FORMULATION OF A MODEL FOR CONTROLLING THE PASTEURIZATION PROCESS IN BOTTLED BEER

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Abstract. *Pasteurization is one of the most important processes applied in drinking industry. It is the process that provides the product the needed durability in order to ensure a secure human consumption by applying a thermal treatment. In case of beers, the product is pasteurized already bottled in large equipments called tunnel pasteurizers, in order to eliminate the microorganisms that may be present also in the bottle. The thermal effects of pasteurization also affect the organoleptic properties of beer and its chemical stability and, therefore, resulting in damaged products that cannot be sold at the market. This work has the purpose to investigate the physical phenomena's that occurs during beer pasteurization, and to elaborate an analytical model that describes the thermal problem, acquiring the global heat transfer coefficients, as the analysis of the thermal resistances involved, allowing the construction of a control system for real machines. In order to achieve this goal it is designed and constructed an analysis machine that creates all the conditions that can be found in real machines. The obtained global heat transfer coefficients are implemented in the thermal model proposed achieving very high precision in simulating the heating and cooling process that occurs in the bottle. Finally, the complete model is implemented as a control solution on a Brazilian machine. Some results of measures made at this machine are presented, showing that it can ensure an efficiency of 95% for the process. This result turns to be good enough in order to approve the control for operations in the domestic market.*

Keywords*: Heat transfer, Natural convection, Pasteurization*

1. INTRODUCTION

The food industry is increasingly requiring equipment that combines high-volume production with high accuracy in processes. These requirements mean that equipment operating in a production line have to ensure high levels of profitability, ensuring processes with narrow margins of tolerance.

In the beverage industry, the brewing industry is one of the largest and most traditional ones and, perhaps, involving the largest number of processes from raw material handling procedures to inventory the final product.

Pasteurization is the last process to which the beer is subjected. The process follows the same concept invented by French scientist Louis Pasteur in 1864 (Ziemann-Liess Ltd., 1985). Pasteurization basically consists of submitting the bottled beer to a gradual warming up to a standard temperature and kept for an established time. After this period, beer bottles are subjected to a gradual cooling to ambient temperature for storage. Beer is pasteurized already bottled in order to eliminate the microorganisms that may be on the container, since the majority of beer bottles are of the returnable type.

This process occurs in a large device called tunnel pasteurizer, as shown in Figure 1. In these tunnels the containers suffer several baths with different temperatures, which promote the gradual heating and cooling of the product. Pasteurization is assuming an increasingly important role in quality and productivity of industrial brewers. This is because the tunnel pasteurizer is responsible to large quantities of containers, with narrow tolerances in relation to the standards required for the process with virtually no human intervention, requiring a high level of automation.

The only machines available on the market that meet these requirements are of foreign origin. However, the Brazilian industrial park of beer still has a fair amount of older machines without a control procedure. These machines only makes the monitoring of the temperatures of the baths, following a pre-established pattern, not correcting deviations in case of quick stops of the filling line and, therefore, can produce beer outside of the desired quality standards.

With this background, the design of a mathematical model that can be implemented in software to control these machines, allowing it to make adjustments in the baths according to the level of pasteurization of the containers inside is extremely welcome. This model must take in count the properties of the bottle and the product being processed.

The basic problem lies in the conduction of heat through the bottle and the resulting natural convection of the internal fluid. Due to the small size of the container and the temperature differences between the fluid and bottled water in each bath squirted through the tunnel (limited by the thermal shock resistance of the hull material), it is expected behavior where there is a greater velocity near the walls and most of the fluid inside the cavity (the core) is relatively slow and is thermally stratified (Bejan 1995).

(a) (b)

Figure 1. (a) Tunnel Pasteurizer and (b) bottles being heated by water sprays inside the tunnel.

Previous studies show that the flow remains laminar, and for long process times, the speeds drops rapidly with decreasing temperature differential, reaching the limit of conduction on the fluid (Bejan, 1995; Patiño et al. 2001) .

