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THERMAL PERFORMANCE OF OF A LOW-COST COOLING TOWER INSTALLED IN A CHEESE PRODUCTION FACILITY

Igino Giordani da Silva Guerra
Instituto de Inovação Tecnológica da Univercidade de Pernambuco, Várzea, Recife – PE, 50950-050.
igsg@poli.br

Lorena Barros Guimarães
Universidade Federal de Pernambuco, Cidade Universitária, Recife – PE, 50740-540.
lorena.bguimaraes@ufpe.br

Vânia Freire Lemos
Centro Tecnológico Instituto de Laticínios – ITEP, Mandaú, Garanhuns – PE, 55290-000.
Vanialemos91@gmail.com

Emmanuel Damilano Dutra
Universidade Federal de Pernambuco, Cidade Universitária, Recife – PE, 50740-540.
emmanuel.dutra@ufpe.br

Luis Arturo Gómez-Malagón
Instituto de Inovação Tecnológica da Univercidade de Pernambuco, Várzea, Recife – PE, 50950-050.
lagomezma@poli.br

Abstract. *Cheese is a product obtained by processing milk in a double jacket tank to process up to 300 liters of milk per batch, through the heating, pasteurization, cooling, fermentation, and coagulation stages. In particular, the cooling process is done by flowing tap water at room temperature through the jacket, and discharging it into the sewage line. To improve the cooling process, this work proposes the use of a low-cost cooling-induced draft counterflow tower to cool and re-circulate the service water. The cooling tower was built using a recycled plastic storage tank of 200 liters, an exhaust fan, a water pump, and polyethylene corrugated plastic tubing as packed material. Temperature measurements of the milk and water at the inlet and outlet of the cooling tower were collected by PT-100 sensors connected to a datalogger. Results showed that the proposed solution contributes to a decrease in the cooling time per milk liter by about 65% and reuses almost 100% of the cooling water that would be discharged. Therefore, the use of a low-cost cooling tower in small facilities leads to an increase in productivity due to the time reduction and also mitigates operational costs and negative environmental impacts due to water reuse.*

Keywords: *milk processing, pasteurization, cheese production, cooling tower.*

1. INTRODUCTION

The Pernambuco State has clusters named as Local Productive Arrangement (LPA), which are defined as "territorial agglomerations of economic, political and social agents, focusing on a specific set of economic activities" (SECTI/PE, 2017). Due to the diversity of economic activities, the Pernambuco State has production clusters mainly in agriculture, food and drinks, beekeeping, dairy cattle, goat and sheep farming, fashion, creative economy, plaster; fish farming and information technology. In particular, the dairy cluster or Local Productive Arrangement for dairy Products is located in the Agreste region of the State, produces more than 20 products including dairy drinks, butter, and cheese, and has about 176 industries, from them, about 95.4% are considered micro and small companies (Ximenes, 2021), based predominantly on the manufacture of artisan cheeses (SECTI/PE, 2017). The dairy sector in the rural area of Pernambuco presented a production of 1 billion and 64 thousand liters of milk in 2021, which gave the 9th place in the national production ranking (Ximenes, 2021).

The milk employed in cheese manufacturing passes through the stages of heating, pasteurization, cooling, fermentation and coagulation. All these processes occur in a stainless-steel double jacket tank. During the heating process, steam or hot water is inside the double jacket to increase the milk temperature. Typically, this process takes an hour. After that, the slow pasteurization is started keeping the milk temperature in the range of 62° C to 65 °C for 30 min under slow mechanical agitation (BRASIL, 2015).

After that, the cooling process is started by the circulation of cold water inside the jacket to decrease the milk temperature to about 35 °C. Finally, enzymes are added to start the milk fermentation process. Under slow agitation, the milk whey and the mass of coagulated milk are produced, the whey is drained, the mass is removed from the tank and compressed into molds. The molded mass is put into a brine solution to obtain the cheese, which can be commercialized or stored in a maturation chamber between 60 and 90 days to produce special cheese with high added value.

Each of these stages can be improved from the technical point of view to increase productivity and energy efficiency, and also to mitigate negative environmental impacts. In particular, here in this paper, the cooling process is analyzed and a low-cost solution is proposed to decrease the processing time and to improve the water use.

