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DYNAMIC MODELING AND SIMULATION OF A PLATE HEAT EXCHANGER IN BEER PRODUCTION USING THE EFFECTIVENESS METHOD (NTU)

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Abstract: The waste of drinking water in the cooling of the wort in the production of craft beer is a worrying fact, especially in view of the growth potential of this market. In this sense, the objective of this work was the modeling and simulation of the heat transfer involved in this process through a model implemented in Scilab, to determine the best scenario for cooling the wort, which achieves the desired operating conditions and reduces water consumption. treated. From the simulations, the best operational condition was determined, the one that respects the temperature and the ideal time of the process and consists of recycling only the must. However, in this condition there is no reduction in water consumption, but the waste of about 71 liters of water per liter of refrigerated must. Through numerical optimization, it was found as an ideal scenario for time and temperature, the recycling of only the refrigerant fluid using a 500 liter reservoir.
Keywords: Plate changer, wort, NTU, dynamic simulation.

INTRODUCTION

The brewing activity in Brazil has shown sustained growth over the last 20 years. In 2020 alone, Brazil registered 320 breweries, reaching a total of 1383 establishments, distributed in 26 states of the federation (MAPA, 2021).

The state of Rio Grande do Sul has 258 registered beer production establishments, behind only São Paulo, with 285. Porto Alegre is the Brazilian city that leads this market. However, other states such as Rio Grande do Norte, Bahia and Espírito Santo have shown an important growth rate: 57.4, 56.0 and 58.4%, respectively (MAPA, 2021).

The national brewing sector contributes 1.6% of the country's GDP, generating 2.7 million jobs and generating R$ 21 billion in tax (CERVBRASIL, 2021)

The traditional beer production process can be divided into nine main stages: malt grinding, mashing, filtration, boiling, treatment (precipitate removal, cooling and aeration), fermentation, maturation and clarification. After the drink is ready for bottling (VENTURINI, 2018).

Regarding the production of craft beer, according to Venturini (2018), the most important difference in relation to the industrial process is the freedom to customize the product, whether in relation to ingredients or in relation to variations in the process. However, regardless of the nature of manufacture, the flavor and aroma of the product are conferred by the action of yeasts.

Basically, yeasts turn sugars into ethanol, their main waste product. However, in addition to this primary alcohol, other products are also excreted and their nature and concentration can affect the taste of beer. The formation of these by-products is conditioned to the general metabolic balance of the process and some parameters such as pH and temperature are important variables (PIRES and BRÁNYIK, 2015).

In this context, the importance of the treatment process, especially cooling, is highlighted. In addition to interrupting the enzymatic and bacterial activities present in the must and also controlling the formation of compounds that give the product an undesired flavor (KUNZE, 2004), it also guarantees a safe temperature, consistent with the type of fermentation desired. Furthermore, it allows the decantation of proteins that were eventually separated from the liquid, improving the stability of the beer (PALMER, 2006).

To effect this cooling, heat exchangers are used. In the beer brewing process, immersion, counterflow and plate exchangers stand out. Regardless of the physical configuration, with regard to artisanal manufacturing, the heat exchange uses mainly water as a refrigerant fluid (PALMER, 2006).

Of these devices, the immersion exchanger is the simplest. It consists of a coil, usually made of copper, where the water circulates. This equipment is submerged in the wort and efficient only for volumes of up to 20 liters (ZAGO, 2018). Larger volumes can be cooled with a counterflow type exchanger, for example. In this exchanger, the wort needs to pass through the inside of the tube and the water flows in the equipment housing. They are exchangers of more complex construction, however they are more efficient (PALMER, 2006). A disadvantage of this type of system can be the difficulty of cleaning the circuit. Finally, the plate heat exchanger is used in larger production scales, as it is an efficient equipment, easy to maintain and with a low pressure drop (BARRIQUAND, 2022).

