Entropy **2014**, *16*, 2071-2084; doi:10.3390/e16042071

OPEN ACCESS
entropy
ISSN 1099-4300
www.mdpi.com/journal/entropy

Article

The Entropic Potential Concept: a New Way to Look at Energy Transfer Operations

Tammo Wenterodt and Heinz Herwig *

Institute of Thermo-Fluid Dynamics, Hamburg University of Technology, Denickestr. 17, 21073 Hamburg, Germany

* Author to whom correspondence should be addressed; E-Mail: h.herwig@tuhh.de; Tel. +49 40-42878-3044; Fax +49 40-42878-4169.

Received: 4 Febuary 2014; in revised form: 7 April 2014 / Accepted: 10 April 2014 / Published: 14 April 2014

Abstract: Energy transfer operations or processes are systematically analyzed with respect to the way they can be assessed. It turns out that the energy transfer should not only be characterized by the operation or process itself but that it should be seen in a wider context. This context is introduced as the entropic potential of the energy that is transferred. It takes into account the overall transfer from the energy in its initial and finite states, *i.e.*, starting as pure exergy when it is a primary energy, for example, and ending as pure anergy when it has become part of the internal energy of the ambient. With this concept an energy devaluation number can be defined which has several properties with a reasonable physical background. Two examples of different complexity of the process assessed are given and discussed with respect to the physical meaning of the new energy devaluation number.

Keywords: heat transfer; assessment; entropy; energy devaluation; power generation; second law analysis; roughness

---

1. Nomenclature

Indices, Sub- and Superscripts

$\dot{\square}$	rate
$\square'$	value per running length

$\Box_{1\ldots4}$	value at state ...
$\Box_i$	in transfer operation i
$\dot{\Box}_{\mathrm{in}}$	inflow rate
$\dot{\Box}_{\mathrm{out}}$	outflow rate

Variables

c_p	specific heat capacity	J/kg K
D	diameter	m
E	energy	J
E^{a}	anergy	J
E^{e}	exergy	J
$E^{\mathrm{e}}_{\mathrm{l}}$	exergy loss	J
f	friction factor	-
h	heat transfer coefficient	W/m^2 K
k	thermal conductivity	W/m K
K_{s}	relative sand roughness	-
$\dot{m}$	mass flow rate	kg/s
N	energy devaluation number	-
$N_{\ominus}$	energy devaluation number prior to transfer operation	-
$N_{\oplus}$	energy devaluation number after transfer operation	-
NTU	Number of Transfer Units	-
P	power	W
Pr	Prandtl number	-
$\dot{q}'_{\mathrm{w}}$	energy transfer rate in form of heat per pipe length	W/m
Re	Reynolds number	-
s	specific entropy	J/kg K
S	entropy	J/K
S_{∞}	entropic potential	J/K
$\dot{S}_{\infty}$	entropic potential of an energy flow rate	W/K
S_{gen}	entropy generation	J/K
$\dot{S}'_{\mathrm{gen},0}$	entropy generation rate of the smooth pipe per running length	W/m K
$\dot{S}'_{\mathrm{gen,C}}$	entropy generation due to conduction of heat per running length	W/m K
$\dot{S}'_{\mathrm{gen,D}}$	entropy generation due to dissipation per running length	W/m K
$\delta_{\mathrm{irr}}S$	infinitesimal increase of entropy	J/K
St	Stanton number	-
T_{m}	bulk temperature	K

T_∞	ambient temperature	K

Greek letters

η	thermo-hydraulic efficiency	-
η_{ex}	exergetic efficiency	-
μ	molecular (dynamic) viscosity	kg/m s
ϱ	density	kg/m^3

2. Introduction

Energy transfer occurs frequently in our daily life with the human body as a prominent example of the interaction of various transfer mechanisms as there are natural convection heat transfer, two-phase evaporation heat transfer cooling the body by transpiration, performing work by moving the body and so forth. In technical applications like energy conversion in a power plant numerous energy transfer operations occur which may be regarded as unit operations when they only comprise one single mechanism (like a special kind of heat transfer or a specific way in which work is performed).

Such unit operations often should be improved in order to optimize a process in which they are incorporated. Then, however, they must be assessed with respect to their quality and its improvement. Here the *quality of an energy transfer operation* has two aspects

- the amount of energy transferred under certain conditions
- the degree of devaluation of the energy during the transfer operation

The first aspect typically is addressed by applying the First Law of Thermodynamics whereas the second aspect is accounted for by the Second Law of Thermodynamics and therefore often is called “Second Law Analysis” (SLA).

A first law analysis can assess a heat transfer operation, for example, with respect to its effectiveness in terms of a heat transfer coefficient h or in terms of NTU (Number of Transfer Units), both of which are related to the *energy* of the transfer operation.

