Exergetic Analysis and Exergy Loss Reduction in the Milk Pasteurization for Italian Cheese Production

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Abstract: The cheese industry has high energy consumption, and improvements to plant efficiency may lead to a reduction of its environmental impact. A survey on a sample of small-medium Italian cheese factories was carried out in order to assess the efficiency of heat recovery of the milk pasteurization equipment for the cheese production. Then, an exergetic analysis to calculate the related exergy loss was carried out together with a cost-benefit analysis to identify the optimized value of the heat efficiency. The exergy loss reduction was determined throughout an exergy analysis that takes into account this last value and the comparison with the previous exergy losses. Finally, the feasibility and the consequent additional reduction of exergy losses were verified, if a cogeneration heat and power (CHP) combined to the pasteurization equipment is assumed. Results show a current heat recovery efficiency of 93.2% in the Italian cheese factories; a close connection between the exergetic losses and the efficiency of the heat recovery exchanger; the optimized recovery efficiency equal to 97.3% obtained from the cost-benefit analysis; a related important exergetic loss reduction of −45% in the heat exchangers, as a second result of the exergetic analysis; a similar reduction of the exergy loss (−42%) of the whole system, as a third result of the exergetic analysis; a total exergy loss reduction of 22.9 kJ kg^{-1}milk, which corresponds to a lower environmental impact due to CO_2 reduction; a further reduction of the exergy loss of −10% when the cogeneration heat and power CHP are used.

Keywords: cost-benefit analysis; plate heat exchanger; exergy analysis

1. Introduction

The Italian annual production of cow's milk is more than 12 million ton y^{-1}; of this amount, about 2.5 million ton y^{-1} are used as food without transformation, while the remaining production is transformed in Italian cheese [1]. There are approximately 2000 cheese factories, including the cooperatives, only 90 of them transforming the 50% of almost 10 million ton/year of milk with 40 ton y^{-1} average per capita production. The other half of milk production is transformed into cheese by most cheese factories [1], which are connoted to be mainly like a partially craft activity, but with a high regional diversification of dairy products highly appreciated by consumers that stimulates food and wine tourism and increases the positive effects on local economy. At the time, these small factories have a reduced inclination to invest in equipment leading to higher production costs, also related to the low energetic efficiency of the plants.

However, it is important to observe that in other European Countries the presence of few large dairy factories is more frequent, equipped with new high efficiency plants. For example, in France there are about 700 factories with an average per capita production about 22,000 ton y^{-1}, in Germany

less than 300 factories with 54,000 ton y^{-1}, and in Netherlands the dairy factories are only 52 with 105,000 ton y^{-1} average per capita production [2–5].

Specifically, regarding the topic dealt with in this work, namely the heat recovery treatments of milk before cheese making, it can be said that they are in fifth place in terms of energy demand, after the processes relating to the oil, chemical, paper, and steel industry [6]. The energy consumed in the dairy sector is mostly derived from the burning of fossils such as oil, natural gas, and coal. This means two things: (1) a non-negligible contribution to environmental pollution; (2) a dependence on fossil fuel supplies, which makes food production a hostage of the changing prices due to international crises [7–11]. A valid way to help to reduce these problems is the use of energy improvement strategies [6].

To achieve the aim of energy efficiency, the exergetic balance is a modern and powerful tool, introduced in the middle of the previous century [12,13], based on the linear combination of the other two balances: the energy balance (First Law of Thermodynamics) and the entropy balance (Second Law of Thermodynamics) [14]. With exergetic analysis, it is easier to understand the dissipative phenomena accompanying the use of energy [15–22].

In light of the excellent results obtained from the exergetic analysis applied to some processes carried out in the dairy factories [23–32] and other sectors of the food industry [33–35], this work aims to assess the exergy loss reduction in the milk pasteurization as a consequence of an increase in heat efficiency in the Italian dairy production systems through: (a) a sample survey on Italian cheese factories to measure the efficiency of energy recovery of the milk pasteurization equipment for dairy production; (b) the study of the exergy losses related to the low efficiency based on an analysis method already successfully used [34]; (c) cost-benefit analysis to find the best coefficient of energy recovery efficiency; (d) the assessment of the resulting reduction of exergy losses if the industries adopted the modification of the milk pasteurization equipment able to increase to the optimal value the efficiency of energy recovery; (e) the verification of the feasibility and the consequent additional reduction of exergy losses, if the use of a cogeneration heat and power (CHP) combined to the pasteurization equipment was assumed.

The results of these analysis and verifications could be of interest to engineers and plant managers to develop improvements and to adapt the management of industrial pasteurization plants for milk destined for transformation into dairy products.

2. Methods

2.1. Pasteurization System with Heat Recovery Exchanger

A sample survey on 40 small-medium Italian cheese factories was carried out. In all the factories the high temperature/short time (HTST) milk pasteurization occurred by operating the milk in three plate heat exchangers (PHEs) [25] at a temperature T_{mpo}. The first exchanger is used for the heat recovery between the warm pasteurized milk and the cold milk to be treated. The other two PHEs are used, respectively, to heat the milk to the pasteurization temperature T_{mpo}, using warm water, and to cool the milk, using cold water, to 4 °C temperature T_{mco}, equal to the input milk temperature T_{mi}, suitable for subsequent conservation awaiting cheese making (Figure 1).