Although the importance of this drink in the national market has been presented, there is a worldwide concern about the impacts of brewing beer. One of these concerns is the global consumption of water, which is the subject of several studies (FILLAUDEAU et al., 2006). In this scenario, there is a particular concern associated with small-scale artisanal manufacturing. Often this type of production cools the must through an exchanger with drinking water circulating in an open circuit (SOUZA, 2018), which results in its high consumption and waste.

Therefore, the objective of this work is the modeling and numerical simulation of the heat transfer involved in this process to determine the best scenario for cooling the must, achieving the desired operating conditions and reducing the consumption of treated water.

METHODOLOGY

MATHEMATICAL MODEL USED

To model a heat exchanger, it is necessary to relate the global heat transfer rate with the inlet and outlet temperatures of hot and cold fluids, with the area and the global heat transfer coefficient (INCROPERA, DEWITT, et al., 2007).

When the difference between the heat transfer rate between the hot and cold fluids and the heat transfer between the system and its surroundings is negligible, as well as the kinetic and potential energies, the application of the steady-state energy equation is given. by equation 1 for the hot fluid and 2 for the cold fluid:

$$Q = \dot{m}_q(h_{q,in} - h_{q,out}) \quad (1)$$

$$Q = \dot{m}_f(h_{f,out} - h_{f,in}) \quad (2)$$

Where "$\dot{m}_q$" is mass flow, "Q" is the total rate of heat transfer between the hot and cold fluid and "h" is the enthalpy of fluids and the subscripts "q", "f", "in", "out" are, respectively, hot, cold, inlet and outlet.

Considering that there is no phase change and that the physical properties of the fluids are constant, equations 1 and 2 can be rewritten according to equations 3 and 4, respectively, in which "C_p" the specific heat of the fluids and "T", the average temperature.

$$Q = \dot{m}_q C_{p,q}(T_{q,in} - T_{q,out}) \quad (3)$$

$$Q = \dot{m}_f C_{p,f}(T_{f,out} - T_{f,in}) \quad (4)$$

The NTU method was used since only the inlet temperatures are known. Thus, for the definition of effectiveness, it is necessary to know the maximum rate of heat that can be transferred in a heat exchanger, given by equation 5.

$$Q_{max} = C_{min}(T_{q,in} - T_{f,in}) \quad (5)$$

Where "C_{min}" is the lowest value among the products: "$Cp_q \dot{m}_q$" and "$Cp_f \dot{m}_f$".

Effectiveness, therefore, is the ratio of the rate of heat transferred to the maximum rate of heat, as per equation 6.

$$\varepsilon = \frac{Q}{Q_{max}} \quad (6)$$

And, finally, the NTU, number of transfer units, a dimensionless one that represents a thermal length, is obtained according to equation 7.

$$NTU = \frac{UA}{C_{min}} \quad (7)$$

Where "U" is the global heat exchange coefficient.

The NTU method also presents other relationships for effectiveness, according to the value of

"C", the ratio between "C_{min}" and "C_{max}". O "C_{max}" is the highest value among the products "$Cp_q\dot{m}_q$" and "$Cp_f\dot{m}_f$".

If this reason "C<1", then the effectiveness is given by equation 8. On the other hand, if "C=1", effectiveness is calculated according to equation 9.

$$\varepsilon = \frac{1 - e^{-NTU(1-C)}}{1 - C\, e^{-NTU(1-C)}} \quad (8)$$

$$\varepsilon = \frac{NTU}{1 + NTU} \quad (9)$$

Developing the energy balance for the hot fluid and for the cold fluid, in the reservoirs where they will be recirculated, it is observed that there is no energy generation in the system. Also, accumulation is a negative term for the hot fluid and a positive term for the cold fluid, as the hot fluid is experiencing a reduction in temperature while the cold fluid warms up. Therefore, it follows that:

$$\dot{m}_f C_{p,f}\left(T_{f,in} - T_{f,out}\right) = m_f C_{p,f} \frac{dT_{f,in}}{dt} \quad (10)$$

$$\dot{m}_q C_{p,q}\left(T_{q,in} - T_{q,out}\right) = -m_q C_{p,q} \frac{dT_{q,in}}{dt} \quad (11)$$