It is possible to perform experimental studies to obtain the global coefficients of heat transfer, with the temperature measurement at strategic points at the bottle, usually at the central axis of the vessel (Brandon et al. 1984; Gava, 1998 ; Larsen, 2006). This procedure is relatively simple to run on a special installation, made for laboratorial analysis, and is enough to calculate the intensity of pasteurization.

It is desired to know these factors and study them for the most common situations that occur inside the tunnels, for the 600ml glass container, since it is the most widely used in the market.

As a reliable measurement of temperatures of the inner walls of the vessel becomes difficult as the dimensions of temperature gauges, however small, can substantially modify the system of boundary layer from the point in question, since it assumes that this layer boundary has a small thickness, it is used a computational tool to perform numerical simulations for knowing the velocity fields and temperature distribution, validated by comparing the temperature of some points of the fluid with the experimental results.

Thus, we can give numerical results and those obtained through a proper assessment of the thermal problem knowing the fluid dynamic behavior and its influence on temperature distribution inside the container.

2. PASTEURIZATION

Pasteurization is the application of relatively low temperatures and times, achieving a moderate prolongation of life of the product in exchange for keeping a good preservation of their nutritional value and organoleptic qualities. It's a mild heat treatment, as opposed to sterilization, which is a much more intensive treatment. The latter aims to a complete elimination of microorganisms present in the product causing, as a side effect, a deep change in their properties.

Pasteurization can be quantified with a very simple equation, resulting from the analysis of the kinetic thermal death of microorganisms (Buzrul, 2006). This equation, applied to the beer properties has the following form (Ziemann-Liess Ltd., 1985; Patiño et al. 2001):

$$PU = 1{,}393^{T_{CS}-60}\, t \tag{1}$$

Where PU is the pasteurization unit, T_{CS} is the temperature of the coldest spot inside the bottle at each instant of the process, in °C, and t is the time of the process, in seconds. Pasteurization must be calculated always in the coldest point of the bottle in order to guarantee that even in this point the pasteurization parameters are met.

2.1. Problems due to a Bad Pasteurization

When a pasteurization process has not reached the minimum requirements to be guaranteed the destruction of microorganisms, it is said that the product has been *under-pasteurized*. However, when the product has remained too long in the pasteurization temperature, or temperature applied was too high, it is recognized that the product has been *super-pasteurized*.

During the process of pasteurization, the beer always suffers slight variations in flavor, aroma and color. Beer is also subject to changes in its chemical stability (Clerk, 1958), because it is intrinsic to the drink the presence of numerous proteins in its composition, which have a natural tendency to clumping. Super-pasteurization make the oxygen that exists in beer to promote or accelerate chemical reactions that break this stability, besides the occurrence of a strong variation in flavor. Beer may also have more aerated strong color change, also by the reactions with oxygen. Pronounced color changes can lead to mistrust of the consumer, since the product does not have a normal appearance (Clerk 1958).

Another factor to consider is the pressure inside the container caused by the presence of carbon dioxide. The containers are filled leaving a headspace about 5-6% of the bottle volume. At very high temperatures or if the container was filled with a larger volume, it could break the container inside the machine.

All these conditions lead to a real need of controlling the beer pasteurization process.

3. MATHEMATICAL MODELLING

As mentioned in Chapter 1, the tunnel pasteurizer is divided in several zones, for gradual heating and cooling. This condition is shown in Figure 2.