The milk has to receive a total heat transfer rate q_{tot} to raise from the temperature T_{mi} to the pasteurization temperature T_{mpo}, equal to:

$$q_{tot} = c_m \times G_m \times \left(T_{mpo} - T_{mi} \right) \tag{1}$$

A part of this heat transfer rate q_R is obtained by the recovery exchanger:

$$q_R = c_m \times G_m \times \left(T_{mro} - T_{mi} \right) \tag{2}$$

where: c_m is the milk specific heat capacity (kJ kg^{-1} K^{-1}); G_m is the milk flow rate (kg s^{-1}); T_{mi} is the milk input temperature; T_{mpo} is the milk pasteurization temperature; T_{mro} is the milk output temperature from the recovery exchanger.
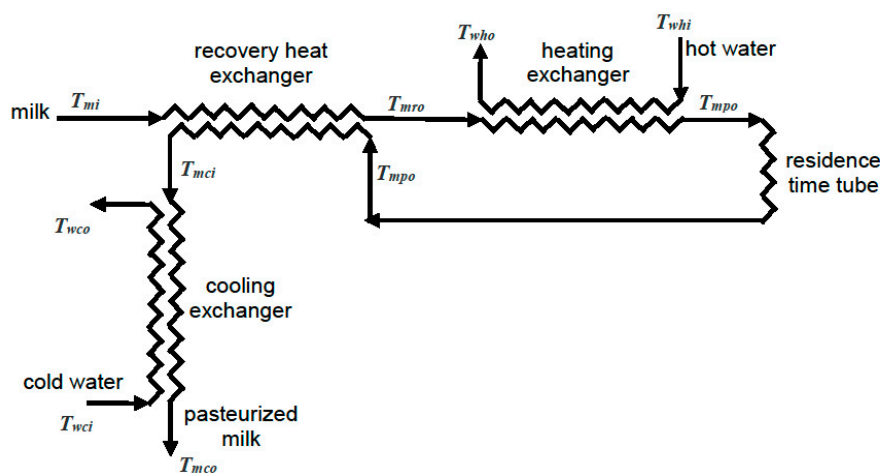
Figure 1. Flow chart of thermal exchangers system of the milk pasteurization.

We define the energy recovery efficiency ε (%) as:

$$\varepsilon = \frac{q_R}{q_{tot}} \times 100 = \frac{T_{mro} - T_{mi}}{T_{mpo} - T_{mi}} \times 100 \qquad (3)$$

The values of the temperatures T_{mi}, T_{mpo}, and T_{mro} were measured in a representative group of 40 small-medium Italian cheese factories. The measured average values allowed to calculate, by Equation (3), the average actual efficiency ε_A in Italy.

2.2. Exergetic Analysis of Thermal Exchangers

2.2.1. Recovery Exchanger

Energy analysis can be carried out using the First Law of Thermodynamics. In fact, it imposes a first condition to which all systems must undergo, that is the energy, in its various forms (kinetic, gravitational, internal, chemical, electrical, etc.), must be in balance with the heat exchanges, work exchanges, and mass exchanges.

However, the systems must undergo also the Second Law of Thermodynamics, which adds another condition, establishing that a balance concerning entropy must always be satisfied. With it, it is established that not all the energetic transformations are possible and specially the various forms in which the energy is manifested are qualitatively different. The two balances of the First and Second Laws for almost a century have remained almost completely disconnected from each other.

The intuition of Rant [12] and of Bosniakovic [13] was to do a linear combination of the two balances, so that the First and Second Laws are expressed in a single equation, so-called exergetic balance. In this way the Second Law is more practically taken into account than the entropic treatment and this type of analysis is becoming almost universal, since it facilitates the exact understanding of energy phenomena.

In the first part of the study, the exergetic analysis is carried out specifically on the heat exchangers, being the elements on which to act to reduce losses.

We start with the recovery exchanger, doing a simple energy balance (First Law) and then an entropy balance (Second Law) only for this one, to proceed then with the linear combination of the

two balances as proposed by Rant to obtain the exergetic balance. In this way we recall the conceptual basis to emphasize the importance of the process and make it more understandable.

The First Law of Thermodynamics sets (about temperature T_{mci}, T_{mco}, T_{mro} and T_{mpo} see Figure 1):

$$c_m \times G_m \times (T_{mpo} - T_{mci}) - q_{dr} - c_m \times G_m \times (T_{mro} - T_{mi}) = 0$$
$$\Rightarrow G_m \times (h_{mpo} - h_{mci}) - q_{dr} - G_m \times (h_{mro} - h_{mi}) = 0 \tag{4}$$

where specific enthalpy is introduced as $h = c_m \times T$.

Thermal power loss due to heat dispersion into the ambient, q_{dr}, are assumed to be null. Consequently, the energetic efficiency is:

$$\eta_{en} = \frac{(T_{mro} - T_{mi})}{(T_{mpo} - T_{mci})} \times 100 = 100\% \tag{5}$$

Therefore, the thermal power loss of the recovery exchanger is:

$$c_m \times G_m \times (T_{mpo} - T_{mci}) - c_m \times G_m \times (T_{mro} - T_{mi}) = 0 \tag{6}$$

As you can see, the energy balance highlights, in this case, the lack of energetic losses.

With reference to the Second Law, if the recovery exchanger is considered as an open system in steady state flow, the entropic flux balance equation is:

$$-\frac{q_{dr}}{T_a} + G_m (S_{mpo} - S_{mci}) - G_m (S_{mro} - S_{mi}) - G_m \left(\frac{\Delta p_r}{\rho \overline{T}_{mR}} + \frac{\Delta p_r}{\rho \overline{T}_{mP}} \right) + \frac{\delta S_{irr}}{dt} = 0 \tag{7}$$

where S is the specific entropy.

For the fluids working inside of the PHEs S can be calculated with: $S = c \times \ln \frac{T}{273.15}$ where c is the fluid specific heat capacity (kJ kg⁻¹ K⁻¹) (c_m for the milk and c_w for the water) and T is the temperature (K).

Entropy fluxes are negative when thermal power leaves the system, as in the cases of heat transfer rate of the dispersion q_{dr}. The entropy fluxes $G_m \cdot S_{mro}$ and $G_m \cdot S_{mci}$ are also negative because of the outgoing thermal power. The entropy flux contribution related to the decrease of the pressure $\Delta p_r = (p_{mi} - p_{mro}) = (p_{mpo} - p_{mci})$ due to the frictions inside the passages of the recovery exchanger should be calculated as the sum of infinitesimal variations of entropy: $G_m \int \frac{dp}{\rho T}$, where T is the temperature in each point of the related pressure loss dp, ρ is the fluid density. It is possible to obtain an acceptably approximated result if the average temperatures $\overline{T}_{mR} = \frac{T_{mi} + T_{mro}}{2}$ for raw milk and $\overline{T}_{mP} = \frac{T_{mpo} + T_{mci}}{2}$ for pasteurized milk are accepted and $G_m \int \frac{dp}{\rho T} \cong G_m \left(\frac{\Delta p_r}{\rho \overline{T}_{mR}} + \frac{\Delta p_r}{\rho \overline{T}_{mP}} \right)$ is placed.

