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Simulating Specific Energy Consumption for an Industrial Production Process

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Abstract: The purpose of this article is the simulation of energy efficiency performance using a mathematical model of a unit process. A dynamic model of the process is used for its control. As the process is used for different production quantities, energy efficiency is investigated. Specific Energy Consumption (SEC) is one of the key performance measures of a plant or equipment. It consists of calculating energy consumed for producing a unit product. Hence, the model is used together with an observer and a controller to iteratively compute the specific consumption. For different trajectory to track (product type) and for different capacity usage, the iteration permits to get the corresponding specific energy consumption curve versus capacity usage. This characterization can be used later when operating to diagnose overconsumption of energy compared to initial equipment setup (equipment and control system). Finally, an industrial example is provided as a comparison to the simulation case.

Keywords: Energy efficiency, Process model, Process control, Specific energy consumption, SEC.

1. Introduction

Energy efficiency has become a topic of importance due to global warming and the forecasted reduction of fossil fuel. Many humans made technologies have an impact on global warming. Industry, agriculture, transportation are among the most impacting activities on the ozone layer. Concerning industry, existing plants and equipment have to be more efficient in using available energy (electricity, heat, and other energy forms.) and raw material. Energy audit activities are important in order to diagnose abnormal energy consumption, propose upgrading technologies and energy saving practices.

In many developing countries, industry is a priority for economic development. However, this means more energy consumption and investment in energy infrastructures including electricity. Despite many efforts for investment, energy consumption for economic activities is still high. Investment for more efficient equipment is expensive and sometime out of reach. However, technology transfer needs to be accelerated if one wants to reduce the impact of industry on climate change while having a positive impact on economic development.

Recent industrial standards such as ISO 50001 are guiding both producers and equipment providers for monitoring and managing energy. Energy management systems are proposed for monitoring energy consumption. However, there is still room for improvement for many processes in both process technology and process operation management.

For new plants, a focus should be made in designing best available technologies (BAT) and developing better production management practices. Control systems and particularly artificial intelligence can help in improving plant energy efficiency. Hence, recent researches have targeted this topic [1-4, 7-12, 15].

In [7], definitions of specific energy consumption are given. The authors also mentioned that despite numerous publications on specific energy consumption (SEC), critical scientific papers are still lacking.

In [8], comprehensive research on publications regarding specific energy consumption in machining operation has been investigated for the period of 2001 to 2020. It shows an increasing interest of the research community for the topic.

As cement industry is known to be one of the most energy consuming industry, many investigations have been undertaken [13, 14], energy consumption benchmarks have been made. In [12], inferred models are used to calculate an average SEC for primary cement industry.

Energy consumption in manufacturing plants is indeed related to production quantities [2-4, 10]. There are different levels for evaluating energy efficiency. The first one is at equipment level by analyzing technologies such as motors, regulatory control and instrumentation. The second level is at process line or plant level. At this level, it required in addition to equipment efficiency, to better coordinate production and processes. This, in turn, can help reduce waste and use energy optimally. Also, maintenance and quality monitoring to keep production performance is required. The third level is at supply chain level where all the components have to be coordinated with efficient energy usage. At plant level, operators need to be aware of energy efficiency measures to be able to apply such techniques. In addition, operators may need training on energy efficiency. Energy management systems can also be used for better efficiency and SEC management.

In some industries, there has been several research publications such as steel making [9, 10], cement industries, cotton ginning. For the latter, one of the world's oldest and largest industry, several studies have been undertaken [2]. It is shown in particular that power consumption is related to production rate. Energy consumption is also linearly related to production quantities and production key performance indicators.

While most papers are dealing with industrial data, using process models to simulate and predict energy consumption behaviour of a plant can help in predicting and characterizing future operations and also for planning energy consumption. In addition, in most published papers, an average SEC is computed and studied. However, SEC depends on the capacity usage at plant level [4]. At equipment level, it depends on production rate.

The purpose of this article is to use process models for simulating specific energy consumption versus process utilization. Process behaviour is then simulated with a feedback control and the resulting specific energy consumption is computed. Given a production schedule of several quantities and types of products, the simulation computes iteratively SEC so as to provide with an energy characterization of the process. For different products, SEC characterization can be computed for each of the product. Simulation as well as real data are used to show the results.