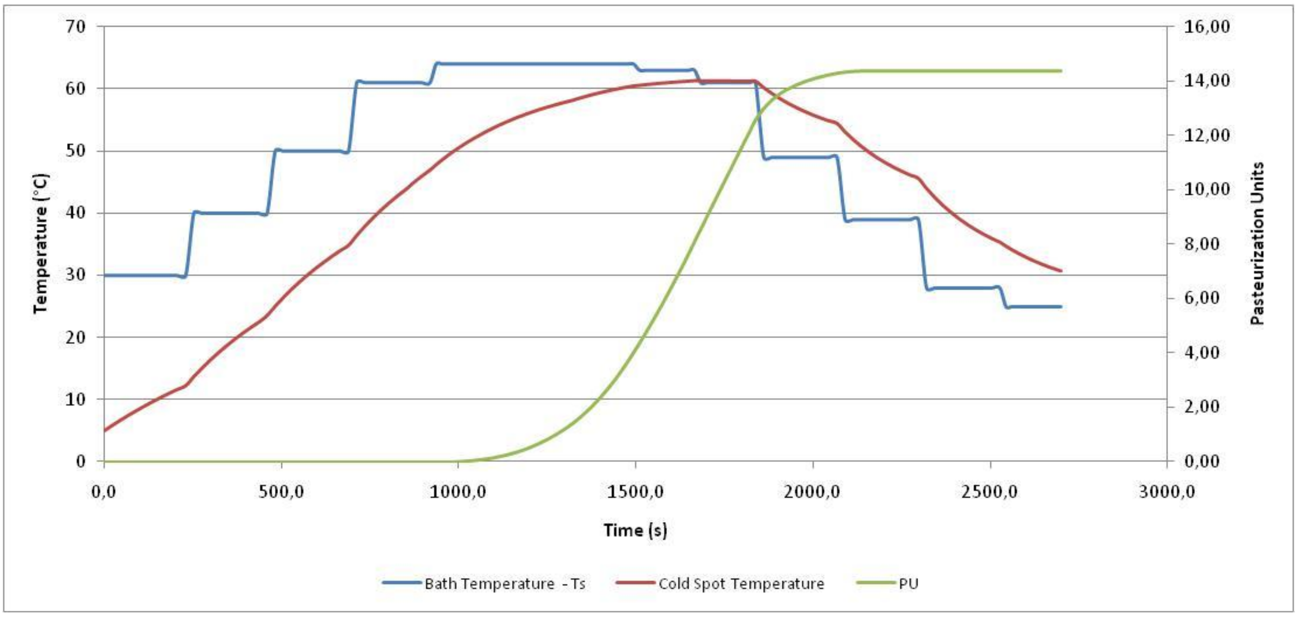

Figure 2. Typical pasteurization curve.

The present work concentrates studying the heat transfer from the water baths up to the cold spot, inside the bottle, allowing the calculation of the temperature at this location in every point of the machine. As this is a transient problem and it has a very strong coupling between the solid and liquid domain, where the velocity profiles and temperature the distribution is unknown, it is treated with a simple energy balance equation (see Figure 3).

$$\frac{dE}{dt} = q_{IN} - q_{OUT} + q_{GEN} \tag{2}$$

Where E is the internal energy, q_{IN} the rate of energy entering the bottle domain, q_{OUT} the rate of energy leaving the bottle domain and q_{GEN} is the heat generation inside the bottle which, in this case, is taken as zero. Equation 2 can be expanded to:

$$\left(\rho C_P V\right)_{SIST} dT_{CS} = \bar{U}A \cdot [T_S - T_{CS}(t)]dt \tag{3}$$

Where $\left(\rho C_P V\right)_{SIST}$ is the thermal capacitance of the bottle-beer system, $\bar{U}$ is the global heat transfer coefficient and A is the heat exchange area. Finally, equation 4 is written as the final form of the model:

$$T_{CS}(t) = T_S - [T_S - T_{CS}(0)]e^{-t/f} \tag{4}$$

Where,

$$f = \frac{\left(\rho C_P V\right)_{SIST}}{\bar{U}A} \tag{5}$$

And *f* being a time constant of the bottle-beer system. This is the classical Lumped Capacity Method and it cannot be applied if the goal was finding the temperature distribution, but since pasteurization is computed with basis in the temperature of a single representative point (Cold Spot) it can be used as a reliable tool. All the work consists about finding the values for *f* for each time step, t, inside the machine. This time step is set up with a established value.

