



ANALYSIS AND CONTROL OF A DISTRIBUTED PARAMETER REACTOR FOR PYROLYSIS OF WOOD

ANÁLISIS Y CONTROL DE UN REACTOR DE PARÁMETROS DISTRIBUIDOS EN EL PROCESO DE PIRÓLISIS

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Received May 26, 2014; Accepted May 11, 2015

Abstract

This document introduces a methodology for the design of a Proportional Integral + Sliding Mode Control (PI+SM) and its application to a biomass pyrolysis process. The objective of the proposed controller is to promote the transformation of wood into gaseous products, which have high energy value. First, a distributed parameter model of a pyrolysis reactor (from specialized literature) is analyzed and modified in order to be implemented in Matlab. After that, a based sliding mode controller is developed considering the reactor temperature as the controlled variable and the applied heat as the control input. Different scenarios are considered and the performance of the designed controller is compared with a classical PI controller and the process open loop behavior via numerical simulation. The results show that the proposed control strategy enhances the gaseous components in the process output.

Keywords: pyrolysis, sliding mode control, alternative energy

Resumen

En este documento se presenta una metodología para el diseño de un control Proporcional Integral + control por Modos deslizantes (PI+SM), así como su aplicación en un proceso de pirólisis de biomasa. El objetivo del controlador propuesto es promover la transformación de madera en componentes gaseosos, los cuales cuentan con alto valor energético. En primer lugar se analiza un modelo de parámetros distribuidos planteado en literatura especializada, que corresponde a un reactor de pirólisis; este modelo es modificado e implementado en Matlab. Después, se diseña un controlador basado en modos deslizantes considerando a la temperatura del reactor que se obtiene en cada iteración discreta como la variable controlada y el calor aplicado como entrada de control. Se toman en cuenta diferentes escenarios para evaluar el comportamiento del controlador y para comparar su desempeño via simulación numérica, con la operación en lazo abierto y con un controlador PI clásico. Los resultados muestran que la estrategia propuesta mejora la producción de componentes gaseosos en la salida del proceso.

Palabras clave: pirólisis, control de modos deslizantes, energía alternativa.

1 Introduction

The pollution global warnings and the hypothesis of the fossil fuels end have led the scientific community to search for reliable alternatives. One of them is biomass since it is a renewable source

and it can be transformed in several products with high energy value, see Vicencio-de la Rosa, (2015), Morales-Díaz *et al.* (2010) and Sacramento-Rivero *et al.* (2010). In this paper, biomass is understood as the residue or waste of a living organism which could be used for energy production.

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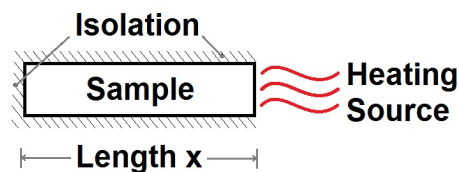


Fig. 1: One-dimension sample reactor.

It implies that biomass is included on the carbon cycle; hence the amount of CO₂ produced from the different transforming processes is balanced with the consumption of this gas by the natural recycling methods. Among those processes, thermo-chemical ones represent interesting options due to its high transformation yields, short reaction time, versatility in relation with raw materials and byproducts, see Morales-Martinez *et al.* (2014) and Evangelista-Flores *et al.* (2014). Pyrolysis is the process of accelerated degradation of a solid fuel (in this case, biomass) via an indirect heating source, in absence of oxidizing agents; these operating conditions allow to condensate or synthesize specific compounds, such as bio-oils and gases with high energy potential, for example methane and hydrogen. The use of these products as fuels is considered clean energy because the byproducts of its combustion are balanced with the carbon cycle. However, pyrolysis is a complex process; it requires specific studies in order to determine the best operating conditions to profit of its advantages. The application of the automatic control theory could help to improve the operation protocols and to enhance the process performances. Besides, a controlled environment on pyrolysis processes allows the minimization of undesired components or pollutant elements for post-processing and recycling methods. In this document, a fixed-bed wall-heated pyrolysis reactor is studied. For this particular case, the degradation of the sample of wood is simplified as one-dimensional consumption process as shown in Figure 1, where the wood sample is exposed to the heat source on only one face, isolating the rest of the sample to the external and neighboring reactions. Once the operational conditions were identified, a control strategy based on PI+SM control was designed for the regulation of the proposed heating path obtained in the dynamical analysis in order to obtain a maximum rate of gas mixture.