A second law analysis determines the energy devaluation, again for example in a heat transfer operation, and thus is related to the *exergy* of the transfer operation. Here exergy, sometimes called available energy or more precisely available work, is the precious part of the energy which can be arbitrarily used after the transfer operation, cf. [1]. See [2] for a comprehensive discussion of the second law analysis.

The heat transfer operation will often be a convective heat transfer. It may, however, also be one induced by radiation. In both cases exergy and lost exergy can be determined and used for the assessment of the operation, see [3] and [4] for the case of radiation heat transfer.

As far as heat transfer is concerned (as an important example of energy transfer in general) many different criteria for a second law analysis have been proposed and discussed in the heat transfer literature. Some have been introduced as early as 1959, see [5], later Bejan [6] proposed his famous *entropy generation number* and more recently Fakheri [7] suggested to use his *entropy flux criterion*. With these many different approaches comparisons may help to better understand their similarities as well as their differences and peculiarities. Such comparisons are found in [8] and [9], for example. Recent review papers about the physics of entropy generation are for example [10] and [11].

Almost all of these second law criteria end up as nondimensional numbers, which in one or the other way are a measure of the devaluation of the energy. Therefore, they all have to answer the questions

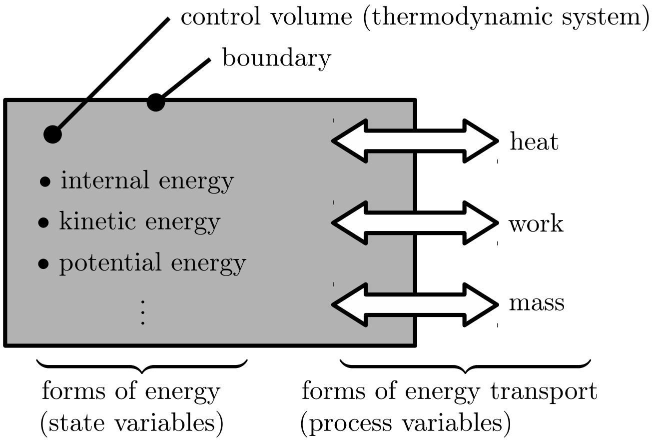
- which aspect of the energy under consideration is crucial for the degree of energy devaluation?
- which aspect can serve as a reference quantity in order to put the devaluation into the right perspective?

In the following we want to answer these questions as generally as possible based on a global view at the energy transfer operation and its context.

3. Energy, Its Use and Its Devaluation

In order to have clearly defined quantities in the following the starting point should be a short recapitulation of the generally accepted concept of energy and its transfer. In a thermodynamic system, confined against the ambient as a control volume, that in general is permeable for mass and energy, there are various forms of energy which are categorized as state variables. Figure 1 shows such a system together with the three fundamentally different forms of energy transport across the boundary of the system. They are *process variables* and as such of a different kind compared to the forms of energy within the system which are *state variables*. This sometimes gets lost with the traditional technical terms like "heat transfer" and "heat capacity". Neither can a process quantity like heat be transferred nor can it be stored since "heat" by definition is the transfer process itself (note that also work cannot be transferred or stored). For a consistant use of technical terms "heat transfer" might instead be called "energy transfer in form of heat" and "heat capacity" might be called "thermal energy capacity".

Figure 1. State and process variables in the general thermodynamic energy concept.



A similar clarification is appropriate with respect to an imprecise terminology when "energy is used", or even worse, "energy is consumed". Actually both phrases are used in situations where energy is transferred as a whole or in parts. Since energy according to the First Law of Thermodynamics is a conserved quantity it cannot be consumed in the sense of destruction. It can, however, be consumed in the sense of devaluation. This is very well illustrated by introducing the well known exergy concept. It splits an energy E into two parts:

- E^{e}: exergy as that part of the energy that can be completely transferred to the internal energy of the ambient by work (also named "available work")
- E^{a}: anergy as all of E that is not exergy.

Figure 2. Energy devaluation by consecutive energy transfer operations illustrated by the decrease of exergy during the energy transfer operations. Progress in time for finite energies (progress in process steps for finite energy rates) .