The term $\frac{\delta S_{irr}}{dt}$ represents the entropy rate linked to irreversibility, always positive according to the Second Law.

According to Rant [12], the exergy flux balance equation is obtained by linear combination of the two previous balances and, precisely, by multiplying Equation (5) by the ambient temperature (T_a) and subtracting it from Equation (1):

$$G_m\left[\left(h_{mpo}-T_aS_{mpo}\right)-\left(h_{mci}-T_aS_{mci}\right)\right]-G_m\left[\left(h_{mro}-T_aS_{mro}\right)-\left(h_{mi}-T_aS_{mi}\right)\right]+$$

$$+G_mT_a\frac{\Delta p_r}{\rho}\left(\frac{1}{\overline{T}_{mR}}+\frac{1}{\overline{T}_{mP}}\right)-T_a\frac{\delta S_{irr}}{dt}=0 \tag{8}$$

The first term $G_m\times[(h_{mpo}-T_aS_{mpo})-(h_{mci}-T_aS_{mci})]$ is the exergy/transformation flux [14] available from pasteurized hot milk, given by the difference between exergy/transformation flux of the inlet pasteurized milk $G_m\times(h_{mpo}-T_aS_{mpo})$ and exergy/transformation flux of the outlet pasteurized milk $G_m\times(h_{mci}-T_aS_{mci})$.

The second term $G_m\times[(h_{mro}-T_aS_{mro})-(h_{mi}-T_aS_{mi})]$ represents the exergetic/transformation power from cold raw milk.

Therefore, it is clear that the exergy flux balance of Equation (8) may be a very valuable tool for the thermodynamic assessment including both conservation of energy according to the First Law, and entropy considerations from the Second Law.

The exergy/transformation flux is the maximum available mechanical power that is achieved through a reversible process on the fluid operating inside the thermodynamic system, in this case the recovery exchanger. In the first term the fluid under consideration is the pasteurized milk, and in the second term it is the raw cold milk.

The third term $G_mT_a\dfrac{\Delta p_r}{\rho}\left(\dfrac{1}{\overline{T}_{mR}}+\dfrac{1}{\overline{T}_{mP}}\right)$ is the exergy flux related to the friction phenomena of the fluids in the recovery exchanger and represented by the decrease of the pressure Δp_r.

The fourth term $T_a\dfrac{\delta S_{irr}}{dt}$ is related to the increase in entropy rate due to irreversible processes. The irreversibility could be internal (for example, due to friction) or external (related to heat exchange due to temperature differences). In both cases the work is reduced. Since the energy available for use in the system is partially wasted, this fourth term can be considered an exergy flux loss produced by irreversibility (L). We can also consider the specific exergy loss as: $\ell = L/G_m$ (kJ kg^{-1}milk):

$$\ell=\left[\left(h_{mpo}-T_aS_{mpo}\right)-\left(h_{mci}-T_aS_{mci}\right)\right]-\left[\left(h_{mro}-T_aS_{mro}\right)-\left(h_{mi}-T_aS_{mi}\right)\right]+Ta\frac{\Delta p_r}{\rho}\left(\frac{1}{\overline{T}_{mR}}+\frac{1}{\overline{T}_{mP}}\right) \tag{9}$$

Further, the exergetic efficiency of the recovery exchanger can be defined as the ratio between the net exergy/transformation of the raw cold milk, $\left[\left(h_{mpo}-T_aS_{mpo}\right)-\left(h_{mci}-T_aS_{mci}\right)\right]-\ell$, and the exergy/transformation $\left[\left(h_{mpo}-T_aS_{mpo}\right)-\left(h_{mci}-T_aS_{mci}\right)\right]$ related to the pasteurized hot milk:

$$\eta_{ex}=1-\frac{\ell}{\left(h_{mpo}-T_aS_{mpo}\right)-\left(h_{mci}-T_aS_{mci}\right)}\times100 \tag{10}$$

2.2.2. Heating Exchanger

Similarly, the exergetic analysis for the heating exchanger was established, first to calculate the specific exergy loss:

$$\ell=\frac{G_w}{G_m}\left[\left(h_{whi}-T_aS_{whi}\right)-\left(h_{who}-T_aS_{who}\right)\right]-\left[\left(h_{mpo}-T_aS_{mpo}\right)-\left(h_{mro}-T_aS_{mro}\right)\right]+$$

$$+T_a\frac{\Delta p_h}{\rho}\left(\frac{G_w}{G_m}\frac{1}{\overline{T}_{wH}}+\frac{1}{\overline{T}_{mH}}\right) \tag{11}$$

where G_w is water flow rate and G_m is the milk flow rate (kg s^{-1}).

On the second, to calculate the exergetic efficiency:

$$\eta_{ex} = 1 - \frac{\ell}{\dfrac{G_w}{G_m}\left[\left(h_{whi} - T_a S_{whi}\right) - \left(h_{who} - T_a S_{who}\right)\right]} \times 100 \tag{12}$$

2.2.3. Cooling Exchanger

The exergetic balance and the related efficiency of the cold water cooling exchanger are:

$$\ell = \left[\left(h_{mci} - T_a S_{mci}\right) - \left(h_{mco} - T_a S_{mco}\right)\right] - \frac{G_w}{G_m}\left[\left(h_{wco} - T_a S_{wco}\right) - \left(h_{wci} - T_a S_{wci}\right)\right] +$$

$$+ T_a \frac{\Delta p_c}{\rho}\left(\frac{G_w}{G_m}\frac{1}{\overline{T}_{wC}} + \frac{1}{\overline{T}_{mC}}\right) \tag{13}$$

$$\eta_{ex} = 1 - \frac{\ell}{\left(h_{mci} - T_a S_{mci}\right) - \left(h_{mco} - T_a S_{mco}\right)} \times 100 \tag{14}$$

Definitely, the total exergetic losses of the heat exchanger system for the milk pasteurization are the contribution of the three exchange subsystems seen above.