This way, the rate of heat exchange will be given only by the temperature difference between inlet and outlet. This way, the temperature of the wort in the pot and the temperature of the water in the tank can be obtained from solving equations 10 and 11, resulting in equations 12 and 13.

$$T_{q,in}\big|_t = T_{f,in} + e^{\frac{-\varepsilon C_{min}}{m_q C_{p,q}}t}\left(T_{q,in}\big|_0 - T_{f,in}\right) (12)$$

$$T_{f,in}\big|_t = T_{q,in} - e^{\frac{\varepsilon C_{min}}{m_f C_{p,f}}t}\left(T_{q,in} - T_{f,in}\big|_0\right) (13)$$

And, finally, the heat exchanger outlet temperatures for the hot and cold fluids are calculated according to equations 14 and 15, respectively.

$$T_{q,out} = T_{q,in} - \frac{\varepsilon\, C_{min}(T_{q,in} - T_{f,in})}{\dot{m}_q C_{p,q}} \quad (14)$$

$$T_{f,out} = T_{f,in} + \frac{\varepsilon\, C_{min}(T_{q,in} - T_{f,in})}{\dot{m}_f C_{p,f}} \quad (15)$$

SYSTEM CHARACTERIZATION AND OPERATING CONDITIONS

The simulations performed were based on the experimental cooling system proposed by Silveira and Pereira (2021), consisting of an aluminum brewing pot with a capacity of 25 liters and a flow regulation register of ½ inch. In addition, a plate heat exchanger (PHE) with 20 Chevron-type plates, specified as shown in figure 1. The circulation of hot and cold fluids is provided by means of silicone hoses and recirculation pumps suitable for transporting food. The system also has a coolant reservoir with a capacity of 100 liters.

Different scenarios of fluid circulation through the heat exchanger were analyzed, using water from the distribution network both for cooling and to simulate the wort. In the latter case, 20 liters of water at 100°C were used (thermal properties are similar to those of the must). The cooling circuit was proposed in countercurrent, without flow

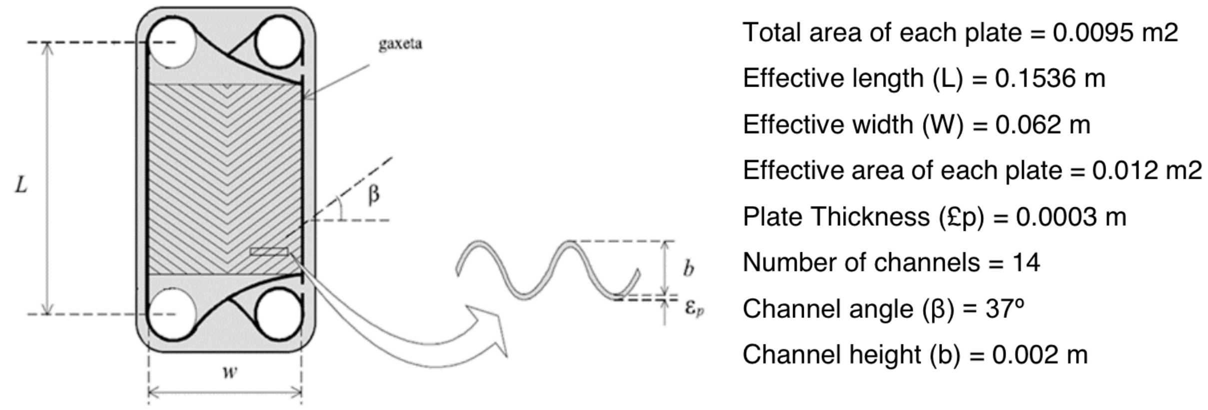

Figure 1: Specifications of the PHE used. Adapted from GUT (2003).

