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Defining the Potential of Usable Waste Heat in Industrial Processes with the Help of Pinch and Exergy Analysis

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This paper aims at giving a definition for waste heat in analogy to the definitions of natural resources and reserves. It aims also at presenting a method for identifying, characterizing and quantifying the available waste heat of an industrial system that can be converted into a useful form. A distinction is made between avoidable and unavoidable waste heat. In order to measure the entire useful potential of waste heat, exergy is used for characterization.

1. Introduction

The importance of energy efficiency has been emphasized by economic and political actors (more than 50 % contribution to CO_2-abatement in IEA 450 Scenario (IEA, 2009)). Cost savings, the conservation of fossil resources and the limited space availability of renewable resources are the driving forces behind the development of more efficient processes. One way to increase the value added per unit of energy spend is the use of waste heat to produce additional services. This has to be done in a way that future improvements of a process are not inhibited by investments in waste heat recovery systems that might become obsolete. Thus a methodology is needed to identify the potential of usable waste heat, pointing out economic commitments attached.

1.1 Use of the term "waste heat"

Waste heat is a commonly used term in literature (Hung et al., 1997). Even though or because everybody has an idea of its' meaning, formal definitions are scarce and most of the time insufficient. Synonymously used terms are low grade heat (Ammar et al., 2012), secondary heat and in some cases conversion losses or more general inefficiencies (IEA, 2009). The majority of the literature and legislators define waste heat simply as heat dissipated to the environment, often disregarding of its temperature and possible use (Goldstick and Thumann, 1986; IEA, 2011). Ammar et al. (2012) go a step further in their analysis, introducing a notion of usefulness within the process. That means heat which is in a temperature range viable for the process is not considered as low grade heat. The available waste heat is then defined as the heat available for temperatures below a temperature $\mathrm{T_h}$ such that:

$$T_{h,min} > T_h > T_c + \Delta T_{min} \tag{1}$$

With T_c as the cold source/heat sink temperature and ΔT_{min} the minimum temperature difference in the heat exchange, $T_{h,min}$ is the lowest temperature needed in the process. This dentition conveys the idea of heat recycling and thus process optimization with a clear hierarchy:

1. heat recycling within the process (reduction of resource consumption by reuse of available heat).

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2. heat recovery by a secondary process (delivering other useful services and thus increasing the system boundaries).

This definition does not take into account the quantity of heat available at different temperature levels with the risk of ”loosing” opportunities for recovery in a secondary process. It neither considers the overall energy balance which indicates that not all the heat can necessarily be recovered. In order to identify and quantify the residual heat it is therefore necessary to apply the concepts of maximum heat recovery as considered in the *Pinch Analysis* and *Process Integration* that allows to handle the system boundaries in a systematic way.

2. Pinch-Analysis and Process Integration

Pinch-Analysis was developed by Linnhoff (Linnhoff and Flower, 1982) and is a way to identify maximum heat recovery by counter current heat exchange within a process such that the overall energy consumption of the process is minimal (Minimum Energy Requirement (MER)). A detailed description of the method can be found in (Maréchal, 2008; Kemp 2007). Shortly described, in a Pinch Analysis processing steps are analyzed in order to identify the needs for heating or cooling to perform their function/transformation from raw materials to useful products and byproducts. From this analysis results a list of heating and cooling requirements, stating the temperatures and the quantities (enthalpies) of the needed heat streams. If heat has to be evacuated from a unit we talk about a hot stream because it can be used as a hot source. If a process unit needs heating we talk about a cold stream since it needs to be heated up (heat sink). Subsequently all hot and all cold streams are summed up to form the hot and cold composite curve, respectively. Once the composite curves, including all hot and cold streams, are prepared they are used to identify the amount of heat that can be recovered, reusing the heat of the hot streams to (pre-)heat the cold streams.