The paper is organized as follows. The first section after the introduction is dedicated to some recalls and definitions on energy efficiency. The second part of the article is dedicated to the problem statement and the methodology used to demonstrate the result The third section describes the used case. The fourth section presents the simulations' results. The firth part of the paper describes an industrial example. Finally, discussions are undertaken as for the utilization of the results. Some concluding remarks are given.

2. Some Recalls and Definitions

Specific energy consumption (SEC) has been a topic of interest during the last two decades. This is due to recent concerns on global warming and the increase of energy prices. Improving energy usage seems to be the best way of reducing Green House Gases (GHG). Although industry has improved its energy usage throughout several government programs and internal efforts, there is still room for lowering its global warming impact. Better use of energy for production activities is measured through energy efficiency.

Specific energy consumption is an energy efficiency measure of production processes. It can be defined as total energy consumed for producing a unit product [1-3, 6].

$$SEC = \frac{energy\ used}{product\ amount}$$

The energy used can be measured in kWh, kJ or kcal or other energy units. The energy consumed includes all form of energy (electricity, heat or other fossil fuel or renewable energy usage etc.) All are converted in the same units for example kiloWatthour (kWh). In this article energy unit considered is kWh. SEC is calculated over a time period such as day, week, month, depending on the utilization (monitoring, planning etc.). Energy management systems should take into account SEC values. Instantaneous SEC can also be calculated for a machine.

$$SEC_i = \frac{Power(in\ kW)}{Production\ rate(in\ unit/hour)}$$

Energy efficiency is influenced by several other parameters including the quality of the raw material processed, the process technology, the quality of the control system and the management system. Raw material is converted to product depending on its quality, and energy used as shown in the Fig. 1.

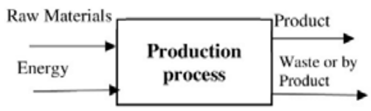

Fig. 1. Production process.

For example, clinker quality affects energy usage in the grinding process of the cement industry. In several processes, having well-tuned control systems reduces variability of product quality and therefore energy consumption. Process wastes are an indicator of process inefficiencies including energy consumption as less products are produced for the same quantity of energy consumed.

Improved energy efficiency helps in reducing waste and increase production. As such, measuring energy efficiency can help diagnosing process problems.

Process capacity utilisation is the ratio of actual production quantity versus theoretical capacity of the plant (machine). Il is shown that SEC depends on capacity utilisation in some plants [3, 4]. Process capacity utilisation Cu can be linked to equipment performance by the following formula:

$$Cu = \frac{Pr}{Pth} = \frac{Cp}{Cpth} * \frac{D}{Dth} * \eta, \quad (1)$$

where Pr is the actual production quantity; Pth is the theoretical production; Cp is the actual production rate, Cpth is the theoretical production rate of the considered equipment, D is the effective production duration while Dth is the total duration; η is a ratio for measuring good product over total products. In fact, At equipment level, Cu is known as Overall Equipment Effectiveness (OEE).

Another important term is the power used to during operation. Power consumption is related to rate of production. The higher the rate, the higher the power consumed. In [2], it is shown that power consumed is linearly depends on the production rate for cotton ginning.

Given a process, the model can be related to the energy consumed using energy and mass balance. There are well known modelling techniques such as Euler-Lagrange energy-based system modelling.

In the following section, the problem statement and the methodology used for implementing SEC computation is explained.

3. Problem Statement and Methodology

In order to characterize the utilization of energy in a process, a simulation using process models can be used. In a unit operation defined by a recipe, several products can be made in the same vessel depending on the processing conditions of the recipe. One of well-known conditions is related to temperature control. Temperature control is very important is most processes including chemical processes, food and beverages, air conditioning etc.

Given a process model, a control strategy is implemented for production depending on a recipe. It is well known that state space control requires state estimation. As such an observer is used to estimate the required states. This allows the estimation of the states used to compute power and energy variables and specific energy consumption. Batch processes can be operated for different batch sizes for a given product, production capacity can be then varied. Varying production batch sizes affects specific energy consumption. Lower sizes may lead to more energy consumption. Higher batch sizes while having lower SEC may lead to unnecessary product inventory. This means that depending on the context, the optimal level of production has to be found.