2. DESCRIPTION OF THE PROCESS

The process described here is typical of small producers located in the LPA of dairy products in Pernambuco State. Milk collected by local producers is sent to the cheese factory to be processed. The milk is put into a stainless-steel double jacket tank of 300 liters to exchange heat with the fluid inside the jacket in order to obtain pasteurized milk through the slow pasteurization process. Initially, steam or hot water are produced to increase the milk temperature from room temperature up to 65°C. This process is achieved by filling the jacket partially with water and heating it using burners fed by Liquified Petroleum Gas (LPG). Once the desired milk temperature is achieved, it is kept for 30 min. After that, the cooling process is initialized by circulating water through the tank jacket. It is important to note here that the producers employ two different routes to decrease the milk temperature. The first one is by circulating cold water through the tank jacket coming from a heat exchanger coupled to a refrigeration system using a compression chiller, and the second one is by circulating tap water and discharging it into the sewage line, as shown in Figure 1 and Figure 2, respectively. Although the first option is technically feasible, some producers do not use it due to the costs associated with electricity and maintenance. Then the second option is the alternative that some producers found to be competitive. Finally, the enzymes are used to coagulate the milk to produce the cheese.

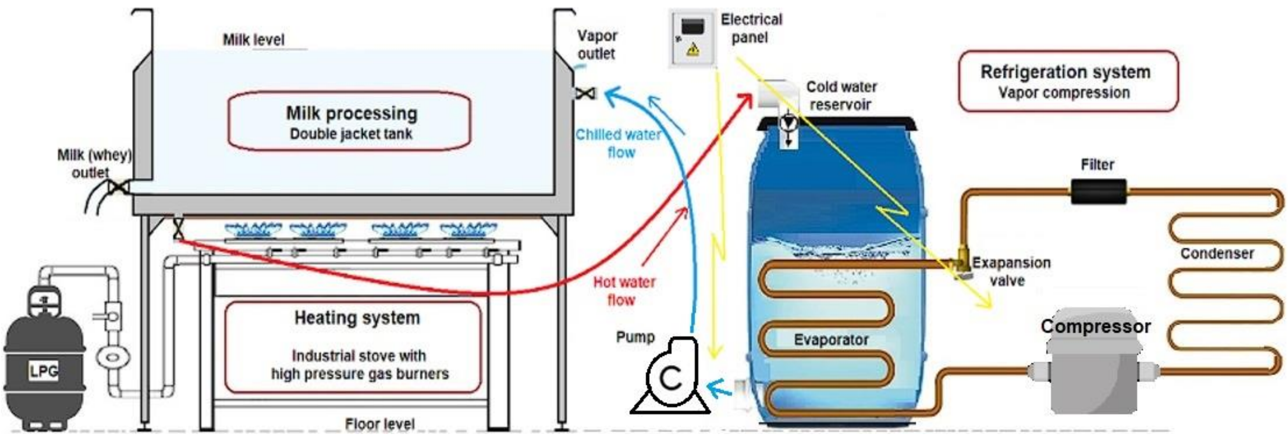

Figure 1. Setup of the tank to process milk by heating using LPG and cooling using a heat exchanger and a vapor-compression refrigeration system.

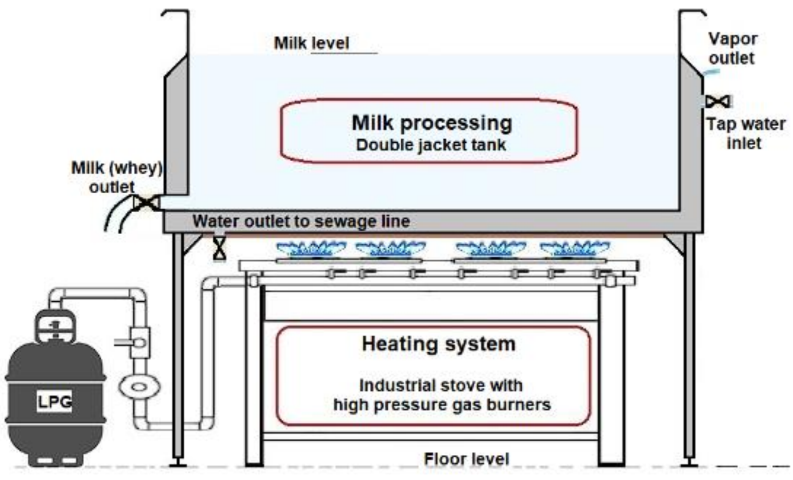

Figure 2. Setup of the tank to process milk by heating using LPG and cooling using tap water that is discharged into the sewage line.