2 Background

This work focuses on the pyrolysis of wood wastes. Large amounts of this raw material are produced from different human activities; besides, the specialized literature indicates that wood wastes present a regular structure of its elemental components (50% carbon, 42% oxygen, 6% hydrogen and 2% nitrogen and other elements). The thermal degradation mechanism of materials with vegetable origins has been well identified and documented by many authors. In next lines, some related works are mentioned and briefly analyzed.

Grønli (1995,1996) presents a variety of mathematical models that satisfy the behavior of the pyrolysis process in an experimental environment, and the necessity to analyze the heat dispersion at a particle level.

Basu (2006) explains that pyrolysis is a partial gasification because the process does not reach the temperature of gasification (900 to 1700 K), and a high amount of liquid substance is created. This kind of gasification produces less volatile, generating high amounts of different kinds of solid residues.

Agblevor *et al.* (2010) sets the methodology and strategies for the catalytic reaction of pyrolysis for obtaining selective products, using hybrid poplar wood in a fluidized bed reactor. In his experiments, Agblevor explains that the selective products are the result of a filtered condensation of steam and gases, with this method, the amount of char in the mixture decreases, making the oil residue more stable than the normal gas production of an ordinary pyrolysis process.

Mangut *et al.* (2006) characterizes the thermal properties of the tomato by a thermogravimetric analysis, in order to improve the efficiency of commercial pyrolysis, gasifiers and combustors. The fuel used in the experimentation is tomato waste in a pulper-finisher machine. Once the obtained data was analyzed by a mathematical model based on the thermal decomposition of biomass pyrolysis, the kinetic parameters were optimized via a least-square method.

Xue *et al.* (2011) proposes the use of Euler-Euler multiphase computational fluids dynamic for the fast pyrolysis reaction of biomass in a fixed-bed reactor. The reactant fuel has variable porosity, the author uses this physical property to perceive the dynamical change of the degradation of the fuel as a result of the different temperature exposures during the devolatilization of the sample. The numerical solution

proposed by Xue is based on the equality:

$$\text{Biomass} = \text{Cellulose} + \text{Hemicellulose} + \text{Lignin} \quad (1)$$

The authors also separate kinetic parameters for each species sub-products contained in the wood, generating a matrix composed of the individual kinetic properties of each bio-polymer, obtaining an accurate simulation model.

Tsamba *et al.* (2006) says that the lignin starts the degradation process at low temperatures (433 to 443 K) and ends at 1173 K, meanwhile the cellulose starts decomposition in the rank of 473 to 673 K. The degradation of these two cellular walls marks the beginning of the decomposition of the solid substance. Tsamba also states that at over 673 K, the decomposition rate of the solid substance diminishes. The experimental work consists in the use of cashew and coconut shells and the preparation of the samples by a shredding process to obtain regular particle sizes.

Tingting *et al.* (2011) determines the experimental composition of the gas and tar residues from the pyrolysis process. The gas mixture is composed mainly by CO, CO₂, CH₄ and H₂, while the liquid mixture is composed of ketones, aldehydes, acids, esters, alcohols, alkenes, benzenes, phenols, carbohydrates and other biological residues. The author also states that the carbohydrates and phenols are a direct product of the decomposition of the cellulose, the main source of the phenols is the lignin, and the acids, ketones, aldehydes and phenols are produced by the decomposition of xylose.

Di Blasi (2008) explains that the complicated chain of reactions within pyrolysis process can be simplified by two main stages of the degradation: the primary pyrolysis, at a range of 400 to 500 Celsius, which indicates the beginning of the degradation of the solid substance in its two main components, gaseous phase and liquid residues (tarry mixture); and the secondary pyrolysis, from 500 to 900 Celsius, which starts with the gasification of the liquid substance, mixing with the gaseous phase and increasing the amount of condensate volatile.

Westerhof *et al.* (2010), using pine wood in a fluidized-bed reactor with a feeding rate of 1 kg per hour, states that the production rate of the liquid species increases during the exposure to temperatures between 330 and 450 Celsius, the rate remains constant between the 450 and 530 Celsius and this rate decreases with temperatures above 580 Celsius.

As a thermodynamic process, a system with pyrolysis reaction is controllable. The importance of control in this type of process is mentioned by several

authors, Wu *et al.* (2012) reveals that the pyrolysis process has an elevated amount of uncertainty among the critical facts that enhance the production of the different subspecies, and there is no reliable model to predict these features. Wu proposed the utilization of intelligent control (fuzzy control, neural networks, genetic algorithms and expert systems) for the control of these kinds of reactions.