Each type of product is characterized by a different tracking profile. As such, given one type of products, it is necessary to iterate the computation while varying the production size. The computation leads to an energy specific consumption profile. For several products, a set of curves can be obtained versus capacity utilisation. Given a production schedule including several products, the resulting curve can be derived from the combination of the individual product curves plotted. The algorithm is depicted in Fig. 2. For an equipment, having these productions SEC for different products gives the user an energy pattern that can be used later.

These curves can be used later for the monitoring and diagnostic of the production. For instance, one can evaluate deviation from reference SEC and diagnose the underlying problems.

The purpose of this article is to show the integration of all these concepts using process models and process control. It is shown how to obtain an energy specific consumption with simulations. Note that the same method can be used in machine learning algorithms.

The following figure present the computation iteration for obtaining SEC characteristic curve.

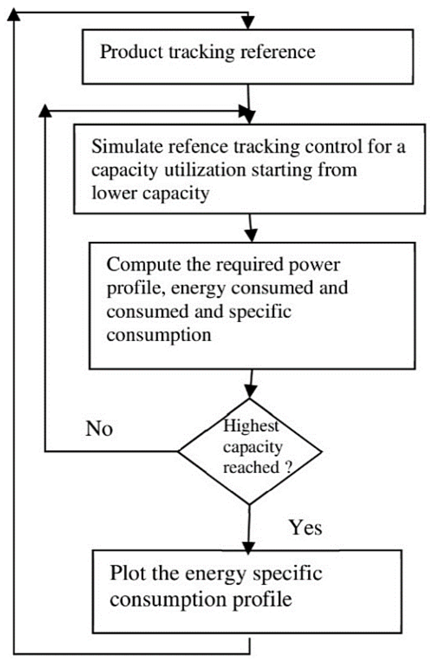

Fig. 2. Energy Specific consumption computation.

In the following section, the use of process models and process control methods in order to simulate iteratively a process SEC is discussed.

4. Using Process Model and Control for Energy Specific Consumption Computation

For the clarity of the text, a linear model is considered. As such, a batch process has a model of the following form.

$$\begin{cases} \dot{x} = A_0 x + B_0 u + Dd \\ y = Cx \end{cases}, \quad (2)$$

where x, u and y are respectively the state, the control and the output variables. The A_0 are matrices of dimension nxn. B_0 and C are the input and output matrices. D is a disturbance matrix of a measured disturbance d. Such models can be obtained using mass and energy balances in particular Euler-Lagrange or based formulations.

An example of used control strategy can be $u(t) = g(r(t), y(t), x(t))$ where x is estimated using an observer. $r(t)$ is a desired trajectory.

The overall power and energy terms can be expressed as functions of the state variable x and the input variable u.

$$P_e = f(x(t), u(t)) \text{ and } E = \int_{t0}^{tf} Pe(t)dt, \quad (3)$$

where the production takes place form t_o to t_f. For a given weight of production M and assuming that there is no rework, specific energy consumption SEC is given by:

$$SEC(t_f, t_0) = \frac{E}{M}, \quad (4)$$

where SEC is computed over a period of time $T = t_f - t_0$.

The considered application is a temperature cooling and heating process used in many industries (e.g. beverages, pharmaceuticals, dyeing in textile industry). It can also be applied to other cooling systems. It has been used to demonstrate the computation of SEC. The following figure shows the basic configuration of the unit operation. It is supposed that there are three sources of energy:

- Agitator electrical power, P_{ae};
- Thermal heat and cooling power, P_{th};
- Electrical pumping power, P_{ep}.

Also, it is assumed that the mixture is not viscous. Therefore, there is not dissipation of heat provided by the agitator.

The model can be obtained as follows. A mixture inside the vessel has to be treated thermally. Hence, it is first heated to reach a desired temperature and cooled down after. The resulting energy balance is as follows.

Energy balance of the mixture (inside the vessel)

$$\frac{d(\rho_l C_{pl} V T)}{dt} = \eta UA(T_w - T) + kair(Tair - T), \quad (5)$$

where $kair$ represents the convective heat exchange between air and the mixture of temperature T. $Tair$ is the air temperature. η represents the capacity utilization that is to say the percentage of the available volume of the vessel that is used. In fact, this term is used to model capacity usage of volume for mixing. Here, capacity usage is varied between 50 % and 100 %.

