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A fuzzy–split range control system applied to a fermentation process

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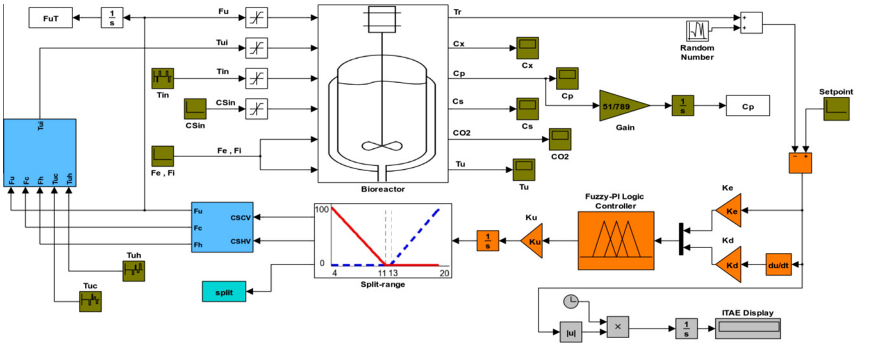
HIGHLIGHTS

- Fuzzy–split range control system is able to regulate a fermentation process.
- Reducing control effort is possible for similar performance index.
- Reducing utilities demands is possible for similar performance index.
- Fuzzy–split range control system provides smooth control output.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study it was proposed the application of a fuzzy-PI controller in tandem with a split range control strategy to regulate the temperature inside a fermentation vat. Simulations were carried out using different configurations of fuzzy controllers and split range combinations for regulatory control. The performance of these control systems were compared using conventional integral of error criteria, the demand of utilities and the control effort. The proposed control system proved able to adequately regulate the temperature in all the tests. Besides, considering a similar ITAE index and using the energetically most efficient split range configuration, fuzzy-PI controller provided a reduction of approximately 84.5% in the control effort and of 6.75% in total demand of utilities by comparison to a conventional PI controller.

1. Introduction

The increasing demand for energy and the environmental, economic and geopolitical issues related to the exploration and consuming of fossil fuels are a major cause of apprehension when world leaders discuss sustainable development strategies. Therefore, renewable sources of energy have become an attractive alternative (Cardona and Sánches, 2007; Andrade et al., 2007; Amillastre et al., 2012). In this context, ethanol has a prominent role, its worldwide production indicators having risen from 10,770 million gallon in 2004 (Renewable Fuels Association, 2005) to 22,356 million gallon in 2011 (Renewable Fuels Association, 2012). Most of this ethanol is produced by the anaerobic fermentation of six-carbon sugars by *Saccharomyces cerevisiae* (Ngwenya et al., 2012; Xu et al., 2010). It must be pointed out that the primary sources of sugar constitute renewable feedstock, such as corn (in the United States of America) or sugarcane (in Brazil).

During the fermentation, process variables must be maintained within a narrow range near optimal operating condition (Andrade et al., 2007). Thus, temperature becomes a particularly important variable. Temperature influences fluid dynamics in the fermentation vat, affects the metabolism of *S. cerevisiae* (Amillastre et al., 2012) directly and participates in the wild yeast contamination