From Figure 2 it is observed that, during the cooling process, the water is not recirculated, which is not considered a good practice due to the scarcity of water in the Agreste region. Also, due to low energetic efficiency, the time spent to complete the process at full capacity is between 120 min and 180 min, which is considered long by the producers and contributes to an increase in the costs associated with human resources to operate the facility.

3. METHODOLOGY

In order to improve the technical performance of small local producers of cheese located in the Agreste region of the Pernambuco State, a cheese facility located in the rural area of the Garanhuns/PE municipality was chosen to study the process from an energetic and environmental point of view. Tests were performed in March 2023. In particular, the temporal behavior of the milk and water temperatures used in the cooling process were monitored using temperature sensors (PT-100) positioned in a tank with the capacity to process up to 300 liters of milk, and in the inlet and outlet ports of water. The temperature signals were collected by a data logger. Data was processed and plotted to visualize the results. A test of the cooling process using tap water without recirculation was performed in a tank containing 118 liters of milk. From the results, the amount of heat exchanged by the milk on time was calculated to quantify the thermal behavior of the process. In order to improve the technical performance of the process and mitigate the negative environmental impacts due to the non-reuse of water, a low-cost cooling tower was proposed. The prototype was built and evaluated in a second test, cooling 215 liters of milk. From the temperature data, the approach, range and cooling tower efficiency were calculated. Also, the demand and tower characteristic curves were obtained for two conditions: high/low approach and low/high range value. A comparison between the tests was performed and the conclusions were outlined. The proposed setup for the cooling process using a cooling tower is shown in Figure 3.

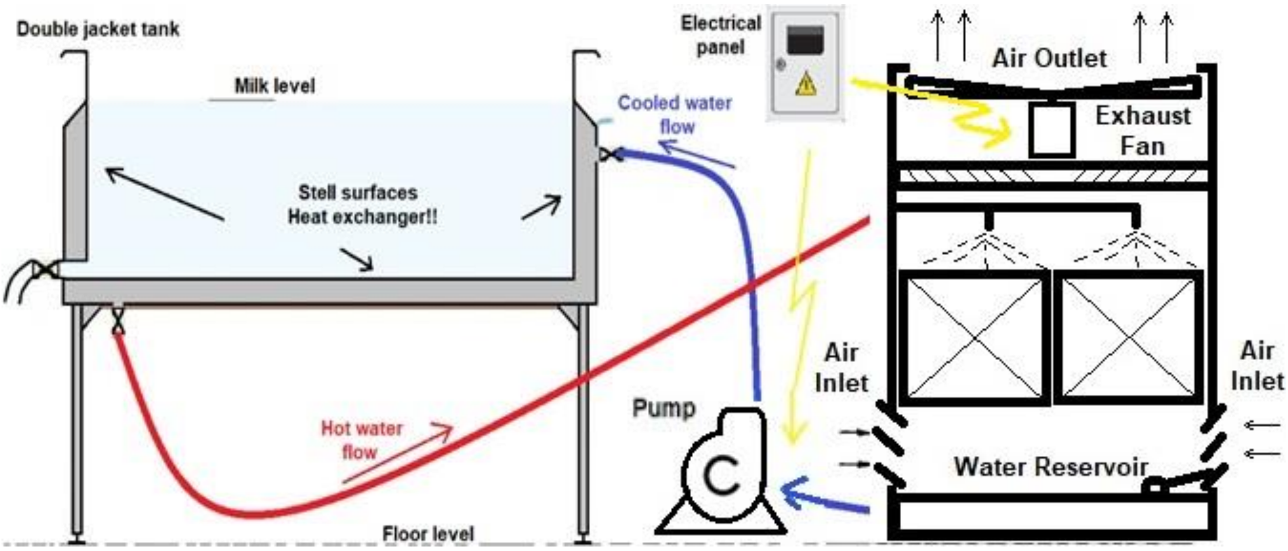

Figure 3. Setup of the tank to process milk by heating using LPG and cooling using a cooling tower.

