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Energy Efficiency Improvement through Technology Optimisation and Low Grade Heat Recovery – Industrial Application

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Small and Medium-sized Enterprises (SMEs) form the backbone of national economies and especially of the food industry, which in Ireland is made up of over 90 % SMEs. These foods related SMEs have very similar structures, usually containing a small or medium boiler, ovens, chillers, heat exchangers and an extended water network. Another common characteristic is the low energy efficiency due not only to the relatively small size of equipment but also to the non optimisation of the heat network and substantial waste heat and effluent emissions. Therefore, it is an excellent environment to apply system analysis, process integration and optimisation methods, waste heat recovery and waste emission reduction technology with expected high economic and environmental impacts.

In this paper the opportunities for energy efficiency improvement with the example of a medium-sized company which produces sliced cooked meats are presented. For this purpose a complex analysis of the heat network is carried out using guided redesign of the technology based on Process Integration, improving the internal heat exchange in order to increase and consequently to minimise the exit exergy (available useful heat) reducing the energy supply. Additionally the application of an advanced technology for boiler flue gas low grade heat recovery with preliminary humidification of the combustion air using waste heat is proposed. As a result an overall efficiency improvement of 20-25 % (respectively less fuel consumption and carbon emission reduction), about 68 % water consumption and effluent reduction and up to 3.8 times less NO_x gas emissions is estimated.

1. Introduction

Energy efficiency is a key word in modern industry being the basic factor of competitiveness, sustainability and environment protection. At the same time it is estimated (USDOE, 2008) that still as much as 20 % to 50 % of all industrial energy consumption is ultimately released as a waste heat. Three main ways to improve energy efficiency can be pointed out, ranked in order of descending capital investments:

(1) Development and implementation of new energy effective technologies and equipment.
(2) Retrofitting existing technologies improving the energy efficiency, based on the best practices and reducing the waste heat through system integration.
(3) Development and application of effective techniques and equipment for waste heat recovery and reuse in the technological process.

While the first approach is the most capital expensive and is somewhat linked generally to scientific and technical progress, both others lead to the discovery of large and relatively cheap opportunities for energy efficiency improvement. The aspiration for recovering these resources is reflected in intensive research work developing advanced methodologies in System Integration, Heat Exchanger Networks (HEN), Pinch and Exergy analysis. As a result substantial progress in this field has been achieved. However in the majority of the works either problems that are too general are discussed (Feng et al., 1997) or contrariwise, the interest is focused on solving concrete technological cases in detail, using specific and sometimes complicated physical and mathematical interpretations, for instance: direct contact flue gas

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heat recovery (Zhelev and Semkov, 2004) or subambient cooling for natural gas liquefaction (Aspelund et al., 2007).

The aim of the present work is to propose a simplified method for the quick estimation of the potential energy improvement in existing industrial systems. This method is built on a comparative basis, requiring limited system analysis and with no pretensions to full optimisation is rather orientated towards achieving better performance through reducing the local exergy losses in a system, combined by low grade heat recovery.

The method is demonstrated in the case study of a medium-sized food enterprise, with very typical energy and water management structures.

2. Theoretical

Usually the heat network system analysis leans on the mass and heat balance, based on the first law of thermodynamics. This also applies to Pinch Analysis for discovering the thermal pinch points and the potential internal heat integration possibilities. As is shown in many works e.g. in Feng et al. (1997), the energy balance is only a quantitative characteristic while the exergy also indicates energy quality. The exergy balance is based on the second law of thermodynamics and generally reflects the useful available energy taking into account the irreversibility of the processes and their thermodynamic parameters related to the environmental ones. Exergy is not subject to the law of conservation and any thermodynamic irreversibility leads to exergy destruction, when some exergy transforms to *anergy* and thereby is definitely lost.

