CHEMICAL ENGINEERING TRANSACTIONS Volume 21, 2010
Editor J. J. Klemeš, H. L. Lam, P. S. Varbanov
ISBN 978-88-95608-05-1 ISSN 1974-9791
DOI: 10.3303/CET1021161

Dynamic Optimization of Porous Media Combustor through Flame Positioning

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In this work we study the dynamic optimization of the burner power by positioning of the combustion front in a uniform porous media combustor by using a model predictive control (MPC) scheme. In this approach the combustion front, and indirectly the power burner, can be fixed to a desired value by changing the velocity of the combustion wave by the manipulation of the operational variables: filtration velocity and composition of the gas mixture. The study was carried out by means of simulations considering an experimental filtration combustion (FC) burner (CH4/air mixtures) manipulating the gas filtration velocity and fuel equivalence ratio. Controlled variable was the flame position along the burner and the power firing rate. The MPC control strategy was a receding horizon control scheme. A second order (under damped) model was used to describe the combustion wave dynamics. Several test for set point tracking scheme, and periodically reversible operation were conducted. Results showed excellent stability, fast response and zero offset.

1. Introduction

Filtration combustion (FC) is generated when an incoming fuel/oxidizer mixture flows and reacts in the interstitial space of a porous matrix. Due to its better thermal properties, the porous material allows efficient redistribution of the energy released in the gas-phase chemical reaction (Barra and Ellzey, 2004).

The simplest reactor where the FC can develop is a tube filled with a uniform inert porous material through which a fuel/oxidizer mixture is flowing. In terms of operations, this reactor presents an operation time determined by the combustion wave speed and the distance left for travel towards the reactor's outlet for which the combustion wave is headed. Due to the unsteady nature of the FC phenomenon confinement methods for the combustion wave such as, the reciprocal flow burner (Kennedy et al., 2003) and stabilization in two sections of porous materials with different properties or based on modified Peclet number (Smucker and Ellzey, 2004), have been developed. The ability to position the combustion front at any point of the burner can be seen as a way to optimize the combustion process by means of an increase in the life-cycle of the burner, the planning of the combustion profiles in the burner and a better control of the combustion process oriented to reduce the pollutants

Please cite this article as: Henriquez L., Bubnovich V. and Cubillos F., (2010), Dynamic optimization of porous media combustor through flame positioning, Chemical Engineering Transactions, 21, 961-966 DOI: 10.3303/CET1021161

formation. In this work we propose a method for control the position of the combustion front and the combustor power based on advanced control algorithms, specifically Model Predictive Control (MPC).

2. Model and simulation

1.1 2.1. Experimental burner

The system to be controlled is a porous media burner represented in figure 1. It consists of a 50 cm long quartz cylinder with inner diameter of d_t = 3.8 cm and wall thickness of 4 mm. To minimize heat losses both the inner and outer surface of the cylinder were covered with a 2 mm and 30 mm thick high temperature insulation material. A reduction of approximate 65 % in heat losses, with respect to a bear quartz tube, is acquired in this manner. The porous media consists of randomly arranged alumina spheres with diameter d_m = 5.6 mm, resulting in a volumetric porosity m = 0.4. The CH4/air gas mixture enters at the bottom of the burner at interstitial velocity u_g and temperature T_0 = 300 K. The composition of the mixture is characterized by the equivalence ratio Φ.

1.2 2.2. First Principles Model

The physical system will be represented by a first principles model. The one dimensional set of equations describing the combustion waves in inert porous media with one step kinetics has the form (Bubnovich et al., 2007):

$$\frac{\partial\left(\rho_g \cdot u_g\right)}{\partial z} = 0 \tag{1}$$

$$\rho_g \frac{\partial w}{\partial t} + \rho_g \cdot u_g \frac{\partial w}{\partial z} = \frac{\partial}{\partial z} \rho_g \cdot \left(D_m + D_d\right) \frac{\partial w}{\partial z} + W \tag{2}$$

$$W = -K_0 \cdot w \cdot \rho_g \exp\left(-E / R \cdot T_g\right) \tag{3}$$

$$\rho_g \cdot c_g \frac{\partial T_g}{\partial t} + c_g \cdot \rho_g \cdot u_g \frac{\partial T_g}{\partial z} - \frac{\partial}{\partial z}\left(\lambda_g + D_d \cdot \rho_g \cdot c_g\right) \frac{\partial T_g}{\partial z} = \frac{\alpha_{vol}}{m}(T_s - T_g) - W \cdot Q \tag{4}$$

$$(1-m)\rho_s \cdot c_s \frac{\partial T_s}{\partial t} - \frac{\partial}{\partial z}\left(\lambda_{eff} \frac{\partial T_s}{\partial z}\right) = \alpha_{vol}(T_g - T_s) - \beta(T_s - T_{ext}) \tag{5}$$

Equations (2), (4), (5) have boundary and initial conditions:

$$\left.\frac{\partial w}{\partial z}\right|_{z=0,L} = \left.\frac{\partial T_g}{\partial z}\right|_{z=0,L} = \left.\frac{\partial T_s}{\partial z}\right|_{z=0,L} = 0$$
$$w = w_0 \;;\; T_g = T_s = T_0 \;;\; t = 0 \tag{6}$$

The governing equations are finite-differenced, treating the convective terms with up-winded scheme and the diffusive terms are discretized using a second-order technique. The solution of the system is performed via the Thomas algorithm.