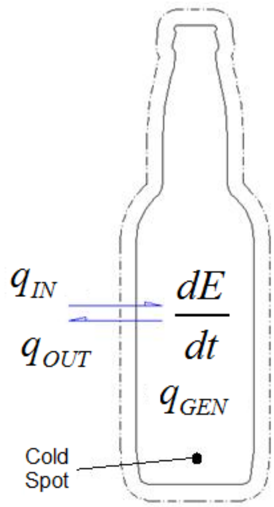

Figure 3. Heat balance for a beer bottle.

It is only needed to known the initial temperature $T_{CS}(0)$ at the tunnel inlet and the temperature of the baths at each zone T_S. The initial temperature can be found only measuring the cold spot temperature with a simple temperature probe and the baths temperatures are usually indicated by the machine controller system, by using PT-100 temperature probes. This values are inserted in equation 4 at every time step and the *f* value can be easily calculated.

4. METHODOLOGY

For obtaining the values of f, a testing plant is built in order to reproduce all the conditions found in a real tunnel pasteurizer. Therefore, special bottles with special probes can evaluate the temperature at the cold spot and the bath temperature for each time step for many conditions that can occur inside the tunnel.

The testing plant is formulated in order to allow some bottled to be tested inside its structure. It is formulated with the same auxiliary devices found in a real machine, such as spray pump, heating and cooling systems that are needed to reproduce the pasteurization process. Figure 4 shows the schematic of the testing plant.

The machine is provided with a hot water tank (TAQ) that contains water up to 85°C, in order to provide a quick heating of the bath. This heating is performed with a control valve (TCV), so the machine can maintain a selected bath temperature for a determined level and make a quick heating in order to simulate the next zone in the heating curve, as shown in Figure 2. The same works for the cold water reservoir (TAF). The hot or cold water are injected by the heat water pump (MBAQ) and cold water pump (MBAF) at the spray water pump suction (MBPR) and controlled by the temperature probes (TT) that are connected to a PLC controller.

The testing set is designed with the same bathing system, that means with the same spray pattern and the same flow rate and pressure used for the real machines, controlled by a flow rate measurer (FE). The spraying nozzles are made with reinforced plastic and provide a full water cone with 60° aperture. The bottles are supported over the same plastic belt type used for the real machines, in order to keep the same supporting condition. Figure 5 shown the testing plant built with a partnership with Ziemann-Liess Máquinas e eEquipamentos Ltda.

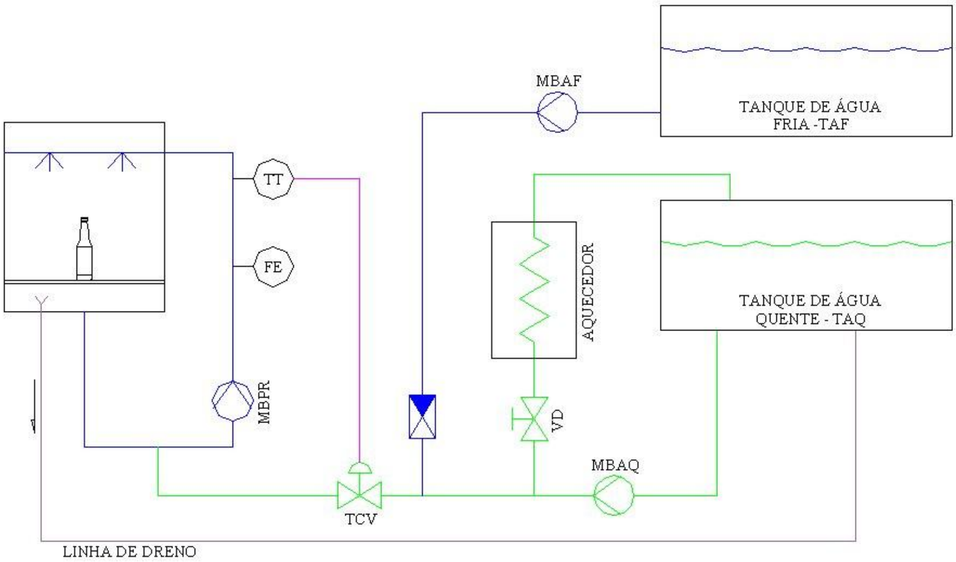

Figure 4. Schematic assembling of the testing plant.