2.1 Principal (basic) expressions

The total exergy of a stream is the sum of the mechanical (kinetic and potential) and the thermal exergy. In the heat network systems usually the mechanical exergy can be neglected being much less than the thermal exergy. Thus, according to technical thermodynamics (Kimenov, 1981), the total exergy can be expressed by the equation:

$$E = (H - H_0) - T_0(S - S_0) + E_{ch}\,, \tag{1}$$

where (H) is the enthalpy, (S) is the entropy and the index "$_0$" refers to the environmental conditions. The chemical exergy (E_{ch}) drops out if no chemical reaction and mixing or/and separation heat is present. In our study we will use it only for the fuel combustion in the boiler. Eq.(1) can be applied either to heat and thermo-mechanical processes, acquiring specific forms for maximum obtainable work at constant pressure or temperature (Aspelund et al., 2007). The heat exergy of a heat stream (Q) can be expressed also as:

$$E = Q\left(1 - \frac{T_0}{T}\right), \tag{2}$$

where

$$\eta_C = 1 - \frac{T_0}{T} \tag{3}$$

is the *Carnot-Factor*. If a process in the stream operates at variable temperatures e.g. from T_1 to T_2 the temperature in Eq.(1) and Eq.(2) can be calculated as a mean temperature

$$T = \frac{T_2 - T_1}{\ln\dfrac{T_2}{T_1}}\,. \tag{4}$$

2.2 Method concept

The main concept of the proposed method can be elucidated with the help of Figure 1. A system with dashed line boundary is presented, which consists of *N*-number P_i processes, each one with input and output exergy streams. The input exergy is represented as an exergy (heat) supplying (hot) stream $\left(E_i^Q\right)$ and an external exergy input (cold) stream $\left(E_i^{in}\right)$. The $\left(E_i^{out}\right)$is the output exergy stream from the process P_i. The stream (I_i) is the inevitable exergy loss due to the irreversibility of the process.

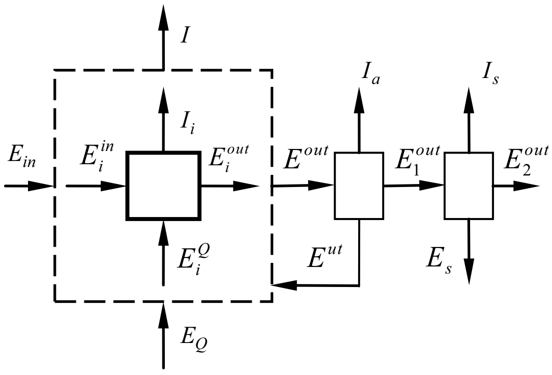

Figure 1: Individual process and system exergy balance

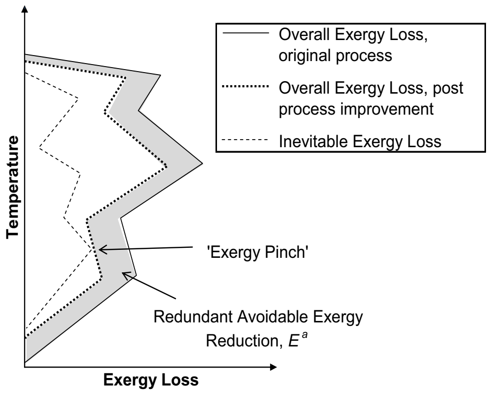

Figure 2: Exergy Composite Curves

Thus the exergy balance of a local process is:

$$E_i^{in} + E_i^Q = E_i^{out} + I_i \tag{5}$$

As the (I_i) is the exergy which definitely is transformed to anergy in the process P_i the total exergy loss of the system will be:

$$I = \sum_{i=1}^{N} I_i \tag{6}$$

The output exergy from one process can be considered as a sum of two exergy streams.

$$E_i^{out} = E_i^{ut} + E_i^a , \tag{7}$$

where $\left(E_i^{ut}\right)$ is the utility exergy for the process, e.g. in the case of a heat exchanger it is the exergy of the heated stream; $\left(E_i^a\right)$ is the avoidable output exergy, e.g. the hot stream from a heat exchanger. The quality of the process is expressed by the *Internal exergy performance factor*, representing the ratio of the useful and introduced exergy. Using the Eq.(5) and Eq.(7) it is obtained:

$$\xi_i = \frac{E_i^{ut} - E_i^{in}}{E_i^Q - E_i^a} = 1 - \frac{I_i}{E_i^Q - E_i^a} \quad . \tag{8}$$

