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# Analysis and optimization for the process of glass tempering using autoclave

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**Abstract.** A mathematical analysis of the glass tempering process was carried out using an autoclave, varying the operating parameters of the system. It was found that the process time can be reduced by up to 3.23% by changing the resistance to 15 $\Omega$ , but increasing the resistance more than this value would mean compromising the quality of the final product. Thus, it is advisable to make variations of the resistance between 10 $\Omega$  and 15 $\Omega$ , which will allow the optimization of the process time and pressures without affecting the quality of the result.

## 1. Introduction

Autoclave is one of the oldest and most widely used processes for a wide range of composite materials [1]. Considering the advantages of the type of heating offered in this process, its use not only refers to the area of engineering, it is also widely used in the branch of industry, medicine and domestic. The induction heating of this process is applied uniformly on the body to be heated, such that the heating is optimal and at a higher speed. Also, the heating being non-contact, allows to ignore the heating of the environment [2].

Due to the advantages offered by the autoclave process, a quantitative study was made of the effects of its use in different applications, including the implications of its use in brick production with respect to the mechanical strength [3] or in the reactivity that may offer additives to concrete [4]. A study was also carried out to compare the effects of autoclave sterilization and cold chemical sterilization on the deflection characteristics of a load on coated wires [5].

As mentioned earlier, the type of heating offered by the autoclave has led to its widespread use in a variety of branches, one of which is the pharmaceutical industry, due to its great effectiveness in removing germs. However, it is always necessary to verify the effectiveness of the process, so a good complement to this is neural networks. For the implementation of the neural networks, it is necessary to train them with the largest number of variables possible, a process known as Deep Learning. In order to validate the methodology, 13 temperature sensors and one pressure sensor were used, such that the pressure value obtained from the model and that obtained by means of the pressure sensor were compared [6].

The steels without tempering have great hardness, but depending on their use, they can become too brittle, so it is necessary to apply a heat treatment to increase the mechanical properties of the material [7]. As with steel, the tempering process also applies to glass. However, in this case, the tempering



process consumes large amounts of energy in air management systems [8]. This is why a different form have been proposed to what has been done since antiquity [9]. In addition, it is important to consider that the glass is subjected to different types of stress, so it is generally in a state of tension and compression and the risk of breakage is imminent. This is why the study of the fragmentation of material and energy lost in this case is also a case study [10].

In the vast majority of industrial applications, energy cost is a main consideration, especially in energy-intensive areas such as the metal and glass processing industry, which will ultimately lead to reduced manufacturing costs [11]. The most effective way to achieve a process optimization is to characterize the phenomenon to be studied in a mathematical way and study in a quantitative manner the parameters that affect the behavior of the process over time [12]. This is why many investigations are devoted to developing methods to estimate accurate parameters in real time [13] with technically viable optimization solutions thanks to the use of powerful computers [14].

Therefore, this article aims to optimize the process of tempering glass, evaluating which process variables can be modified in order to reduce operating costs without affecting the quality of the final product, also considering that the glass does not become too fragile.

## 2. Methodology

In this section are presented the fundamental equations of the dynamic model, a brief detail of the glass tempering process, and the main blocks of the model in Matlab Simulink including the control law applied to the autoclave process.

### 2.1. Fundamental equations

For the analysis of the system, mass balances in the autoclave, energy balance for the air and energy balance for the glass were considered, considering that there is no heat loss to the environment, ideal gas model for the air, constant specific heat, constant air density, i.e., it remains the same at the entrance and exit. The temperature of the glass is also considered homogeneous over the entire surface and pressure drops in the pipes are ignored. The mass balance for the autoclave is presented in Equation 1.

$$0.001m_i(t) - C_{val}m_2(t)\sqrt{P(t)[P(t) - P_2]} = \frac{V_{air}}{R_g\rho} \frac{d}{dt} \left[ \frac{P(t)}{T(t)} \right], \quad (1)$$