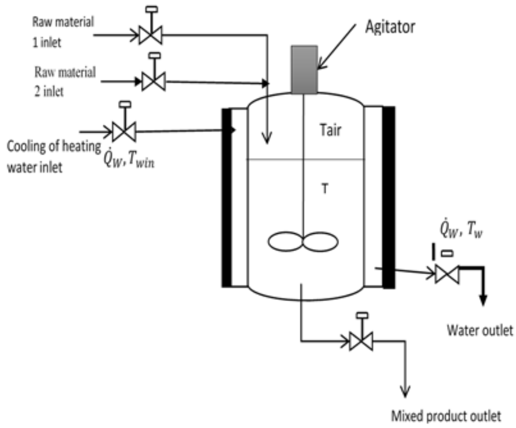

Fig. 3. Mixing reactor process.

Water energy balance (cooling or heating water)

$$\begin{aligned} \frac{d(\rho_w C_{pw} V_w T_w)}{dt} &= \dot{Q}_{eau}\big(\rho_{win} C_{pwin} T_{win} - \\ &-\rho_w C_{pw} T_w\big) + (1-\eta)UA(T_{air} - T_w) + \\ &+\eta UA(T - T_w) + U_2 A_2 (T_{amb} - T_w), \end{aligned} \quad (6)$$

where T_{amb} is the ambient air temperature. T_{win} is the water temperature entering the jacket for cooling or heating. Above the mixture there is air, its volume increases when the vessel in not full.

Air energy balance

$$\begin{aligned} \frac{d(m_{air} C_{pair} Tair)}{dt} &= kair(T - T_{air}) + \\ &+(UA)_9 (T_{amb} - T_{air}) + \\ &+(1-\eta)UA(T_w - T_{air}), \end{aligned} \quad (7)$$

From these equations a state space model can be derived and used for control purpose. The main goal is to study energy consumption with respect to a batch size. The model is slightly nonlinear because of the term $T_{eau}\dot{Q}_{eau}$. The model is then linearized into the following form by a change in the input variable:

$$\frac{dx}{dt} = Ax + B\bar{u} + Ed,$$

where the matrices defined as follows.

$$A = \begin{pmatrix} -k_1 - \frac{k_5}{\eta} & k_1 & \frac{k_5}{\eta} \\ \eta k_2 & -k_2 - k_6 & (1-\eta)k_2 \\ k_7 & (1-\eta)k_9 & -(1-\eta)k_9 - k_8 - k_7 \end{pmatrix},$$

$$B = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}; \text{ the state vector is } x = \begin{pmatrix} \bar{T} \\ \bar{T}_w \\ \bar{T}_{air} \end{pmatrix},$$

where $d = T_{amb}$ the ambient temperature is considered as a measured disturbance variable.

$$E = \begin{pmatrix} 0 \\ k_6 \\ k_8 \end{pmatrix}$$

It is assumed that T is measured that is to say $C = (1 \quad 0 \quad 0)$.

The model parameters are:

$$k_1 = \frac{UA}{\rho_l C_{pl} V}; \; k_2 = \frac{UA}{\rho_w C_{pw} V_w},$$
$$k_3 = \frac{1}{Vw}; \; k_4 = \frac{\rho_{win} C_{peauin} T_{ein}}{\rho_w C_{peau} V_{eau}},$$
$$k_5 = \frac{kair}{\rho_l C_{pl} V} \; k_6 = \frac{U_2 A_2}{\rho_w C_{pw} V_w},$$
$$k_7 = \frac{kair}{m_{air} C_{pair}}; \; k_8 = \frac{(UA)_9}{m_{air} C_{pair}},$$
$$k_9 = \frac{UA}{m_{air} C_{pair}},$$
$$m_{air} = m_{air0} + (1-\eta) V \rho_{air}$$

It is assumed that the process of heating is quickly enough to neglect the production of steam. Different feedback controls with integral error are applied to the system to track the profiles. Power consumption is calculated as follows

$$Pe = \dot{Q}_w \left(\rho_{win} C_{pwin} T_{win} - \rho_w C_{pw} T_w \right) + \\ + \frac{1}{\gamma} \rho_w g H \dot{Q}_w + P_{ea},$$

where P_{ea} is the agitator power and H is the net head pressure height term. γ is the motor efficiency. $P_{eth} = \dot{Q}_{ew} \left(\rho_{win} C_{pwin} T_{win} - \rho_w C_{pw} T_w \right)$ is the thermal power (expressed in kW, in fact there is yield term to relate to the electricity used for cooling and heating). The power term can be put into the form:

$$Pe = \dot{Q}_w \left(\Delta H + \frac{1}{\gamma} \rho_w g H_M \right) + P_{ea}$$

However, due to the fact that instantaneous equation are considered, a nonlinear relation is obtained.

$$\Delta H = \rho_{win} C_{pwin} T_{win} - \rho_w C_{pw} T_w$$

It corresponds to the heated or cooled water energy losses during the production. T_{win} takes two values depending on whether the fluid is heated or cooled. ΔH is related to the energy consumption (by adding an efficiency term for the heating or cooling part).

