Temperature control of a bioreactor subject to external temperature oscillations

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Bioreactors are commonly used to produce ethanol from glucose fermentation (Pachauri et al., 2017). During alcoholic fermentation, glucose is degraded into ethanol, generating carbon dioxide during anaerobic processes. In contrast, in the fermentation phase, the yeast's metabolism converts sugars into ethyl alcohol, carbon dioxide, and Saccharomyces cerevisiae (Basso et al., 2011). The internal temperature of bioreactors is a crucial variable, as it interferes with the fermentation efficiency and denaturation process of microorganism proteins (Basso et al., 2011). The use of mathematical models to describe the behavior of bioreactors has helped in the development of process control projects. By controlling the internal temperature of the bioreactor, it is possible to optimize ethanol production (Sultana et al., 2017). In this context, this work presents a Pole Allocation control system acting in the flow of the cooling system fluid that passes through the fermenter jacket to maintain the ideal temperature in the bioreactor, taking into account the effects of the bioreactor's inlet temperature variation, which influences the internal temperature of the bioreactor. The proposed control aims to design a system of practical control that provides the desired operational performance.

The proposed refrigerant flow control in the bioreactor jacket is shown in Figure 1.

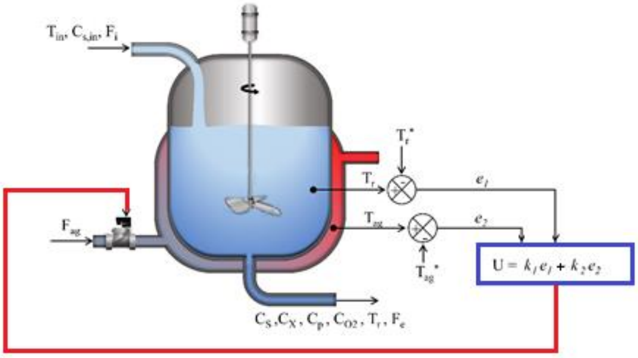

Fig. 1. Reactor temperature control proposal.

In equation (1), the mathematical model of the bioreactor with the proposed control (shown in Figure 1) is presented.

$$\begin{cases} \dfrac{d(C_x)}{dt} = \mu_x C_x \dfrac{C_s}{K_s + C_s} e^{-K_p C_p} - \dfrac{F_e}{V} C_x \\ \dfrac{d(C_S)}{dt} = -\dfrac{1}{R_{SX}} \mu_x C_x \dfrac{C_S}{K_s + C_S} e^{-K_p C_p} - \dfrac{1}{R_{SP}} \mu_P C_x \dfrac{C_S}{K_{S1} + C_S} e^{-K_{p1} C_p} + \dfrac{F_i}{V} C_{S,in} - \dfrac{F_e}{V} C_S \\ \dfrac{d(C_P)}{dt} = \mu_P C_x \dfrac{C_S}{K_{S1} + C_S} e^{-K_{P1} C_P} - \dfrac{F_e}{V} C_P \\ \dfrac{d(C_{O_2})}{dt} = (k_{la})\left(C^*_{O_2} - C_{O_2}\right) - r_{O_2} \\ \dfrac{d(T_r)}{dt} = \dfrac{F_i}{V}\left(T_{in} + 273\right) - \dfrac{F_e}{V}\left(T_r + 273\right) + \dfrac{r_{O_2} \Delta \mathrm{H}_r}{32 \rho_r C_{heat,r}} - \dfrac{K_T A_T \left(T_r - T_{ag}\right)}{V \rho_r C_{heat,r}} \\ \dfrac{d(T_{ag})}{dt} = \dfrac{F_{ag}}{V_j}\left(T_{in,ag} - T_{ag}\right) + \dfrac{K_T A_T \left(T_r - T_{ag}\right)}{V_j \rho_{ag} C_{heat,ag}} \end{cases} \quad (1)$$