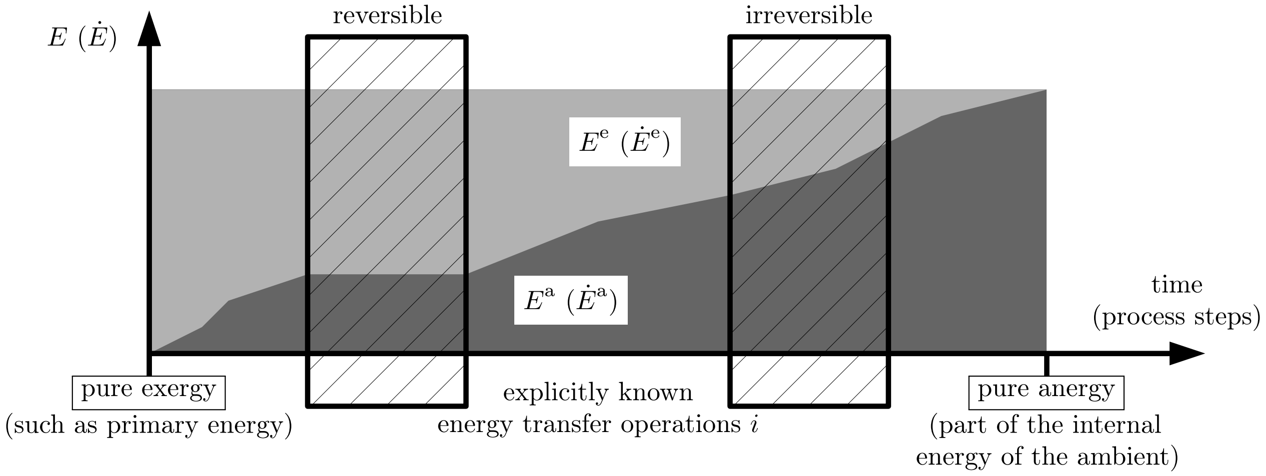


Figure 2 shows the devaluation with time of an energy which initially is 100 % exergy since, for example, it is a primary energy. This initial energy in progressive times can either be left as it is or it can undergo consecutive energy transfer operations. During such a transfer operation it will be partly and further devaluated (assuming transfer operations have occurred before already) when the transfer operation is irreversible. This devaluation manifests itself in a (further) decrease of the exergy part in E. Only when a transfer operation would be reversible E^{e} would not decrease further. In Figure 2 two energy transfer operations are assumed to be explicitly known (one reversible, one irreversible). Before, between and after these two operations the energy E undergoes further yet here not explicitly known transfer operations. Finally the energy E will be part of the ambient internal energy and then per definition is 100 % anergy. What we call "a new way to look at energy transfer operations" is always to have in mind that a single operation is part of a "devaluation chain".

Thermodynamically the decrease of exergy is an exergy loss that is immediately related to the generation of entropy by the so-called Gouy-Stodola theorem, see for example [12], p. 21,

$$\mathrm{d}E_{\mathrm{l}}^{\mathrm{e}} = T_{\infty}\,\delta_{\mathrm{irr}}S \tag{1}$$

Here $E_{\mathrm{l}}^{\mathrm{e}}$ is an exergy loss, T_{∞} the ambient temperature and $\delta_{\mathrm{irr}}S$ the infinitesimal increase of entropy by its generation in an irreversible operation. Here we prefer $\delta_{\mathrm{irr}}S$ instead of δS_{irr} in order to emphasise that S is a unique quantity that can be changed by various processes, here an irreversible one.

For a single transfer operation number i in a finite time there is the exergy loss

$$E^{\mathrm{e}}_{\mathrm{l},i} = T_\infty \, S_{\mathrm{gen},i} \tag{2}$$

with $S_{\mathrm{gen},i}$ as entropy generation during the transfer operation number i.

For the sum of all single transfer operations that completely devaluates the energy E from $100\,\%$ exergy to $100\,\%$ anergy then

$$E^{\mathrm{e}}_{\mathrm{l}} = E = T_\infty \, S_{\mathrm{gen}} \quad \longrightarrow \quad S_{\mathrm{gen}} = \frac{E}{T_\infty} \tag{3}$$

Here S_{gen} is the entropy increase of the ambient, when E becomes part of its internal energy.

This quantity from now on is called *entropic potential* $S_\infty = E/T_\infty$ of E and will be used in the subsequent considerations as the crucial reference quantity.

4. Energy Transfer Assessment

From what has been said so far about the devaluation of an energy E by a certain energy transfer operation which is part of the overall devaluation chain the first question raised at the beginning (which aspect is crucial with respect to energy devaluation?) can be answered immediately: the exergy loss during this operation, *i.e.*, the entropy generated by it.

The second question (how to put it into the right perspective?) is less obviously answered satisfactorily. Several options exist, but one turns out to be especially attractive: When the entropy generation during an energy transfer operation is referred to the entropic potential of that energy, it turns out that:

- this ratio gives the percentage of the overall entropic potential consumed by the specific operation, which is a relevant physical statement
- these ratios of subsequent operations add up to form an assessment criterion for combined unit operations,
- these ratios of all transfer operations from the energy status as pure exergy to that one as pure anergy add up to a mere 1.