4. RESULTS AND DISCUSSION

4.1 Test using tap water

The process tank is a double jacket tank heated by LPG burners located on the down surface as shown in Figure 2. During the cooling processes, water at room temperature goes into the tank by the inlet port, exchanges heat with the milk, and gets out for the outlet port as shown in Figure 2. During the heating process, the vapor can exit by the vapor exit as shown in Figure 2. For a test using 118 liters of milk, the temporal profile of the milk and inlet and outlet temperatures were recorded and shown in Figure 4. At the end of the heating process, the temperature is about 63°C, and it is kept constant for 30 min. The cooling process starts by opening the outlet port to drain hot water and adding cold water simultaneously by the inlet port for 8 min decreasing the milk temperature to about 58°C. After that, the system is in a stationary regime for 15 min until the milk temperature is about 47°C. At this point, the output port is closed-opened twice times to avoid water losses. This procedure is a common practice employed during the cooling process to decrease the amount of water that goes to the sewage line. At the end of this process, the milk temperature is about 41°C. The cooling process took about 80 min to be completed.

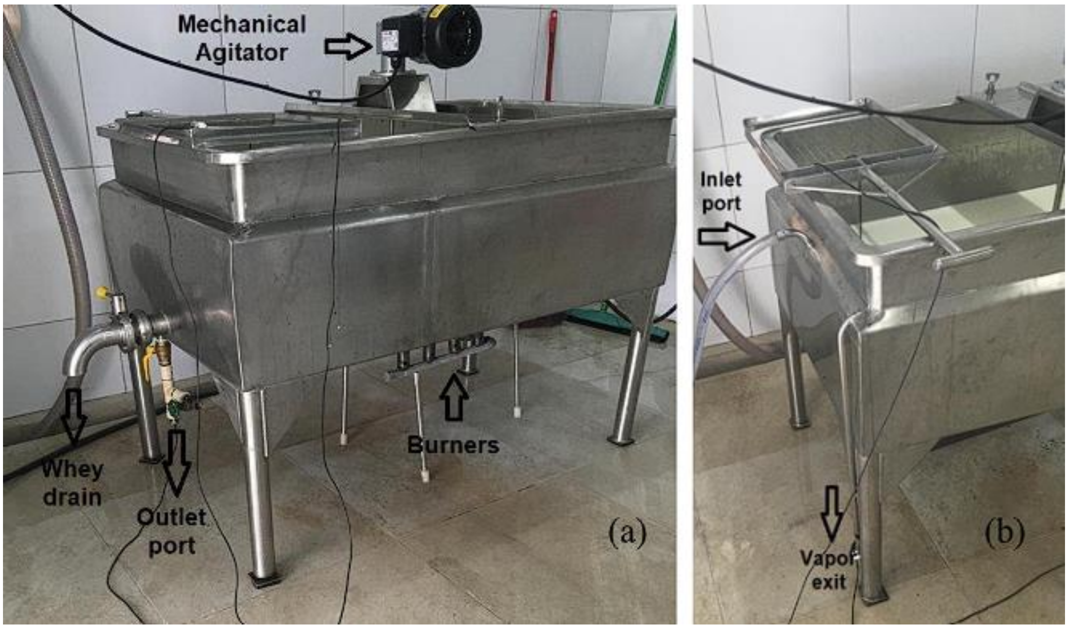

Figure 4. Pictures of the process tank showing the LPG burners, whey drain, outlet port and mechanical agitator in (a) and inlet port and vapor exit in (b).