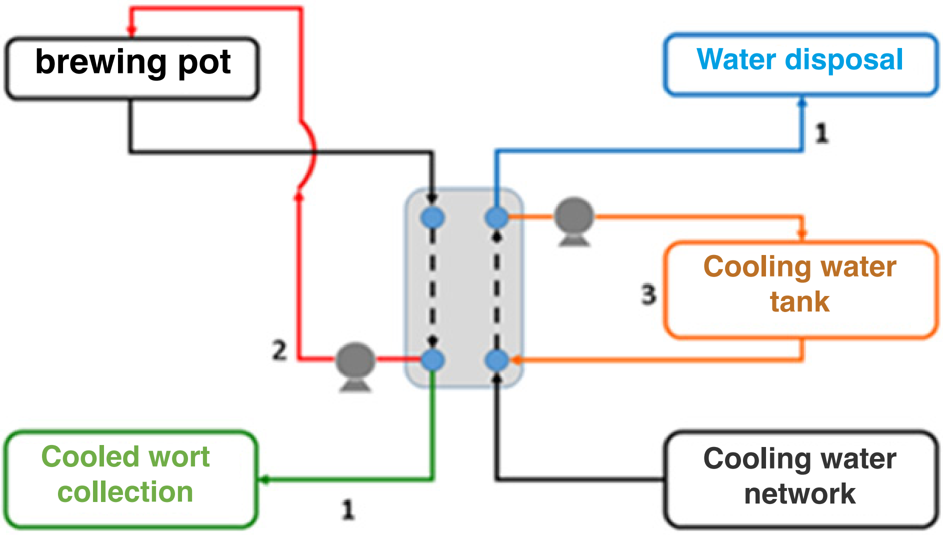

Figure 2: Simulated scenarios: (1) open circuit operation; (2) closed-loop operation of the wort; (3) closed-loop operation of the cooling water.

Variable	Scenario 1	Scenario 2	Scenario 3
Cold fluid inlet temperature	17,80°C	16,9°C	17°C
Hot fluid inlet temperature	99,60°C	89,0°C	100°C
Cold fluid flow	6,11 L/min	6,11 L/min	6,72 L/min
Hot fluid flow	3,64 L/min	6,91 L/min	3,65 L/min

Table 1: Operating conditions of simulated scenarios.

control of the fluids, which flowed without recirculation and by gravity, while in the other scenarios the flow was determined by the power of the pump and manually regulated by control valves. The simulated scenarios will be described below.

The scenarios proposed for evaluation included the single passage of hot and cold fluids through the exchanger, closed-circuit operation of only the refrigerant fluid and closed-circuit operation of only the hot fluid, as shown in figure 2. While the operating conditions used in the simulations are summarized in Table 1.

The simulations were performed in Scilab software and compared with experimental data. It was evaluated whether the operating conditions of wort outlet temperature and cooling time were less than 25°C (OLAJIRE, 2020) and 25 minutes (MORTON, 2018), respectively.

RESULTS AND DISCUSSION

The simulations of the scenario without recirculation of any of the fluids allowed obtaining the global heat transfer coefficient, which was compared with the experimental value, given in Table 2.

Experimental	Model	relative mistake
2537,90	2690,63	6%

Table 2: Values obtained for [W/m^2/K]

Among the hypotheses for this observed difference, the most probable is the heat loss by convection between the heat exchanger wall and the external environment observed experimentally, since there is no thermal insulation and the model considers the heat exchange only through the plates.

In the closed circuit operation of the wort only, it is observed that the experimental data are superior to those modeled (Figure 3). This difference can be attributed, in part, to the considerations made in determining the "U".