Therefore we define the dimensionless number to assess a single energy transfer operation from now on called *energy devaluation number* as:

$$\boxed{N_i \equiv \frac{S_{\mathrm{gen},i}}{S_\infty} = \frac{T_\infty \, S_{\mathrm{gen},i}}{E}} \ \text{energy devaluation number of operation } i \tag{4}$$

When the transfer operations are not time limited but part of a steady process, $S_{\mathrm{gen},i}$ and S_{gen} are replaced by their rates (change of the quantity per time), so that

$$\boxed{N_i \equiv \frac{\dot{S}_{\mathrm{gen},i}}{\dot{S}_\infty} = \frac{T_\infty \, \dot{S}_{\mathrm{gen},i}}{\dot{E}}} \ \text{energy devaluation number of the steady operation } i \tag{5}$$

This number is always between 0 and 1 with both limits as:

- $N_i = 0$: reversible energy transfer operation
- $N_i = 1$: energy transfer operation that completely devaluates the energy (rate).

The energy devaluation number N formally corresponds to $1 - \eta_{\text{ex}}$ where η_{ex} is the often used exergetic efficiency defined as $\eta_{\text{ex}} = 1 - E^{\text{e}}_{\text{l}}/E^{\text{e}}$. This efficiency applied to a single operation i would be $\eta_{\text{ex},i} = 1 - E^{\text{e}}_{\text{l},i}/E^{\text{e}}_i$ *i.e.*, the reference quantity is E^{e}_i in $\eta_{\text{ex},i}$ while it is E in N_i. Only with this E as a reference quantity the operation i is evaluated as part of the whole "devaluation chain".

When the overall devaluation of the energy E or $\dot{E}$ prior to the energy transfer operation under consideration is given by the energy devaluation number $N_{\ominus}$ and that after by $N_{\oplus}$ the overall devaluation corresponds to

$$N_{\ominus} + N_i + N_{\oplus} = 1 \tag{6}$$

5. How to Apply the Energy Devaluation Number

In order to determine specific values of N_i for a certain energy transfer operation its entropy generation (rate) must be known. There are basically two ways to determine $S_{\text{gen},i}$ or $\dot{S}_{\text{gen},i}$ for an energy transfer operation.

Either it is determined from a global entropy balance taking into account the in- and outflowing entropies as well as that transferred by energy flows in form of heat into or out of the system, or the entropy generation is determined locally from the velocity gradients in the flow field and the temperature gradients in the temperature field and then integrated over the entire flow and temperature fields. This, however, can only be done with numerical solutions of the problem. The first method is called *indirect method* of determining entropy generation, while the second way is called the *direct method*, see [13] for more details. Here "direct" means that the local entropy generation is integrated "directly" in order to determine $S_{\text{gen},i}$.

Once $S_{\text{gen},i}$ or $\dot{S}_{\text{gen},i}$ is known, N_i can be determined since the reference quantities are the known energy (rate) and the ambient temperature (thermodynamic temperature in Kelvin (K)).

Figure 3. The entropic potential and its use on the way of the energy becoming part of the internal energy of the ambient, here: contribution of an energy transfer operation i .

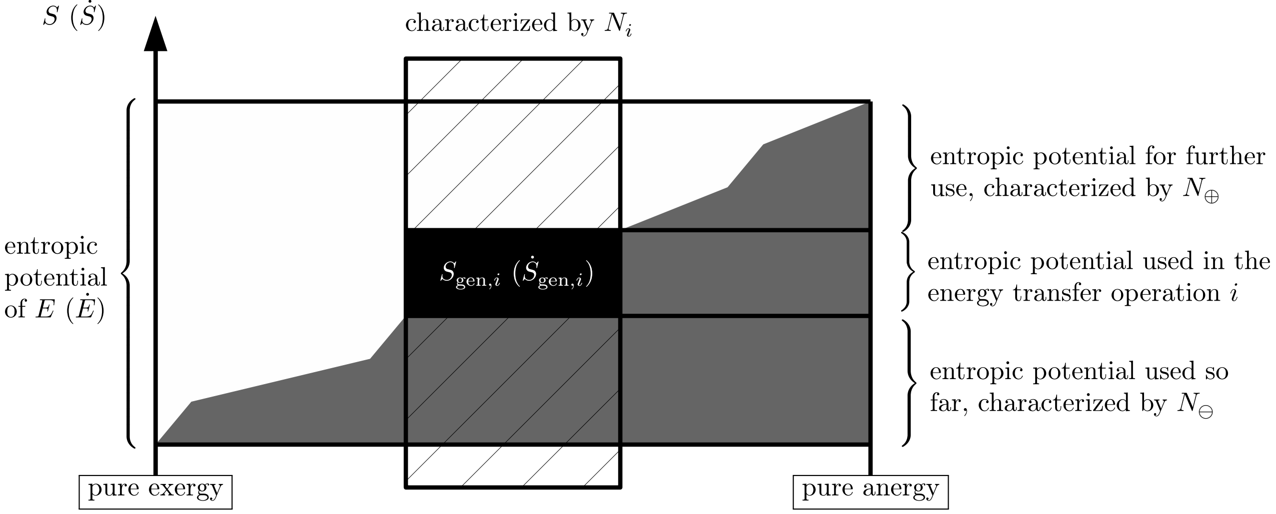


Figure 3 shows, how the N_i-value (energy devaluation number of the transfer operation under consideration) characterizes the contribution of a single energy transfer operation i to the overall transfer of the initially precious (primary) energy to the energy on ambient level without any potential with respect to further energy transfer operations.