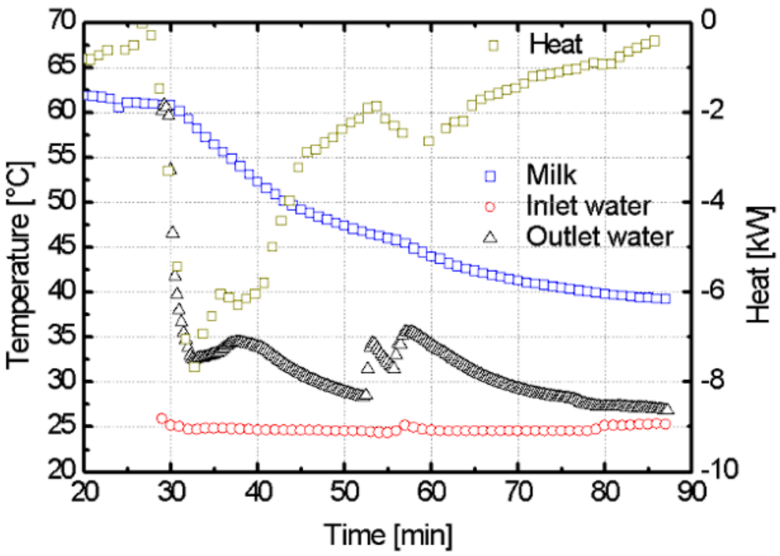

Figure 5. Using tap water. Temperature profile of milk, outlet and inlet water, and rejected heat from the milk.

From the milk temperature profile, the amount of rejected sensible heat on time is shown in Figure 5 and is calculated as:

$$\dot{Q}_{milk} = \frac{m_{milk} \cdot C_{p,milk} \cdot \Delta T_{milk}}{\Delta t}, \quad (1)$$

where m_{milk} is the milk mass ($m_{milk} = V_{milk} \cdot \rho_{milk}$; $\rho_{milk} = 1020.3$ kg/m³; $V_{milk} = 118$ liters), $C_{p,milk}$ is the heat capacity of milk ($C_{p,milk} = 3.8$ kJ/kg/K) and ΔT_{milk} is the temperature difference in a time interval Δt. Analyzing the cooling process, the amount of energy removed from the milk is obtained by integrating the heat curve on time. Results revealed that about 9.2 MJ were removed during the process, being 50% removed during the first 15 min. After that, the rejected heat rate is almost constant during the following 8 minutes and increases during the next 5 minutes due to the closed-opened procedure of the outlet port. This last procedure showed to be an efficient strategy to remove energy.

In the regime where the water mass through the tank jacket at the input is equal to the output, the heat absorbed by the milk during the heating process is not completely transferred to the water in the cooling process due to the heat losses to the surroundings. Then, the heat transfer efficiency between the water and milk can be written as:

$$\eta = \frac{\dot{Q}_{water}}{\dot{Q}_{milk}} = \frac{m_{water} \cdot C_{p,water} \cdot \Delta T_{water}}{\dot{Q}_{milk}}, \tag{2}$$

where m_{water} is the mass flux of water (6.5 liters/mim), $C_{p,water}$ is the heat capacity of water ($C_{p,water} = 4.18$ kJ/kg/K) and $\Delta T_{water} = T_{out,water} - T_{in,water}$ is the water temperature difference. Then, considering data from $t = 38$ min to $t = 52$ min, the efficiency can be estimated from the experimental results for ΔT_{water} and Eq. (1) and Eq. (2). Efficiency values of about 70% were calculated, which are expected considering losses to the surroundings and convective heat transfer coefficients considering mechanical agitation (Bergman et al., 2014).

4.2 Test using the cooling tower

An evaporative cooling tower was chosen to be used in the cooling process because it is a well-known technology that can be built using low-cost materials. In our case, the body of the tower is a recycled plastic storage tank of 200 liters, that contains polyethylene corrugated plastic tubing as fill material and uses an exhaust fan (VENTISOL, model: 30 cm) in a counterflow. The water is recirculated using a water pump (TEXIUS, Model: TBHX-BR 100W), and the level of cold water in the storage tank is kept constant using a ball float valve. Figure 6(a) shows the fill material and the piping system to distribute water in the cross-section, and Figure 6(b) shows the cooling tower installed in the outside area of the dairy facility.

Figure 6. Low-cost cooling tower. a) Cross section showing the fill material and water distribution system. b) Cooling tower installed in the outside area of the dairy facility.