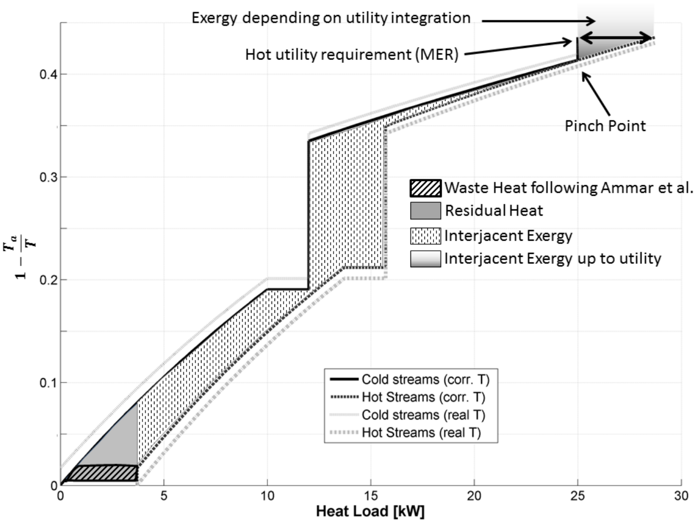

Figure 1: Hot and cold composite curves with Carnot-Factor, showing interjacent exergy.

In order to do so, minimum temperature differences ΔT_{min} between hot and cold streams for the heat exchanges are defined. ΔT_{min} depends on the heated and cooled fluids and thermodynamic states as well as the needed heat exchanger surface. Oftentimes, and thus also in this paper, if not mentioned otherwise, the corresponding $\frac{\Delta T_{min}}{2}$ is directly added or subtracted to or from the respective stream temperature, leading to a composite curve with corrected temperatures which shows the available heat or needed cooling requirements of the process. The correct choice of ΔT_{min} is crucial since it represents a trade-off between the investment in heat exchanger surface and energy savings. The

value is selected for given economic conditions, from an energy and investment point of view. It guarantees that an identified heat recovery will be economically feasible.
To describe the “usefulness” of the heat, which is recovered or not, the concept of exergy can be used. In order to represent the thermal exergy in the composite curve diagram, the temperature is replaced by the corresponding

$$Carnot-Factor = \Theta = 1 - \frac{T_a}{T} \quad (2)$$

Where T_a is the ambient temperature. In this representation the surface is representing the heat exergy in the notation of Borel and Favrat (2010):

$$Heat\ exergy\ (received)\ [W] = \dot{E}_q^+ = \int \Theta \delta \dot{Q}^+ \quad (3)$$

Following this approach, the hot composite curve also defines a given amount of exergy available, while the cold composite curve defines a given amount of exergy required. The balance therefore represents the net exergy balance of the system.
The Pinch Analysis divides the process into two subsystems, above and below the pinch temperature, where the minimum temperature difference occurs (the so called *pinch point)*. Above the pinch point, it is characterized by an overall heat requirement. Below, there is an overall necessity for cooling. This requirement is however divided into two parts, a part above the ambient temperature that defines an amount of heat to be evacuated to the environment and below the ambient temperature, which is heat to be extracted from the process streams using refrigeration cycles. In consequence this means that no stream above the pinch point should be cooled by a cold utility but rather by internal heat exchange, and no stream below the pinch point should be heated by means of a hot utility but rather by heat recovery. Additionally no internal heat exchange should cross the pinch point (no stream below the pinch should be heated with a stream from above,) if one wants to reach maximum heat recovery.
Recovering heat internally with the help of a heat exchanger network (HEN) is not the only way to reduce the MER, other techniques of process integration show that introducing heat pumps, vapor re-compression, pressurized condensers etc. can reduce the MER by bringing streams from below to above the Pinch (Maréchal and Kalitventzeff, 1998).
A further important measure for a successful analysis of the available waste heat is to consider the state in which the streams enter and leave the system. Considering the possibility that these streams can be out of equilibrium with the environment, heat exchange may therefore allow for further heat recovery. That means any analysis should include the possible energy gains by cooling leaving streams to the temperature of the environment, expand to ambient pressure or for waste streams, bring to a chemical state where the exergy content is used (which can mean oxidation e.g. in an incinerator, gasification for internal use or use as a commodity etc.). One of the drawbacks of conventional pinch analysis is that it defines a heat requirement to balance the needed heat; it does not represent the way the energy is converted to supply the heat requirement.
Examples for the application of the process integration methods are available e.g. for sites with heat exchange restrictions in pulp and paper industry (Becker and Maréchal 2012) and for the agro-food industry (Muller et al. 2007).

3. Defining Waste Heat

The definition of waste heat is intended to define the amount of heat that can be converted into useful forms like electricity or district heating, without increasing the Minimum energy requirement.

