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# Second law analysis for sustainable heat and energy transfer: The entropic potential concept

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## HIGHLIGHTS

- A new concept for process assessment is introduced.
- Entropy based assessment criteria are introduced.
- The new concept is applied to a plate heat exchanger as an example.

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## ABSTRACT

The choice of an assessment criterion for heat exchangers is crucial regarding the sustainability of processes and has troubled engineers for decades. In this paper it is shown that the basis for a physically meaningful assessment of *every* energy transfer (including conversions from one form of energy to another) lies in the correct interpretation of entropy generation. First it is shown that the effect of components in energy transfer situations on the available work (e.g. the power outcome of a working process) results from the flows of energy and entropy and the generation of entropy in a component. Next the *entropic potential loss number* assessment criterion is introduced, based on the *entropic potential* of an energy flow. It is explained how this universal criterion allows the assessment of arbitrary situations in energy transfer, illustrated by showing the advantages over the often used thermo-hydraulic performance parameter. Two examples show how the concept can be applied in numerical assessments and optimizations of heat exchangers and other components as well as in the assessment of processes.



## 1. Introduction

Every time a heat exchanger design is to be improved, the question arises “What does *better* mean?” If the heat transfer is intensified maintaining the same temperature levels *and* the pressure loss is reduced, the situation definitely can be called *better*. Unfortunately, most measures that intensify the heat transfer also increase dissipation and measures that reduce dissipation in most cases have a negative impact on the intensity of heat transfer. This is why heat transfer and pressure losses have to be weighed up against each other in heat exchanger design. Mostly a situation is assessed by a combination of the Nusselt number Nu for the intensity of the heat transfer and the friction factor $f$ for the dissipation.

Since, however, both of these numbers are 1st law criteria they are not influenced by the temperature levels of the fluid and the ambient. Thus, these dimensionless numbers only yield information regarding *quantity* but not *quality* of a heat transfer situation and therefore they are not best suited for an assessment with regard to sustainability. This becomes most obvious for low temperature heat flows e.g. in waste heat recovery or geothermal processes. Incorporating the 2nd law into the assessment (i.e. entropy and its generation) on the other hand leads to a meaningful and physically founded assessment.

### 1.1. Energy, entropy and their transfer

Strictly speaking only energy can be transferred, entropy not. The entropy of a system in a certain (macroscopic) state is nothing but a measure of the number of the possible microscopic configurations of the atoms of the system at the same (macroscopic) state. However, the result of an energy transfer between two systems either by conduction or by convection is that the entropy of one system is reduced while the entropy of the other is increased, just as if entropy was something that can be transferred. This is why entropy can only be “transferred” along with internal energy and

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**Nomenclature**

| | |
|---|---|
| $\dot{E}$ | energy flow rate [W] |
| $\dot{E}_{\text{in}}$ | energy flow rate at inlet [W] |
| $\dot{E}_{\text{out}}$ | energy flow rate at outlet [W] |
| $\dot{E}^{\text{ex}}_{\text{loss}}$ | exergy loss rate [W] |
| $f$ | friction factor [–] |
| $K_s$ | relative sand roughness [–] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $N_{\text{EPL}}$ | entropic potential loss number [–] |
| $N_{\text{EPL,c}}$ | entropic potential loss number of the cold side [–] |
| $N_{\text{EPL,h}}$ | entropic potential loss number of the hot side [–] |
| $N_{\text{EPL,w}}$ | entropic potential loss number of the wall [–] |
| Nu | Nusselt number [–] |
| $P$ | power [W] |
| Pr | Prandtl number [–] |
| $\dot{Q}_{\text{W}}$ | heat transfer rate at the wall [W] |
| Re | Reynolds number [–] |
| $\dot{S}$ | entropy flow rate [W/K] |
| $\dot{S}'_{\text{C}}$ | entropy generation rate due to conduction of heat per running length [W/K m] |
| $\dot{S}'''_{\text{C}}$ | entropy generation rate due to conduction of heat per volume [W/K m$^3$] |
| $\dot{S}'_{\text{D}}$ | entropy generation rate due to dissipation per running length [W/K m] |
| $\dot{S}'''_{\text{D}}$ | entropy generation rate due to dissipation per volume [W/K m$^3$] |
| $\dot{S}_{\text{gen}}$ | entropy generation rate [W/K] |
| $\dot{S}'_{\text{gen}}$ | entropy generation rate per running length [W/K m] |
| $\dot{S}'''_{\text{gen}}$ | entropy generation rate per volume [W/K m$^3$] |
| $\dot{S}_{\text{gen,c}}$ | entropy generation rate on the cold side [W/K] |
| $\dot{S}_{\text{gen,h}}$ | entropy generation rate on the hot side [W/K] |
| $\dot{S}_{\text{gen,w}}$ | entropy generation rate inside the wall [W/K] |
| $\dot{S}'_{\text{gen,0}}$ | entropy generation rate of the smooth pipe per running length [W/K m] |
| $\dot{S}_{\text{in}}$ | entropy flow rate at inlet [W/K] |
| $\dot{S}_{\text{out}}$ | entropy flow rate at outlet [W/K] |
| $\dot{S}_{\text{w,c}}$ | entropy flow rate at cold side of the wall [W/K] |
| $\dot{S}_{\text{w,h}}$ | entropy flow rate at hot side of the wall [W/K] |
| $\dot{S}_{\infty}$ | entropic potential [W/K] |
| St | Stanton number [–] |
| $T_{\infty}$ | ambient temperature [K] |
| $T_{\text{m}}$ | bulk temperature [K] |