The test using the cooling tower employed 215 liters of milk. The cooling process started in t = 30 min keeping closed the output port and filling the tank jacket with water coming from the reservoir of the cooling tower at room temperature. This strategy was adopted because it was observed in Figure 5 that keeping water inside the tank jacket for a short period of time contributes to a better heat transfer to the water. After 10 minutes, the output port was opened and kept in this position until the end of the process. The temperature profile of the milk and water in the process tank, and the heat rejected calculated using Eq. (1) are shown in Figure 7, where it is observed that during the first 10 min, the temperature of the inlet water was constant. When the output port is opened, the cooling water recirculates through the cooling tower increasing the inlet temperature in the tank achieving its maximum value (T = 37.5°C) after 15 min. Then, the temperature decreases to about 31°C at the end of the process. Similar behavior was observed for the outlet water temperature. From the heat curve, the amount of energy rejected by the milk was obtained integrating it on time.

Calculations showed that 21.1 MJ were removed from the milk, being 50% removed during the first 25 min after started the cooling process. Just for comparison, the cooling process of milk from 63°C to 40°C using the tap water and the cooling tower employed 55 min for 118 liters and 60 min for 215 liters, respectively. It means that the use of the cooling tower reduced the time consumption per milk liter by about 66% ((65 min/215 liters)·(118 liters/50 min)).

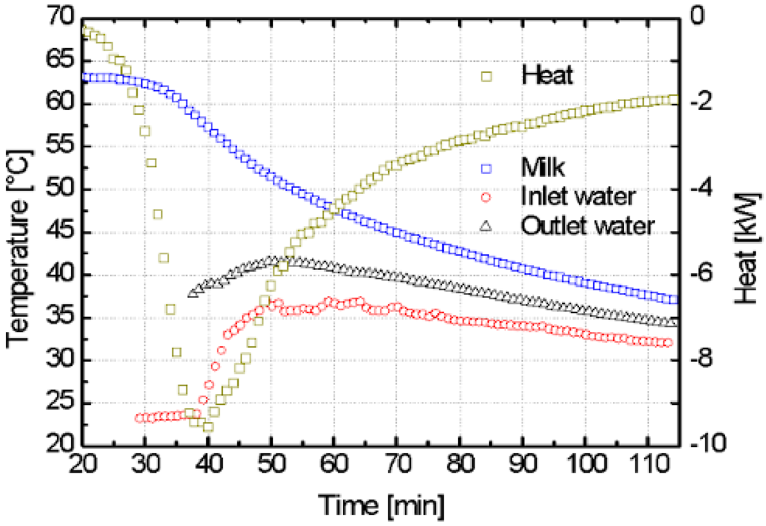

Figure 7. Operation with the cooling tower: Temperature profile of milk, outlet and inlet water, and rejected heat from the milk.

On the other hand, in order to characterize the cooling tower behavior, the approach, range and efficiency were calculated as:

$$Approach = T_{coldWater} - T_{wetBulb}, \quad (3)$$

$$\text{Range} = T_{hotWater} - T_{coldWater}, \quad (4)$$

$$\eta_{coolingTower} = \frac{Range}{Range + Approach}, \quad (5)$$

where the wet bulb temperature, $T_{wetBulb}$, was considered 20.5°C for the Garanhuns city (INMET, 2023). The approach, range, and cooling tower efficiency, $\eta_{coolingTower}$, change on time, as shown in Figure 8, due to the temporal behavior of the inlet and outlet water temperatures in the cooling tower, as shown in Figure 7. Results revealed that the approach has similar behavior to the outlet cold water temperature, and the range and efficiency decrease on time. It means that the cooling tower performance is high at the beginning of the process and decays at the end of the process.