Observing Equation (3) we note that an increase in energy recovery efficiency ε is accompanied by an increase in the output temperature of the recovery exchanger T_{mro} and, therefore, with a constant T_{mpo}, a reduction in the temperature difference between the two fluids of the recovery exchanger certainly occurs.

As can be seen from Equation (9), this reduction leads to a decrease of the difference between the exergy/transformation flux available from pasteurized hot milk and that one from raw cold milk and therefore to an exergetic loss $\ell = L/G_m$ and an increase of the exergetic efficiency.

The result is that only increasing the heat exchange efficiency ε in the recovery exchanger an adequate contraction of this loss can be obtained. At the limit, it will be null if the temperature difference between the two fluids is null. Clearly, this is a non-feasible limit condition because it involves an infinite exchange surface.

Only with economic budget considerations between the higher cost of the PHEs and the reduction of the energy cost it is possible to optimize the efficiency value ε_{opt}. A method for the optimization is shown below.

2.3. Cost-Benefit Analysis

2.3.1. Unit Cost of Thermal and Electric Energy vs. Recovery Efficiency

Considering all the exchangers without heat transfer rate of the dispersion q_{dr}, close to the truth because they are PHEs, the thermal power consumed in the heating exchanger (Figure 1) is $q_{tot} - q_R = c_m G_m\left(T_{mpo} - T_{mro}\right)$. By placing the temperature of the recovery exchanger T_{mro}, obtained from (3), we have:

$$q_{tot} - q_R = c_m G_m\left(T_{mpo} - T_{mi}\right)\left(1 - \frac{\varepsilon}{100}\right) \tag{15}$$

It is less the higher the efficiency is, and resets when $\varepsilon = 100\%$.

To produce the heat transfer rate $q_{tot}-q_R$ by a heat boiler with an efficiency η_{hb} it is necessary to consume fuel, like the natural gas, with a net heating value HV (kJ Sm^{-3}) and a cost C_F (Euro Sm^{-3}). Therefore, the heat unit cost C_H (Euro kg^{-1}milk) is:

$$C_H = \frac{C_F\left(q_{tot}-q_R\right)}{\eta_{hb}\times HV\times G_m} = \frac{C_F}{\eta_{hb}\times HV}c_m\left(T_{mpo}-T_{mi}\right)\left(1-\frac{\varepsilon}{100}\right) \tag{16}$$

The heat transfer rate to be disposed in the cooling heat exchanger is the same supplied to the milk in the heat exchanger given by Equation (15). This flux $q_{tot}-q_R$ is transferred to the cold water and therefore to the refrigerating fluid of the refrigerating machine having a coefficient of performance $COP = (q_{tot}-q_R)/P$. The mechanical power required by the refrigerator compressor P related to the milk flow rate G_m and multiplied by the unit cost of the electrical energy C_W (euro kWh^{-1}) becomes the unit cost for refrigeration C_M (Euro kg^{-1}milk):

$$C_M = \frac{C_W\left(q_{tot}-q_R\right)}{COP\times G_m} = \frac{C_W}{COP\times 3600}c_m\left(T_{mpo}-T_{mi}\right)\left(1-\frac{\varepsilon}{100}\right) \tag{17}$$

Finally, it is necessary to consider the energy costs for the functioning of the deaerator and of the pumps activating the flows of milk, warm water, and cold water in the exchangers (Figure 1).

E_D (kWh kg^{-1}milk) defines the unit consumption of electricity of the deaerator and it is independent from the recovery efficiency ε. The E_D average value was found through the survey on the Italian cheese factories sample.

The electricity unit consumption of the four pumps is defined with E_{Phw}, E_{Pcw}, E_{Prm}, and E_{Ppm} (kWh kg^{-1}milk), working on warm water, cold water, raw milk, and pasteurized milk, respectively.

E_{Phw}, E_{Pcw}, E_{Prm}, and E_{Ppm} depend on the recovery efficiency ε. In fact, increasing its value there is a corresponding increase in the surface area of the exchangers A_{tot}. As they are PHEs with a mixed series/parallel assembly, the increase of the exchange surface implies both a proportional increase in the length of the milk and service fluids path and an increase of the number of the flow deviations. Therefore, the pressure exerted by the pumps to overcome the load losses and consequently the unit electrical consumption of all four pumps E_P will increase linearly with the area A_{tot}, which will be a function of the efficiency $A_{tot} = f(\varepsilon)$, as will be shown in the next paragraph, according to Equation (18):

$$A_{tot} = \frac{c_m\times G_m}{U}\left[\frac{\varepsilon}{100-\varepsilon}+\left(T_{mpo}-T_{mi}\right)\left(\frac{100-\varepsilon}{100}\right)\left(\frac{1}{\Delta T_H}+\frac{1}{\Delta T_C}\right)\right] \tag{18}$$

where T_{mi} is the input temperature of the raw milk, T_{mpo} is the output temperature of the pasteurized milk, ΔT_H and ΔT_C are the average differences of temperature of the heat exchanger and the cool exchanger, respectively.

