A method for energy optimization and product quality improvement in manufacturing processes

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Abstract

Manufacturing processes are diverse by nature. Consequently, energy efficiency of each process requires a specific analysis leading to significant costs, SMEs (Small and Medium-sized-Enterprises) cannot always sustain such costs.

The present paper introduces a method for Energy Optimisation of manufacturing processes and product quality improvement during manufacturing. This innovative method is based on a 4-step analysis that allows to rapidly identifying the potential energy savings in industrial processes.

The 4-step method consists in: (1) the process definition, (2) the analysis of the detailed synopsis of production lines (considering energy and mass fluxes), (3) the analysis of energy consumptions and production volumes, and (4) energy efficiency assessment by identification of energy savings and technical option proposals.

The first step is based on the preliminary expertise of the considered process. Process efficiency is analysed based on the theoretical minimum energy requirement, leading to the identification of the best available technologies (BATs) for the considered process, and the optimal energy efficiency.

For the second and third steps, specific data of the process are collected. The process energy consumption and the production information are obtained from the production manager. When needed, measurements could be performed to complete the energy and mass balances. The actual energy efficiency of the manufacturing process is then calculated.

The fourth step consists in the comparison of the different energy ratios. Based on these ratios and on the knowledge of the actual process, energy savings are evaluated, technical solutions for energy efficiency improvement are proposed and first economic analysis is carried out.

Introduction

Manufacturing processes are diverse by nature. Consequently, energy efficiency[1] assessment of each process requires a specific analysis leading to high costs, which are not always sustainable for SMEs. This paper proposes an energy analysis methodology to improve energy efficiency in industrial processes, based on the product quality and plant productivity, which can also be improved in some cases. It is intended for use in the energy analysis of SME manufacturing plants, and proposes a systematic way to identifying with minimum cost, energy saving opportunities and energy efficient solutions with a technical-economical assessment.

Two different actions should be held separately, the energy diagnosis and the energy analysis. This paper analyses both, defining a new systematic method containing both energy auditing and analysis. This method is called Process Energy Analysis (PEA).

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[1] Energy efficiency has many different definitions, each used in the proper context (IPPC [3]). When energy efficiency term is used in this paper, it does not mean a particular value defined for a particular operation analysis, it is used as a general meaning.

ENERGY AUDITS

Many authors have proposed systematic approaches to performing energy audits. The level and type of the energy audit is usually determined by the cost of the audit, and therefore the duration and the type of measurements (Thumann 1995). The AFNOR best practices referential defines the energy audit (or energy diagnosis) objectives as to establish an industrial plant assessment of the energy situation in order to determine energy saving opportunities (AFNOR 2006). According to the ambition of the energy audit, the results can be more or less precise. The IPPC directive (Integrated Pollution Prevention and Control) defines the energy audit as an energy usage analysis to identify the main consuming operations and types of energy used, where it can also lead to identifying cost effective energy saving opportunities (IPPC 2006).

Two essential parts define the energy audit (Thumann 1995): data acquisition, and data analysis. The accuracy of the results depends on the type of the energy audit performed (IPPC 2006). The energy analysis as defined above is the data analysis leading to the proposed solutions.

ENERGY OPTIMISATION METHODS FOR INDUSTRIAL PLANTS

Energy optimisation methods are common for analysing data collected from the data acquisition of the energy audit. Considerable research and improvements in industrial process energy analysis have been made over the past decades, especially after the energy crisis of the 70s. Two good examples of these methods are the Process Integration based on the Pinch analysis developed by Linnhoff and March (Linnhoff March 1998), and the industrial systems exergy analysis based on the combined first and second laws of thermodynamics (Le Goff 1979, Tondeur, Bejan). However, most developed energy optimisation methods lead frequently to high cost incremental improvement in site energy consumption (Kissock 2001, IPPC 2006).

The Pinch analysis as defined by Linnhoff and March (Linnhoff March 1998), is a cost optimisation process to recover thermal energy available in circulating fluids. This method of analysis can be applied to the process or the plant utilities, but remains an "outside-in" approach, based on the given data and operating modes of the existing system. An "outside-in" approach, as defined by K. Kissock from the university of Dayton USA (Kissock 2001) is an analysis method that concentrates on the energy conversion system itself rather than its end-use.

Technically, the Pinch analysis is limited by the three major constraints: the geographic locations of the energy streams which may lead to great losses during energy transportation across the plant, the time dispersion of the same energy streams which implies the need of energy storage that may lead to extremely high costs, and the technological difficulty occurring in the heat exchanger design in case for some energy streams, such as waste water that may generate biofilm leading to fouling and inefficient heat exchange.