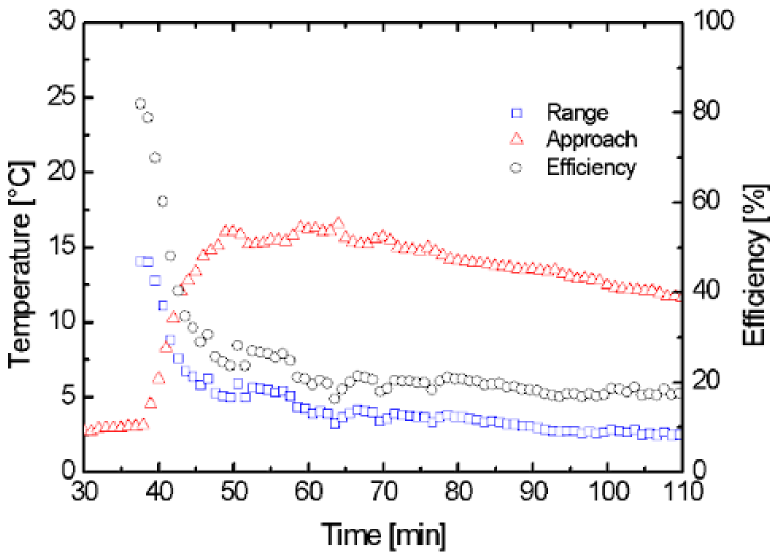

Figure 8. Approach, range and cooling tower efficiency.

From the cooling tower theory developed by Merkel, the energy balance of a particle of water surrounded by a film of saturated air establishes that heat transferred from the particle to the film and from the film to surrounding air as (Deshmukh, et. al., 2020):

$$L \cdot C_{p,water} \cdot dT = \kappa \cdot a \cdot dV \cdot (h' - h) = G \cdot dh, \tag{6}$$

Integrating, the Number of Transfer Units (NTU) or tower-characteristic is defined as:

$$NTU = \frac{\kappa \cdot a \cdot V}{L} = \int_{T_{w,out}}^{T_{w,in}} \frac{C_{p,water}}{(h' - h)} \cdot dT, \tag{7}$$

$$NTU = \frac{\kappa \cdot a \cdot V}{G} = \int_{h_1}^{h_2} \frac{1}{(h' - h)} \cdot dh, \tag{8}$$

where κ is the unit conductance, corresponding to the mass transfer from the water droplet to the interface, measured in $W/m^2 \cdot K$, a is the area of interface per unit total volume measured in m^2/m^3, V is the cooling volume in m^3, L is water mass flow rate, G is air mass flow rate, h' is the enthalpy of saturated air at water temperature and h is the enthalpy of air stream.

The representation of the counterflow cooling diagram is shown in Figure 9. Water at the top of the tower is surrounded by an interfacial film, considered as saturated air at the bulk water temperature, represented by the point A. As the water temperature decreases, the film enthalpy follows the saturated air curve to the point B. The air operating line starts in the point C, where the air is considered to have enthalpy at the wet bulb temperature. Heat removed from the water to the air increases the air enthalpy to the point D following a straight line with slope ($L \cdot C_{p,water}/G$). This trend is related to the Eq. (6). In our case, as the range and approach are changing on time, it is expected that the NTU also changes. For comparison, two states are represented in Figure 9. These states are represented by the ABCD and A'B'C'D' regions, considering ranges of 14°C and 6.5°C and approaches of 4°C and 15.5°C, respectively. For these regions, and from Eq. (7), the NTUs calculated were 2.065 and 0.307 respectively considering (L/G=0.26).

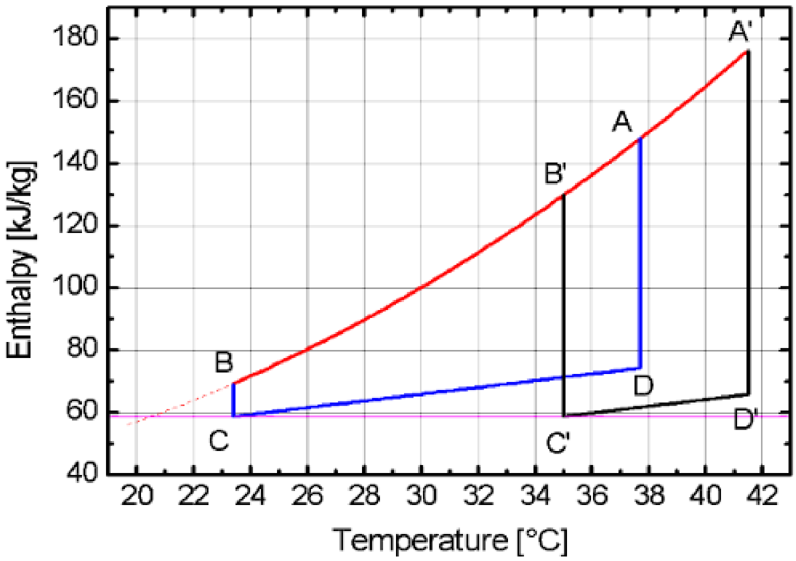

Figure 9. Counterflow cooling diagram.