1.3 2.3. Open loop results

Figure 2 presents simulation of the temperature burner profiles with time in open loop operation, i.e., without a feedback control action. The combustion front position z_w, is defined in this work as the position of the solid temperature peak.

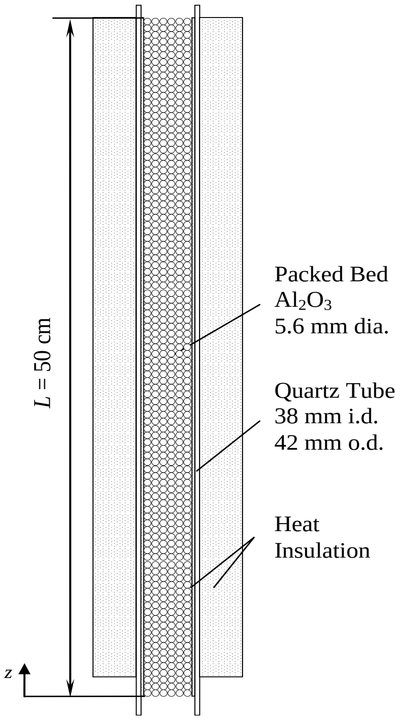


Figure 1: Experimental Setup

3. Control Problem

Due to the combustion front mobility, the porous media combustor has a limited operation time, given by the combustion wave speed and the distance left to travel towards the reactor outlet. The flame position inside the reactor is determined by the combustion wave velocity which can be changed through operational variables manipulation. The control strategy to be implemented will be a receding horizon control scheme, see Alamir and Bornard (1994). The objective function formulated penalizes the deviations of the controlled variable from a reference trajectory xd(□), and the control effort:

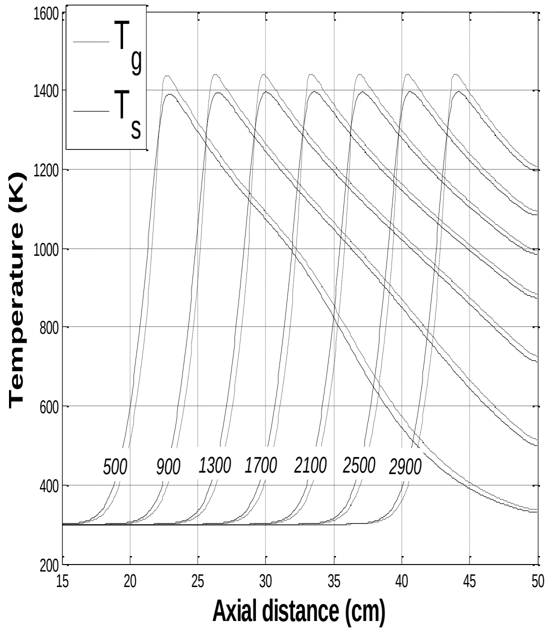


Figure 2: Combustion fronts, numbers indicate seconds past from ignition

Min V

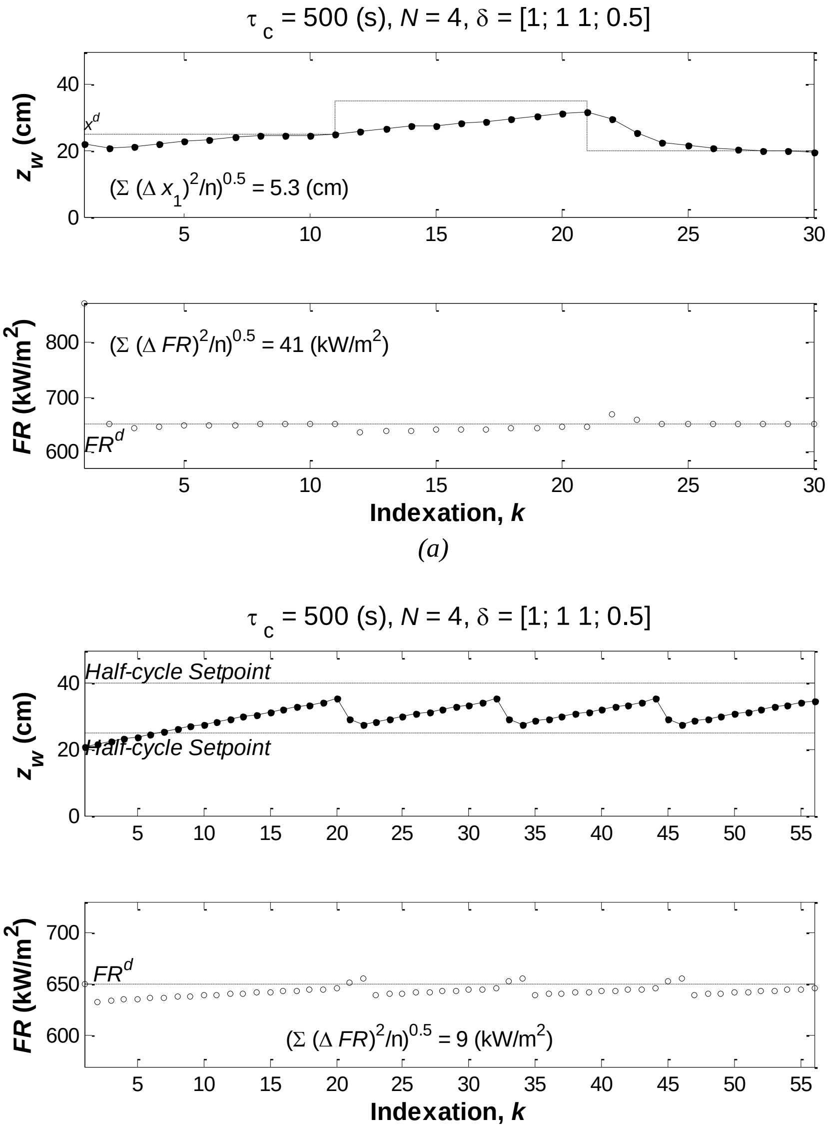
$$V\left(x\left(k\right),\mathbf{u}\right)=\sum_{i=1}^{N}\left[\delta_x(i)\cdot\left\|x_1^{\mathbf{u}}\left(k+i-1;x\left(k\right)\right)-x^{\mathbf{d}}\left(k+i-1\right)\right\|^2+\delta_u(i)\cdot\left\|\Delta u\left(k+i\right)\right\|^2\right]$$

$$\begin{aligned} x_{\min} &\le x_1^{\mathbf{u}} \le x_{\max} \\ u_{\min} &\le u \le u_{\max} \\ \Delta u_{\min} &\le \Delta u \le \Delta u_{\max} \end{aligned} \tag{7}$$

$$x=\left[x_1\ x_2\ x_3\ x_4\right]^T=\left[z_m\ u_w\ u_g\ \Phi\right]^T,\ u=\left[u_1\ u_2\right]^T=\left[u_g\ \Phi\right]^T$$

The constrained optimization problem was solved with the sequential quadratic programming algorithm implementation presented in the *Matlab Optimization Toolbox*. All results generated were computed from the initial state:

$$x_0=\left[0.22\ \text{-}3.125\cdot10^{-5}\ 0.8\ 0.8\right]^T$$



(a)

(b)

Figure 3: Closed loop results. (a) Front position tracking, (b) Cyclic operation.

Figure 3a shows tracking of an imposed set point profile for front position at time steps increments of $10\cdot\tau_c$. Constant power firing must be constant at 650 (kW/m^2). Another alternative for the confinement of the combustion front, apart from the set point tracking scheme, is accomplished by periodically reversing the set points values when the combustion front reaches a tolerance distance from them. Figure 3b illustrates this idea with the set points values: x^d = 15 and 40 cm, and a tolerance of 5 cm imposed for alternating the set points.

The power firing rate must be constant at 650 (kW/m^2). The combustion front evolution is then periodically reversed and consequently maintaining both, the sub and super adiabatic effect, along up and down stream directions respectively. In both operation ways the MPC approach is able to maintain constant the power requirements.

4. Conclusions

A method for positioning the combustion wave at constant power in a FC burner by changing the inlet mixture conditions was successfully developed. A MPC algorithm with a second order (underdamped) inner model was used for the implementation. Simulation results have proven a simple way for obtaining a porous media burner that can operate as long as the user determines.

The algorithm was able to positioning the combustion front at the desired values as well as operation in cyclic mode. The use of the presented approach allows the user to decide the combustion region position in the reactor, giving flexibility for applications for instance, in energy conversion and fuel reforming.

Also, may it be seemed as a way to optimize the combustion process by means of an increase in the life-cycle of the burner, the planning of the combustion profiles in the burner and a better control of the combustion process oriented to reduce the pollutants formation.

Acknowledgements

The support of CONICYT Grants Fondecyt 1090062 and 1090550 is greatly acknowledged.

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