3.1 Residual heat – Unavoidable Waste Heat

The use of the heat cascade allows to identify the pinch point and to deduce the amount of heat to be evacuated below the pinch, which requires the use of a cold utility. This heat that *has to be evacuated* will be called the *residual heat*. The temperature enthalpy profile of the residual heat can be deduced from the heat cascade calculation and the corresponding Grand composite curve. The residual heat can be used for any purpose without affecting the minimum energy requirement of the process. This heat is the *unavoidable* amount of waste energy that a process produces. The residual heat can be significantly more and with higher temperature than the secondary heat as it was defined by Ammar et al. (2012). Figure 1 shows heat recovery in a process (Carnot composite curves), “secondary heat” as defined by Ammar et al. (2012) and the above defined residual heat.

3.2 Avoidable Waste Heat

All additional heat that is used from the process for waste heat valorization is the creation of inefficiency and leads to a cementation of an inefficient operation due to the “more in more out” principle. That means that the additional heat is in fact the result of a surplus of heat that has been spent in the process. This waste heat is avoidable and does not have to be used for a secondary application.

3.3 Residual heat of the utility

The residual heat of the utility system is the residual heat calculated from the heat cascade when integrating the utility system. The residual heat of the utility system results from the fact that the minimum energy requirement is supplied to the industrial system by converting energy resources. The conversion process generates hot and cold streams that are integrated with the process streams and therefore can profit from synergies with the process streams. The difference to the process streams is that the utility streams have flow rates that are obtained by minimizing the cost of the heat delivery. This considers therefore the different forms of energy. As a consequence supplying heat means optimizing the combined heat and power production.

3.4 Interjacent Heat Exergy

If a process is represented as a cold and a hot composite curve in a diagram that uses the Carnot-Factor over Heat, following Eq. 3, the surface below the cold composite curve is the exergy that has to be spend ideally to satisfy the heating needs, the surface below the hot composite curve represents the work that ideally can be extracted from the process’ cooling needs. Of course there is no ideal heat pump and no ideal (Organic) Rankine Cycle, thus it is evident that it is advantageous to use the exergy from the hot streams to satisfy the needs of the cold streams. These streams only touch in pinch points, this leaves a certain amount of exergy “lying” between the hot and the cold composite curve (Maréchal and Favrat, 2005). Due to its character we call this interjacent heat exergy.

$$Interjacent\ heat\ exergy\ [W] = \int \Theta \delta \dot{Q}^{+}_{hot\ streams} - \int \Theta \delta \dot{Q}^{+}_{cold\ streams} - \dot{E}^{-}_{residual\ heat} \quad (4)$$

In a simple heat exchanger network this exergy is destroyed and thus called transformation loss. Minimizing the transformation losses, which means using as much of the interjacent exergy as possible

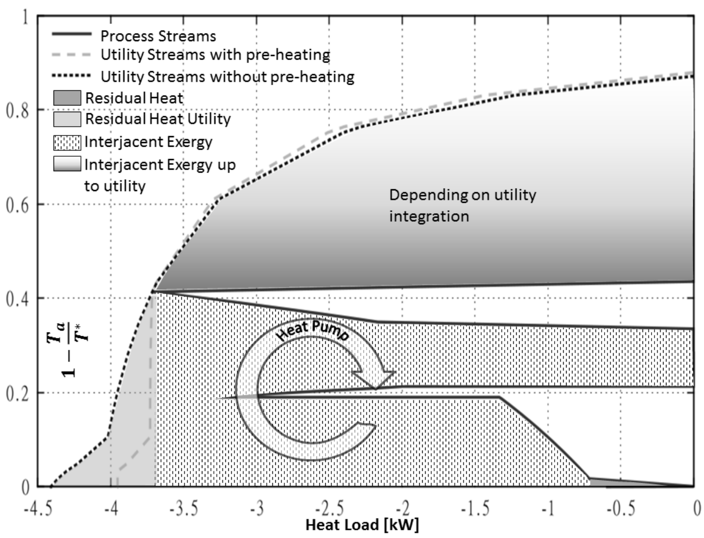

Figure 2: Grand composite curves with Carnot-Factor, showing interjacent exergy and residual heat and a possible location for a heat pump in order to access an exergy pocket, as well as a utility.

improves the overall efficiency of a system. Since this exergy, if it is below the pinch point, can be used without affecting the MER, it is part of the waste exergy potential and should be counted as waste heat, even though it is no heat in a narrow sense of the term. Figure 1 illustrates the potential of the interjacent heat exergy.