Where C_x is biomass concentration, C_s is the glucose concentration in the reactor, C_p is the Ethanol concentration, C_{O_2} is the oxygen concentration, T_r is the outlet temperature and T_{ag} is the temperature of the thermal jacket. For numerical simulations, the following parameters will be considered: $K_s = 1.03$, $K_p = 0.139$, $F_e = 51$, $V = 1000$, $R_{SX} = 0.6070$, $R_{SP} = 0.4350$, $\mu_P = 1.79$, $K_{S1} = 1.68$, $K_{p1} = 0.07$, $F_i = 51$, $K_{la} = 38$, $\Delta \mathrm{H}_r = 518$, $\rho_r = 1080$, $C_{heat,r} = 4.18$, $K_T = 360000$, $A_T = 1$, $V_j = 50$, $T_{in,ag} = 15$, $\rho_{ag} = 1000$, $C_{heat,ag} = 4.18$, $T_i(t) = 25 + (10 sin((\pi/12)t))$ (Pachauri et al., 2017). With initial conditions: $C_{x_0} = 1$, $C_{S_0} = 28$, $C_{P_0} = 17$, $C_{O_{2_0}} = 0.7$, $T_{r_0} = 30$ and $T_{ag_0} = 28$. $T_r^* = 32°\mathrm{C}$ and $T_{ag}^* = 24°\mathrm{C}$ are set as desired temperatures, the optimum temperature for the alcoholic fermentation of Saccharomyces cerevisiae according to (Amillastre et al., 2012). The refrigerant flow control signal is given by $F_{ag} = U = -4691.5(32 - T_r) - 55.9(24 - T_{ag})$, control gains obtained by imposing the poles ($-5.9557 \pm 5.7684j$) for the last two equations of system (1) and disregarding the other equations in the coolant flow control project. In Figure 2, it is possible to verify the behavior of the bioreactor with the control of the jacket coolant flow.

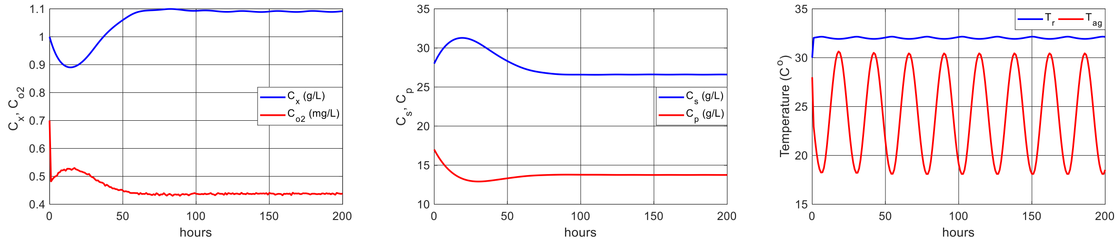

Fig. 2. Behavior of the bioreactor with the inclusion of jacket coolant flow control ($F_{ag} = U$).

Figure 3 presents the case in which a constant flow of refrigerant fluid is used, in which flow control is not considered.

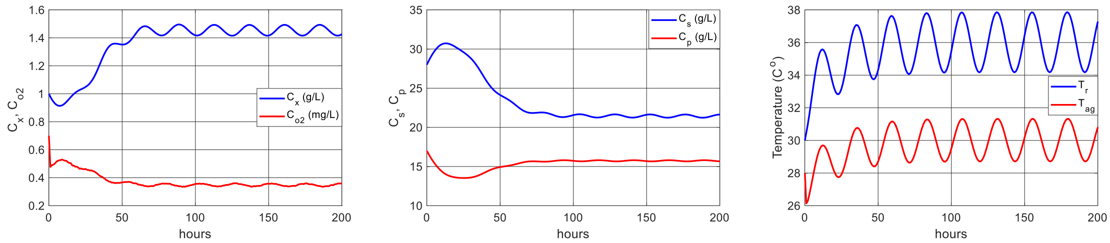

Fig. 3. Behavior of the bioreactor without including jacket coolant flow control ($F_{ag} = 34.4$ L/h).

According to the results presented in Figure 2, the reactor temperature is, on average, 32.03°C, maximum 32.15°C and minimum 31.92°C, maintaining the temperature close to the desired temperature, with a maximum error of 0.46%, demonstrating the effectiveness of the proposed control. However, when we observe the temperature for a constant flow of 34.4 L/h, we see that the maximum temperature reaches 37.86°C, with an average of 36.015°C, an undesirable temperature, as Saccharomyces cerevisiae proteins begin to denature at 36°C, consequently producing glycerol, which is undesirable in the process (Amillastre et al., 2012).

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