6. Applying the Energy Devaluation Number N_i

When it comes to optimizing a process which often is comprised of several single energy transfer operations the energy devaluation number of the whole process should be a minimum while maintaining its original purpose. This implicitly assumes that the least energy devaluation is the optimization target as it will often be the case in a process in which the exergy and its use is the crucial objective. Nevertheless there may be additional constraints that have to be taken into account.

The devaluation number concept is applicable for a wide variety of single or combined energy transfer operations, ranging from a single unit operation within one component (e.g. in an evaporator, condenser, heater, cooler, . . .) to the whole component as part of a cycle (power plant, cooling cycle, . . .).

Two examples will be given for which the least energy devaluation is the target of optimization. The first one is a whole steam power cycle, the second one a detailed analysis of the cold side of a heat exchanger. These examples should show that the energy devaluation numbers can be applied on very different detail levels of the “energy path from exergy to anergy”. They can be as comprehensive as that for a whole boiler in the steam power cycle or as detailed as that for the cold side of a heat exchanger (which may be implemented in a steam power cycle, for example). Whichever level is chosen the corresponding energy devaluation number for a single component or operation is one N_i in the overall energy devaluation chain for which $\sum\limits_i N_i = 1$ holds, see Equation (6).

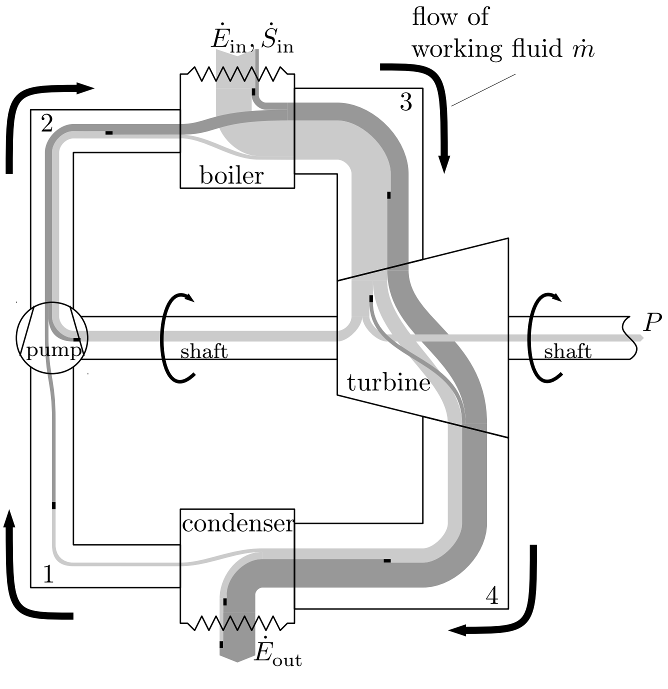
6.1. Assessment of a Steam Power Cycle Process

In Figure 4 a schematic diagram of the energy transfer operations in a steam power cycle is shown. The process as a whole is characterized and assessed by the four transfer components (pump (p), boiler (b), turbine (t), condenser (c)) and their performance. For simplicity the exergy losses in the pipes are assigned to the components between the corresponding interfaces 1 to 4, those in the ambient are assumed to be part of the condenser exergy losses.

Table 1. Energy devaluation numbers N_i for the four energy transfer components of the steam power cycle sketched in Figure 4.

N_i	energy transfer	$\dot{S}_{\text{gen},i}$	N_i
N_p	adding mechanical energy in a pump	$\dot{m}(s_2 - s_1)$	$\dfrac{\dot{m}(s_2 - s_1)\,T_\infty}{\dot{E}_\text{in}}$
N_b	adding thermal energy in a boiler	$\dot{m}(s_3 - s_2) - \dot{S}_\text{in}$	$\dfrac{\left(\dot{m}(s_3 - s_2) - \dot{S}_\text{in}\right)\,T_\infty}{\dot{E}_\text{in}}$
N_t	extracting mechanical energy in a turbine	$\dot{m}(s_4 - s_3)$	$\dfrac{\dot{m}(s_4 - s_3)\,T_\infty}{\dot{E}_\text{in}}$
N_c	extracting thermal energy in a condenser	$\dot{m}(s_1 - s_4) + \dot{S}_\text{out}$	$\dfrac{\left(\dot{m}(s_1 - s_4) + \dot{S}_\text{out}\right)\,T_\infty}{\dot{E}_\text{in}}$

Figure 4. Energy transfer in a steam power cycle (qualitatively); light grey: exergy, dark grey: anergy, black box: entropy generation.



