}} \quad \text{and} \quad \Delta E_{1,C} = n \bar{c}_p (T_{1C} - T_{2C}) - n \bar{c}_p T_0 \ln \frac{T_{1C}}{T_{2C}}$$

From Equation (01) the irreversible entropy production  $\Delta S_{\text{irr}}$  in the technological heat exchange process will be to

$$\Delta S_{\text{irr}} = -\frac{\Delta E_{1,H} + \Delta E_{1,C}}{T_0} = -\frac{n \bar{c}_p (T_{1H} - T_{2H}) - n \bar{c}_p T_0 \ln \frac{T_{1H}}{T_{2H}} + n \bar{c}_p (T_{1C} - T_{2C}) - n \bar{c}_p T_0 \ln \frac{T_{1C}}{T_{2C}}}{T_0}$$

According to the *Second Law* the last formula should deliver a positive numerical result, i.e. greater than one. Because the temperature of the natural environment  $T_0$  is always greater than zero, either, the (dimensionless) equation

$$\frac{\Delta S_{\text{irr}}}{n\bar{c}_p} = -\frac{(T_{1\text{H}} - T_{2\text{H}}) - T_0 \ln \frac{T_{1\text{H}}}{T_{2\text{H}}} + (T_{1\text{C}} - T_{2\text{C}}) - T_0 \ln \frac{T_{1\text{C}}}{T_{2\text{C}}}}{T_0} > 0 \quad (02)$$

should give a positive numerical value. It will be proved in following, if it is always the case. The problem is, however, the too many variables in the equation. To reduce them every temperature will be referred to the natural environment temperature  $T_0$ , i.e. with  $\tau = T/T_0$  can be stated, if the temperature is higher ( $\tau > 1$ ) or less ( $\tau < 1$ ) than  $T_0$ . Hence, Equation (02) will be to

$$\frac{\Delta S_{\text{irr}}}{n\bar{c}_p} = (\tau_{1\text{H}} - \tau_{2\text{H}}) - \ln \frac{\tau_{1\text{H}}}{\tau_{2\text{H}}} + (\tau_{1\text{C}} - \tau_{2\text{C}}) - \ln \frac{\tau_{1\text{C}}}{\tau_{2\text{C}}}$$

The next modification that can reduce the number of four variables can be the use of the so-called thermodynamic mean temperature difference  $\Delta T_m$ , (it is not the same as the LMTD: mean logarithmic one applied in dimensioning the apparatus):

$$\Delta T_m = \Delta T_{\text{mH}} - \Delta T_{\text{mC}} = \frac{T_{1\text{H}} - T_{2\text{H}}}{\ln \frac{T_{1\text{H}}}{T_{2\text{H}}}} - \frac{T_{2\text{C}} - T_{1\text{C}}}{\ln \frac{T_{2\text{C}}}{T_{1\text{C}}}}$$

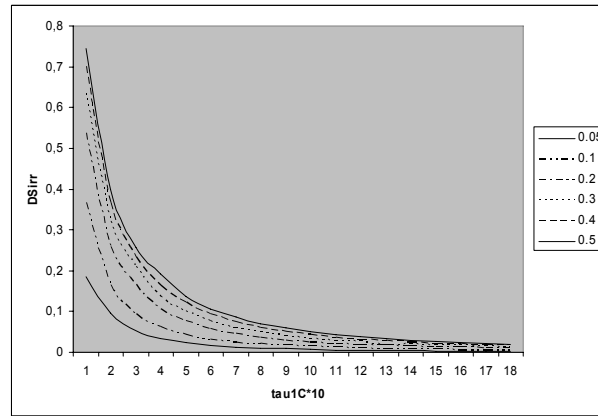
or in a dimensionless form

$$\Delta \tau_m = \frac{\tau_{1\text{H}} - \tau_{2\text{H}}}{\ln \frac{\tau_{1\text{H}}}{\tau_{2\text{H}}}} - \frac{\tau_{2\text{C}} - \tau_{1\text{C}}}{\ln \frac{\tau_{2\text{C}}}{\tau_{1\text{C}}}} = \frac{\Delta \tau_{\text{H}}}{\tau_{1\text{H}} - \Delta \tau_{\text{H}}} - \frac{\Delta \tau_{\text{C}}}{\ln \frac{\tau_{1\text{C}} + \Delta \tau_{\text{C}}}{\tau_{1\text{C}}}} \quad (= \Delta v)$$