According to the IPPC directive on energy Efficiency (IPPC 2006), Pinch is a heavy and expensive tool for companies, where a great number of data is needed to perform the analysis. Experts and software simulations are needed to apply the Pinch analysis to a plant.

Pinch analysis can optimize the energy flow in the plant but cannot determine the best-suited energy source or technique to produce the required product. Kissock (Kissock 2001) proposed a new way of identifying the process best-suited technique and energy source, the "inside-out" approach.

The Kissock "inside-out" approach based on exergy analysis provides a new approach to determine the best-suited energy source to the required process. It has though some limitations, as to comparing different energy conversion systems, where sometimes the exergy analysis can be insufficient as to determine the best available technique. This is well illustrated when comparing a steam-based energy equipment to an electric-based energy equipment. In fact, the exergy absorbed by the product is identical in both systems, while the exergy given by the energy source is larger in the electric case. This difference between available exergy in the different energy sources often results in higher exergy efficiency of the steam-based system, while in some cases, the electric system can be much more efficient economically and energetically.

These limitations in the pinch and exergy industrial analysis led to the necessity of determining a low cost way to systematically identify the best opportunities to save energy.

Robert Scott Frazier (Frazier 2006) proposed a systematic method for identifying energy management opportunities in manufacturing plants. The main common point between the Frazier method and the proposed PEA method is the determination of the minimum required energy (MRE) to transform the raw materials or the semi products in one or several products. The MRE concept allows comparing the energy profiles of different elementary operations as well as complete processes. Comparison of MREs of competing technical options is an essential part of the PEA method. The Frazier method identifies energy management opportunities, and can possibly lead to incremental improvements of energy efficiency of the process after deciding which process operations are to be further more studied. Alone, the Frazier method does not involve determining Best Available Techniques (BATs) suited for the particular product transformation, nor does it propose incremental and/or radical options to improve the energy efficiency of the production line, but it helps the engineer deciding what operations present the highest energy saving opportunities. The PEA method proposed in this paper is derived from the Life Cycle Analysis (Ciambrone 1997). The LCA is an analysis method designed to be performed on a product or a process "from cradle to grave", where all environmental impacts of the specified product are evaluated (environmental LCA). The proposed methodology is based on a production energy analysis "from raw material to final product", taking into consideration every energy consumption involved in the manufacturing process, it is therefore an analysis developing the energy profiles of all the process operations.

The PEA method goes one step further to analyse the core of an industrial plant, the product transformation. An industrial plant is made for mainly one objective, producing the required product. Thus the minimum energy consumption is based on the requirements on the product and leaves open the technical options available for the transformations.

Proposed PEA Methodology

The PEA methodology is a systematic methodology of energy auditing and analysis that can be applied to different energy audit levels and types. Four steps form the main analysis method.

STEP 1: DEFINING THE PROCESS

The first step of the methodology is the definition of the energy profiles of all the process operations. It begins by a classical process mapping, describing all product transformation operations (see Figure 1). A molecular analysis of the product transformation operations is then performed, in order to determine the MRE to perform each operation. The ideal energy consumption per product unit mass is then calculated. The MRE is sometimes very simple to determine, like the theoretical energy required to melting 1 ton of steel in a steel foundry. On the other hand, and in many processes found for example in the food industry, determining this value could be very complex, like determining the minimum amount of energy required to dry a ton of lettuce. A ton of lettuce can be dried in the sun with no energy consumption and takes days to be accomplished, while drying the same amount with a thermodynamic dryer consumes energy but increases the plant productivity and product quality. The MRE is defined regarding a production intensity defined by the company and a referenced quality standard. Once the product quality and the plant productivity are defined, the possible technical options for process operations are compared taking into account energy efficiency but also production of by-products, pollutants and waste.

After determining the MRE to produce the product with the required quality, this step goes further as to determining the BAT to produce this product. In this case, many studies such as the IPPC BATs (IPPC) can be used, or sometimes the design of a new technique best suited for the particular process at hand can be achieved. This design will involve either high level research studies for emerging techniques, or the application of existing techniques to the particular process is possible (see example step 1). The BATs energy efficiency[2] is then defined as the optimal efficiency.

EXAMPLE STEP 1

For example, the milk pasteurization in the dairy industry is usually followed by milk storage at a temperature near 5°C, and then the milk is heated to 35°C for the following steps of the manufacturing process. The milk pasteurization is not crucial for short time storage at low temperatures (Veisseyere 1979), therefore the pasteurization can occur right before the following manufacturing operations reducing the refrigeration energy required to cool the milk from 35 to 5°C and the heating energy needed to reheat the milk to 35°C before manufacturing.