Likewise, Natarajan *et al.* (2009) proposed the use of tubular fixed-bed reactor for the pyrolysis of rice husk with wall heating from an external furnace controlled by a PID. This control maintains the reactor temperature between 400 and 600 Celsius. The experimental results of this author set that the particle size is proportional to the production of the liquid residue, this behavior responds to the improvement of the hydrocarbon cracking. The author explains that the length increasing of the tube reactor raises the time of residence, and this parameter decreases the final production of liquid mixture.

The variable structure control is a relatively new methodology for the pyrolysis process, Mingzhong *et al.* (2001) remarks that the methodology for the implementation of a sliding mode control in a non-linear process by the setting of limits in the chattering phenomenon that is characteristic in this kind of variable-structure control, improves the results of a controlled chemical reaction. This phenomenon consists on a series of fast direction changes in the control signal approaching the convergence to the sliding plane, and is induced by the fast response of the sliding mode control.

Hanczyc *et al.* (1995) described that the distributed parameters in first-order non-linear partial differential equations can be simplified by a series of ordinary differential equations without the need of a parameter approximation, and apply geometrical methods to use sliding mode control in this process.

According to several works few authors have developed an experimental analysis to obtain products of interest such as Agblevor *et al.* (2010) and Westerhof *et al.* (2010), and few others mention the control necessity to obtain favorable operational conditions that enhance certain kinds of energetic products, such as gas, biodiesel or tar (see for instance Wu *et al.* (2012) and Natarajan *et al.* (2009)).

Therefore, in this work a feedback control for a distributed parameters pyrolysis reactor is proposed. The dynamic model is based on that one proposed by Grønli (1995) and uses a heating source due the wall thermal transference, the energy balance equation was uncoupled to its main parameters to improve

computational costs; this is a common strategy to ease the study of complex processes, some other works has been reported to deal with this situation, see for instance Jimenez Islas *et al.* (2014). Once this solution was tested, a PI+SM control was implemented to regulate different heating paths.

The remainder of this work is organized as follows: In section 3 the model and its numerical solution are introduced, in Section 4 the PI+SM control strategy and numerical results are presented, and finally, in Section 5 some conclusions are discussed.

3 Model and numerical solution

By the analysis of the kinetic and dynamic thermal properties of the solid substance by Grønli (1996), the degradation of the solid sample is represented by four main stages as seen in Figure 2 where the solid sample kinetic transformation is represented by its 3 main components, gas (k_1), liquid (k_2) and char (k_3), which are the result of the primary pyrolysis described by Di Blasi (2008), and as a secondary product, the gasification of the liquid phase (k_4). The kinetic scheme leads to the sub-product transformation dynamics, defined by Grønli and Melaaen (2000) as:

$$\dot{\omega}_s = -\rho_s(k_1 + k_2 + k_3) \quad (2)$$

where $\dot{\omega}_s$ is the solid primary dynamical transformation rate and ρ_s is the initial density of the solid substance. The gas mixture production rate (ω_i) can be separated in its principal contributors, the gas

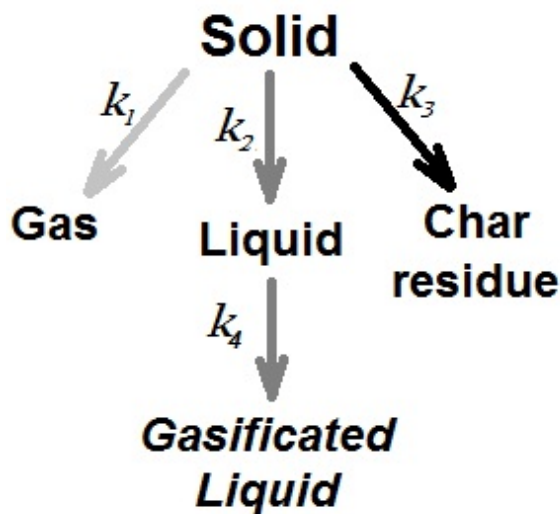


Fig. 2: Kinetic of the phase transformation.

($\dot{\omega}_g$) (3), and the liquid or tarry residues ($\dot{\omega}_T$) (4):

$$\dot{\omega} = \rho_s k_1 + \rho_T^g k_4 \quad (3)$$

$$\dot{\omega}_T = \rho_s k_2 - \rho_T^g k_4 \quad (4)$$

By assuming thermal equilibrium between the solid and gas mixture phases (see Figure 1) and that the changes in energy and mass are more important in the x direction, the energy conservation equation developed in Grønli and Melaaen (2000) is given as:

$$\rho_g^g V_g C_{pg} \frac{\partial T}{\partial x} + (\rho_s C_{ps} + \epsilon_g \rho_g^g C_{pg}) \frac{\partial T}{\partial t} = k_{eff} \frac{\partial^2 T}{\partial x^2} - \sum \dot{\omega}_i \Delta h_i \quad (5)$$

The first term is the convective heat transfer caused by volatile movement, and the second term represents the accumulation of energy; the third term is the conductive heat transfer, which is represented by an effective thermal conductivity; and the last term is the net heat of reaction due the pyrolysis process.