Where  $m_i$  is the mass flow of the compressor,  $m_2$  the mass flow of the valve,  $C_{val}$  is the heat capacity of the air,  $P$  is the air pressure,  $P_2$  is the atmospheric pressure,  $V_{air}$  is the volume of air,  $R_g$  is the ideal gas constant of air,  $T$  is the air temperature. The convective heat transfer is calculated as shown in Equation 2.

$$Q_{CV} = h_c A_c [T(t) - T_{glass}(t)], \quad (2)$$

The energy balance is shown in Equation 3.

$$0.001m_i(t)C_p \frac{P_1(t)}{R_g} + \frac{V^2(t)}{R} - \rho C_p C_{val} m_2(t) \sqrt{P(t)[P(t) - P_2]} T(t) - Q - Q_{CV} = \frac{C_v V_{air}}{R_g} \frac{dP(t)}{dt}, \quad (3)$$

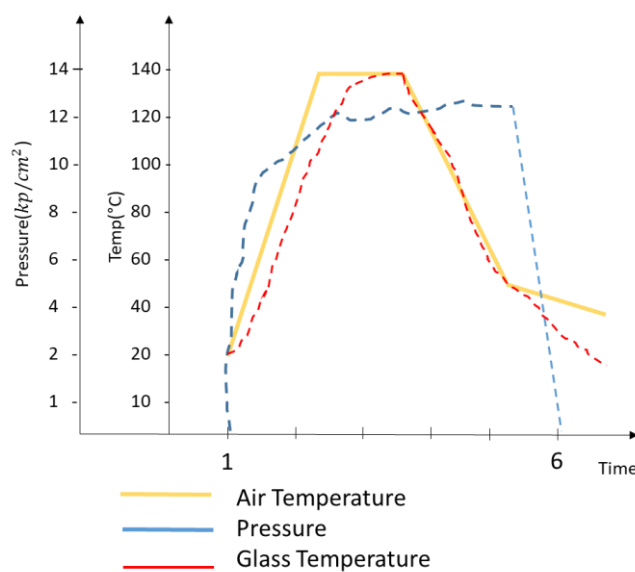
where  $Q$  is the water flow rate,  $C_p$  is the specific heat of glass,  $T$  is the temperature in the autoclave and  $T_{glass}$  is the temperature of glass. In addition, the energy balance for the glass is shown in the Equation 4.

$$h_c A_c [T(t) - T_{glass}(t)] = C_{v,glass} m_{glass} \frac{dT(t)}{dt}, \tag{4}$$

where  $h_c$  is the convective coefficient,  $C_{glass}$  is the  $C_v$  of glass,  $m_{glass}$  is the mass of glass.

### 2.2. Glass tempering process

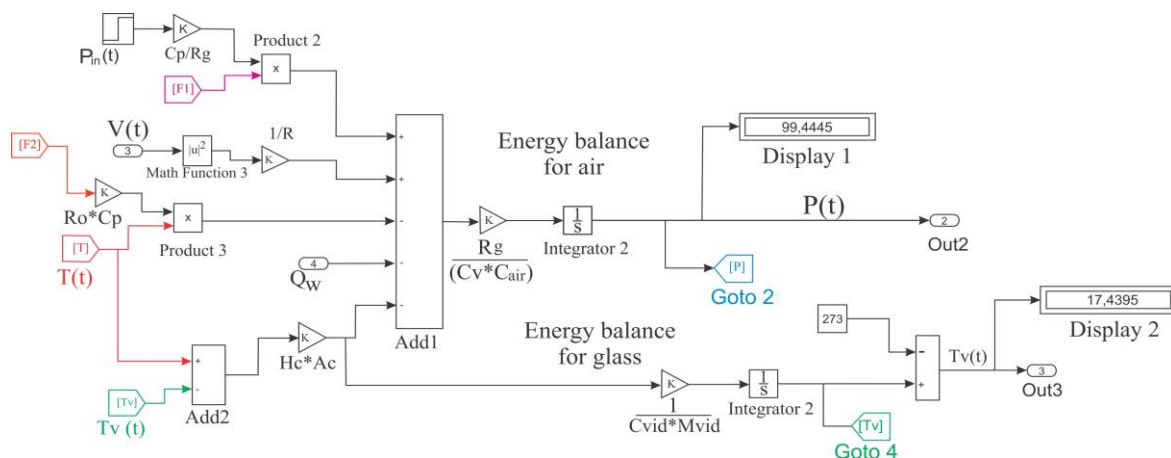
The correct tempering of the glass as shown in Figure 1 depends on the process. This process is carried out following standards established. A standard tempering cycle consists of several phases, the first phase consists of opening and closing the door, which usually takes 5min, the second phase is the heating and pressurization, the third is the holding phase, which lasts about 20min, the fourth is the cooling and depressurization.



