CHEMICAL ENGINEERING TRANSACTIONS

VOL. 87, 2021

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Laura Piazza, Mauro Moresi, Francesco Donsì

ISBN 978-88-95608-85-3; **ISSN** 2283-9216

New modelling approach for the energy and steam consumption evaluation in a fresh pasta industry

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The agri-food industry has a fundamental role in the Italian and European economy and is characterized by the need to reduce energy costs and emissions. Therefore, it is essential for food companies to give due consideration to the energy efficiency of the processes, to reduce production costs, without sacrificing the quality of primary production and maintaining adequate levels of competitiveness on the market. In this study, a theoretical and experimental mass and energy balance of the production process of fresh pasta was made, also considering the energy contributions of a cogeneration plant recently built in the company subject of the experimental study. The final aim was to determine scientific values of specific energy consumption for this type of production by mean a new modelling approach. The mass and energy balances were carried out for the production line of fresh semolina pasta, as well as for the cogeneration plant; monitoring the flows of raw materials and steam that characterize the production process. The results of this study can be generalized to all production processes of the same type and, in the specific case, constitute a decisive logical step for the definition of the energy recovery solutions to be adopted in the company studied, in relation to their economic-production needs.

1. Introduction

All food processes characterized by a heat exchange with the product being processed have the need to become a competitive system in terms of quality, functionality, reduce emissions and energy savings (Bianchi et al., 2013; Ayr et al., 2015; Bianchi et al., 2015). Energy and steam consumption are essential subjects to evaluate sustainability of food processessing, then energy and water saving allows any factory to be low impact and competitive taking in any case the quality of the product (Galitsky et al., 2003; Leone et al., 2015a; Perone et al., 2017). Therefore, energy and water can be considered in all respects as well as all other raw materials used to obtain a high-quality product (Leone et al., 2015b; Tamborrino et al., 2017). To this aim it is necessary to carry out a mass and energy balance of a food process to (Sturm et al., 2012):

- determine the flow rates of raw materials (water included), finished products and exchange fluids; these values are inserted in appropriate balance equations;
- determine energy consumption both total and per unit of product;
- develop recovery strategies and make the correct choice and general design of recovery plants.

Following this type of evaluation, the results that can be obtained are (Bianchi et al., 2020):

- reduction of electricity and heat bills;
- reduction of production costs;
- acquisition by the product of the added value, thanks to the environmental commitment adopted in the production process;

- increase in the economic margin on the food product.

In particular, modelling energy and mass flows is a not new technique applied to pasta factor (Moraitis et al., 1997; Panno et al., 2007) but never a complete dynamical approach was used. Therefore, in the present paper the analysis outlined above was carried out using a new dynamical modelling approach (Catalano et al., 2020; Tamborrino et al., 2019a; Difonzo et al., 2021) to study the mass and energy balance of a fresh semolina pasta production process equipped with a cogeneration plant.

2. Materials and Methods

The factory needs high amount of heat which is produced as pressured steam, and electricity. The steam is mainly used in the pasta production process and generated by a afterburner located downstream of a cogeneration plant (CHP) and, when necessary, by a traditional boiler. On the other hand, the electricity is partly purchased and partly produced by the cogenerator. The cogenerator is powered by a mixture of air and methane and consists of 3 microturbines. The afterburner is powered by a mixture of high temperature burnt gases from the cogenerator plus methane (Figure 1).

Figure 1: Cogeneration plant (CHP) serving the pasta factory studied: microturbine (left), after-burner (right)

To achive the results the following quantities were measured during each production phase:

- temperature;
- relative humidity;
- thermal flow;
- radiation;
- atmospheric pressure;
- air speed;
- gas concentration;
- water level;

In particular, the water-steam flow rates were measured by mean of the Coriolis type SITRANS FCS400 sensor and a SITRANS FCT030 transmitter. The other probes (temperature, humidity, pressure, etc.) were connected to a BABUC / A / M, a multi-channel data logger.

The used analytical model was taken from a recent paper (Catalano et al., 2020) where was proposed a new dynamical procedure, using deep and detailed mass and energy analysis of the entire production process of a frozen food production factory.