(a) (b)

Figure 5. (a) Side view of the testing plant at Ziemann-Liess Máquinas e Equipamentos Ltda and (b) bottles under testing inside the machine.

The control valve is adjusted with established values for PID in order that the bath temperature can be changed with minimum distortions, like overshohting. For measuring the bottle cold spot temperature it is used a special equipment, that is the same used by the largest breweries in Brazil. It is composed by a PT-100 RTD type with 4 wires connection, installed in a metallic probe down to the cold spot. It is connected to a central that collects the data for later downloading and analysis. The equipment adopted has a uncertainty of ±0,2°C. The temperature probe is designed for 600ml Type A glass bottles, which are the most common beer bottles used for the Brazilian market. For the tests it is used Pilsen beer as test fluid.

4.1. Planning and Execution of the Tests

The test are executed putting the instrumented bottle inside the machine among other bottles, in order to mantainf the same condition of a real machine. The test machine is only switched on when the hot and cold water reservoir are full and at the desired temperature. After each test the cold spot bath temperatures are used to feed the mathematical model and the f value is simply calculated.

Since the *f* coefficient incorporates de global heat transfer coefficient and, therefore, the thermal driving force generated by the temperature difference, the tests are executed in order to cover a huge cases of temperature differences and bath times. The tests are performed with emphasis to the bottle heating curve, since the pasteurization is mostly determined by this region of the process.

5. EXPERIMENTAL RESULTS

The main tests were executed applying the same parameters used in real tunnel pasteurizers. The bath temperatures and time can be found in Table 1.

Table 1. Values used for heating tests.

Bath	Bath Temperature (TS)	Bath time
1	30°C	280s
2	40°C	280s
3	50°C	280s
4	60°C	280s

The results can are shown in Figure 7. The behavior for the temperature curve of the cold spot was as expected. There is a initial inertia that represents the time that heat takes to the cold spot region. This inertia is found to be very similar to major parto of the tests carried out and can be adopted as a characteristic values for this bottle-beer system. For reference, this inertia period is established as the time for the cold spot modifies 1°C from its initial temperature.

Figure 8 shows the goal of this work, the values of *f*. These values were calculated at each 2 seconds from the curve obtained in Figure 7. As for temperature, the *f*-values also shows a common behavior in these heating tests with a very high value for the inertia period and quick decrease until a constant value that remains almost the same for all the heating curve. It is used, for this case study, a $\overline{f}$ mean value for each process stage. The numerical results are shown in Table 2.