**Figure 1.** Typical tempering diagram.

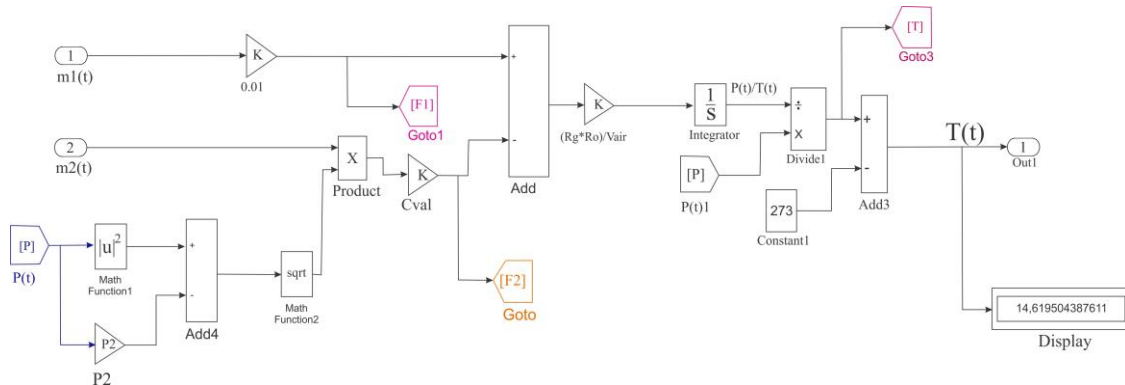
### 2.3. Modelling and simulation in Simulink

The above equations were solved in Simulink, obtaining the blocks shown in Figure 2, for the case of the energy balance in the glass and air.