It is easy to correlate the unit electric consumption E_P of the four pumps, variable with the efficiency ε, to the value of the average consumption E_{PA} resulted by the survey on the sample of cheese factories operating at the current average efficiency ε_A:

$$E_P = E_{PA}\frac{\dfrac{\varepsilon}{100-\varepsilon}+\left(T_{mpo}-T_{mi}\right)\left(\dfrac{100-\varepsilon}{100}\right)\left(\dfrac{1}{\Delta T_H}+\dfrac{1}{\Delta T_C}\right)}{\dfrac{\varepsilon_A}{100-\varepsilon_A}+\left(T_{mpo}-T_{mi}\right)\left(\dfrac{100-\varepsilon_A}{100}\right)\left(\dfrac{1}{\Delta T_H}+\dfrac{1}{\Delta T_C}\right)} \tag{19}$$

Definitely, with C_W the unit cost electric energy (Euro kWh^{-1}), the unit cost of the electricity consumed by the deaerator and the pumps C_{DP} (Euro kg^{-1}milk) is:

$$C_{DP} = C_W \times E_D + C_W \times E_P \tag{20}$$

2.3.2. Unit Cost of Heat Exchanger Area vs. Recovery Efficiency

The area of the recovery heat exchanger is calculated as:

$$A_R = \frac{q_R}{U \times \left(T_{mpo} - T_{mro}\right)} \tag{21}$$

where U is the overall heat transfer coefficient (kW m^{-2} K^{-1}).

Using Equations (1) and (3), Equation (21) becomes:

$$A_R = \frac{c_m \times G_m}{U}\left(\frac{\varepsilon}{100 - \varepsilon}\right) \tag{22}$$

Likewise, we calculate the heating exchanger area (Figure 1):

$$A_H = \frac{q_{tot} - q_R}{U \times \Delta T_H} = \frac{c_m \times G_m \left(T_{mpo} - T_{mi}\right)}{U \times \Delta T_H}\left(\frac{100 - \varepsilon}{100}\right) \tag{23}$$

where ΔT_H is the average temperature difference between the of the warm water and the milk, considered constant throughout the exchanger. Observing the Figure 1, the cooling exchanger is symmetrical to the heating exchanger, as the exit temperature T_{mco} is equal to the entry temperature T_{mi}, and therefore has the same exchanged heat transfer rate $q_{tot} - q_R$. Consequently, the area A_C is:

$$A_c = \frac{q_{tot} - q_R}{U \times \Delta T_c} = \frac{c_m \times G_m \left(T_{mpo} - T_{mi}\right)}{U \times \Delta T_c}\left(\frac{100 - \varepsilon}{100}\right) \tag{24}$$

where ΔT_C is the average temperature difference between the cold water and the milk, considered constant throughout the exchanger; U is the transmittance or overall heat transfer coefficient (kW m^{-2} K^{-1}).

Definitively, by adding Equations (22), (23), and (24), we obtain the heat exchange total area A_{tot} related to the recovery efficiency (see Equation (18)).

The unit cost of the equipment C_E (Euro kg^{-1}milk) is calculated as:

$$C_E = \frac{C_A \times A_{tot}}{G_m \times B \times N \times 3600} = \frac{C_A \times c_m}{U \times B \times N \times 3600}\left[\frac{\varepsilon}{100 - \varepsilon} + \left(T_{mpo} - T_{mi}\right)\left(\frac{100 - \varepsilon}{100}\right)\left(\frac{1}{\Delta T_H} + \frac{1}{\Delta T_C}\right)\right] \tag{25}$$

where C_A is the equipment cost per unit of area (Euro m^{-2}); G_m is the milk flow rate (kg s^{-1}); B is the useful life of the equipment (y); N is the running time for pasteurization (h y^{-1}).

2.3.3. Optimization of Recovery Efficiency

The total unit cost C_{tot} is the sum of the equipment cost C_E, the heating energy cost C_H and the electrical costs C_M and C_{DP}, or the sum of Equations (25), (16), (17), and (20) and it is a cost function related to the recovery efficiency:

$$C_{tot} = C_W \times E_D + \left[\frac{C_A \times c_m}{U \times B \times N \times 3600} + \frac{C_W \times E_{PA}}{\frac{\varepsilon_A}{100 - \varepsilon_A} + \left(T_{mpo} - T_{mi} \right) \left(\frac{100 - \varepsilon_A}{100} \right) \left(\frac{1}{\Delta T_H} + \frac{1}{\Delta T_C} \right)} \right] \times$$

$$\left[\frac{\varepsilon}{100 - \varepsilon} + \left(T_{mpo} - T_{mi} \right) \left(\frac{100 - \varepsilon}{100} \right) \left(\frac{1}{\Delta T_H} + \frac{1}{\Delta T_C} \right) \right] +$$

$$+ \left(\frac{C_F}{\eta_{hb} \times HV} + \frac{C_W}{COP \times 3600} \right) c_m \left(T_{mpo} - T_{mi} \right) \left(\frac{100 - \varepsilon}{100} \right) \tag{26}$$

We need to find the minimum of this function (Equation (26)) through the derivation and the search for zero:

$$\frac{dC_{tot}}{d\varepsilon} = \left(\frac{C_A \times c_m}{U \times B \times N \times 3600} + \frac{C_W \times E_{PA}}{\frac{\varepsilon_A}{100 - \varepsilon_A} + \left(T_{mpo} - T_{mi} \right) \left(\frac{100 - \varepsilon_A}{100} \right) \left(\frac{1}{\Delta T_H} + \frac{1}{\Delta T_C} \right)} \right) \times$$

$$\left[\frac{100}{\left(100 - \varepsilon \right)^2} + \frac{T_{mpo} - T_{mi}}{100} \left(\frac{1}{\Delta T_H} + \frac{1}{\Delta T_C} \right) \right] +$$

$$+ \left(\frac{C_F}{\eta_{hb} \times HV} + \frac{C_W}{COP \times 3600} \right) c_m \frac{T_{mpo} - T_{mi}}{100} = 0 \tag{27}$$

The optimal efficiency is:

$$\varepsilon_{opt} = 100 -$$

$$- \frac{100}{\left[\frac{\left(\frac{C_F}{\eta_{hb} \times HV} + \frac{C_W}{COP \times 3600} \times c_m \right)}{\frac{C_A \times c_m}{U \times B \times N \times 3600} + \frac{C_W \times E_{PA}}{\frac{\varepsilon_A}{100 - \varepsilon_A} + \left(T_{mpo} - T_{mi} \right) \left(\frac{100 - \varepsilon_A}{100} \right) \left(\frac{1}{\Delta T_H} + \frac{1}{\Delta T_C} \right)}} + \left(\frac{1}{\Delta T_H} + \frac{1}{\Delta T_C} \right) \right]^{\frac{1}{2}} \left(T_{mpo} - T_{mi} \right)^{\frac{1}{2}}} \tag{28}$$

3. Results and Discussion

3.1. Survey of Energy Recovery Efficiency of the Italian Milk Pasteurization

The results of the survey on the Italian small-medium Italian cheese factories showed, as reported in Table 1, a standardized input temperature of milk T_{mi} of 4 °C, an average pasteurization temperature T_{mpo} of 77 °C, with a 2 °C standard deviation, an average recovery temperature T_{mro} of 72 °C, with a 2 °C standard deviation. According to Equation (3), the average energy recovery efficiency ε_A is 93.2%.