The internal exergy performance factor depends solely on the equipment type and the required exergy supply i.e. (I_i) and the difference $\left(E_i^Q - E_i^a\right)$ are constant. Therefore the more supplied exergy $\left(E_i^Q\right)$ compared to the required is introduced more avoidable exergy $\left(E_i^a\right)$ is released, and vice versa, decreasing the supplied exergy decreases the released avoidable exergy. The minimum is the avoidable exergy which is thermodynamically sufficient for the required utility exergy $\left(E_i^{ut}\right)$ and covering the inevitable loss (I_i). All additional avoidable output exergy is redundant and is to be reduced. The efficiency can be generally improved by the integration of a few processes rearranging the flow chart structure e.g. heat exchangers connected in series from point of view of the hot stream. The exergy supply stream for each process, except the first, can be replaced by the avoidable exergy exit from the previous process. After some uncomplicated algebraic transformation the overall exergy performance factor, received, of such a system is:

$$\xi_{ov} = 1 - \frac{\sum I_i}{\sum \frac{I_i}{1 - \xi_i}} \quad . \tag{9}$$

A similar approach can be applied to the entire system using the Eq.(7) and Eq.(8) with removed index *(i).* Here the exit exergy $\left(E^{out}\right)$ from the system can be considered as a sum of the utility part, which can be reused in the system and an avoidable part $\left(E^{a}\right)$, which cannot be used in the system because of no remaining integration capacity. To recover this utility exergy a new heat recovery process is to be inserted where the exergy balance is described as

$$E^{out} = E^{ut} + E_1^{out} + I^a \ . \tag{10}$$

Here $\left(I^{a}\right)$ is the exergy destruction (inevitable loss) from the process and $\left(E_1^{out}\right)$ is the exergy output not yet avoidable in this system. However some part of it $\left(E_s\right)$ could be used eventually for secondary purposes outside of the examined system. In this case an additional heat recovery process must be inserted as it is shown in Figure 1.

Returning to $\left(E_1^{out}\right)$ it is important to mention that even if not recoverable in the system it usually offers an additional opportunity for efficiency improvement. As with the above comment for a separate process regarding the minimal required and redundant released exergy there is also a minimum required waste exergy, limited by a single process in the system with the least driving force. This process and the minimum exergy loss equal to the inevitable exergy loss can be formally called “Exergy Pinch” and could be determined from the composite curves in the Temperature – Exergy diagram (Figure 2). All exergy output above this value is redundant and is released as waste exergy according to the principle supply. “more in more out” as shown in (Bendig et al. 2012). This redundant waste heat is a result of the surplus of energy supply and can be avoided by decreasing this supply.

Now the guide lines of the proposed method can be systemised in the following steps:

(1) Identification of non effective elements (processes and equipment) in the system using simple heuristic rules (such as too hot a stream is used for heating too cold a stream, mixing heating with condensate loss etc.)
(2) Improving the efficiency by replacing the ineffective processes by better ones with less inevitable losses – Eq.(6).
(3) Improving the efficiency by retrofitting the heat exchange structure aspiring to more serial reuse of the energy – Eq.(9).
(4) Improving the overall efficiency of the system by introducing external heat recovery processes.
(5) Reducing the overall heat consumption by decreasing the redundant output heat to the allowed minimum, determined by the Exergy Composite Curves.

Following these steps it is not necessary to have a full detailed exergy analysis of the system; it is enough to estimate the exergy efficiency improvement of given elements of the system on a comparative basis only.