In the technological heat exchange process the lowest temperature is the temperature of the cold medium before the process has started, i.e.  $T_{1\text{C}}$  or  $\tau_{1\text{C}}$ . Additional simplification can be made by giving the temperature change of the medium in the process. E.g. setting  $T_{2\text{H}} - T_{1\text{H}} = 50$  K (i.e. with  $n_{\text{H}} = n_{\text{C}}$  gives  $T_{2\text{C}} - T_{1\text{C}} = 50$  K, either) the above expression will be only a function of  $\tau_{1\text{C}}$  with  $\Delta \tau_m$  as a parameter, i.e.

$$\frac{\Delta S_{\text{irr}}}{n\bar{c}_p} = (\tau_{1\text{H}} - \tau_{2\text{H}}) - \ln \frac{\tau_{1\text{H}}}{\tau_{2\text{H}}} + (\tau_{1\text{C}} - \tau_{2\text{C}}) - \ln \frac{\tau_{1\text{C}}}{\tau_{2\text{C}}} = f(\tau_{1\text{C}}, \Delta \tau_m)$$

and can be eventually presented in Figure 2. Calculations have been made setting  $T_0 = 290$  K.



**Fig. 2** Irreversibilities  $\Delta S_{\text{irr}}$  ( $DS_{\text{irr}}$ ) in a counter-current technological heat exchange as a function of the lowest temperature in a process  $\tau_{1\text{C}}$  (start temperature of the cold medium  $\tau_{1\text{C}}$ ) with  $\Delta \tau_m$  from 0.05 through 0.5 as a parameter

### 3 EXERGY RATING

With Equation (01) the exergy rating quotient according to Eq.(21) in [1] will be

$$\eta_{\text{HC,ex}}^* = \frac{E_{2\text{H}} + E_{2\text{C}}}{E_{1\text{H}} + E_{1\text{C}}} = \frac{n\bar{c}_p(T_{2\text{H}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{2\text{H}}}{T_0} + n\bar{c}_p(T_{2\text{C}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{2\text{C}}}{T_0}}{n\bar{c}_p(T_{1\text{H}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{1\text{H}}}{T_0} + n\bar{c}_p(T_{1\text{C}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{1\text{C}}}{T_0}} \quad (03)$$

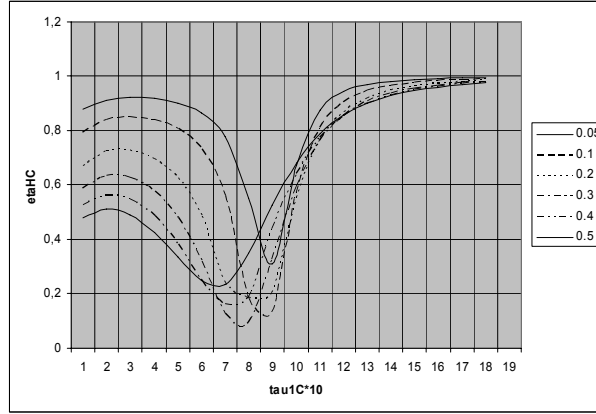
and finally

$$\eta_{\text{HC,ex}}^* = \frac{(\tau_{2\text{H}} - 1) - \ln \tau_{2\text{H}} + (\tau_{2\text{C}} - 1) - \ln \tau_{2\text{C}}}{(\tau_{1\text{H}} - 1) - \ln \tau_{1\text{H}} + (\tau_{1\text{C}} - 1) - \ln \tau_{1\text{C}}}$$

or

$$\eta_{\text{HC,ex}}^* = \frac{(\tau_{2\text{H}} + \tau_{2\text{C}} - 2) - \ln(\tau_{2\text{H}} \cdot \tau_{2\text{C}})}{(\tau_{1\text{H}} + \tau_{1\text{C}} - 2) - \ln(\tau_{1\text{H}} \cdot \tau_{1\text{C}})} \quad (04)$$

Calculations give numerical results presented in the approximate diagram Figure 3.