### 3.2. Exergetic Analysis of Heat Exchangers of Actual Pasteurization Equipment

As reported in Section 2.2, the exergetic analysis was first conducted on the current pasteurization system, characterized by efficiency ε_A = 93.2%, and specifically on the PHEs being the elements on which to act to reduce exergetic losses.

The values of the various quantities needed to calculate the exergy flows and therefore to calculate the exergetic losses in the heat exchange system for pasteurization, are reported in Table 1.

Table 1. Technical characteristics of pasteurization process used in the exergetic analysis, detected during the survey on the Italian dairies sample.

Symbol	Name	Unit	Value
c_m	Milk specific heat capacity [36]	kJ kg^{-1} K^{-1}	3933
c_w	Water specific capacity	kJ kg^{-1} K^{-1}	4187
T_a	Ambient temperature	°C	20
T_{mi}	Raw milk input temperature	°C	4
T_{mci}	Cooling exchanger milk input temperature	°C	9
T_{mco}	Cooling exchanger milk output temperature	°C	4
T_{mpo}	Pasteurized hot milk output temperature	°C	77
T_{mro}	Recovery exchanger milk output temperature	°C	72
T_{wci}	Cooling exchanger water input temperature	°C	1
T_{wco}	Cooling exchanger water output temperature	°C	6
T_{whi}	Heating exchanger water input temperature	°C	82
T_{who}	Heating exchanger water output temperature	°C	77
Δp_r	Recovery exchanger pressure drop	kPa	125
Δp_c	Cooling exchanger pressure drop	kPa	50
Δp_h	Heating exchanger pressure drop	kPa	50

In Figure 2 the specific exergetic losses are reported. It can be noted that the recovery exchanger shows much higher exergetic losses than the others and equal to 4.27 kJ kg^{-1}milk.
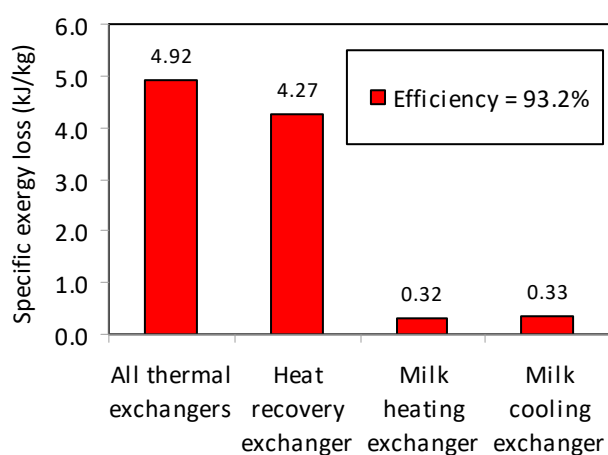
Figure 2. Exergetic losses in all thermal exchangers system and in each exchanger referred to the current Italian condition with actual efficiency ε_A = 93.2%.

3.3. Cost-Benefit Analysis and Assessment of Optimized Efficiency

The results of the survey show that on average the deaerator requires a unit electricity consumption E_D of 0.00136 kWh kg^{-1}milk equal to 4.9 kJ kg^{-1}milk, independent from the recovery efficiency ε. All data used in the cost-benefit analysis are reported in Table 2.

In particular, in the current condition, the two pumps operating for the milk movement are working at an average pressure of 125 kPa, while the pumps operating on hot water and on cold water both work at an average pressure of 50 kPa (Table 1). These are pressure values corresponding to the current average recovery efficiency ε_A of 93.2% and for which a current unit consumption of electricity E_{PA} of 3.06·10^{-4} kWh kg^{-1}milk = 1.1 kJ kg^{-1}milk was found.

Table 2. List of the data used in the cost-benefit analysis, detected during the survey on the Italian dairies sample.

Symbol	Name	Unit	Value
B	Useful life of the equipment	y	10
C_A	Area unit cost of pasteurization equipment	Euro m^{-2}	600

C_F	Fuel unit cost	Euro Sm^{-3}	0.86
C_W	Electric energy unit cost	Euro kWh^{-1}	0.18
COP	Coefficient of performance of refrigerator	-	2.68
E_D	Electric consumption of deaerator	kWh kg^{-1}milk	$1.36 \cdot 10^{-3}$
E_{PA}	Actual unit electric consumption of pumps	kWh kg^{-1}milk	$3.06 \cdot 10^{-4}$
HV	Heat value of natural gas	kJ Sm^{-3}	34,333
N	Running pasteurization time	h y^{-1}	8000
T_{cond}	Condensation temperature of refrigerator	°C	45
T_{ev}	Evaporation temperature of refrigerator	°C	−5
U	Overall heat transfer coefficient	kW m^{-2} K^{-1}	1.5
ΔT_C	Temperature difference in cooling exchanger	°C	3
ΔT_H	Temperature difference in heating exchanger	°C	5
η_{hb}	Thermal efficiency of the heating boiler	-	0.95

Additionally, with the current average recovery efficiency ε_A of 93.2% and at the values of T_{mi} and T_{mpo} of 4 and 77 °C, respectively, the values of the temperature differences of the heating and cooling exchangers ΔT_H and ΔT_C have been quantified equal to 5 and 3 °C, respectively.