3. Method application, industrial case study

The proposed method was tested on the example of a medium-sized company producing sliced cooked meat (chicken). The simplified technological flow chart of the production and the main parameters are shown in Figure 3. The energy source is a liquid fuel fired boiler with 3 t/h maximum productivity. The major steam consumer is the Main oven, which is a continuous operation, convection-based system, impingement type oven (Kerry and Kerry, 2011). There are three main zones in the oven. The central zone is the essential cooking zone where the steam is directly introduced, additionally, from the top, heat is supplied *(Q_p)* by a coil, heated by hot flue gas from propane burners. The zones before and after the central zone are complementary, the first one is for preheating the meat, the last one is for after cooking. The belt with the meat moves above the surface of a hot water bath. The water is heated by the direct introduction of steam. Overall about half-half steam amount is introduced in the central and peripheral zones. Another relatively small steam consumer is the Batch oven. There is substantial consumption of hot water in the production. Analysing the flow chart at a first glance the non effective processes from energy and exergy point of view can be seen: water heating by direct high potential steam introduction and the condensate loss. There are also big hot gas waste streams – boiler flue gas and the exhaust from the Main oven. The latter, according the mass balance, contains water vapour approximately equal to the overall steam introduced into the oven. The only heat recovery is from the effluent by the heat exchanger (HE).

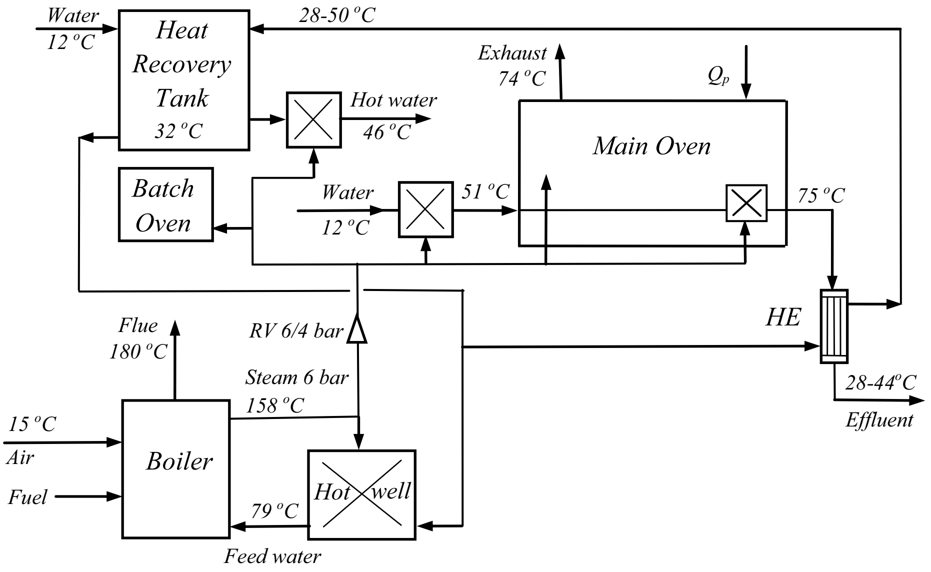

Figure 3: Simplified flow chart of the cooked meat production

Applying the above described method an improved version of the flow chart is proposed (Figure 4). The parameters of the Main oven are not changed, even though there is big potential for further reduction of steam consumption. In the new flow chart there is no more - heating by direct steam mixing. Instead the water to the Main oven is preheated by the heat exchanger (HE1) using low grade heat from the exhaust recovered by the First generation contact economiser system (CE1). The preheating of the boiler feed water through mixing is excluded. Instead two heat exchangers in series are introduced: the interim reboiler (RB) and the heat exchanger (HE2). The condensate is returned through the reboiler *(RB)* where secondary low pressure steam is generated for the water bath heating in the Main oven. Furthermore the