**Fig. 3** Rating quotient  $\eta_{\text{HC,ex}}^*$  (etaHC) according to Equation (04) as a function of the lowest temperature in a process  $\tau_{1\text{C}}$  (tau1C) and  $\Delta\tau_m$  from 0.05 through 0.5 as a parameter

Numerical values are very logical in the whole temperature range; hence, they can be very useful for comparing different process operations. The only disadvantage is, it cannot be derived from the in the literature hitherto formulated exergy efficiencies. The last rating quotients cannot be seemed as special cases of these exergy efficiencies.

It is interesting, however, how will be calculated values for such rating quotient, but using absolute values of the exergy streams. With absolute exergy values, i.e. from Equation (03)

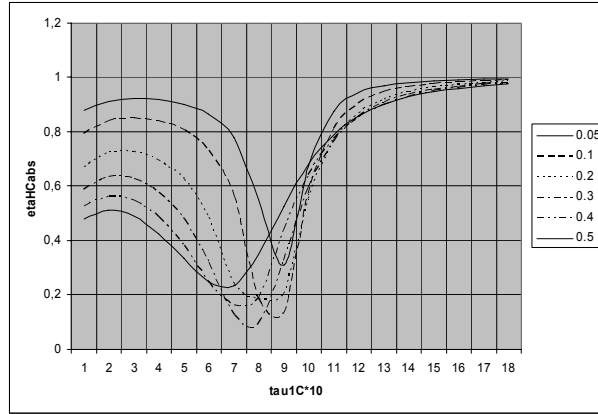
$$\eta_{\text{HC,ex}}^{\text{abs}} = \frac{|E_{2\text{H}}| + |E_{2\text{C}}|}{|E_{1\text{H}}| + |E_{1\text{C}}|} = \frac{\left| n\bar{c}_p(T_{2\text{H}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{2\text{H}}}{T_0} \right| + \left| n\bar{c}_p(T_{2\text{C}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{2\text{C}}}{T_0} \right|}{\left| n\bar{c}_p(T_{1\text{H}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{1\text{H}}}{T_0} \right| + \left| n\bar{c}_p(T_{1\text{C}} - T_0) - n\bar{c}_p T_0 \ln \frac{T_{1\text{C}}}{T_0} \right|}$$

and

$$\eta_{\text{HC,ex}}^{\text{abs}} = \frac{\left| (T_{2\text{H}} - T_0) - T_0 \ln \frac{T_{2\text{H}}}{T_0} \right| + \left| (T_{2\text{C}} - T_0) - T_0 \ln \frac{T_{2\text{C}}}{T_0} \right|}{\left| (T_{1\text{H}} - T_0) - T_0 \ln \frac{T_{1\text{H}}}{T_0} \right| + \left| (T_{1\text{C}} - T_0) - T_0 \ln \frac{T_{1\text{C}}}{T_0} \right|}$$

$$\eta_{HC,ex}^{abs} = \frac{|(\tau_{2H} - 1) - \ln \tau_{2H}| + |(\tau_{2C} - 1) - \ln \tau_{2C}|}{|(\tau_{1H} - 1) - \ln \tau_{1H}| + |(\tau_{1C} - 1) - \ln \tau_{1C}|} \quad (05)$$

following approximate numerical values will be calculated, as shown in Figure 4 below.