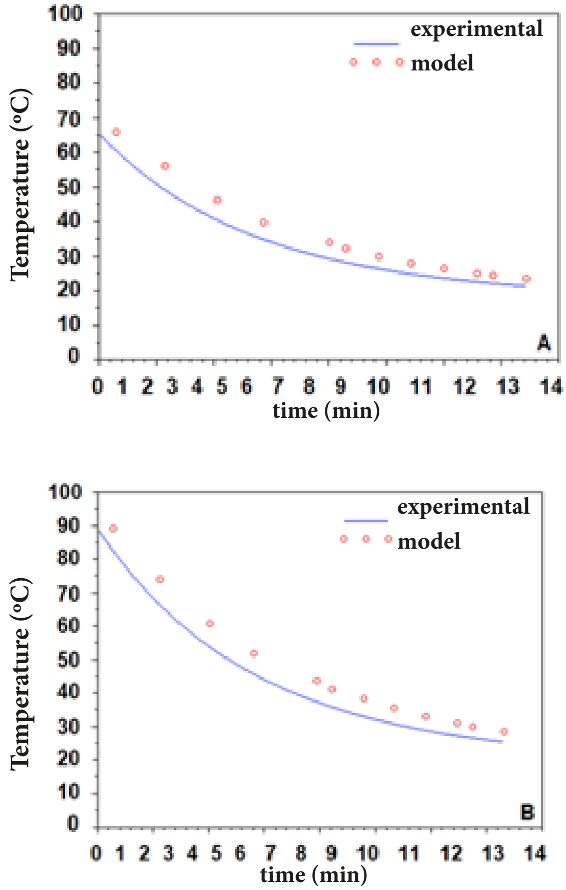

Figure 3: Water temperature at the exchanger outlet (A); Temperature of the wort in the pot (B).

In this situation, it is observed that the "U" decreases over time. This behavior was expected, since once the wort temperature in the pot decreases as a function of time (Figure 5B), there is an increase in specific heat, an increase in viscosity and a reduction in thermal conductivity. Thus, there is also a reduction in the convective coefficient of the hot fluid, ultimately resulting in a reduction in the global coefficient of heat exchange.

In addition to the influence of the "U", the operation with recycling may also have affected the results, as it was considered a perfect mixture in the brewing pot, that is, the temperature was modeled only as a function of time and not of space. Therefore, it was assumed that the temperature at the inlet of the exchanger is equal to the temperature in the pan. However, in reality, this temperature will be lower. The volume of 20 liters takes some time to homogenize, so the temperature at the inlet of the heat exchanger is overestimated. Thus, real heat is always calculated higher than it actually is, underestimating the temperature of the wort and overestimating the temperature of the water at the exit of the heat exchanger.

In order to quantify the model-experiment difference, the mean absolute error was calculated between the experimental issues and the values calculated by the model for the wort temperature in the pot and for the wort and water temperatures at the exit of the heat exchanger, according to Table 3.

	absolute mean error (°C)
Wort in the pot	5,42
Wort at the exit of the PHE	4,89
Water at the outlet of the PHE	3,97

Table 3: Absolute mean error values (°C), wort recirculation.

According to the model, the temperature of 25 °C was reached with a time of 11 minutes and 33 seconds. However, considering that the flow of cooling water is 6.11 L/min, approximately 71 liters of this resource were consumed, which were not reused. This scenario requires 3.53 liters of water/liter of wort.

In the simulation of the operation with recirculation of the cold fluid, the temperature of the water in the cooling reservoir (initially with 50L) and of the cooled must as a function of time was evaluated. In this situation, it is observed that the model is slightly above the experimental data for the cold fluid (Figure 4A). This difference may be a consequence of the mixing effect of the reservoir, which is neglected in the modeling. A perfect mixture is considered in the model, so that the inlet temperature in the heat exchanger will always be slightly above the real temperature of the water in the recycle tank.