The pasteurization process is hence reformulated to best suite the MRE to maintain the same product quality. In order to further improve the process energy efficiency, the composite curves of the Pinch method (Linnhoff 1998) are elaborated, the heat energy given to heat the cold milk is reused while cooling it to heat the new cold milk (see Figure 2). This technique is already proposed by pasteurizing equipment manufacturers in a cost effective way. However, heating the milk cannot be done using only heat recovery from hot milk, especially with the pasteurizing system that does not imply cooling the milk to its original inlet temperature. Therefore a hot utility is needed to heat the milk. According to the composite curves pinch value (see Figure 2 a) and b)), the hot utility can be provided at the high level or the low level of the milk temperature. Then an exergetic and economic analysis of the process implies that maximising the low temperature hot utility will lead to lower energy costs and higher energy and exergy efficiency. In this case, the obvious technique is to use the minimum pinch allowed by heat exchanger technologies in order to minimize the high temperature hot utility capacity (see Figure 2 a)), and therefore the main hot utility is needed at a lower temperature (35/40°C). This kind of hot utility is best generated by heat pumps that can reach very high COPs (Coefficient Of Performance). This example shows that by analysing the inside molecular transformation of the product, a suited utility can be designed for the process operation, with optimized energy consumption.

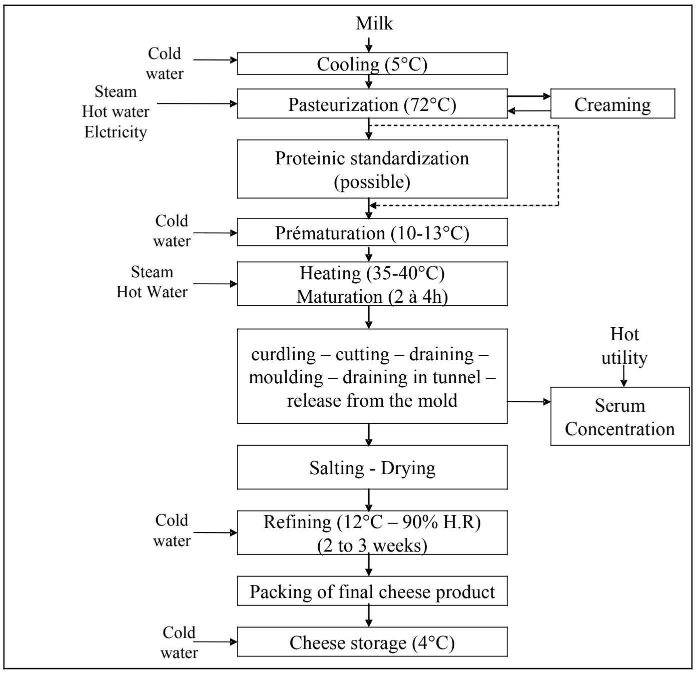

Figure 1. Cheese manufacturing Process generic mapping.

Step 1 of the proposed methodology is generic. The engineering analysis can be carried out once for every type of product, with simple calculations left for specific product information particular to some industrial plants. The major energy consuming operations have to be systematically covered by exergy analysis and the composite curves have to be elaborated.

STEP 2: PLANT PROCESS MAPPING

This step of the PEA is applied to the studied plant. It consists in determining the manufacturing process operations and the energy vector going from the primary energy source to the product (see Figure 3. Example of a milk treatment process mapping).

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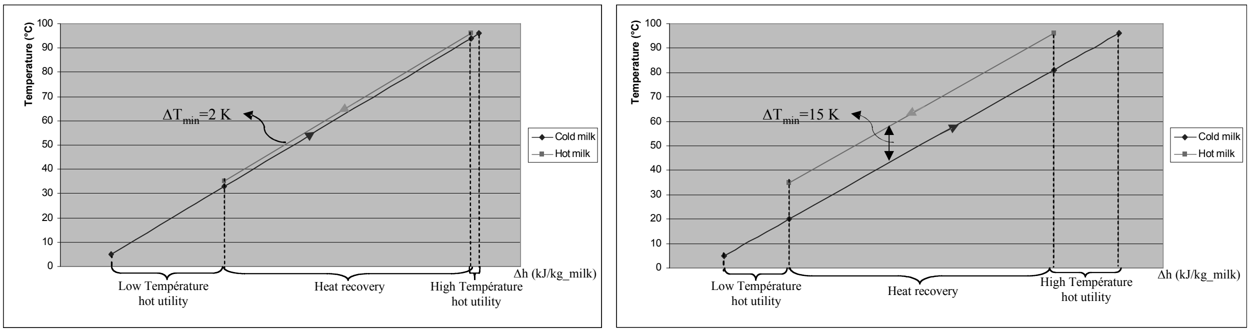
[2] In this context, energy efficiency can mean the ratio of the theoretical energy to the actual energy used, but in some particular cases, the energy efficiency can only mean the energy consumption of the operation per product unit mass.