In Figure 1, the heat source is considered in the boundary conditions as follows:

$$F_{flux} - h_T(T_s - T_\infty) - \omega_s \sigma(T_s^4 - T_\infty^4) = -k_{eff} \frac{\partial T}{\partial x} \quad (6)$$

h_T , ω_s , σ are the convective heat transfer coefficient, surface emissivity, and Stefan-Boltzmann constant, respectively. Subscript ∞ denotes ambient and s denotes surface. The pressure at the irradiated surface is assumed to be equal to the atmospheric pressure:

$$(P_g)_s^g = (T_s)_\infty g = P_{atm} \quad (7)$$

The most important assumptions of the mathematical model (1)-(7) are: (a) all the phases are at the same temperature; (b) the transport of bound water is modeled as a diffusion process given by a diffusion coefficient that is function of the local moisture content; (c) binary diffusion in the gas mixture; (d) Darcy's law for the bulk flow of gas mixture and liquid water; (e) a linear variation between the virgin wood and char for the properties related to the solid structure; (f) wood shrinkage and crack formation are not considered.

In equation (6) F_{flux} term represents the radiant heat source, which is considered constant for chosen periods of time in Grønli and Melaaen (2000). In the present work the heat source is considered to be *variable* in order to match a desired temperature in the pyrolysis reactor. Then, the heating source affecting the system is modeled by:

$$Q = H_{wall}(T^* - T) \quad (8)$$

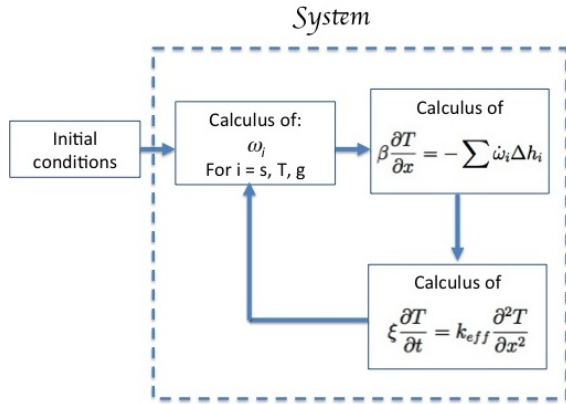


Fig. 3: Integration methodology for the open-loop pyrolysis reactor.

with $Q_{F_{flux}}$ as the variable heat applied through the wall, and is the result of the differences between the controlled temperature (T^*), which represents a virtual control input and is defined in the control section, and the system temperature T , which for the simulation becomes as T_k , i.e., the system temperature in the discrete iteration k , see Figure 3; with a substantial loss through the wall heat transfer coefficient H_{wall} , see Figure 1, this wall in the schematic diagram of the experimental setup in Grønli and Melaaen (2000), corresponds to the fused silica window that is direct in contact with the variable-power xenon arc lamp capable of combustion-level heat fluxes that was used as the source of energy to sustain pyrolysis. With these assumptions the energy balance equation (7) can be simplified as can be seen in the following equations:

$$\beta = \rho_g^s V_g C_{pg} \quad (9)$$

$$\xi = \rho_s C_{ps} + \varepsilon \rho_g^s C_{pg} \quad (10)$$

Therefore, the energy balance equation is defined as follows:

$$\beta \frac{\partial T}{\partial x} + \xi \frac{\partial T}{\partial t} = k_{eff} \frac{\partial^2 T}{\partial x^2} - \sum \dot{\omega}_i \Delta h_i \quad (11)$$

where the first part represents the convection heat transfer caused by the gas flow, the second part is the accumulation of energy in the system via the specific heat of the sub-compounds, the third part is the thermal effective heat conductivity and the final part is the net heat production of the chemical degradation. To compute a numerical solution, the energy balance equation can be uncoupled in its main parameters as shown in equations (12) and (13). The numerical values used in the solution are shown in Tables 1

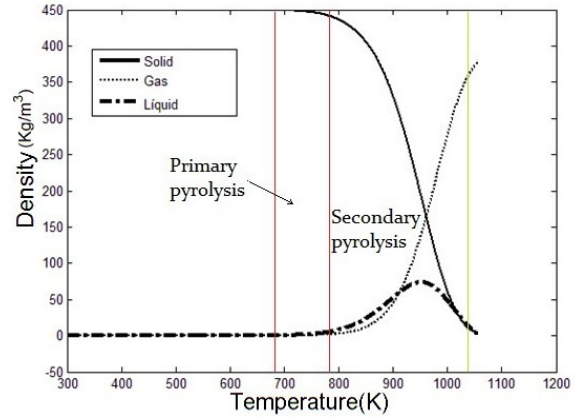


Fig. 4: Pyrolysis dynamic process in open-loop.