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Nomenclature

A_{T}	heat transfer area (m^2)
A_1, A_2	exponential factors in Arrhenius equation
CE_i	control effort for valve i
$C_{\mathrm{O_2}}$	Oxygen concentration in the liquid phase ($mg\,L^{-1}$)
$C^*_{\mathrm{O_2}}$	equilibrium concentration of oxygen in the liquid phase ($mg\,L^{-1}$)
$C^*_{\mathrm{O_{2,0}}}$	equilibrium concentration of oxygen in distilled water ($mg\,L^{-1}$)
C_P	ethanol concentration ($g\,L^{-1}$)
C_S	glucose concentration ($g\,L^{-1}$)
$C_{S,\mathrm{in}}$	glucose concentration in the feed stream ($g\,L^{-1}$)
C_X	Biomass concentration ($g\,L^{-1}$)
$C_{\mathrm{heat,U}}$	heat capacity of the cooling agent ($J\,g^{-1}\,K^{-1}$)
$C_{\mathrm{heat,r}}$	heat capacity of the fermentation medium ($J\,g^{-1}\,K^{-1}$)
e	controlled variable error (°C)
E_{a1}, E_{a2}	activation energy ($J\,mol^{-1}$)
F_c	cold utility flow ($L\,h^{-1}$)
F_e	bioreactor downstream flow ($L\,h^{-1}$)
F_h	hot utility flow ($L\,h^{-1}$)
F_i	bioreactor feed flow ($L\,h^{-1}$)
F_u	total utility flow ($L\,h^{-1}$)
H	specific ionic constant
I	ionic strength
$K_{\mathrm{L}}a$	product of the mass-transfer coefficient for oxygen and gas-phase specific area (h^{-1})
$K_{\mathrm{L}}a_0$	product of the mass-transfer coefficient at 20 °C for O_2 and gas-phase specific area (h^{-1})
$K_{\mathrm{O_2}}$	constant for oxygen consumption ($mg\,L^{-1}$)
K_{P}	constant of growth inhibition by ethanol ($g\,L^{-1}$)
K_{P1}	constant of fermentation inhibition by ethanol ($g\,L^{-1}$)
K_{S}	constant in the substrate term for growth ($g\,L^{-1}$)
K_{S1}	constant in the substrate term for ethanol production ($g\,L^{-1}$)
K_{T}	heat transfer coefficient ($J\,h^{-1}\,m^{-2}\,K^{-1}$)
M	quantity of inorganic salt (g)
M	molecular/atomic mass ($g\,mol^{-1}$)
$r_{\mathrm{O_2}}$	oxygen uptake rate ($mg\,L^{-1}\,h^{-1}$)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)
R_{SP}	ratio of ethanol produced per glucose consumed for fermentation
R_{SX}	ratio of cell produced per glucose consumed for growth
T	time (h)
T_{in}	temperature of the substrate flow entering to the bioreactor (°C)
T_{Uc}	temperature of cold utility (°C)
T_{Uh}	temperature of hot utility (°C)
T_{Ui}	temperature of the utility entering to the jacket (°C)
T_{Uo}	temperature of the outlet utility (°C)
T_{r}	temperature in the bioreactor (°C)
$u_{\mathrm{k,i}}$	control signal to valve i at moment k (mA)
V	volume of the bioreactor (L)
V_j	volume of the jacket (L)
$Y_{\mathrm{O_2}}$	the amount of oxygen consumed per unit biomass produced (mg/mg)
$\Delta\mathrm{Hr}$	reaction heat of fermentation ($kJ\,mol^{-1}$ O_2 consumed)
Δu_i	normalized control signal variation
$\mu_{\mathrm{O_2}}$	maximum specific oxygen consumption rate (h^{-1})
μ_{P}	maximum specific fermentation rate (h^{-1})
μ_{X}	maximum specific growth rate (h^{-1})
ρ_{U}	density of the utility ($g\,L^{-1}$)
ρ_{r}	density of the fermentation medium ($g\,L^{-1}$)

control (Ngwenya et al., 2012). Indeed the effects of inadequate temperature conditions include reduction of fermentation yield, changes in cell viability and decrease of yeast tolerance to ethanol (Amillastre et al., 2012). Besides, fermentation under suboptimal temperatures can favor wild microorganism which will compete with *S. cerevisiae* for substrate. As a consequence, the production of undesirable by-products increases, in turn, enhancing the formation of scum and imposing the application of antibiotics. However, the alcoholic fermentation process is exothermic and temperature inside the fermentation vessel varies in accordance to the activity of yeast. Consequently, heat must be continuously removed from the system.

In order to improve the temperature control in a fermentation bioreactor, Lawrynczuk (2008) proposed and recommended the application of nonlinear model based predictive control (MPC) strategy, using neural networks as a black box model. Unfortunately, this strategy requires the on-line solution of a quadratic programming problem for each sample. A simpler alternative is the application of fuzzy logic based controllers (FC). The advantages of fuzzy logic based controllers are simplicity, implementation easiness, robustness, and the ability to deal with complex nonlinear relationships using even imprecise, incomplete and noisy data (Wakabayashi et al. 2009; Eker and Torun, 2006; Silva et al., 2012). Sagüés et al. (2007) successfully implemented fuzzy controllers to control a biomass gasification process. The proposed control strategy proved successful in dealing with multivariable coupling and process nonlinearities and showed a good overall performance. The benefits of the application of fuzzy-based control are also commented by Wakabayashi et al. (2009) when controlling the temperature inside a polymerization reactor. In this case the fuzzy-PI controller was implemented using a split range configuration with two control valves, one for a hot utility and one for a cold utility. In split range control, the output of the controller is sent to two or more control valves and each of them acts upon a certain range of the controller output. The aim of this split ranging is to improve the controller by expanding its performance range (Shen-Huii et al., 2011).

In this study the application of a fuzzy-PI and fuzzy-PID controllers alongside a split range strategy is proposed to control the temperature inside a fermentation vessel by manipulating both the hot water and the cold water flows entering the jacket. Besides, better split range configuration and the number of membership functions of fuzzy controllers and operational issues are investigated. Therefore, this study proposes the application of an unconventional control strategy for temperature control in continuous fermentation process.

2. Methods

Alcoholic fermentation vessels can be modeled as a continuous stirred tank reactor (CSTR), using a convenient modification of Monod equation to describe the microorganism growth kinetics. Nagy (2007) presented a mathematical model of a continuous fermentation process including equations that express the effects of heat and mass transfer on the process (Appendix A). Besides, equations defining the influence of temperature on kinetic parameters and on mass transfer coefficients were also considered. Therefore, Nagy's model suitably describes the behavior of temperature inside