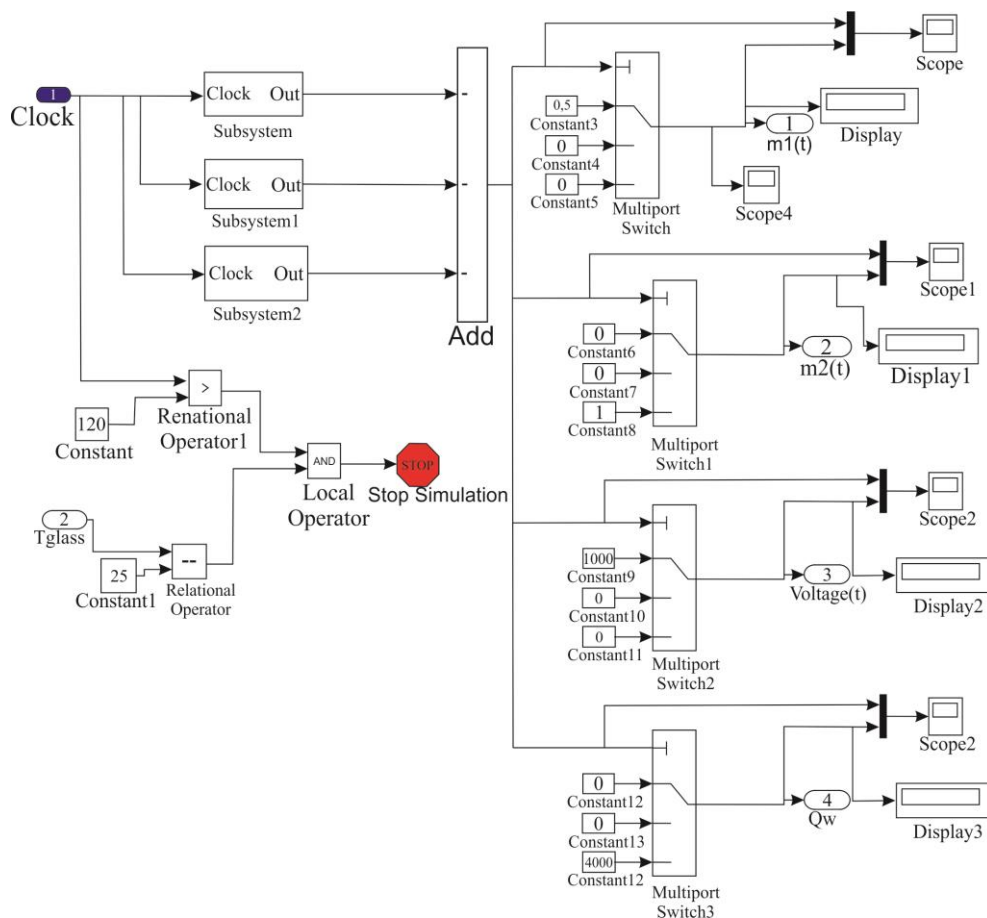
**Figure 2.** Block diagram for the energy balance of glass and air.

Similarly, the mass balance for the autoclave as shown in Figure 3, which corresponds to a first-order non-linear differential equation, was solved numerically with the help of the Simulink software.



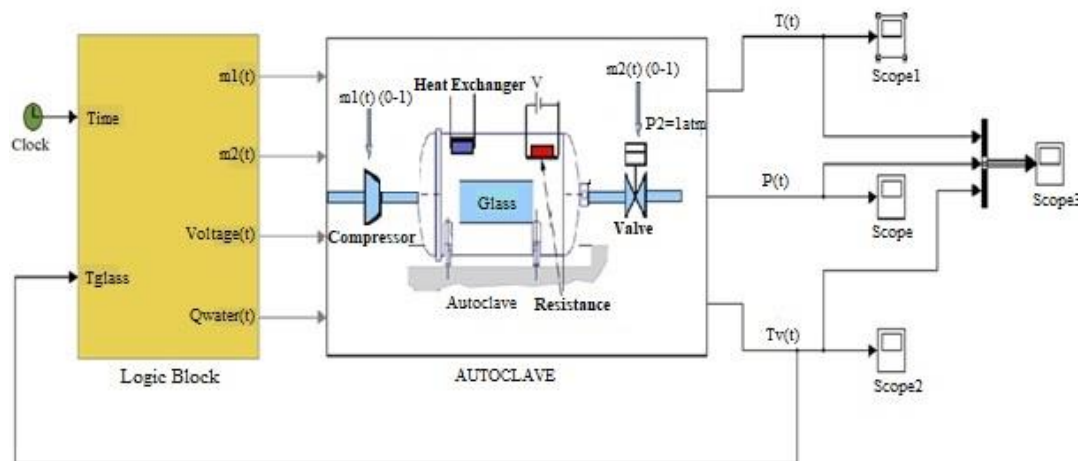
**Figure 3.** Autoclave mass balance block diagram.

The process is carried out by controlling 4 input signals as shown in Figure 4, where the compressor signal  $m1(t)$ , the signal at the output valve  $m2(t)$ , the voltage and the heat extracted by the heat exchanger. In the first part of the logic block, there are three subsystems for defining three time intervals, in which the values of the inputs will vary. The intervals are  $t > 79\text{min}$ ,  $79\text{min} < t < 109\text{min}$  and  $t > 109\text{min}$ , the first interval ensures that the air temperature reaches  $140^\circ\text{C}$ , the second interval controls the holding time of the glass, which in this case is 30min.