therefore e.g. in a power plant the entropy can only leave the working fluid in the condenser along with energy, resulting in a reduction of the power outcome of the process. Since this interpretation of "entropy transfer" does not impose any constraints but improves understanding, it will be used throughout this paper.

### 1.2. Energy transfer processes

In Fig. 1 an arbitrary energy transfer process is shown. The transfer may include the conversion of the energy from one form to another (e.g. from internal to electrical energy). An energy flow rate $\dot{E}_{\text{in}}$ along with an entropy flow rate $\dot{S}_{\text{in}}$ (which may be equal to zero) enters the system, e.g. as the result of a combustion. Part of the energy can leave the system as power $P$, e.g. in form of mechanical or electrical power, carrying no entropy. The rest $\dot{E}_{\text{out}}$ is discharged to the ambient along with the entropy flow rate $\dot{S}_{\text{out}}$, e.g. through a cooling tower. The 1st law of thermodynamics (energy balance) reads

$$P = \dot{E}_{\text{in}} - \dot{E}_{\text{out}} \tag{1}$$

In this process entropy is generated at a rate $\dot{S}_{\text{gen}}$, yielding $\dot{S}_{\text{out}} = \dot{S}_{\text{in}} + \dot{S}_{\text{gen}}$. With the ambient temperature $T_{\infty}$ and $\dot{S}_{\text{out}} = \dot{E}_{\text{out}}/T_{\infty}$ follows

$$P = \dot{E}_{\text{in}} - \left(\dot{S}_{\text{in}} + \dot{S}_{\text{gen}}\right)T_{\infty} \tag{2}$$

This shows that if entropy is brought into an energy transfer process or is generated within it, not all energy can leave the system as power, because some of it is needed to discharge the entropy to the ambient. Furthermore the reduction of power by entropy generation, i.e. the loss of exergy $\dot{E}^{\text{ex}}_{\text{loss}}$ is

$$\dot{E}^{\text{ex}}_{\text{loss}} = \dot{S}_{\text{gen}}T_{\infty} \tag{3}$$

which is called the *Gouy–Stodola theorem*. Therefore losses are a synonym for entropy generation, so that a physically meaningful assessment criterion for the process must incorporate the entropy generation.

## 2. Assessment of energy transfers

### 2.1. The entropic potential concept

In Fig. 2 the course of an arbitrary energy flow rate $\dot{E}$ is shown. The component or process which is to be assessed is depicted as gray box in the background. According to our definition of a reference level on its start (0) the energy flow is not accompanied by entropy. In case of a conventional power plant this may be e.g. when the energy is present in form of fuel. In geothermal processes it is a virtual starting point, since the flow of thermal water is already accompanied by entropy. Due to the transfer entropy may be increased and carried by the energy flow. Upon entering the component the amount of entropy is $\dot{S}_{\text{in}}$. Inside the component entropy is generated ($\dot{S}_{\text{gen}}$), so that the accompanying entropy flow rate grows to be $\dot{S}_{\text{out}}$ upon leaving. At some point later the energy flow is finally released to the ambient ($\infty$). The entropy flow rate at this point is called the entropic potential of the energy flow

$$\dot{S}_{\infty} = \frac{\dot{E}}{T_{\infty}} \tag{4}$$

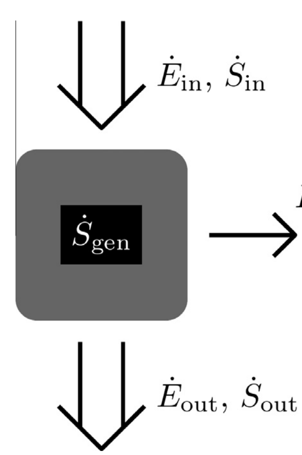


**Fig. 1.** Arbitrary energy transfer process.