Then, applying the indirect method to determine the entropy generation of each component, $\dot{S}_{\text{gen},i}$, energy devaluation numbers for all four components can be determined as shown in Table 1. The corresponding assessment number for the whole cycle is

$$N_\text{cycle} = N_\text{p} + N_\text{b} + N_\text{t} + N_\text{c} = \frac{\left(\dot{S}_\text{out} - \dot{S}_\text{in}\right)\,T_\infty}{\dot{E}_\text{in}} \tag{7}$$

$$\text{or rewritten with } \dot{E}_\text{out} = \dot{E}_\text{in} - P, \dot{E}_\text{out} = \dot{S}_\text{out}\,T_\infty \tag{8}$$

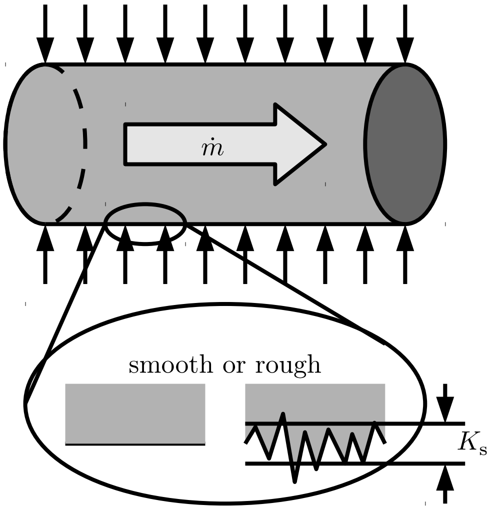
$$N_\text{cycle} = 1 - \underbrace{\frac{P}{\dot{E}_\text{in}}}_{\text{I}} - \underbrace{\frac{\dot{S}_\text{in}\,T_\infty}{\dot{E}_\text{in}}}_{\text{II}} \tag{9}$$

This example shows how information about the occurrence of energy devaluation gets lost when the detail levels of the analysis are changed. When all four components are analyzed individually like in Table 1 energy devaluations can be attributed to the single components. When they are combined, however, in order to end up with the N_{cycle} according to Equation (7) or (9) this information gets lost. Note that in Equation (9) the term I corresponds to the thermal coefficient of performance with respect to the whole cycle and term II represents $N_{\ominus}$ introduced in Equation (6). According to this Equation (6) term I also represents $N_{\oplus}$ which means, that the exergy P will eventually completely get lost (when used for subsequent processes) and as anergy will be part of the ambient internal energy. Then the entropic potential $\dot{E}_{\text{in}}/T_{\infty}$ has been used completely and nothing is left for a further use.

6.2. Assessment of the Cold Side of a Heat Exchanger

Now an example of a very detailed analysis will be given. It is about the heat transfer performance on the cold side of a heat exchanger. Here a mass flow rate $\dot{m}$ is heated by a constant energy transfer rate in form of heat per pipe length $\dot{q}_{\text{w}}'$ such that there is a certain gradient in bulk temperature $\mathrm{d}T_{\text{m}}/\mathrm{d}x$. The question to be addressed is whether a rough wall might perform better than a smooth wall and when this is the case, which degree of roughness performs best. The idea behind this question is the option that a better mixing of the fluid by wall roughness may decrease the exergy loss due to heat conduction such that it outweighs the increase of exergy loss due to increased frictional losses.

Figure 5. Details at the cold side of a heat exchanger that might operate with rough instead of smooth walls, assuming constant properties with values at $T = 293.15\,\text{K}$.



symbol	value	meaning
K_{s}	$0\,\%\ldots5\,\%$	roughness
$\dot{q}_{\text{w}}'$	$2093\,\text{W/m}$	energy transfer rate in form of heat per pipe length
$\dot{m}$	$0.05\,\text{kg/s}$	mass flow rate
$\mathrm{d}T_{\text{m}}/\mathrm{d}x$	$10\,\text{K/m}$	gradient of the bulk temperature
D	$3.6\,\text{mm}$	diameter
Re	17 000	Reynolds number
T_{m}	$323.15\,\text{K}$	considered bulk temperature level
ϱ	$998.21\,\text{kg/m}^3$	density
μ	$1001.6 \times 10^{-6}\,\text{kg/m s}$	dynamic viscosity
k	$5.985 \times 10^{-1}\,\text{W/m K}$	thermal conductivity
c_p	$4.185\,\text{kJ/kg K}$	specific heat capacity
Pr	7.004	Prandtl number
T_{∞}	$293.15\,\text{K}$	ambient temperature

Figure 5 is a sketch of this situation along with all details with respect to the operational parameters and fluid properties.