a) Milk composite curves with 2 K pinch

b) Milk composite curves with 15 K pinch

Figure 2. Milk pasteurization composite curves

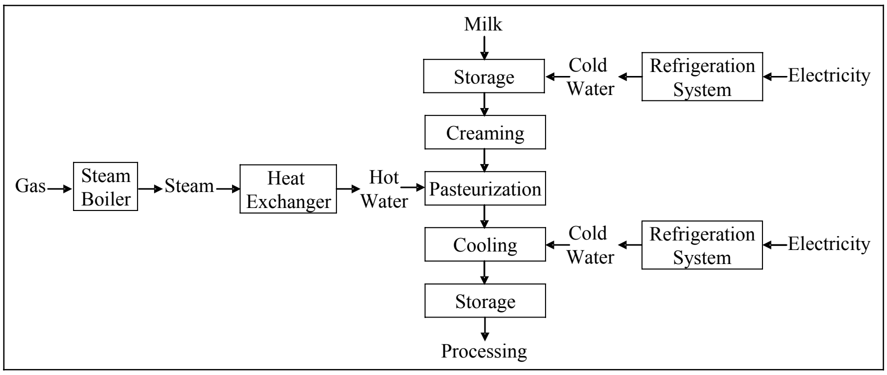


Figure 3.Example of a milk treatment process mapping.

Depending on the audit level, this step is performed by the auditor and the industrial manager responsible of the audit follow-up. In this step, each product transformation operation should be noted in the map, and the step 1 mapping can be used with particular adaptation to the audited plant. The goal of this step is to determine the actual manufacturing process with the utilities linked to each operation.

STEP 3: CONSUMPTION INVENTORY

In the third step, an energy consumption inventory by product mass unit is performed. This energy consumption inventory is conducted with various degrees of details, depending on the audit type and level. For low-cost energy audit levels, it is recommended that the inventory should be only performed on the major operations detected in step 1. The inventory borders fix the analysis borders. From an industrial and economical point of view, the reasonable border should be set at the level of the energy source bought by the company (electricity or fuel), whereas from an environmental point of view, the energy transformation used in the country should be included in the inventory, not to analyse the energy transformation in the power plant itself, but to analyse the environmental impact of the transformation process. Therefore, when analysing the industrial process for the industrial manager's benefit, the economical factor (that is the centre of interest of the company) should be taken into consideration, and the energy source bought by the company should be determined in order to establish the energy efficiency of the studied operation. However, from an environmental point of view, an environmental correction factor can be determined to compare electric energy efficiency and fossil fuel energy efficiency. This part is not treated in this paper.

The consumption inventory is accomplished by studying the energy vector from the primary energy source to the product (defined in step 2), measuring as well the energy transformation equipment efficiency. Using this data, the actual energy efficiency of the process operation is determined, as well as the energy cost of the studied operation..

For example, in a food steam sterilization process, the analysis should be performed going from the product transformation to the energy source bought by the company (natural gas if a gas steam boiler is used), passing through energy efficiency of the steam boiler and the possible refrigeration systems. Energy saving opportunities based on the product specifications and not only on the actual process is determined using the MRE approach.

STEP 4: ANALYSING DATA

In the fourth step, the energy analysis is carried out on a two level basis, incremental and radical. Both levels of analysis are based on a MER analysis and product quality criteria.