In particular, the model is based on transient mass and energy balance equations of each component of the different equipments in the plant,: these equations together determine a system of general linear and nonlinear differential-algebraic equations solved with a semi-implicit stable scheme. In figure 2 shows the flow chart of the dynamical analysis and performance optimization scheme of the cogeneration plant: this reprenents an example of the complete dynamical analysis scheme that allows, in this case, to highlight how power tracking and the correspondent performance optimization algorithm work. Therefore, the whole scheme, flow charts and equations are not shown for brevity.

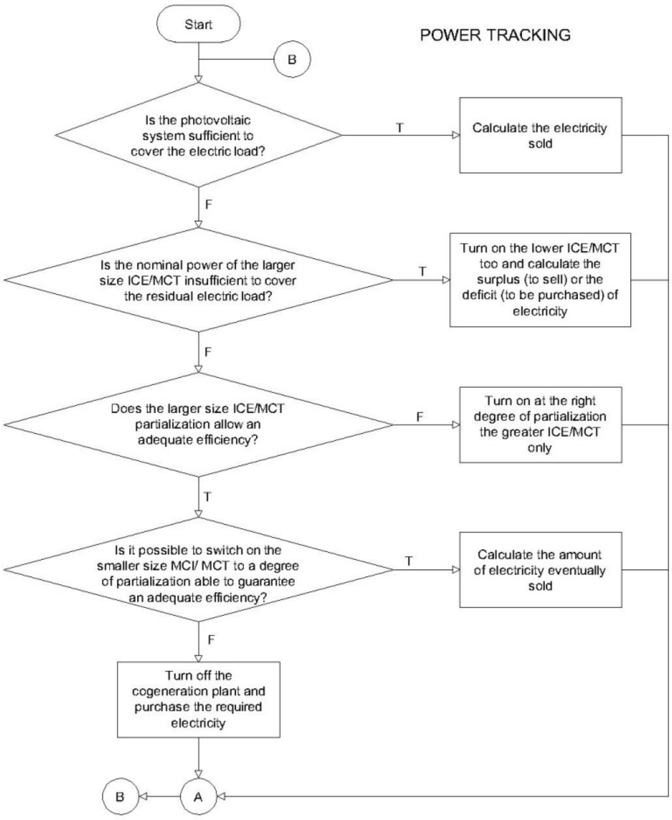

Figure 2. Schematization of the operating logics for power tracking. The "A" operator stands for "calculation of process parameters" (not shown), "B" represents "go back".line

The method, based on a dynamic simulation, has been adapted to several cases of food industry (Tamborrino et al., 2019b); in this case, considering the specific energetic characteristics of the studied pasta factory, the method allowed to evaluate the energy efficiency of the fresh semolina pasta processing plant involved in the experimental test.

3. Results

Here are shown the results of the energy and mass balance carried out for fresh semolina pasta where 10,000 kg/day are produced which is the most representative production. The machines considered are (Figure 3):

- mixer;
- trainer;
- pasteurizer and pre-dryer;
- cooling units;
- packaging machine;
- second pasteurizer.

The amount of mass processed by the mixer is 755 kg/h, with a loss coefficient of 5%. In the pasteurizer, 700 kg/h of wet product are processed with a 2% mixture loss using 343 kg/h of steam. This energy exchange leads to obtain a pasteurized product which is then treated in the dryer for the unpackaged product, using appropriately treated and dehumidified air as an exchange fluid. In this machine 617 kg/h of dehumidified product are obtained to be used for subsequent cooling and packaging and 103 kg/h of water that is transferred from the product to the surrounding air as steam.

The afore mentioned values, together with those determined with the same methodology for all the other lines, have been included in the equations relating to the energy calculations carried out for the pasteurizers of each line, in which the maximum consumption of thermal energy occurs.