In a conventional approach the performance assessment might have been based on the often used and still popular thermo-hydraulic performance parameter proposed by Gee and Webb [14], which is

$$\eta = \frac{\mathrm{St}/\mathrm{St}_0}{(f/f_0)^{1/3}} \tag{10}$$

Here the Stanton number St_0 and the friction factor f_0 correspond to the smooth wall case, St and f are these parameters when wall roughness K_s is non-zero.

The influence of wall roughness for increasing roughness heights K_s is directly accounted for in f by

$$f^{-1/2} = -2\,\log_{10}\left(\frac{K_\mathrm{s}}{3.7} + \frac{2.51}{\mathrm{Re}}\,f^{-1/2}\right) \tag{11}$$

proposed by [15] and indirectly in St by

$$\mathrm{St} = \frac{f/8\,(\mathrm{Re}-1000)}{\mathrm{Re}\,\left(1+12.7\,(f/8)^{1/2}\,(\mathrm{Pr}^{2/3}-1)\right)} \tag{12}$$

proposed by [16] and recommended for tubes with wall roughness of sand-grain type in [17].

Figure 6. Roughness effects at the cold side of the heat exchanger, see Figure 5, in terms of f, St and η.

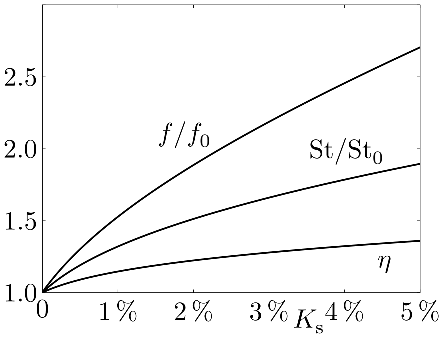


Figure 6 shows f/f_0, $\mathrm{St}/\mathrm{St}_0$ and their combination as η according to Equation (10). With increasing K_s there is a monotonous increase in all three quantities. Especially η increases above $\eta = 1$ which is claimed to be an improvement though without physical explanation. According to these results K_s should be as high as possible.

Alternatively this problem can be assessed by applying the energy devaluation number N_i which then will account for the exergy loss, *i.e.*, entropy generation due to the dissipation of mechanical energy in the flow field, that due to heat conduction along finite temperature gradients in the temperature field, and the entropic potential of the transferred energy.

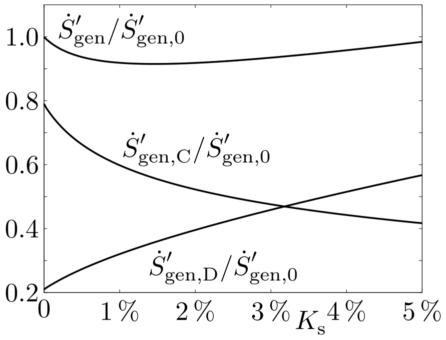
In a direct method approach CFD results with respect to the flow and temperature fields could provide the local rates of entropy generation per length. Here, however, we relate these generation rates to the friction factor f and Stanton number in way proposed in [18], p. 80, which is

$$\dot{S}'_{\mathrm{gen,D}} = \frac{32\,\dot{m}^3}{\pi^2\,\varrho^2\,T_\mathrm{m}\,D^5}\,f \tag{13}$$

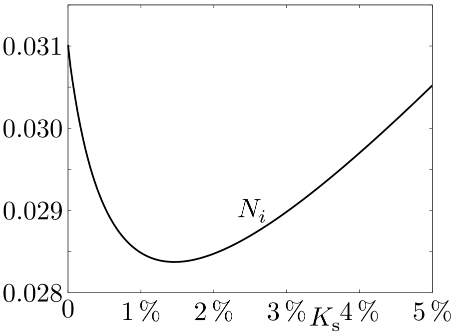
$$\dot{S}'_{\text{gen,C}} = \frac{\dot{q}'^{2}_{\text{w}}}{\pi\, k\, T_{\text{m}}^{2}\, \text{Re}\, \text{Pr}}\, \text{St}^{-1} \tag{14}$$

Equations (13) and (14) show that the entropy generation rate per length due to dissipation increases when f increases but that the entropy generation due to heat conduction decreases when St is increased and thus the heat transfer is improved.

Figure 7. Roughness effects at the cold side of the heat exchanger, see Figure 5, in terms of $\dot{S}'_{\text{gen,D}}$, $\dot{S}'_{\text{gen,C}}$ and N_i.



(a) Entropy generation.



(b) Energy devaluation number.