Changing the L/G value, the demand curve is obtained as shown in Figure 9. From this figure, it is observed that by increasing the approach and reducing the range, the NTU value decreases for a fixed L/G value, and the NTU differences for L/G values up to 1 is approximately constant. On the other hand, the experimental performance of a cooling tower is given by the tower characteristic curve described in the literature (ASHRAE, 1996). The relation of the NTU and L/G is expressed as:

$$NTU = C \cdot \left(\frac{L}{G}\right)^{m}, \tag{9}$$

where C is the cooling tower constant and m is a constant obtained from experimental tests that varies from -0.6 to -0.8.

Considering $m=-0.6$, $L/G=0.26$ and different approaches and ranges from Figure 8, the values of C were obtained and the results are shown in Figure 10.

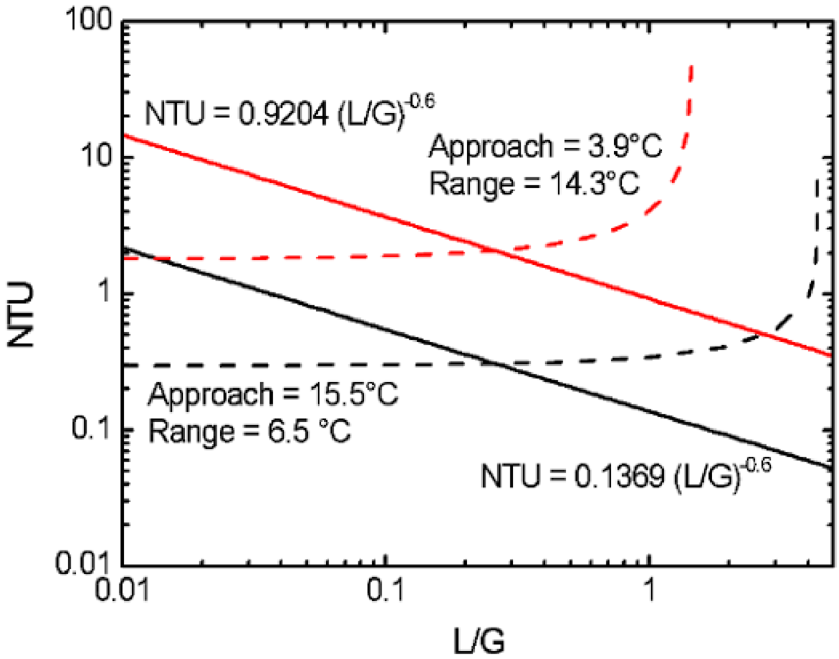

Figure 10. Demand (dashed line) and tower characteristic (solid line) curves for different approaches and ranges.

From Figure 10 it is observed that during the cooling operation at $L/G=0.26$, different values of NTU were obtained ranging from about 0.3 to 1.86. These results are compatible with the values of NTU reported in the literature between 0.5 to 2.5 for practical applications (Costelloe,et. al., 2009). In contrast with applications in stationary state, these results show that the performance of the cooling tower changes on time. At the beginning of the cooling process, a high value of NTU was determined and it decreased on time.

5. CONCLUSIONS

The cheese manufacturing process employed by small producers in the Pernambuco State can be improved using low-cost technologies to reduce the energy consumption and mitigate negative environmental impacts associated with the water use. Comparing the traditional practice for the cooling process using tap water and the use of a low-cost cooling tower, the use of the proposed equipment reduced the time consumption per milk volume and also significantly reduced the water consumption employed during the process. The cooling tower performance analysis indicated that the efficiency is high at the beginning of the process and decreases on time. This behavior was attributed to the decreasing of the range and the increasing of the approach on time.

6. ACKNOWLEDGEMENTS

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