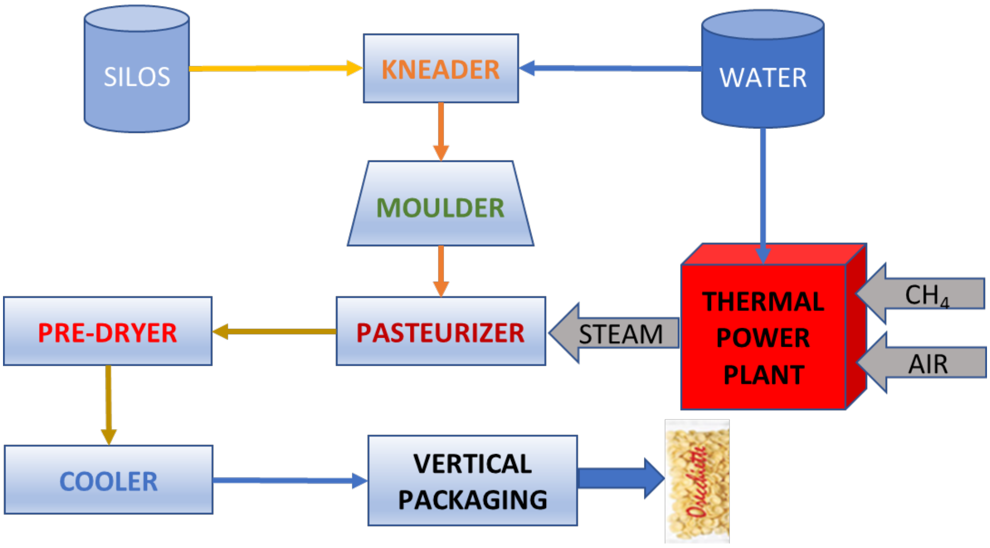

Figure 3. Total mass balance of the fresh semolina pasta production line

As said before, the equations, describing the mass and energy flows for each equipment of the analyzed process, can be found in Catalano et al. (2020) therefore, for the sake of brevity, are not shown here.
The same method, shows also that the heat inputs in all the equipments are much lower than in pasteurizers (Figure 4).

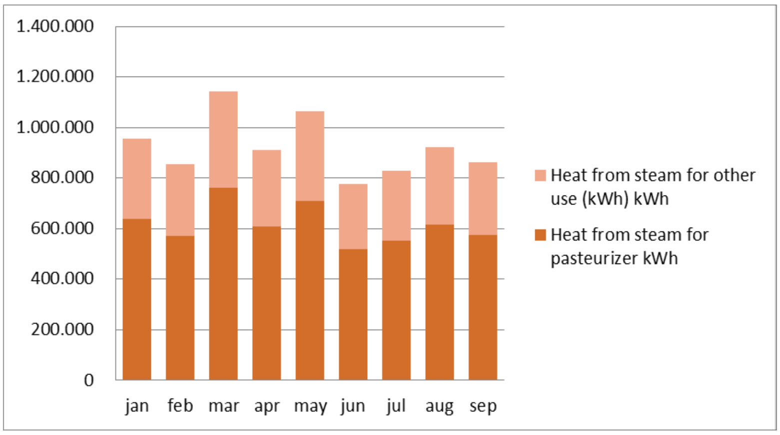

Figure 4. Monthly distribution of thermal consumption for steam production divided into; thermal energy for steam used in pasteurizers and steam used in the remaining thermal users of the production lines

The monthly amount of steam used for the fresh pasta production process and the relative specific consumption expressed in $kg_{vap}/100kg_{pasta}$ was obtained considering that the process steam is used in a closed circuit and that the losses can be considered negligible. The highest steam value is required by all lines in May, while relatively small amount of steam is used in June. It is not possible to identify an immediate correlation between the consumption of steam and the corresponding production; for example, in the months of February and September there are production values close to the maximum ones, which correspond to steam consumption similar and comparable to the minimum, on the contrary, in the May there is a similar production but a much higher steam consumption. The lowest specific consumptions are found, first of all, when production is close to the maximum values and, secondly, when the use of steam tends to minimum values. When a variation in production does not correspond to a correct adjustment of the steam used, the specific consumption tends to assume the maximum values.

From the above results, for this type of systems, it is possible to define a value of 100.0 kg_{vap}/100 kg_{paste} for the maximum sizing adjustment, considering however that it would be useful to study a specific system for monitoring and measuring the steam flow rate, in in relation to the flow rate of the product being processed, which could allow a saving in steam consumption of up to 24%.

From the analysis of the results of the overall thermal energy balance, an average value for the maximum sizing can be defined equal to 134 kWh / 100 kg_{pasta}; this value is obtained by considering the monthly consumption, the trend of which is fairly consistent with the consumption of steam, confirming that in the company studied this is the main vector of thermal energy.