**Fig. 4** Rating quotient  $\eta_{HC,ex}^{abs}$  (etaHCabs) according to Equation (05) as a function of the lowest temperature in a process  $\tau_{1C}$  (tau1C) and  $\Delta\tau_m$  from 0.05 through 0.5 as a parameter

Results are in principle logical. The only difference to the previous dependence is a character of the function in the case of crossing the temperature  $T_0$  by one of the two heat exchanging media. The disadvantage is just like in the previous case: the rating quotient does not refer to the hitherto formulated exergy efficiencies.

Thus, another form of the exergy balance Equation (01) should be applied to determine another process rating quotient. From the second form of Equation (01) two rating quotients can be formulated, i.e.

$$\eta_{ex}^* = \frac{\Delta E_{I,H}}{\Delta E_{I,C}} = \frac{E_{I,1H} - E_{I,2H}}{E_{I,1C} - E_{I,2C}} = \frac{\Delta I_H - T_0 \Delta S_H}{\Delta I_C - T_0 \Delta S_C} = \frac{(T_{H1} - T_{H2})\bar{c}_p - \bar{c}_p T_0 \ln \frac{T_{H1}}{T_{H2}}}{(T_{C1} - T_{C2})\bar{c}_p - \bar{c}_p T_0 \ln \frac{T_{C1}}{T_{C2}}}$$

or

$$\eta_{ex}^{**} = \frac{\Delta E_{I,C}}{\Delta E_{I,H}} = \frac{E_{I,1C} - E_{I,2C}}{E_{I,1H} - E_{I,2H}} = \frac{\Delta I_C - T_0 \Delta S_C}{\Delta I_H - T_0 \Delta S_H} = \frac{(T_{C1} - T_{C2})\bar{c}_p - \bar{c}_p T_0 \ln \frac{T_{C1}}{T_{C2}}}{(T_{H1} - T_{H2})\bar{c}_p - \bar{c}_p T_0 \ln \frac{T_{H1}}{T_{H2}}}$$

With assumptions same like above it yields in dimensionless form

$$\eta_{ex}^* = \frac{(\tau_{H1} - \tau_{H2}) - \ln \frac{\tau_{H1}}{\tau_{H2}}}{(\tau_{C1} - \tau_{C2}) - \ln \frac{\tau_{C1}}{\tau_{C2}}} \quad \text{or} \quad \eta_{ex}^{**} = \frac{(\tau_{C1} - \tau_{C2}) - \ln \frac{\tau_{C1}}{\tau_{C2}}}{(\tau_{H1} - \tau_{H2}) - \ln \frac{\tau_{H1}}{\tau_{H2}}} \quad (06)$$

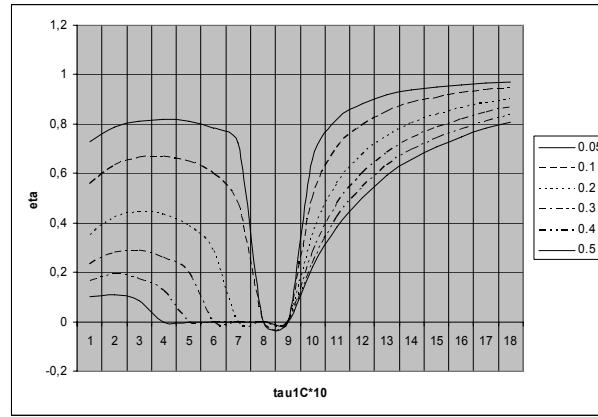
Because one temperature ( $\tau_C$ ) rises and another one falls ( $\tau_H$ ), it is to expect the two quotients to change their sign. That is why absolute values should be taken into account. According to WOLFGANG FRATZSCHER [2]–[4] the convenient forms of the both above rating quotients are

$$\eta_{ex}^* = \frac{|\Delta E_{1,H}|}{|\Delta E_{1,C}|} \quad \text{and} \quad \eta_{ex}^{**} = \frac{|\Delta E_{1,C}|}{|\Delta E_{1,H}|} \quad (07)$$

or with Equations (06)

$$\eta_{ex}^* = \frac{\left| (\tau_{H1} - \tau_{H2}) - \ln \frac{\tau_{H1}}{\tau_{H2}} \right|}{\left| (\tau_{C1} - \tau_{C2}) - \ln \frac{\tau_{C1}}{\tau_{C2}} \right|} \quad \text{and} \quad \eta_{ex}^{**} = \frac{\left| (\tau_{C1} - \tau_{C2}) - \ln \frac{\tau_{C1}}{\tau_{C2}} \right|}{\left| (\tau_{H1} - \tau_{H2}) - \ln \frac{\tau_{H1}}{\tau_{H2}} \right|} \quad (08)$$