and 2, respectively:

$$\beta \frac{\partial T}{\partial x} = \sum \dot{\omega}_i \Delta h_i \quad (12)$$

$$\xi \frac{\partial T}{\partial t} = k_{eff} \frac{\partial^2 T}{\partial x^2} \quad (13)$$

All the reaction dynamics for the three phases (liquid, gas and solid), and the heat produced by the reaction paths related to time with the convective terms are solved by making a discrete integration with a conventional method to solve ordinary differential equations. Meanwhile, for the conductive part, an approximation of the solution is solved by a Taylor second order approximation (see Farlow, 1993):

$$\frac{\partial^2 T}{\partial x^2} = f''(x) \approx \frac{1}{h^2} [f(x+h) - 2f(x) + f(x-h)] \quad (14)$$

Discretization with the integration methodology is depicted in Figure 3. Meanwhile, the behavior of the solid substance degradation without control is shown in Figure 4, which represents a realistic path of degradation in comparison with the experimental results obtained by Grønli et al. (2000), and fits the results reported by Di Blasi (2008) regarding the pyrolysis phases that this author found.

In a previous work Vazquez-Sandoval et al. (2012), the authors provided several trajectories that were tested using various types of conventional controls. From this analysis, two main trajectories with the higher amount of gaseous substance obtained by simulation were chosen. These trajectories were a ramp with two slopes and an exponential curve. To apply the regulation of these heating paths, the starting point of the system was 300K, while the wall temperature of the heating source was 600K. The wall temperature responds to a pre-heating process

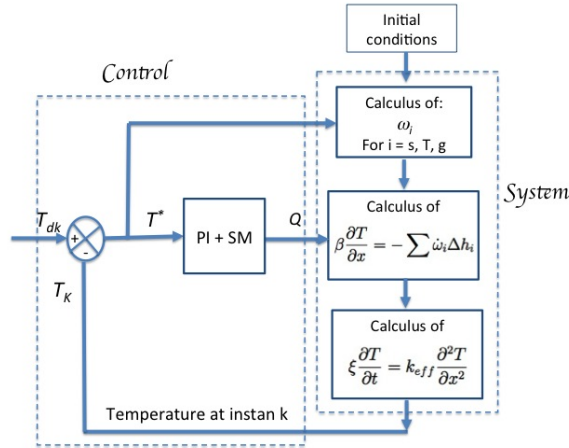


Fig. 5: Scheme of process plus PI+SM controller.

on the walls of the reactor on a temperature near the primary pyrolysis starting point. The path equations are defined by (15) for the ramp and (16) for the exponential path:

$$T_{dk+1} = T_{dk} + x \quad (15)$$

$$T_{dk+1} = T_{dk} + ae^x \quad (16)$$

where $\alpha \rightarrow 0$ and x represents the temperature incremental rate.

4 PI+ Sliding mode

With the sub-product analysis and the degradation response to the temperature presented in Vazquez-Sandoval (2012), the best options in the heating path analysis were selected for the control analysis. For the temperature control a PI+SM control strategy was used to regulate the system along the heating trajectory. Commonly for fast systems the PI+SM presented in this document has been applied for the temperature fast regulation, with a fast profile of controlled temperature responding to certain desired sequences of temperature rates. This kind of control was chosen because it guarantees the convergence of the system in finite time; this behavior minimizes the difference between the desired temperature and the system temperature from the beginning of the simulation, improving gas production. This control operates at the beginning of each iteration in the system as shown in Figure 5. This method increases the effectiveness of the solid transformation in gaseous sub-products against conventional control techniques Vazquez-Sandoval *et al.* (2012).