The power term is then proportional to the flow rate with fixed term that is the agitator power.

In fact, energy consumption is calculated using the following equation:

$$\frac{dE(t)}{dt} = Pe = \dot{Q}_w \left(\rho_{win} C_{pwin} T_{win} - \rho_w C_{pw} T_w \right) + \\ + \frac{1}{\gamma} \rho_w g H \dot{Q}_w + P_{ea}$$

The agitator electricity demand is constant throughout the mixing process. The pumping and thermal energy vary depending of the type of product. Operations such as filling and discharging the vessel with liquid or cleaning are not included for the sake of simplicity.

The model can be put in the form of (2). A control strategy is applied together with a state observer. Three products are considered and the iteration is applied in order to derive the specific consumption.

The following figure shows the control strategy used for the iteration. The extended system for a single trajectory take the following form:

$$\begin{cases} \dot{X}_e = \bar{A}.X_e + \bar{E}.d + \bar{I}.r(t) \\ y = \bar{C} X_e \end{cases}, \tag{8}$$

where the different variables and matrices are given by the following

$$X_e = \begin{pmatrix} x \\ \hat{x} \\ x_e \end{pmatrix}; \bar{A} = \begin{pmatrix} A & -BK_1 & -BK_2 \\ LC & A_1 & -BK_2 \\ -C & 0 & 0 \end{pmatrix},$$
$$\bar{E} = \begin{pmatrix} E \\ E \\ 0 \end{pmatrix}, \bar{I} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \bar{C} = (C \quad 0 \quad 0),$$

where r represents the desired reference to track. This form is only for one reference to track. $A_1 = A - LC - BK_1$ is the resulting matrix for the observer.

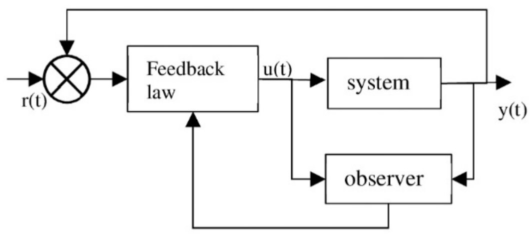

Fig. 4. Process control structure.

For a given product, the reference r(t) is defined. So is the feedback control.

The following simulations show the tracking of the reference for each product, and the related SEC curve. Firstly, the feedback control is implemented. Secondly, iteratively computing SEC for different capacity usage provides the characteristic curve. Finally, discussions are provided on research perspectives and diagnosis purpose.

5. Simulation Results

For the simulations, three different temperature profiles for three different products are presented in this paper. For each profile, a tracking control has been implemented. The volume to be processed is then varied so as to simulate capacity utilization variation. Therefore, the corresponding SEC curve is obtained.

The first simulation shows tracking of temperature representing one product recipe. The temperature is gradually goes to 63 °C (336 K) during 30 min before being cooled down. All energy consumption (heating, pumping, cooling) is then computed and the corresponding SEC curve is plotted versus capacity utilization. Capacity utilization is considered from 50 % to 100 % for all simulations. The following Figures 5-11 present the corresponding tracking curve and the computed SEC curve versus capacity utilization.

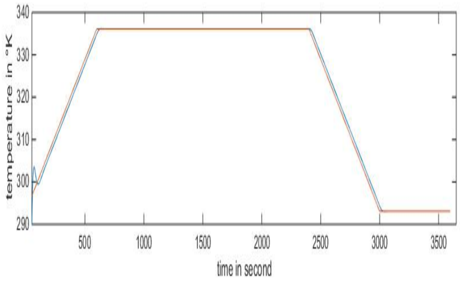

Fig. 5. Temperature profile 1 (63 °C).

The corresponding SEC curve is given by the Fig. 6.