An appropriate form can be used, dependent on the temperature range of a process. By temperatures of the two media below  $T_0$  or above  $T_0$  either the first quotient gives efficiency values in the range between 0 and 1, or the second. In the case, where one medium (or two of them) is crossing the temperature value of  $T_0$  in an analyzed heat exchange process, the exergy efficiency given by Equations (07)–(08) will exceed the only logical range of numerical values between 0 and 1. The first of above two relations give numerical values (only cases  $\tau < 1$  will be considered) presented in the left hand lower part of the diagram, and the second one (only cases  $\tau \geq 1$  will be considered) in its right hand upper half, Figure 5.



**Fig. 5** Rating quotient  $\eta_{ex}^*$  and  $\eta_{ex}^{**}$  (eta) according to Equations (08) as a function of the lowest temperature in a process  $\tau_{1C}$  (tau1C) and  $\Delta\tau_m$  from 0.05 through 0.5 as a parameter

Thus, it can be set

$$\eta_{ex}^* \equiv \eta_{ex}^< \quad \text{and} \quad \eta_{ex}^{**} \equiv \eta_{ex}^> \quad (09)$$

where the superscript  $>$  points to all processes above and  $<$  below the temperature of natural environment  $T_0$ . In ranges, where one of the heat exchanging media crosses the temperature of natural environment  $T_0$  the above exergy efficiency gives unstable numerical values, which are not useful at all. But it can be asked the question: what does occur in the range? The approximate diagram in Figure 5 presents the situation close to the reduced natural environment temperature  $T_0$ , i.e.  $\tau = 1$ .

### 3.1 Thermodynamic Effectivity

The exergy changes while crossing the temperature of natural environment should be parted. From the diagram presented in Figure 6 it will be

$$\Delta E_H = \Delta E_H^< - \nabla E_H^> \quad \text{and} \quad \Delta E_C = \Delta E_C^> - \nabla E_C^<$$

In fact the algebraic signs should be defined. In a technological heat exchange process it is possible to determine the appropriate algebraic signs of

$$\nabla E_H^> < 0 \quad \text{and} \quad \Delta E_H^< > 0 \quad (12a)$$

or

$$\Delta E_C^> > 0 \quad \text{and} \quad \nabla E_C^< < 0 \quad (12b)$$

but not of  $\Delta E_H$  or  $\Delta E_C$ . This results from the above Equations (10). It is convenient to present them as sums of absolute values of partial exergy changes, Equations (10), namely

$$\Delta E_H = |\Delta E_H^<| - |\nabla E_H^>| \quad \text{and} \quad \Delta E_C = |\Delta E_C^>| - |\nabla E_C^<| \quad (11)$$

Using the two above Equations (11) the general form of the exergy rating quotient can be defined. The all four terms, Equations (10), can be divided into disappearing ( $\nabla E_H^>, \nabla E_C^<$ ) and created ( $\Delta E_H^<, \Delta E_C^>$ ) exergy changes. Their quotient will be a generalized form of the exergy efficiencies formulated separately for processes below and above the temperature of natural environment, Equations (07)–(09). It is

$$\varepsilon = \frac{|\Delta E_H^<| + |\Delta E_C^>|}{|\nabla E_H^>| + |\nabla E_C^<|} \quad (12)$$

The rating quotient according to Equation (12) has been named the process thermodynamic effectivity (*thermodynamische Effektivität*), [5]–[9], if the terms are exergy changes, not exergies alone. Some conditions have to be fulfilled to get the positive (i.e. greater than zero) but less than one numerical value, which is the only logical case.