From a product quality point of view, energy losses are divided into two categories, fatal losses and none fatal losses (see Figure 4. SANKE diagram representing energy losses and MER). Fatal energy losses are defined as the energy needed to transform the product using the particular technique at hand, without necessarily transferring this energy to the product itself, as for example the energy required to cooling a product mould in order to cool the product itself. Non-fatal losses are the energy consumption that if removed does not affect the product quality. Determining the non-fatal losses on a MER

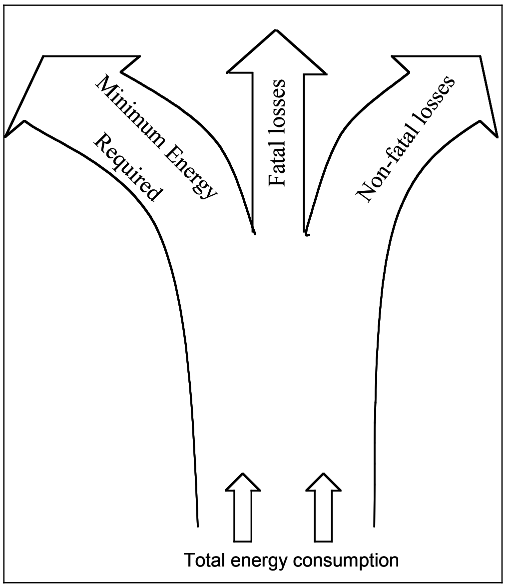


Figure 4. SANKE diagram representing energy losses and MER.

basis is in other words determining the incremental and easy to install energy saving potential.

The difference between radical and incremental improvement analysis is related to the fatal energy losses of the reference process. From an incremental point of view, changing the current production system or equipment is not possible; therefore fatal losses are those of the existing system. In the milk pasteurization example, if the existing system has equal inlet and outlet temperatures, then cooling the milk to the outlet temperature and reheating it to the manufacturing temperature should be considered as a fatal loss, since removing this energy would imply changing the system (radical improvement) or losing product quality.

On the other hand, in the chocolate process, cooling the mould in order to cool the chocolate is considered to be a fatal loss. However, when studying the mould material, s improvements can be made by changing this material and nevertheless keeping the same chocolate quality. The mould material can be changed in order to deliver less heat in the refrigeration tunnel, while of course fitting the chocolate cooling criteria. The energy efficiency of some known equipment such as refrigeration systems and furnaces can also be compared to average energy efficiency values, determining opportunities for incremental improvements.

The radical analysis level is based on the optimal energy efficiency determined from BATs in step 1. A comparison between the current energy efficiency of the process operations, determined in step 3, and the optimal energy efficiency is carried out. This comparison leads to the identification of the energy saving opportunities by radical improvements. According to the current energy consumption of the industrial plant, the cost savings by energy efficiency improvements are calculated. The investment cost analysis is then carried out to determine the Payback Time for Investment (PTI).

Conclusion

This paper shows that the PEA methodology aims at determining the highest energy saving opportunities, opportunities that cannot always be identified with conventional optimization methods. The PEA analysis, concentrated on the product transformation, takes into consideration the product quality, the plant productivity, and strives to benchmark available technical options to the minimum required energy. The PEA does not take as established forever the actual transformation process, the only references are the product specifications in quality and production intensity.

The PEA uses available techniques and analysis methodologies and adds a molecular analysis at the product level, in order to determine the BATs suited for the particular process at hand. The PEA can also be applied to all energy audit types and levels. Economical analysis should be added to the energy analysis in order to determine the economical profitability of the new technical options.

PEA is an analysis method, which combines process and energy engineering in order to determine the best suited techniques for an energy optimized manufacturing process.

References

AFNOR, Référentiel de bonnes pratiques, Association Française de Normalisation, Paris, France, 2006.

Bejan A., Tsatsaronis G. et Moran M., Thermal Design and Optimization.

Ciambrone D., Environmental Life Cycle Analysis, Lewis Publisher, 1997.

Frazier R., A Proposed Systematic Method for Identifying and Characterizing Energy Management Opportunities in Manufacturing Facilities, SAE World Congress, USA, 2006.

IPPC, Draft Reference Document on Energy Efficiency Techniques, Integrated Pollution Prevention and Control, 2006.

IPPC, Reference Documents On Best Available Techniques in industrial manufacturing, Integrated Pollution Prevention and Control, 2006. *(http://eippcb.jrc.es/pages/FActivities.htm)*

Kissock K., Hallinan K. and Bayder W., The Inside-Out Approach for identifying industrial energy and waste reduction opportunities, Journal of Strategic Planning for Energy and Environment, 21-1, 2001.

Le Goff P., Energetique industrielle, 1979.

Linnhoff March, Introduction to Pinch Technology, Linnhoff March, Cheshire, England, 1998.

Thumann A.and Mehta P., Handbook of Energy Engineering, 3rd edition, Fairmont Press, 1995.

Tondeur D., optimisation thermodynamique équipartition de production d'entropie.

Veisseyre R., Technologies du lait, La maison rustique, Paris, France, 1979.