Using the values of the Table 2 in Equation (28), the optimized efficiency of ε_{opt} = 97.3% was obtained, which allowed to obtain, applying Equation (3), the new milk temperature value at the output of the recovery exchanger $T_{mro} = \dfrac{\varepsilon}{100}\left(T_{mpo} - T_{mi}\right) + T_{mi} = \dfrac{97.3}{100}\left(77° - 4°\right) + 4° = 75°C$ and therefore the corresponding temperatures T_{mci} of 6 °C, T_{who} of 80 °C, and T_{wco} of 3 °C.

Finally, using first the value of the current recovery efficiency ε_A = 93.2% and then the optimized efficiency ε_{opt} = 97.3% in Equation (26), we obtain the total unit cost of pasteurization of the milk. It results in the current situation of 0.00127 Euro kg^{-1}milk and drops to 0.00092 Euro kg^{-1}milk in the optimized condition, equal to −27.4%. This economic advantage obviously requires an investment on the greater heat exchange surface. The payback period for this investment is 3.52 years.

3.4. Exergetic Analysis of Heat Exchangers for Optimized Pasteurization Equipment

Using the new temperatures, a new exergetic analysis was carried out related to the optimized value of the efficiency ε_{opt} = 97.3%. The results are reported in Figure 3, where they are compared to those of the previous analysis with ε_A = 93.2%.

An important reduction of the exergy loss of the recovery exchanger can be noted, decreasing from 4.27 to 2.35 kJ kg^{-1}milk and corresponding to 45.2%, that leads to another reduction of the total exergy loss equal to 44.5%. In fact, the increase of the efficiency of the recovery exchanger to 97.3% has a positive impact on the reduction of exergy losses even on the other two exchangers, as highlighted in Figure 3.
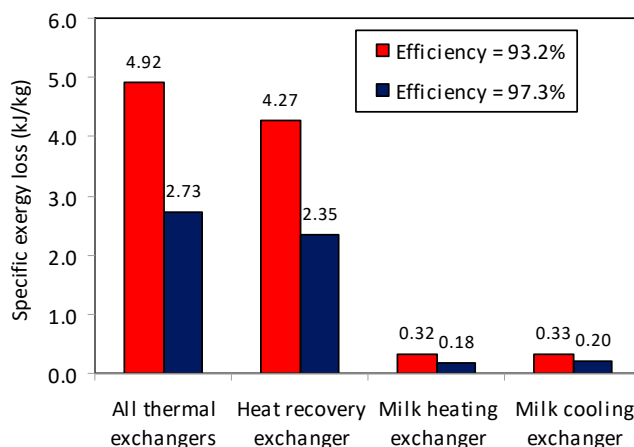

Figure 3. Comparison between exergetic losses in all thermal exchangers system and in each exchanger with the optimized efficiency ε_{opt} = 97.3% and with the current efficiency ε_A = 93.2%.

3.5. Exergetic Analysis of the Whole System and with CHP

The exergetic analysis was applied also to all the additional elements of the pasteurization systems, both with the current efficiency ε_A = 93.4% and the optimized efficiency ε_{opt} = 97.3%. In particular, the analysis concerned the deaerator, the refrigerator, the thermal electric power station, and the boiler. For each one the exergetic analysis allowed to quantify the related exergetic loss.

The results are shown in Figure 4, where also the total loss in the whole system is reported, equal to 54.1 and 31.2 kJ kg^{-1}$_{milk}$, respectively, for the current efficiency and for the optimized efficiency, with a reduction of 42.3%.
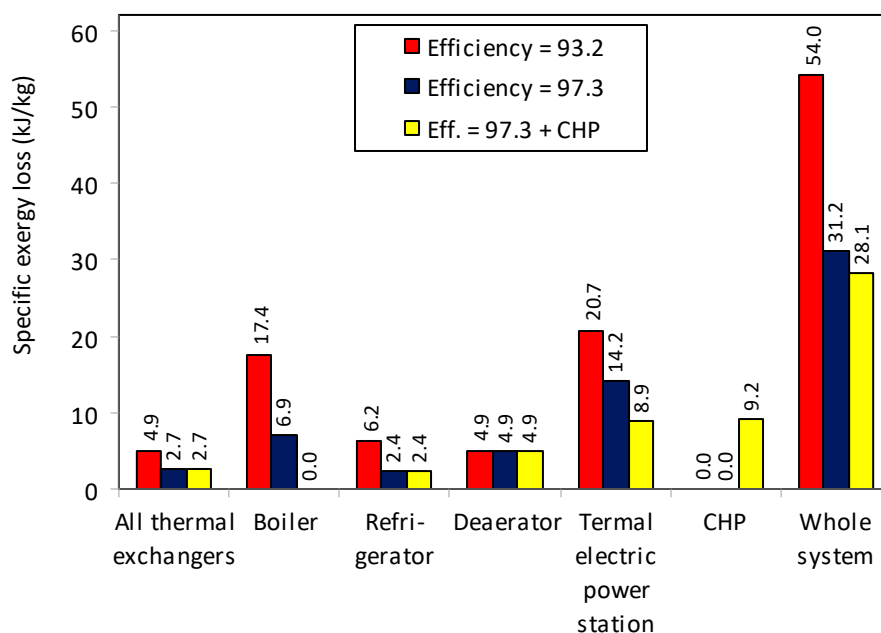
Figure 4. Exergetic losses (kJ kg^{-1}$_{milk}$) in the all thermal exchangers and in the additional elements of the pasteurization systems (deaeretor, refrigerator, thermal electric power station, boiler) for the three efficiencies: current ε_A = 93.4%; optimized ε_{opt} = 97.3%; optimized ε_{opt} = 97.3% plus a cogeneration heat and power (CHP) system.

Ultimately, the efficiency improvement is amplified, not so much in percentage terms, as in absolute value, with a total reduction of exergetic loss of 22.9 kJ kg^{-1}$_{milk}$, that is, an order of magnitude higher than the 2.2 kJ kg^{-1}$_{milk}$ reduction found in Figure 3 on the exchangers only (including the pumps).