With Equations (11) the exergy balance according to Equation (01) will be to

$$-\Delta E_{I,H} - \Delta E_{I,C} = -|\Delta E_H^<| + |\nabla E_H^>| - |\Delta E_C^>| - |\nabla E_C^<| = T_0 \Delta S_{\text{irr}}$$

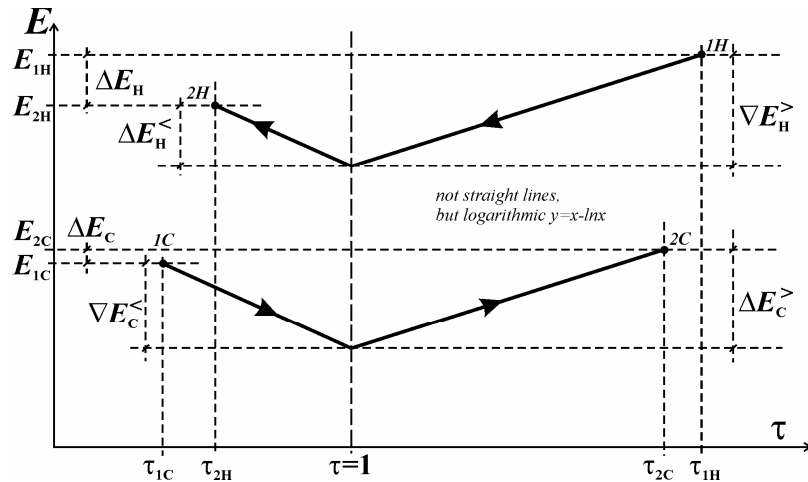
or

$$|\nabla E_H^>| + |\nabla E_C^<| = |\Delta E_H^<| + |\Delta E_C^>| + T_0 \Delta S_{\text{irr}}$$

which has been previously written down as the thermodynamic transformation (*thermodynamischer Übergang*)

$$|\nabla E_H^>| + |\nabla E_C^<| \rightarrow |\Delta E_H^<| + |\Delta E_C^>| + T_0 \Delta S_{\text{irr}}$$

because it was first derived on the pure intuitive way ([5], in the research team of WOLFGANG FRATZSCHER, one of the main pioneers of the exergy method).



**Fig. 6** The (qualitative) dependence of exergy and exergy changes on the reduced process temperature  $\tau=T/T_0$ .

The thermodynamic effectivity of the considered technological heat exchange process, Equation (12) is a generalization of the hitherto used exergy efficiencies. The terms not concerning the analyzed process will be set equal to zero. E.g. for processes above the temperature  $T_0$  terms  $\nabla E_C^< = \Delta E_H^< = 0$ , and Equation (12) is

$$\varepsilon^> = \frac{|\Delta E_C^>|}{|\nabla E_H^>|} \equiv \eta_{\text{ex}}^* \quad \text{and} \quad \varepsilon^< = \frac{|\Delta E_H^<|}{|\nabla E_C^<|} \equiv \eta_{\text{ex}}^{**}$$

for processes below this temperature  $\nabla E_H^> = \Delta E_C^> = 0$ , cf. Equations (07).

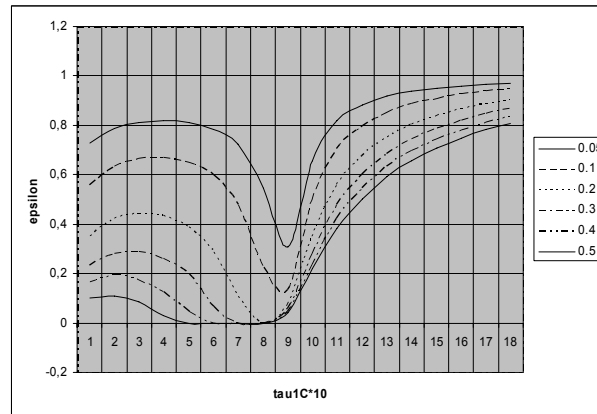
Thus, the appropriate numerical values could be completed and an approximate diagram presented in Figure 7. The special case can be observed, e.g. for  $\tau_{1C} = 0.9$  and  $\Delta\tau_m = 0.5$  yields ( $T_0 = 290$  K):