The greater thermal energy commitment is attributed to the pasteurization phase: approximately 67% of the total thermal energy required by the production process (Figure 6); this results because the heat exchange of this phase is characterized by a higher ” T compared to the other production phases. The remaining 33% of total thermal energy is represented by low temperature thermal energy used in pre-dryers and final pasteurizers.

On the other hand, the experimental data relating to thermal consumption for the sole production of process steam do not coincide with the total thermal consumption of the company obtained from the analysis of the methane bills consumed, also considering the efficiency of combustion (Figure 5).

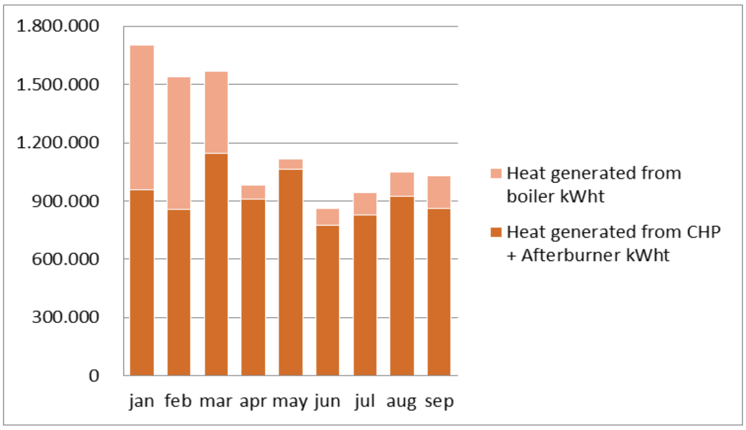

Figure 5. Total monthly thermal energy produced consumed by the plant and divided into thermal energy produced in the boiler and thermal energy produced by the CHP + Post Combustor (values expressed in thermal kWh)

In fact, the methane consumed is higher than that necessary to produce steam useful for the process which represents the only thermal user of the company. Therefore, a reduction in the overall consumption of thermal energy and in production costs could be obtained, through a study of optimization of the production of steam as well as of its use in relation to the actual thermal demand of the production, as well as to any waste and possible recovery of the thermal waste.

As regards the analysis of monthly electricity consumption (Figure 5), in the months of August and February there is a correspondence between the consumption of thermal energy (Figure 3) and electricity. Furthermore, a fairly precise correlation can be defined between the consumption of electricity and production, contrary to what appears for thermal energy; for example, in the months of March, May, August and September, production values are found close to the maximum ones, corresponding to similar and comparable electricity consumption with the maximum. For the maximum sizing, a precautionary value of 37 kWh/100kgpasta can be considered.

In table 1 the real monthly production of electricity and the gas needed by the CHP are shown. These values comes from measures in the plant designed by mean of the classical and standard method that uses stationary conditions for plant management. In table 2 the new method was applied to determine the values in case of dynamicalmanagement of the plant. Comparing the values of the two tables it can be highlighted that there is not only an increase of the energy production but also a decrease in gas consumption showing a net increase in the CHP global efficiency.

Month	Electricity produced from CHP	Gas consumed from CHP	Gas consumed from extra burner of CHP	Electricity consumed from grid	Gas consumed from grid
	kWh	**Smc**	**Smc**	**kWh**	**Sm3**
jan	258.373	82.547	84.460	141.293	167.007
feb	238.287	75.027	74.760	107.193	149.787
mar	330.887	105.335	97.412	135.508	202.747
apr	252.543	80.887	78.924	121.482	159.811
may	314.299	100.983	93.084	166.671	194.067
jun	230.971	75.700	69.937	175.431	145.637
jul	260.942	85.942	75.766	198.090	161.708
aug	290.113	96.214	82.525	220.235	178.739
sep	258.955	85.973	74.501	220.406	160.474

Table 1. Total monthly electricity produced by CHP, and gas consumed in the real case with classical method analysis

Month	Electricity produced from CHP	Gas consumed from CHP	Gas consumed from extra burner of CHP	Electricity consumed from grid	Gas consumed from grid
	kWh	**Smc**	**Smc**	**kWh**	**Sm3**
jan	297.129	89.151	91.217	102.537	180.368
feb	262.115	78.778	78.498	83.364	157.276
mar	370.593	112.708	104.231	95.802	216.939
apr	275.271	84.122	82.081	98.753	166.203
may	370.873	113.101	104.254	110.097	217.355
jun	247.138	77.971	72.035	159.263	150.006
jul	273.989	87.661	77.281	185.043	164.942
aug	333.630	105.835	90.778	176.718	196.613
sep	287.440	92.851	80.461	191.921	173.312