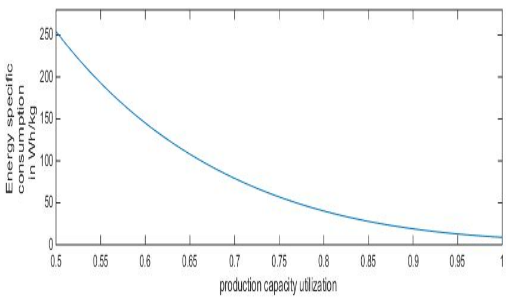

Fig. 6. SEC curve for the first profile.

Il shows that the SEC starts at above 250 Wh/kg at 50 % capacity utilization and reduces to below 30 Wh/kg at 100 % capacity utilization.

The second simulation deals with rising the temperature up to 73 °C during 5 min. The corresponding SEC is then computed.

The resulting SEC profile is given by Fig. 8.

The SEC values can go over 500 Wh/kg at 50 % capacity utilization and reach below 50 Wh/kg near 100 % capacity utilization. In the third simulation, the temperature reaches 90 °C (363K) in a few second and descends quickly to lower values.

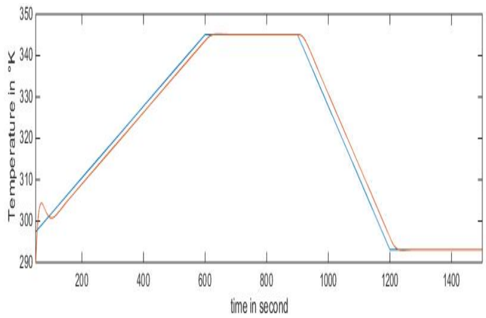

Fig. 7. Temperature profile 2 (73 °C).

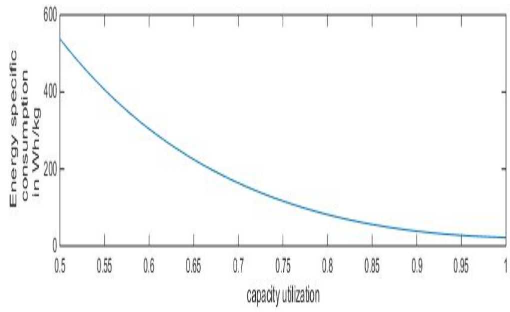

Fig. 8. SEC curve versus capacity utilization for profile 2.

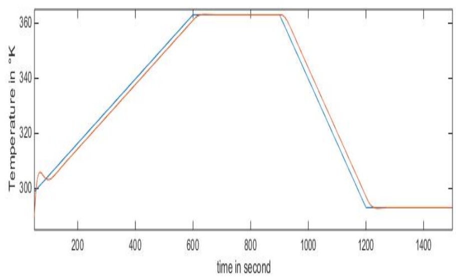

Fig. 9. Temperature profile 3 (90 °C).

The corresponding SEC curve is as follows.

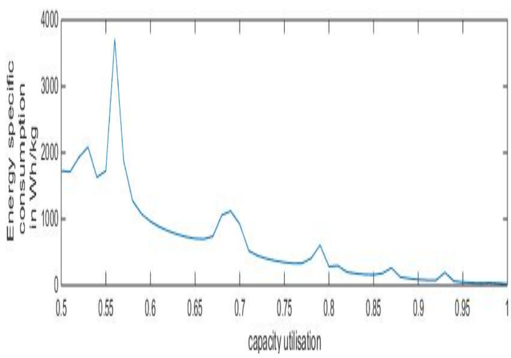

Fig. 10. SEC curve for the profile 3.

Note that the pics are due to the control values and tuning. As such, a good control tuning results in a better SEC in this example. Badly tuned control system thus impacts on SEC.

An aggregated curve over a schedule is also computed based on each production contribution. As such, the following resulting curve is derived.

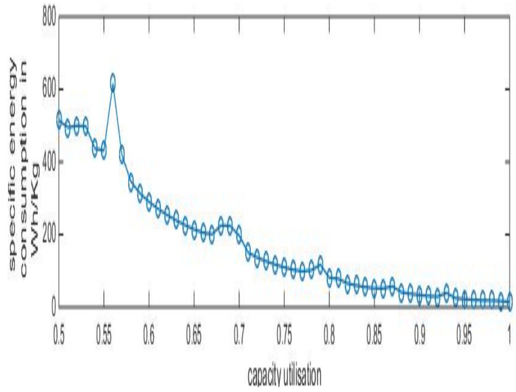

Fig. 11. Aggregated SEC.