The PI+SM controller is defined by equations (17)-(19):

$$T^* = PI + SM \quad (17)$$

$$PI = K_p(T - T_d) + K_i \int (T - T_d) \quad (18)$$

$$SM = \lambda \left(\text{sat} \left(\frac{S}{\varepsilon} \right) \right) + T$$

where $\varepsilon \rightarrow 0$ (19)

T^* represents the controlled temperature of the heating source and is the feedback amount of temperature added to (8), T is the system temperature, and it is considered in the discrete iteration k , i.e., T_k ; T_d is the corresponding temperature of the heating path in the instant k , K_p and K_i are the proportional and integral gains respectively, meanwhile the sliding surface gain is defined by λ . The control gains are given by:

$$K_p = -1.7$$

$$K_i = \frac{K_p}{7} \quad (20)$$

$$\lambda = -0.3$$

It is considered that the settling time for the temperature is approximately 3 min for the higher conversion temperature, i.e. 900 C, accordingly to Grønli and Melaaen (2000). With this in mind the proportional gain (K_p) is chosen approximately the half of this time (1.7), meanwhile, the integral gain (K_i) is selected near to the relation $K_p \geq 10K_i$ that is recommended for process with first order dynamic response, which is the case of the temperature process (see Åström and Hägglund, 1994). Finally, the gain λ for the SM is settled on top of the integral gain K_i to avoid instabilities.

To prevent the inherent chattering from the SM approaching to the sliding surface, a saturation function of the sliding surface S is proposed. Simplified by $\varphi = S/\varepsilon$, $\varepsilon = 0.1$ was fixed on, the solution of the system involves a conditional saturation function (see Khalil, 2002) with an hyperbolic tangent for $|\varphi| > 1$ in order to obtain the approaching softer and provide in S a continuous system defined by (21):

$$\text{sat}(\varphi) = \begin{cases} \varphi & |\varphi| \leq 1 \\ \tanh(\varphi) & |\varphi| > 1 \end{cases} \quad (21)$$

$$S = Y + \dot{Y} = 0 \quad (22)$$

In (22) $Y = T - T_d$, represents the regulation error and \dot{T} is the approximation of the error derivative; and is obtained using a backward difference approximation

(Farlow, 1993):

$$\dot{Y} \approx \left(\frac{T_k - T_{k-1}}{\Delta_k} \right) \quad (23)$$

Δ_k is the discrete interval, T_k and T_{k-1} are the current and the former temperatures.

By deriving the sliding surface function (22) the following equality is obtained:

$$\dot{Y} = -\dot{Y} \quad (24)$$

For the nature of the sliding surface, as can be seen in (22), the error Y and its derivative \dot{T} tend to 0, while the derivative of the sliding surface \dot{S} satisfies the equality shown in (24), therefore this kind of system can be referred as asymptotically stable.

Figure 6 shows the reactor temperature result of the exposure to the heating ramp in closed loop with the proposed control $PI + SM$ (17) and under the PI control; meanwhile, the pyrolysis products curve under the same ramp trajectory for $PI + SM$ and PI controllers is depicted in Figure 7.

The fast response of the control exposes the solid sample to higher temperatures than the uncontrolled system; this phenomenon is produced because of the overshoot in the system response. This exposure leads to higher production rates for gaseous substance. Figure 8 shows the control action T^* along the time of exposure to the ramp trajectory heating path.

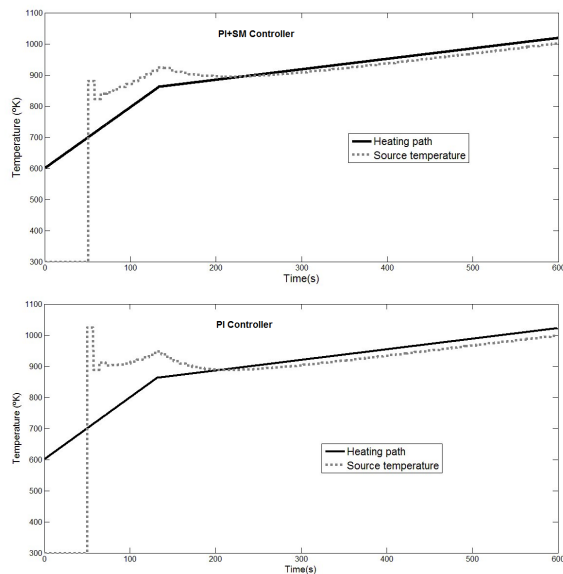


Fig. 6: Control actions ($PI+SM$ and PI) considering a temperature ramp trajectory.

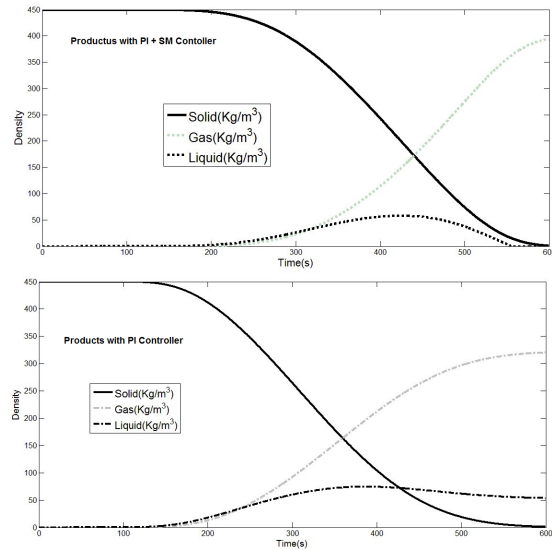


Fig. 7: Products from pyrolysis with $PI+SM$ and PI Controllers under ramp a temperature ramp trajectory.