Furthermore, as discussed above, another positive value must be taken into account: the optimized efficiency value of 97.3% is also associated to a decrease in the total unit cost of the heat treatment process, which, using Equation (26), is equal to 27.4%.

Finally, in Figure 4 the very high exergetic loss in the boiler compared to the exchangers is highlighted. In fact, the greatest jump in temperature can be found here, or that one between the flue gas and the warm water produced.

The exergetic loss can be reasonably lower assuming a co-generation group of heating and electric power (CHP), which electrically powers the deaerator, the pumps, and the refrigerator and thermally powers the pasteurizer, always using warm water.

The results related to the exergetic loss of the co-generation system are also reported in Figure 4. This group is intended to produce all the heat energy for the milk heating exchanger, substituting completely the boiler. Therefore, the column related to the exergetic loss of the boiler is reset.

The CHP cogeneration system, considering it is based on an Otto-cycle engine powered by natural gas with a thermodynamic efficiency of 0.26, produces only a part of the electricity for the

refrigerator, the pumps, and the deaerator. The missing part must be provided by the thermal electric power station. Therefore, the column of the exergetic loss of this last one is present but reduced to 9.2 compared to 14.2 kJ kg^{-1}_{milk} without CHP.

However, mainly due to the low performance of the Otto-cycle engine, the whole system of the CHP group has a total exergetic loss equal to 28.1, to be compared with the loss of the system without CHP of 31.2 kJ kg^{-1}_{milk}, with a reduction limited to 10%.

4. Conclusions

The exergetic analysis carried out on the PHEs used for HTST milk pasteurization in the Italian cheese factories allowed to highlight a close connection between the exergetic losses and the efficiency of the heat recovery exchanger.

The cost-benefit analysis on the heat exchangers allowed then to identify the value of the optimized recovery efficiency ε_{opt} equal to 97.3%, to which is related an important exergetic loss reduction of 45%. With this value of optimized efficiency of 97.3%, a reduction in the total unit cost of pasteurization of milk equal to 27.4% is obtained. This is a smaller reduction than exergetic loss because the optimization is achieved with an increase in the investment cost as a consequence of the increase in the surface of the recovery exchanger. The payback period for this investment is 3.52 years.

Then, considering the whole pasteurization system, constituted by the exchangers, the deaerator, the pumps, the refrigerator, the thermoelectric power plant, and the boiler, the effectiveness of the exergetic analysis has emerged even more evident. In fact, this analysis has allowed to detect the positive reduction of the exergetic loss of the whole system, with a value (42%) similar to the exchangers (45%), but in absolute value the reduction was greater than 10 times (22.9 kJ kg^{-1}_{milk}).

To this important energy advantage, which corresponds to a lower environmental impact with CO_2 reduction, the exergetic analysis highlighted the very high exergetic loss in the boiler, that is, where there is the greatest jump in temperature between the flue gas and the warm water produced.

This led to the hypothesis of using a co-generation CHP system to completely satisfy the thermal requirements, eliminating the boiler and the relative exergetic losses. However, due to the reduced thermodynamic performance of the Otto-cycle engine and the need to integrate electricity with external supply by the thermal electric power station, given that the ratio electricity/thermal energy of the CHP is less than that required by the pasteurization plant, the further reduction of exergetic loss obtainable is only 10%. In this condition the CHP system is not a source of economic savings. It follows that further research will be needed to find a more efficient CHP.

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Abbreviations

CHP	cogeneration heat and power
COP	coefficient of performance of refrigerator
HTST	high temperature/short time
PHE	plate heat exchanger

Nomenclature

A	m²	exchange area
B	y	useful life of the equipment

	Euro kg^{-1}$_{milk}$	unit cost
C	Euro m^{-2}	
	Euro Sm^{-3}	
	Euro kWh^{-1}	
c	kJ kg^{-1} K^{-1}	specific heat capacity
E	kWh kg^{-1}$_{milk}$	electric consumption
G	Kg s^{-1}	flow rate
h	kJ kg^{-1}	specific enthalpy
HV	kJ Sm^{-3}	heat value of natural gas
L	kW Kg^{-1}$_{milk}$	exergy flux loss
ℓ	KJ kg^{-1}$_{milk}$	specific exergy loss
N	h y^{-1}	running pasteurization time
P	kW	mechanical power
p	kPa	pressure
q	W	heat transfer rate
S	kJ kg^{-1}K^{-1}	specific entropy
T	K or °C	temperature
$\overline{T}$	K or °C	average temperature
U	kW m^{-2} K^{-1}	overall heat transfer coefficient
Δp	kPa	pressure drop
ΔT	K or °C	temperature difference
ε	%	energy recovery efficiency
η	%	efficiency

Subscript

A	area unit (cost)
a	ambient
C, c	cooling exchanger
cond	condensation in refrigerator
D	deaerator
DP	deaerator + pumps
dr	heat dispersion
E	Equipment (cost)
en	energetic
ev	evaporation in refrigerator
ex	exergetic
F	fuel unit (cost)
H	heat unit (cost)
H, h	heating exchanger
hb	heating boiler
irr	irreversibility
m	milk
M	unit (cost) for refrigeration

mC	milk in cooling exchanger
mci	cooling exchanger milk input
mco	cooling exchanger milk output
mH	milk in heating exchanger
mi	raw milk input
mP	pasteurized milk in recovery exchanger
mpo	pasteurized hot milk output
mR	raw milk in recovery exchanger
mro	recovery exchanger milk output
opt	optimized
P	pump
PA	actual pump
Pcw	cold water pump
Phw	hot water pump
Ppm	pasteurized milk pump
Prm	raw milk pump
R, r	recovery exchanger
tot	total
w	water
W	electric energy
wC	water in cooling exchanger
wci	cooling exchanger water input
wco	cooling exchanger water output
wH	water in heating exchanger
whi	heating exchanger water input
who	heating exchanger water output

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