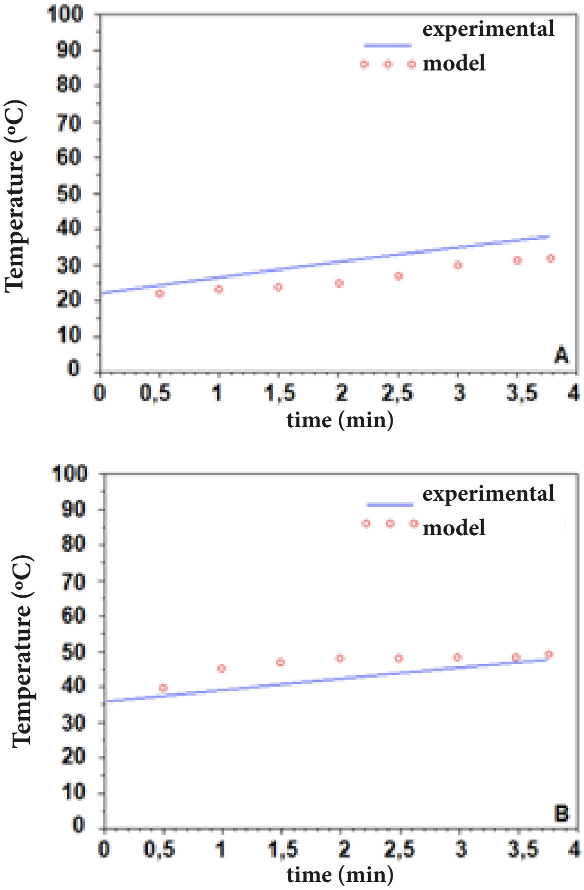

Figure 4: Water temperature in the 50L reservoir (A); Temperature of the wort at the exchanger outlet (B).

However, for the wort at the outlet of the exchanger, the modeled data are lower than the experimental ones (Figure 4B). In this case, the difference can be given by the coefficient “U” which is always calculated with a variable temperature of the cold fluid and a fixed temperature of the hot fluid, which is the temperature in the pan. However, the model ignores the fact that after the cooling time, the wort pot also exchanges heat with the environment. Considering the wort temperature fixed can overestimate the real heat exchanged, and result in values of hot fluid temperature at the exit of the heat exchanger lower than they actually are.

The values of the absolute mean error of the model in relation to the experiment were calculated for each of the temperatures represented in the modeling from this scenario and are represented in Table 4.

	absolute mean error (°C)
Wort at the exit of the PHE	3,90
Water at the outlet of the PHE	4,93
Water in the reservoir	4,80

Table 4: Absolute mean error values (°C), 50 L reservoir.

The model predicts for this scenario that at the end of the process time the temperature reached by the must would be 48.59 °C, outside the recommended range.

To try to reach the criteria of time and temperature, it was decided to use a reservoir with a capacity of 100 liters. The simulation of this new condition resulted in the temperature profiles shown in figure 5.