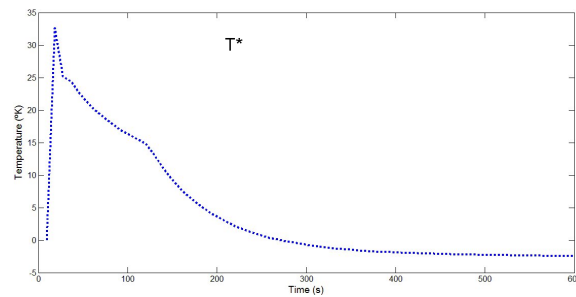


Fig. 8: Temperature control input T^* added to the heating source along the time of exposure.

Comparing the $PI + SM$ and PI under ramp trajectory, Figures 6, the error in the final stage of regulation diminishes with the SM action in the system, which means higher temperatures along the time of exposure, and therefore, a higher amount of gas conversion. The result for both control actions are shown in Table 3 also can be observed further in Figure 9.

Figure 10 shows the pyrolysis products for the $PI + SM$ controller when the system exposure to the exponential and the ramp paths. The exponential trajectory causes less profitable generation of gaseous substance, and the remaining primary solid substance approximates to zero. Figure 11 shows the gradient of temperature added by the control action (T^*) along the time of regulation. Figures 12 and 13 show the exponential heating path, under the control action of a PI controller without the SM action.

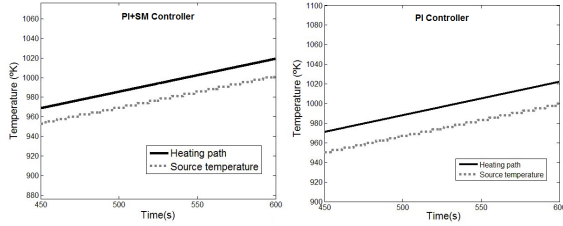


Fig. 9: Zoom for control actions ramp trajectory.

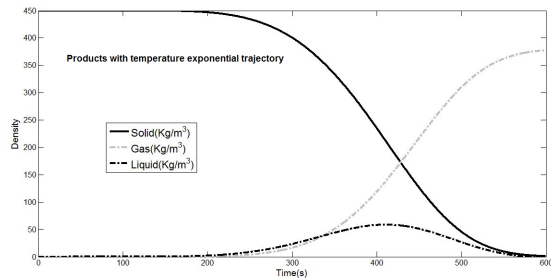
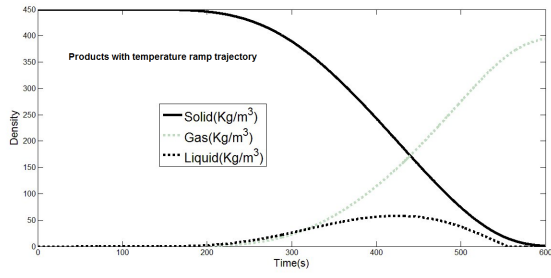


Fig. 10: Pyrolysis products with PI + SM controller under exponential and ramp path.

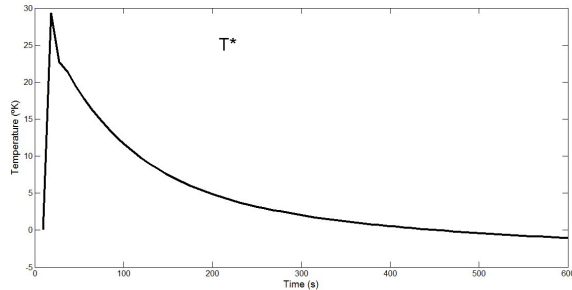


Fig. 11: Control input T^* for the exponential path.

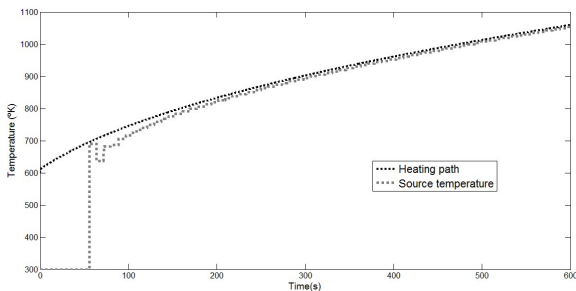


Fig. 12: Reactor temperature (T) with exponential path under PI control action.