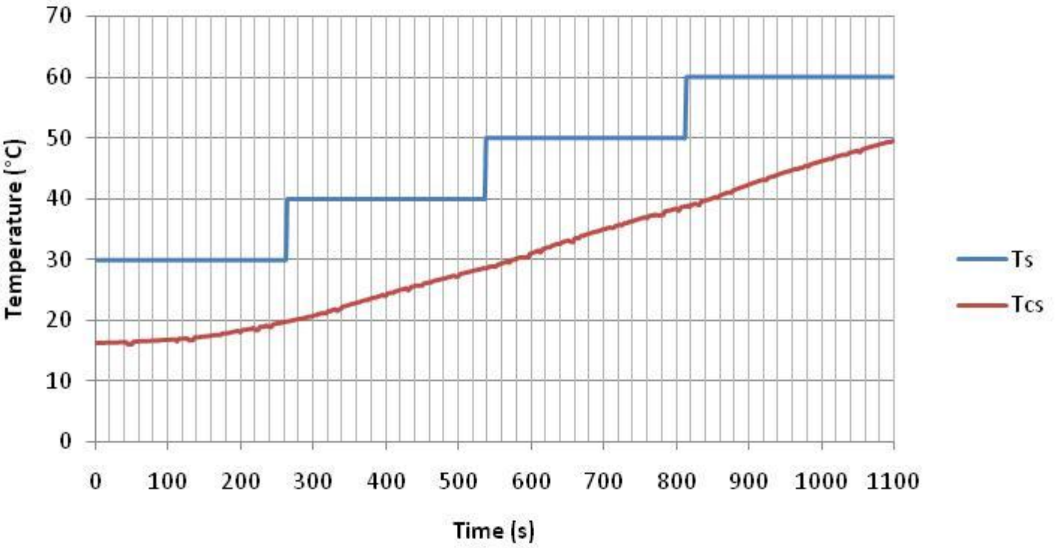

Figure 7. Results for the temperature at the cold spot (Tcs) for the baths temperatures (Ts) used for the heating tests.

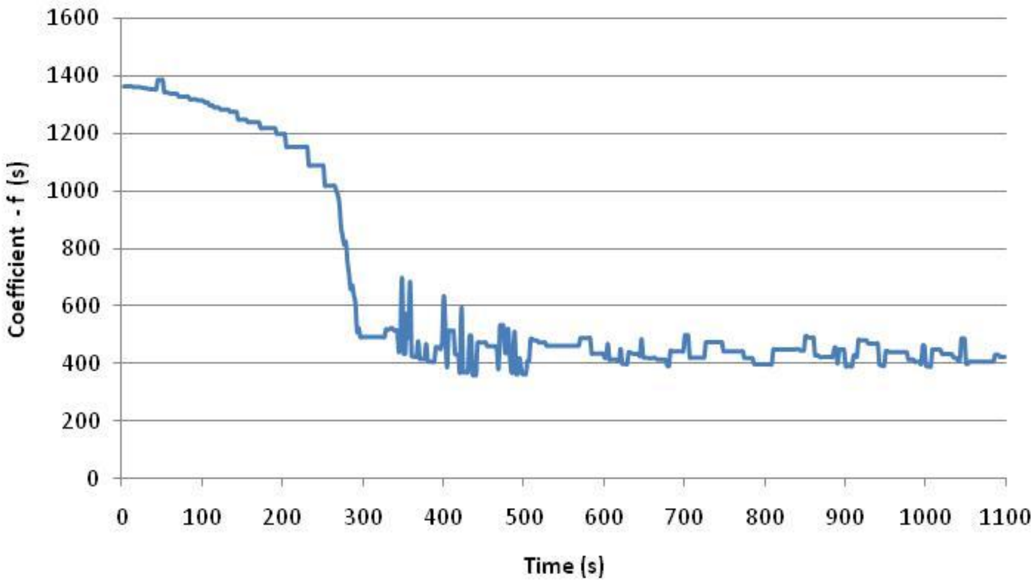

Figure 8. Results for the *f* values.

Table 2. Results for the mean *f*-coefficient for heating tests.

Stage	T_S (°C)	T_{CS} initial (°C)	T_{CS} Final (°C)	Time (s)	$\overline{f}$ (s)
Inertia Period	30	16,3	17,3	176	1389
Transition	30	17,3	19,9	104	700
1	40	19,9	28,6	280	481
2	50	28,6	38,9	280	463
3	60	38,9	49,6	280	458

The values obtained are related to the bath temperature, in order to achieve a valuable relationship that allows to formulate a data sheet with consolidated values for the 600ml glass bottle and Pilsen beer, as shown in Figure 9. The average values of the exponential factor obtained in all tests were grouped in order to build a table of values that allows software to be introduced into a control like a recipe for the 600ml container. This final results are shown in Table 3.