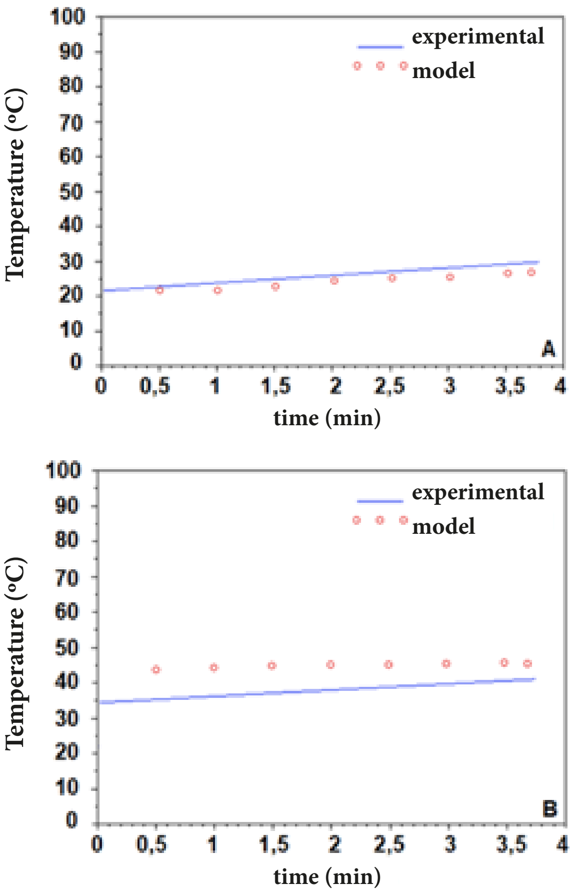

Figure 5: Water temperature in the 100L reservoir (A); Temperature of the wort at the exchanger outlet (B).

Based on the simulations, the same behavior of the model can be seen in relation to the experiments presented for the first reservoir, with a smaller volume. The calculation of the mean absolute error with respect to the experimental data is shown in Table 5.

	Absolute mean error (°C)
Wort at the exit of the PHE	6,73
Water at the outlet of the PHE	2,41
Water in the reservoir	2,18

Table 5: Absolute mean error values (°C), 100 L reservoir.

The errors obtained show that with respect to the previous scenario, the model-experiment error for the wort outlet temperature is higher. In practice, a larger tank allows for a smaller temperature variation, as there is a greater volume to homogenize. In fact, it is observed that the experimental issues present little variation, compared to those calculated in the model.

As the temperatures of the cold fluid are overestimated in the model, it predicts a larger "U" than for a smaller reservoir and, as this coefficient is higher, the heat exchanged between the fluids will also be higher, which results in hot fluid outlet temperatures. smaller than they actually are, increasing the model-experiment error for the 100 L (6.73 K) reservoir compared to the same error for the 50 L (3.90 K) reservoir.

Furthermore, the use of a larger reservoir also did not provide adequate cooling of the must. The final temperature obtained in the model was around 40.62 °C. In order to find an ideal condition of time and volume of the reservoir, a numerical optimization function was used in the Scilab software, with the default settings (convergence criterion of 0.0001 and maximum of iterations equal to the product of 200 by the amount of variables to be optimized, in this case 2). It was found under these conditions that it would be possible to cool the must to 25 °C with a time of 18 minutes, changing the volume of the water reservoir to approximately 500 L.

Another variable to be optimized is the heat exchange area. Keeping the outlet temperature at a maximum value of 25 °C and the time also at the recommended maximum of 25 minutes, it is not possible to find an area that satisfies the optimization requirements. The exchanger would cool the must to approximately 35.7 °C with an area of 1.76 m^2, reaching the maximum of the convergence criterion used.

CONCLUSION

From the results obtained through the modeling and simulation of the beer wort cooling process, it is possible to conclude that the model determined a value above the experimental value for the heat exchange coefficient in situations without recirculation and with recirculation only of the wort. This difference obtained may be a consequence of the lack of thermal insulation of the experimental apparatus not considered by the mathematical model.

With the exception of the scenario with recirculation only of the must in all situations, the cooling time was less than 25 minutes, ranging from 5.5 minutes in the operation without recirculation of the fluids to 17.5 minutes in the condition of recycling of both, but neither of these chilled the wort to less than 25 °C. This temperature was only reached when the experiment was conducted with the recirculation of the wort only in 18 minutes of operation.

In terms of water savings, the scenarios with no recirculation and wort-only recirculation require 34 and 71 liters, respectively, while in closed-circuit cooling water operation, there is no water wastage.

In this context, it is observed that the best operational condition for cooling is the one in which only the wort is recirculated. However, this scenario does not meet the water saving objective. Thus, it is suggested as an alternative to use the scenario with only water recycling, but with a 500-liter reservoir, according to the proposed optimization.

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