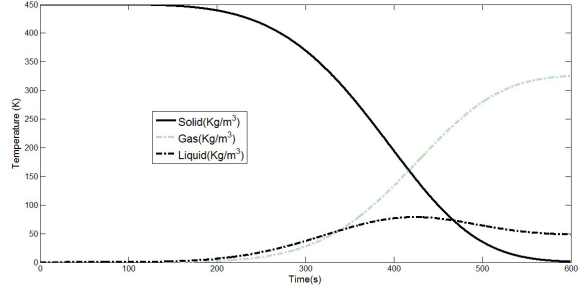


Fig. 13: Pyrolysis products with PI control action under exposure to the exponential trajectory.

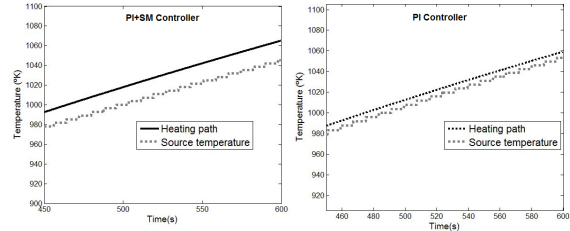


Fig. 14: Zoom in reactor temperature for PI + SM and PI controllers.

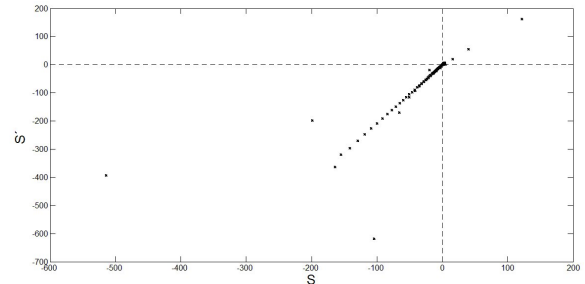


Fig. 15: Behavior of S against dS/dt .

In these figures, the system shows no overshooting at the first iterations and also shows a slow convergence to the desired temperature, reducing the time of exposure of the liquid phase to the heating source, resulting in a low gas count that can be seen in Table 3 and a closer view is shown in Figure 14.

In Figure 15, the graphic shows the plot of S versus \dot{S} , showing the behavior of the control signal approaching to the convergence point at 0. Each X marks the signal S at the end of each iteration of the system. The first points at the left are the chattering phenomena at the beginning of the simulation approaching the sliding plane, ending in the point cloud that converges to 0.

The results displayed in Table 3 are a sample of the importance in the temperature control regulation of the predicted trajectory along the residence time of the solid sample. As Di Blasi (2000) explains, the sequence of the two stages of pyrolysis is necessary

for the development of the process. In this work, the trajectory described by the heating path allows the control to guide the system through a pre-calculated time of exposure to the heating source, allowing the final percentage of gas mixture to increase. This methodology is the basis for the proposal to design a prototype reactor that will set the full-scale methodology of selective production of high energetic sub-compounds.

Conclusions

In the pyrolysis process, temperature is a crucial factor in the final percentage of inert solid substance. With this premise, the control shown in this work based its operation on the variation of the heating source. This allows the modification of the maximum temperature of the system. High temperatures (above 775 Kelvin) are necessary to promote a full transformation of the solid substance.

According to literature, the temperature of the system is a primordial factor in the transformation of the solid substance in its main phases (Grønli et al., 2000, Di Blasi, 2008). The control action presented in this document based its effectiveness on two main parameters: high temperature rising to promote the liquid phase creation during the primary pyrolysis, and high time of exposure at slow increasing temperature to promote the gasification of the liquid at the secondary pyrolysis stage, both in order to improve the amount of final gas substance.

The control based on $PI + SM$ shown to be effective to obtain high gas production rates because the closed-loop pyrolysis process has a fast response to the temperature changes in the prescribed trajectory. The next step is the experimental analysis of the crucial conditions to promote the conversion of the solid substance in selective sub-products such as hydrogen and methane, both highly energetic gases with direct applications as fuel for combustion motors.

As a future work, once the experimental parameters have been settled, some optimization work needs to be done in the field of trajectory planning of the heating process, such that this methodology can maximize the results with an operational prototype of a controlled pyrolysis reactor. Also, for this solution has to be considered and included both the efficiency factor for the heat added in the reactor (Q), and the efficiency of the chemical reactions. This would give a more accurate parameter of how the gas production evolves and to take into consideration variation in the

residence time.

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