$$T_{1C} = 261 \text{ K}; \quad T_{2C} = 311 \text{ K}; \quad T_{1H} = 455,75 \text{ K}; \quad T_{2H} = 405,75 \text{ K}$$

which means

$$\nabla E_H^> \neq 0; \quad \Delta E_H^< = 0; \quad \Delta E_C^> = 0; \quad \nabla E_C^< \neq 0$$

and  $\varepsilon = 0$ . In such a case exergy changes do mean only losses (i.e. they diminish) in a process.



**Fig. 7** Rating quotient, the thermodynamic effectivity  $\varepsilon$  (epsilon) according to the Equation (12) as a function of the lowest temperature in a process  $\tau_{1C}$  ( $\tau_{1C}$ ) and  $\Delta\tau_m$  from 0.05 through 0.5 as a parameter

There is no need to illustrate the sense and importance of the thermodynamic effectivity quotient presenting a numerical example because the technological heat exchange process has been discussed in the literature many times, even by the authors alone, e.g. [10]–[15]. The great advantage of the detailed analysis presented above is the possibility of applying the generalized method to rate processes, in which the rating quotient determination is not that obvious, e.g. in the case of substance exchange processes. In fact the processes below the natural environment temperature are not often analyzed in the power engineering, except of processes in refrigerating engineering. They can be discussed for modern power engineering systems with low  $\text{CO}_2$  emissions (atmospheric air separation in the so-called OxyFuel Technology).

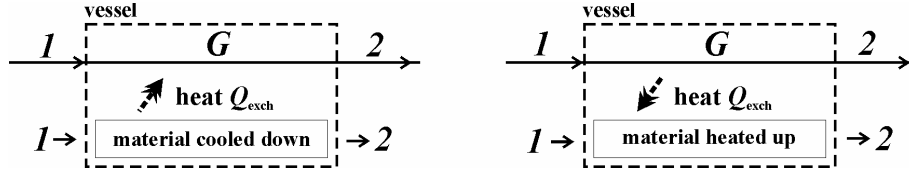
#### 4 HEATING UP AND COOLING DOWN HEAT EXCHANGE PROCESSES

The very similar process of technological heat exchange is heating up or cooling down the material placed in the hot (or cold) gas flow (symbolic  $G$ ), Figure 8. In the same way as above the thermodynamic transition can be formulated, and hence the appropriate thermodynamic effectivity quo-



tient. The balance equations are the same, and the thermal exergy changes can be parted in analogy to above methodic, i.e. up to the change direction and temperature range below or above the natural environment temperature.

In fact, the presented two special cases of technological heat exchange processes can be used for determining thermodynamic transition formula and the unique generalized rating quotient, the thermodynamic effectivity for the technological substance exchange processes, just like drying (or wetting) and absorption.



**Fig. 8** Cooling down (to the left) and heating up (to the right) as technological heat exchange processes in a vessel (apparatus)

The exergy balance for processes showed in Figure 8 will be to

$$E_{I,MCD,1} + E_{I,G,1} = E_{I,MCD,2} + E_{I,G,2} + T_0 \Delta S_{irr}$$

and

$$E_{I,MHU,1} + E_{I,G,1} = E_{I,MHU,2} + E_{I,G,2} + T_0 \Delta S_{irr}$$

with subscripts *MCD* for „material cooled down“, *MHU* for „material heated up“ and *G* for gas stream. From above balances yields their another form

$$-(E_{I,MCD,2} - E_{I,MCD,1}) - (E_{I,G,2} - E_{I,G,1}) = T_0 \Delta S_{irr} \quad \text{or} \quad -\Delta E_{I,MCD} - \Delta E_{I,G} = T_0 \Delta S_{irr}$$

and

$$-(E_{I,MHU,2} - E_{I,MHU,1}) - (E_{I,G,2} - E_{I,G,1}) = T_0 \Delta S_{irr} \quad \text{or} \quad -\Delta E_{I,MHU} - \Delta E_{I,G} = T_0 \Delta S_{irr}$$