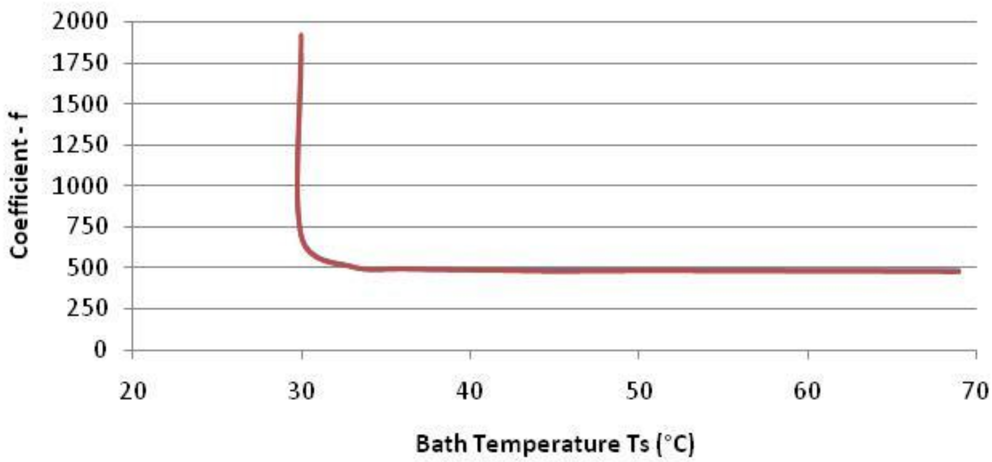

Figure 9. Behavior of the mean $\overline{f}$ coefficient related to the bath temperatures.

The main objective was reached, where a simple theoretical model was presented and its correlation coefficients between the bath temperature T_S and the cold spot temperature of the bottle T_{CS} were obtained. Focusing attention on the factors of Table 3, the process can be divided in three main steps.

Table 3. Final results for the average $\bar{f}$ values for the 600ml bottle.

Bath Temperature	$\bar{f}$
Inertia Period	1679s
Transition	608s
30-40°C	516s
40-50°C	489s
50-60°C	484s
60-70°C	482s

The first step is the inertia period. By equation 5 it can be inferred that in this period the values of the global coefficient to the cold spot is very low. But in this region the equation does not represent a real physical meaning, being just a fitting curve, because the simplified model is based on a formulation similar to the overall capacitance, where there would not be a delay period (since the field should be considered isothermal in this modeling). It can be interpreted as that the high values of *f* indicates that the container absorbs the major part of the energy supplied during the first moments, being the most significant portion of the domain. According Bejan (1995), at the beginning of a process of natural convection of a liquid enclosed, much of energy that passes through the glass is transported directly by the liquid jet near the glass.

The second step is about the transition period. It is understood as the region where the convective currents begin to order, according to the geometry of the bottle. The energy initially passed through the glass to the fluid boundary layer along the wall begins to achieve the cold spot. Still, can be assumed that the there is relative high speed near the internal bottle walls and a very low velocity in the bottle core (maintaining the momentum of the system). In this region, the coefficient of heat transfer by convection starts to become an increasingly important part of the global coefficient heat transfer. In this region, it is considered that the model already allows obtaining real values of $\bar{U}$.

The final step is the ordered natural convection In this region, the convective currents are set according to the geometry of the vessel, indicated by the and the regularity of *f* even at low temperature differences. It is true that some changes in the exponential factor *f* are due to changes in property values of beer, which is temperature dependent. However, this variations can be excluded because of the relative low temperature of the process.

5.1. Testing of the *f* Coefficients

Finally, the experimental results are applied to Equation (4) in order to test the obtained results and certificate that they can be used for a real machine. Figure 10 shows a sample obtained using same thermograph used in the test bench, with the practical results measured in the real machine. This example shows a good model output for the pasteurization process, mainly because the model is tested in its most severe condition, with line stoppages quite pronounced. This stoppages can be seen on the total process time of 4074s, when the normal process time must be 2830s at most (for this specific bottle and beer system).