Figure 7a shows the influence of wall roughness on the single contributions $\dot{S}'_{\text{gen,D}}$ and $\dot{S}'_{\text{gen,C}}$ and on their sum $\dot{S}'_{\text{gen}}$. For a smooth wall the entropy generation due to dissipation is appreciably smaller than that due to heat transfer. For increasing wall roughness, however, this is no longer true. In accordance with the physics of the problem $\dot{S}'_{\text{gen,D}}$ increases while $\dot{S}'_{\text{gen,C}}$ is reduced. Since these effects are antipodal the sum may have an extremum which here is a minimum at $K_{\text{s}} = 1.5\,\%$ as can be seen in Figure 7b. Very different from the results given by η, here a distinct optimum appears as a result of two counteracting effects with a clear physical interpretation in terms of lost exergy.

Moreover, N_i has a rational background. $N_i \approx 0.03$ means that about $3\,\%$ of the entropic potential of the transferred energy are used by this heat transfer operation i on the cold side of the heat exchanger.

7. Conclusions

The energy devaluation number N_i for an energy transfer operation i puts a single operation or process into the perspective of the overall energy conversion from the initial exergy to the final anergy (when being part of the ambient internal energy). This is done by evaluating how much of the entropic potential E/T_∞ of the energy E is used in the "intermediate" operation or process i. Thus the process i is evaluated as part of the "devaluation chain".

Several aspects like the range of N_i between 0 and 1, its additive character and the existence of preceding and subsequent evaluation numbers $N_\ominus$ and $N_\oplus$ help to understand the physics of the process under consideration characterized by the energy devaluation number. Characterized by N_i the single operation or process is evaluated on the background of the whole process it is involved in.

References

1. Rant, Z. Exergie, ein neues Wort fï¿œr technische Arbeitsfï¿œhigkeit. *Forschung im Ingenieurwesen* **1956**, *22*, 36–37.
2. Herwig, H. The Role of Entropy Generation in Momentum and Heat Transfer. *J. Heat Trans.* **2012**, *134*, 031003:1–031003:11.
3. Kabelac, S.; Conrad, R. Entropy Generation During the Interaction of Thermal Radiation with a Surface. *Entropy* **2012**, *14*, 717–735.
4. Wijewardane, S.; Goswami, Y. Exergy of partially coherent thermal radiation. *Energy* **2012**, *42*, 497–502.
5. Bruges, E.A. *Available Energy and the Second Law Analysis*; Academic Press: New York, NY, USA, 1959.
6. Bejan, A. The concept of irreversibility in heat exchanger design: counter-flow heat exchangers for gas-to-gas applications. *J. Heat Trans.* **1977**, *99*, 374–380.
7. Fakheri, A. Second Law Analysis of Heat Exchangers. *J. Heat Trans.* **2010**, *132*, 111802:1–111802:7.
8. Hesselgreaves, J. Rationalisation of second law analysis of heat exchangers. *Int. J. Heat Mass Trans.* **2000**, *43*, 4189–4204.
9. Redecker, C.; Herwig, H. Assessing heat transfer processes: a critical view at criteria based on the second law of thermodynamics. *Forschung im Ingenieurwesen* **2012**, *76*, 77–85.
10. Mahian, O.; Kianifar, A.; Kleinstreuer, C.; Al-Nimr, M.A.; Pop, I.; Sahin, A.Z.; Wongwises, S. A review of entropy generation in nanofluid flow. *Int. J. Heat Mass Trans.* **2013**, *65*, 514–532.
11. Lucia, U. Maximum or minimum entropy generation for open systems? *Physica A* **2012**, *391*, 3392–3398.
12. Bejan, A. *Entropy Generation through Heat and Fluid Llow*; John Wiley & Sons: New York, NY, USA, 1982.
13. Herwig, H.; Kock, F. Direct and indirect methods of calculating entropy generation rates in turbulent convective heat transfer problems. *Heat Mass Trans.* **2007**, *43*, 207–215.
14. Gee, D.; Webb, R. Forced convection heat transfer in helically rib-roughened tubes. *Int. J. Heat Mass Trans.* **1980**, *23*, 1127–1136.

15. Colebrook, C. Turbulent Flow in Pipes with Particular Reference to the Transition Between the Smooth and Rough Pipe Laws. *J. Inst. Civil Eng. (London)* **1939**, *11*, 133–156.
16. Gnielinski, V. New equations for heat and mass transfer in turbulent pipe and channel flow. *Int. Chem. Eng.* **1976**, *16*, 359–368.
17. Incropera, F.P.; DeWitt, D.P.; Bergman, T.L.; Lavine, A.S. *Fundamentals of Heat and Mass Transfer*, 6th ed.; John Wiley & Sons: New York, NY, USA, 2006.
18. Bejan, A. *Entropy Generation Minimization*; CRC Press: Boca Raton, FL, USA, 1996.