Temperature changes in the processes presented in Figure 8 can be, however, very good described, i.e. in the cooling process the gas temperature will raise, and the temperature of the material will diminish. It means, in both ranges of temperature changes below and above the natural environment temperature  $T_0$  it will be for the material cooling process

$$\Delta E_{I,G} = -|\nabla E_{I,G}^<| + |\Delta E_{I,G}^>| \quad \text{and} \quad \Delta E_{I,MCD} = -|\nabla E_{I,MCD}^>| + |\Delta E_{I,MCD}^<|$$

and for material heating up process

$$\Delta E_{I,G} = |\Delta E_{I,G}^<| - |\nabla E_{I,G}^>| \quad \text{and} \quad \Delta E_{I,MHU} = |\Delta E_{I,MHU}^>| - |\nabla E_{I,MHU}^<|$$

Putting the expressions into above exergy balance equations yields

$$|\nabla E_{I,MCD}^>| - |\Delta E_{I,MCD}^<| + |\nabla E_{I,G}^<| - |\Delta E_{I,G}^>| = T_0 \Delta S_{irr}$$

and

$$-|\Delta E_{I,MHU}^>| + |\nabla E_{I,MHU}^<| - |\Delta E_{I,G}^<| + |\nabla E_{I,G}^>| = T_0 \Delta S_{irr}$$

Hence, appropriate thermodynamic transition formulas can be written down, i.e.

$$|\nabla E_{I,MCD}^>| + |\nabla E_{I,G}^<| \rightarrow |\Delta E_{I,MCD}^<| + |\Delta E_{I,G}^>| + T_0 \Delta S_{irr}$$

and

$$|\nabla E_{I,MHU}^<| + |\nabla E_{I,G}^>| \rightarrow |\Delta E_{I,MHU}^>| + |\Delta E_{I,G}^<| + T_0 \Delta S_{irr}$$

The thermodynamic effectivity quotients will be then to

$$\varepsilon_{\text{MCD}} = \frac{|\Delta E_{1,\text{MCD}}^<| + |\Delta E_{1,\text{G}}^>|}{|\nabla E_{1,\text{MCD}}^>| + |\nabla E_{1,\text{G}}^<|} \quad \text{and} \quad \varepsilon_{\text{MHU}} = \frac{|\Delta E_{1,\text{MHU}}^>| + |\Delta E_{1,\text{G}}^<|}{|\nabla E_{1,\text{MHU}}^<| + |\nabla E_{1,\text{G}}^>|}$$

For the most popular processes that run above the natural environment temperature it yields

$$\varepsilon_{\text{MCD}} = \frac{|\Delta E_{1,\text{G}}^>|}{|\nabla E_{1,\text{MCD}}^>|} \quad \text{and} \quad \varepsilon_{\text{MHU}} = \frac{|\Delta E_{1,\text{MHU}}^>|}{|\nabla E_{1,\text{G}}^>|}$$

The exergy changes in above equations can be calculated without problems, so there is no need to present the numerical example in this place.

## 5 CONCLUSIONS

The technological heat exchange processes were processes, for which the huge problems in the exergy analysis have been reported in the literature. The solution of the problem could be achieved in the research team of Professor WOLFGANG FRATZSCHER, whose exergy effectiveness quotient for the processes was the first generalized solution, but not enough for following thermodynamic analyzes, especially of the technological substance exchange processes. For these processes it is not that easy, e.g. in the intuitive way, to find unique advantages (numerator) and expenditures (denominator). The analogue of technological heat exchange is very useful for applying the exergy method even for the technological substance exchange.

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