The accessibility of the *exergy below the pinch point* depends highly on the shape of the composite curve and the desired application; in some cases a turbine with bleeding or extraction can be used, in other cases the use of additional units may be necessary. Figure 2 shows the Grand Composite Curve corresponding to the Composite Curves in Figure 1; T^* indicates the domain of corrected temperatures. It can be seen that the use of a heat pump gives access to a large potential of additional exergy.

Exergy below the ambient temperature can be used as a heat sink e.g. for an ORC or for delivering cooling services for external users (AC for buildings).

A difficulty is the accessibility of the *exergy potential above the pinch point*. A general rule has to be stated: *The interjacent exergy above the lowest pinch point is not accessible without increasing the energy input to the process.* In other words, the use of this exergy is directly linked to the utility that is used to deliver the heat services for the process; the utility has to be sized accordingly if this exergy is to be accessed.

3.5 Technological choices

The results of the integration of a process partially depend on the technology that is used for making the transformations within the process. Oftentimes the technology was chosen without being aware of the global pinch point of the process and prior to integration efforts. These choices can make part of the heat unavailable or increase the need for heating, if no technology shift is performed. This leads to two different sets of hot and cold composite curves; one set (I) that is resulting from the technical analysis (e.g. the needs of an evaporator) and one (II) that actually represents the (chemical/ thermodynamic/ mechanical) needs of the processing steps (e.g. the energy required to evaporate).

The technological choices and constraints lead generally to higher (in the best case equal) MER when compared to the strictly “needs based” analysis. This has the effect of increasing the amount of available exergy, due to the “more in more out “-principle (all the energy that enters the process has to leave it, either included in the product or thermally e.g. by dissipation).

3.6 Economic aspects

By means of the integration, certain economic evaluations are included in the definition of residual heat and interjacent exergy (mainly by the used ΔT_{min} and the integration of equipment (heat pumps etc.)).

On the side of the waste heat use, economic considerations play the same role and decide in the end over the use or dissipation of the waste heat. In order to make the decision a case by case study is necessary. Especially the use of interjacent exergy above the lowest pinch point has to be evaluated carefully, since the need for combustibles increases. Additionally, results are only partially transferable from one site to another because the price structure of energy (sold and bought) may vary significantly from one site, country or company to another. The legislators may encourage investments in some places while they do not accord particular attention to waste heat in others. In the end there are two measures of waste heat; the waste heat (a) that can be used in an economic viable way and the waste heat (b) that is potentially available disregarding economic factors.

3.7 Definition

With these considerations we are able to give a definition on waste heat, that is exploitation oriented and in analogy to natural energy vectors, such as coal or gas:

Reserve: Waste heat as a reserve is the net exergy that unavoidably leaves or is lost within an existing process after its integration, minus the exergy that cannot be recovered for technical or economic reasons.

Resource: Waste heat as a resource is exergy that unavoidably leaves a process or is lost within it independent of the technological choices made within the process.

The waste heat reserve is thus defined in respect to the constraints of the used technology and economic aspects (Ia) while the waste heat resource is a theoretical potential (IIb). With changing energy prices, the results of the process integration change; the values are also influenced by evolving technologies. That means that both values may change. This is another analogy since natural reserves and resources are subject to changes due to changing prices, additional exploration and evolution of exploitation techniques.

A particularity is that the waste heat reserves may be larger than the resources. This is due to the fact that there are two opposed effects: the reserve has a tendency to be bigger than the resource induced by the technology choices that lead to a bigger MER and thus more waste heat; at the same time it is reduced when compared to the resource because of economic constraints. If the first effect is more important, and heavy technological constraints are present, the reserve is bigger than the resource; if the second effect is more important, for example if the temperatures of the residual heat is low or the interjacent exergy is difficult to use, the reserve is less important.

4. Conclusion

We pointed out the difference between avoidable and unavoidable waste heat. We have defined waste heat as the sum of the exergy that is available in a process after pinch analysis and process integration, both as a reserve, considering economic and technological aspects, as well as a resource, stating the theoretical potential that is present in the process.

This definition is exploitation and application oriented and gives a tool for engineers to quantify rigorously the potential for waste heat recovery within their process, without using avoidable waste heat. Additionally it is a useful definition for making statistics, e.g. to help identify future potentials and to measure the impact of political measures.

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