**Figure 4.** Block diagram of the control room.

The second part of the block indicates when the simulation finish, the time stipulated for this is when the elapsed time is greater than 120min and the glass temperature has returned to its initial temperature of 25°C. The last part of the block is the one that indicates which values will be taken by the inputs in the previously defined intervals, each input has a switch with four inputs, and the first one is for the time intervals and the other three for the values that the input must take. With these parameters, the correct tempering process is ensured. Finally, Figure 5 shows the complete block diagram of the process.



**Figure 5.** Complete block diagram.

### 3. Results and discussions

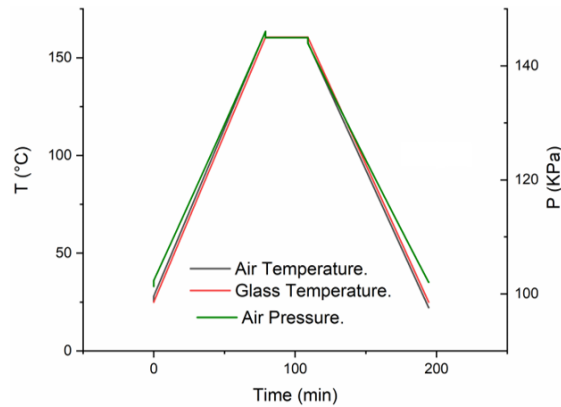
For the analysis of the process, the mass of the glass and the resistance has been changed, to determine the effect they produce on the temperature, pressure, and duration of the process. A parametric analysis of the other variables was rejected, because their effect on the parameters to be studied is not significant. Table 1 shows the initial values with which the comparative process will begin; first, a variation of the mass of the glass has been made from 3000kg to 3500kg, keeping the other parameters constant. After that, the mass of the glass will be maintained and the next parameter to be studied will be varied, in this way a parametric analysis will be carried out that will allow the optimization of the time of the procedure.

**Table 1.** Initial values used to compute the dynamic model of the thermal process.

| Parameters  | Value         |
|---|---------------|
| Atmospheric pressure (kPa)                        | 101.3         |
| Convective area ( $m^2$ )                         | 7.064         |
| Convection heat transfer coefficient ( $W/m^2K$ ) | 200           |
| Specific heat of the glass ( $kJ/kg * K$ )        | 0.837         |
| Mass of glass (kg)                                | 3500          |
| Resistance ( $\Omega$ )                           | 13.880        |
| Air density at reference conditions ( $kg/m^3$ )  | 11.822        |
| $C_p$ of air ( $kJ/kg * K$ )                      | 1.005         |
| $C_v$ of air ( $kJ/kg * K$ )                      | 0.718         |
| Volume of air ( $m^3$ )                           | 13.440        |
| Gas constant ( $kPa * m^3/kg * K$ )               | 0.2867        |
| Valve coefficient ( $m^3/min * kPa$ )             | $4 * 10^{-5}$ |