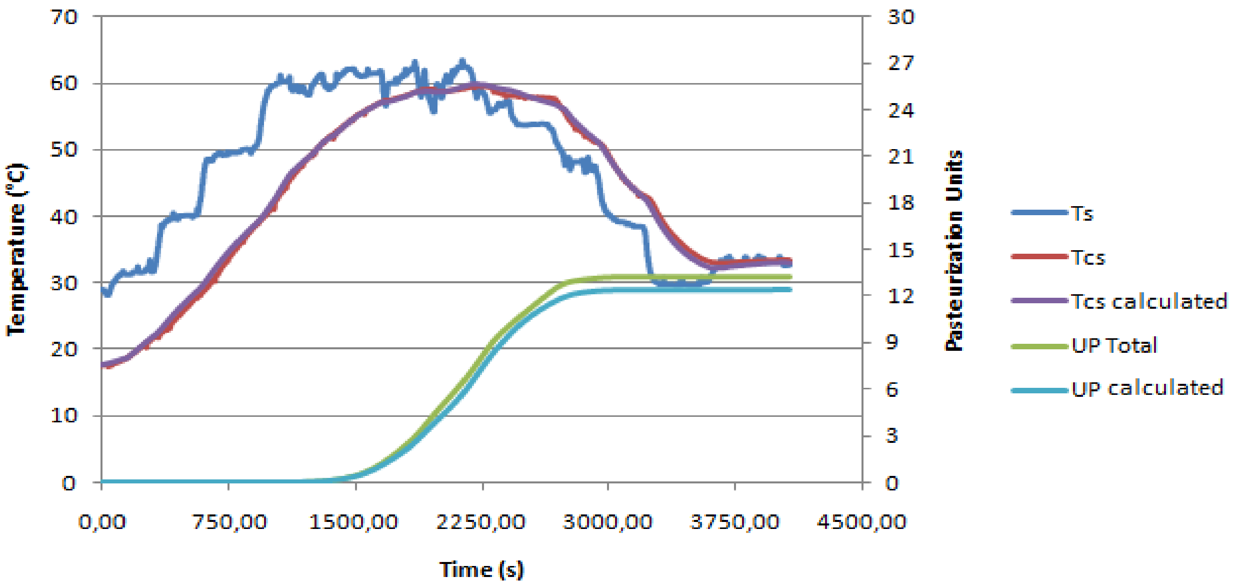

Figure 10. Testing of the model compared to a real pasteurization curve.

The model with the *f* values from Table 3 were permanently implemented in the controller software of a tunnel pasteurizer and the machine showed to have up to 95% of the PU measurements inside desired range, against 83% without the model.

6. CONCLUSIONS

In this paper an analytical model was developed to allow calculation of the temperature and intensity of pasteurization of beer bottled in glass containers during the process in machines called tunnel pasteurizer. The equation is assembled primarily by the balance of rates of heat entering and leaving the whole bottle-beer with the change in internal energy of the same. The modeling allows to calculate the temperature inside the vessel, at a predetermined point called as cold-spot (the coldest point in the pack) through the temperature of the baths made by machine, which are known.

The correlation factor is a function of the characteristics of container and processed product and was obtained through experimental tests performed on a specially constructed bench test in order to simulate all conditions of operation of a real tunnel pasteurizer. On this bench, measuring the temperature of the bath by simple tools such as PT-100 sensors, and also the temperature of the cold spot inside the bottle through a calibrated probe with its tip positioned geometrically at this point of interest. In all the work we used the standard bottle of beer 600ml as this is the container most used in the brewing industry in Brazil.

Tests showed that the factors *f* have a default behavior, with little variation between different situations. Analyzing the different relationships of *f* with the bath temperature, initial temperature of the whole beer-glass, among others, with only the bath temperature TS was able to establish a definitive relation for *f*. Thus, we obtained values for each level of temperature of the bath. Relationships with the temperatures of the baths led to the identification of the existence of three main steps that occur inside the bottle during the pasteurization process: initial inertia, transition and stable convection. The analytical model presented above is fed with these values, and each experiment is reproduced by this model. Deviations obtained were quite low, which allowed the model was actually used in a program to control a real machine. Calculation of a real pasteurization curve with the model and values obtained resulted in a very precise model.

Future prospects are due to the development of a computational model of a structured mesh to obtain efficient results, without the need for experimental tests. These numerical models can be used to obtain the correlation coefficients for other containers commonly used in the beverage industry.

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