The aggregated SEC of a plant or equipment can be derived from collected data. In what follows, a comparison real industrial data is provided.

6. Comparison to Industrial Data

An industrial example is a juice production plant. In this plant, the main energy consuming processes come from pasteurization and sterilization of the juice. Heat is provided by steam coming from a boiler through the use of diesel oil. Cooling water comes from a cooling unit using electricity. Electricity is provided by the national company and a generator set that takes over when there is power cut. While pasteurization involve similar temperature values as in this article, sterilization temperatures go above 110 °C. In this example, the process is comparable to the example above where by a mixture is being pasteurized.

The collected data is the production quantities obtained on a monthly base and the energy data, both electricity consumed and diesel fuel consumed by the generator set. Then SEC is computed by dividing the monthly total energy consumed by production quantities. This is done with a monthly time sampling.

The resulting SEC is show by the Fig. 12.

The values of the SEC start from 1200 kWh/ton of product when the capacity utilization is around 7 %. At capacity utilization of 55 %, the value is around 300kWh/ton of product. Capacity utilization depends on many factors such as maintenance, power cuts, raw material quality, production management (planning and scheduling). Moving from around 22 % to 55 % capacity utilization permits a saving of around 300 kWh per ton of product. Hence, the higher the capacity utilization, the lower the SEC value. Improving Capacity utilization thus reduces the energy consumed to produce a unit product. Thus, this tool can also be used for auditing a plant. It is not rare to encounter in many plants a low capacity utilization due to many reasons; bad sizing of the plant, loss of markets, etc.

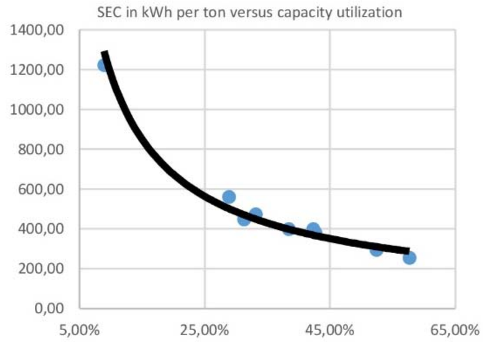

Fig. 12. SEC computed from industrial data.

The use of simulation for computing SEC profile helps forecast the profile of the plant or equipment energy usage. Each product family may have a different characteristic curve. Also, a deviation from the characteristic curve can be analyzed in many ways. Abnormal deviations are caused by problems in the process as mentioned above. Moreover, it can be used for measuring the benefits of the implementation of a new technology such as controllers, new equipment technology. Such measures are usually implemented after an energy audit or diagnostic.

Nota Bene: The shape of the curve depends on the type of process being studied. For systems mostly comprising thermal energy and some electro mechanical aspects such as pumping the shape may be comparable to the one provided by the simulations. For electromechanical or nonlinear systems such as chemical reactions, the shapes may be different.

SEC curves can be seen as a characteristic curve of the equipment being considered. As such, it can be used as an energy sensor. Also, due to the complexity of many systems, a theoretical formulation should be developed.

Another remark is on the use of best available technologies. The curve can be lowered (therefore reducing energy usage) if better technologies are used. For example, using a better cooling technology with better coefficient of performance.

7. Some Concluding Discussions and Remarks

Simulations permit to a priori compute specific energy consumption curves of a production plant. The paper clearly states that SEC is dependent on equipment or plant capacity utilization contrarily to most papers dealing with average values of SEC. With an increase in capacity utilization, SEC values reduce. This can be used to characterize industrial plants or equipment. It can also be used for diagnostic purpose. Control tuning has an impact on SEC. badly tuned controllers can increase SEC values as it can increase process variability. Also, raw material quality which can be models as controlled process input can impact on SEC. Other factors can impact on SEC. For new plants, model-based simulation approached can provide specific energy consumption curves for benchmarking operational behavior. Comparison of different control strategies should be simulated to show their impact on SEC. Future research work can be focused on theoretical formulation of energy efficiency concept for different types of systems.

Also, benchmarking the influence of different control strategies and applications provide a rational for implementing better controllers. Finally, the use of SEC curved for optimization taking into account other plant constraints can be investigated.

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