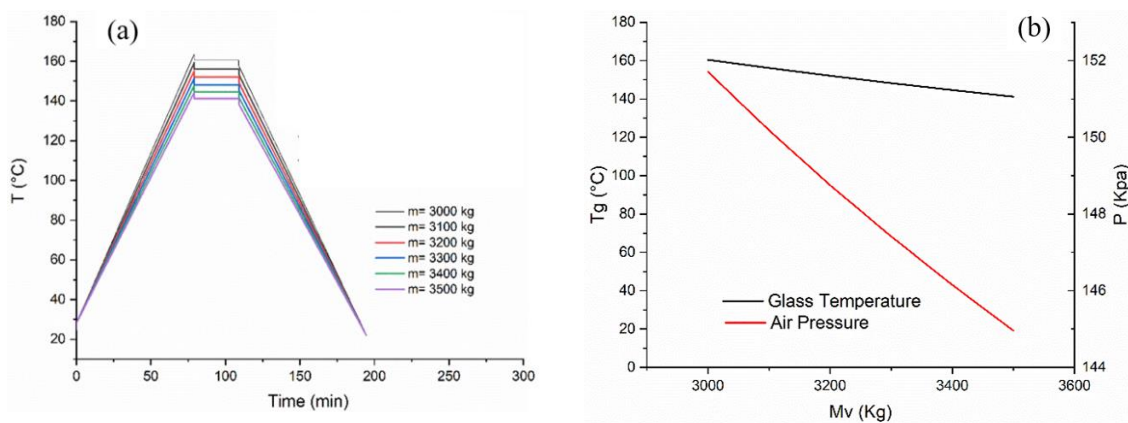
The typical process response for the air, glass temperature and the air pressure is shown in Figure 6, for the process according to the values reported in Table 1, where the all the phases are presented, the

opening and closing the door, the heating and pressurization, the holding phase and the cooling and depressurization.

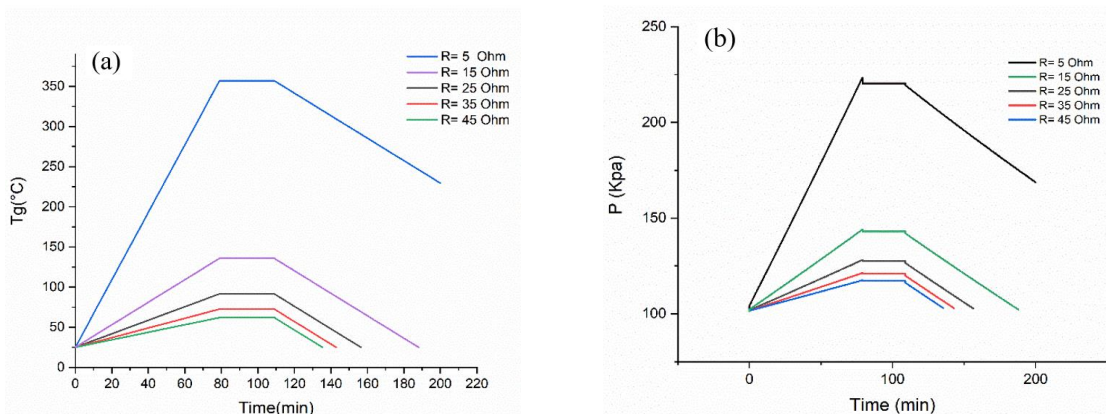


**Figure 6.** Results of the first simulation.

Figure 7 shows that the behavior of the simulated system is consistent with the standard tempering process for glass, so that the model proposed for the process can be considered correct. In addition, the total time from the initial to complete the total process is 194.44min.



**Figure 7.** Dynamic response, (a) Temperature profile when varying the mass of the glass; (b) pressure and temperature profile when varying the mass of the glass.



**Figure 8.** Dynamic response, (a) Glass temperature profile when the resistance changes; (b) air pressure profile when the resistance changes.

It can be observed that the pressure and temperature in the process are inversely proportional to the mass of the glass and the greater the mass of the glass, the longer the heating time will be and the longer the process takes. In Figure 8 it can be seen that having a very small resistance the process could take twice as long as required, while for the other study values, the process not only has the temperature and pressure reduced, but also the time is significantly reduced.

#### 4. Conclusions

It can be concluded that the parameter to be modified to achieve a reduction in process time without affecting the quality of the tempering process is the resistance, in this way not only time will be saved, but also pressures will be reduced, which will lead to a reduction in the energy consumption of the system. However, it should be noted that too much increase in this value would lead to too small temperatures that could affect the tempering process and the end result would not be the best, thus, it is considered that the process would not be feasible taking these parameters into account.

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