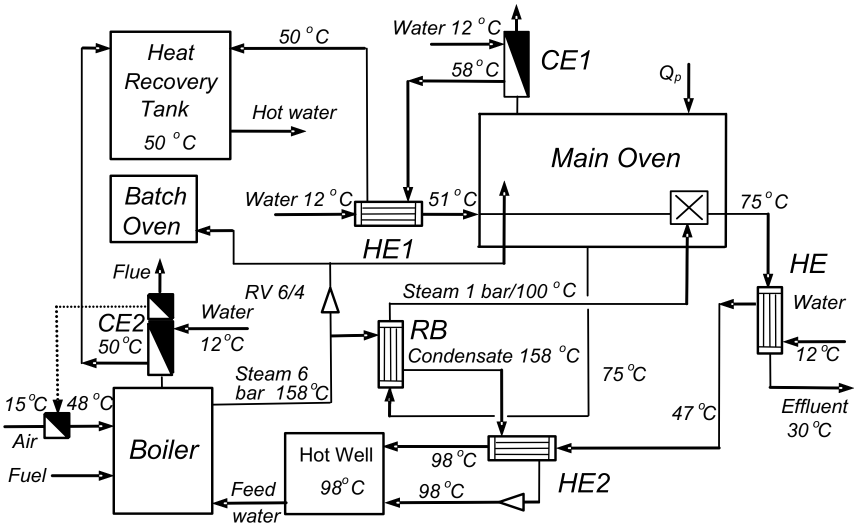

Figure 4: Improved technology flow chart

condensate preheats the feed water in the heat exchanger (HE2) and through the pressure reducing valve enters the feed water storage Hot Well at atmospheric pressure. In addition low grade heat from the boiler flue is recovered by the Second generation contact economiser system (CE2). One part of this heat is used for preheating and pre-humidifying the combustion air, part heats cold water for the hot water demand. The redundant heat from the economiser (CE1) is also used to cover the hot water demand.

Figure 5: First generation contact economiser

Figure 6: Second generation contact economiser system

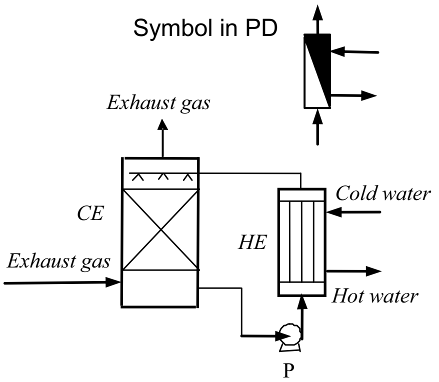

Figure 5: First generation contact economiser

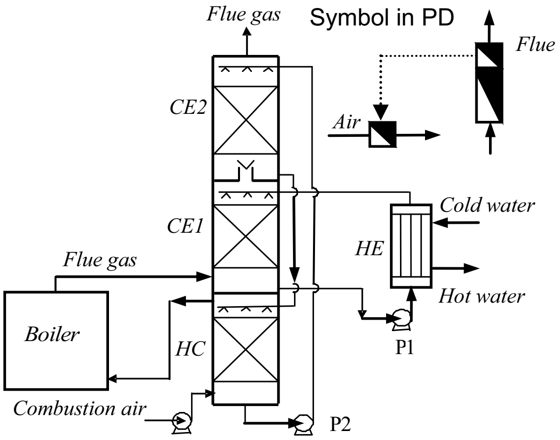

Figure 6: Second generation contact economiser system

Both systems contact economisers operates by direct gas-water heat exchange in packed columns and the recovered heat is transferred to the consumer by heat exchanger.

In the first generation system (Figure 5) the hot gas is cooling in the column (CE) thereby the major part of the moisture in the gas condenses. The second generation system (Figure 6) (Kolev et al. 1986) contains two more packed columns, one (HC) for preheating and pre-humidification of the combustion air and the other (CE2) to supply hot water to (HC) at the expense of further cooling of the flue gas. The advantage of this system is the increased temperature of recovered heat and a reduction of up to 3.8 times in NO_x emissions in the flue gas (Kolev et al. 1993).

4. Conclusions

A simplified method for efficiency improvement of heat networks based on comparative exergy analysis is proposed and the main guidelines for the application are given.

The method was tested on an industrial case study, where advanced technology for direct contact low grade heat recovery from hot gases is also proposed. The overall impact of the improved technology results in 24.5 % reduction of the steam consumption and about 3.8 times reduction of NO_x emissions. Furthermore a reserve of recovered heat of about 71 % of the original steam consumption, as 60 °C hot water, is additionally available.

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