Table 2. Total monthly electricity produced by CHP, and gas consumed in the simulation with the new method analysis

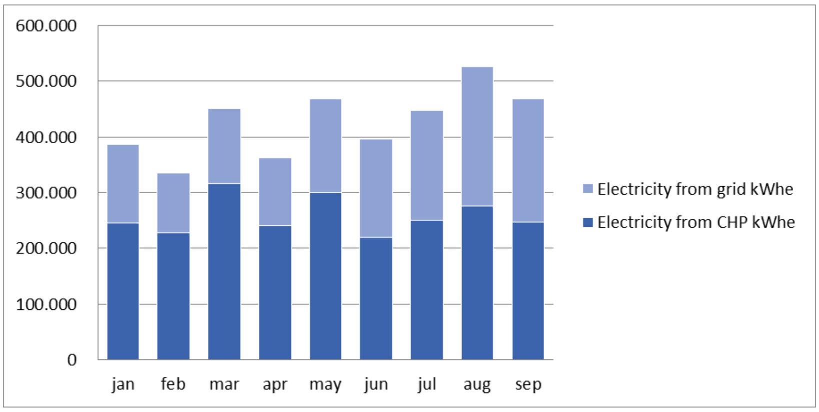

Figure 6. Total monthly electricity consumed divided into: produced by the CHP and purchased from the grid

The cogenerator can cover 60% of the total electricity requirement (Figure 6), 84% of the thermal requirement due to the use of steam and 60% of the total thermal requirement and its electrical power has been set to produce, together with the afterburner, the amount of thermal energy required by the production process. The aforementioned rates are integrated, respectively, with electricity purchased from the grid and with thermal energy produced in the boiler. The electricity purchased from the grid has higher values in the months of June, July, August, and September. Therefore, the results show a greater consumption of electricity from the grid mainly in the summer months.

Therefore, it can be said that, overall, the cogeneration plant is efficient, however a more in-depth energy analysis would be required: not referring to individual lines but to individual machines. In this way it would be possible to accurately evaluate the most suitable efficiency solutions for the specific company situation; for example, it may be sufficient to integrate the electricity needs with a photovoltaic system and reduce heat consumption with an adequate study of recovery of the related waste, rather than inserting an additional microturbine in the cogeneration plant.

4. Conclusions

The aim of this paper is to propose a new method for evaluating the mass and energy balance in a fresh pasta processing factory by using a dynamic simulation analysis. The proposed procedure first of all requires that the designer has to acquire real data about the use of mass and energy and use these data as input to the simulation model. The proposed technique can be used effectively when there is a variability of the electrical and / or heat load.

The results prove that the dynamic analysis carried out in this paper can lead to high profitability in terms of both energetic benefits and environmental impact. For a future perspective, the method could be further enhanced to optimize the monitoring of the CHP plant during operations.

With the cogeneration plant built, the company has an important annual saving on bills compared with the investment (data not shown as not in the aims of the paper.Based on these results, the company is evaluating how to improve the performance of the cogeneration plant, to increase the self-production of electrical and thermal energy, therefore to reduce the consumption of the afterburner and the electricity purchased from the grid, with the aim of further reducing consumption, costs and the environmental impact of production.

The results of this study can be extended to industries that carry out productions similar to the one studied, both in qualitative and quantitative terms, in addition some considerations can be made.

The analysis of the energy aspects of a production offers the food technologist the possibility to carry out the general design of the production plants and layouts, considering:

- aspects related to the quality of production;
- the possibilities of reducing production costs;
- the possibilities of enhancing the environmental commitment of production with an appropriate marketing policy.

This study also shows that the first logical step to undertake an energy saving and recovery path is to carry out an in-depth energy analysis of the company's machines and systems; the purpose is to implement interventions aimed at reducing consumption, and then move on to a correct sizing / choice of the energy self-production system, possibly resorting to a mix of technical solutions that could go beyond individual solutions, such as cogeneration , proposed by the supplier companies and would lead to greater economic savings.

Acknowledgments

The authors have contributed to the same extent to the present study.

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