Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Numerical simulation of the hybrid filtration combustion of biomass

*Mario Toledo**, *Carlos Rosales*, *Claudio Silvestre*, *Sebastián Caro*

Department of Mechanical Engineering, Universidad Técnica Federico Santa María, Av. España 1680, Valparaiso, Chile

ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form
11 August 2016
Accepted 17 September 2016
Available online xxx

Keywords:
Filtration combustion
Biomass
Hydrogen
Syngas

ABSTRACT

Hybrid filtration combustion waves in a porous media were numerically analyzed for biomass and methane-air mixtures. Temperature and products of the combustion waves were studied in the range of equivalence ratio from 0.2 to 1.1. A model, based on a two-temperature approximation and combustion chemistry is developed to analyze temperature profiles and species of the phenomena. The numerical solutions predictions for temperatures and chemical products are in good agreement with experimental data for some biomasses contrasted. It was found that with ultra-lean methane mixtures, the combustion temperature presents essentially higher values than stoichiometric mixtures. Experimental validation suggests that the chemistry of the process is very sensitive to CO formation. For low values of the biomass fraction in the porous medium, it is found that homogenous reactions are dominant whereas for high values (over 40%) the heterogeneous reactions are more influent. Thus, for ultra-lean methane-air mixtures, hydrogen production is enhanced when the biomass fraction in the medium is increased.

Introduction

Strict environmental standards and the extensive use of fossil fuels as primary energy sources have imposed stringent requirements over combustion technologies. This scenario challenges technology developers and scientists to seek the promotion and improvement of techniques that efficiently use the available resources and, moreover, the use of renewable energy sources. In this context, biomass has gained attention, providing an alternative to conventional fossil fuels, reducing petroleum dependence while decreasing the net CO_2 emissions coming from carbon based fuels. Under these circumstances, hybrid filtration combustion is a technology that offers interesting advantages and an efficient energy conversion from solid fuels of this nature [1,2].

During the last years, hybrid porous media reactors have been developed aiming to partially oxidize fossil fuels to produce reducing gases. The gases produced are mainly composed by hydrogen and carbon monoxide, among other products of gasification. This gaseous mixture is produced from carbon rich reactants exposed to the high temperatures of filtration combustion. Hybrid filtration combustion combines porous media combustion processes and gasification of solid fuels by replacing a fraction of the inert solid volume with a solid fuel. Porous media combustion is a well-known technology that has been extensively studied during recent years [3–10]. It is defined as a combustion wave that travels through a medium composed by an inert solid and the interstitial spaces (porosity) that percolate through the solid occupied space. In the case of hybrid filtration combustion, a combustion wave is produced by a flow that can contain hot

* *Corresponding author.*
E-mail address: mario.toledo@usm.cl (M. Toledo).

http://dx.doi.org/10.1016/j.ijhydene.2016.09.120
0360-3199/

Nomenclature

$\vec{u}$	Filtration velocity
θ	Porosity
y_j	Mole fraction of specie j
ρ_g	Molar density of the gas phase
$\vec{w}_j$	Diffusion velocity
D_j	Diffusion coefficient of specie j
λ_g	Thermal conductivity of the gas phase
d	Characteristic size of the solid particle
L	Length of the reactor/domain
η_j''	Stoichiometric coefficient of product j
η_j'	Stoichiometric coefficient of reactant j
λ_s	Thermal conductivity of the solid phase
r_f	Forward reaction rate
$r_\gamma^{(H)}$	Reaction rate of the homogeneous reactions
r_b	Backwards reaction rate
W_j	Molecular weight of specie j
W_S	Molecular weight of the solid
C_i	Heat capacity of the inert solid
ϕ	Equivalence ratio
h_g	Enthalpy of the gas
$\vec{v}$	Velocity of the combustion wave
T_g	Temperature of the gas phase
T_s	Temperature of the solid phase
Cp_j	Specific heat of specie j
ε	Heat fraction retained in the solid particle
h_{fj}°	Enthalpy of formation of specie j
h_{fS}°	Enthalpy of formation of the solid
ξ	Heat transfer coefficient
ν_g	Kinetic viscosity of the gaseous phase
C_f	Heat capacity of the fuel
LHV_j	Lower heating value of specie j
S_j	Summation of source terms
$Q_{R\gamma}$	Standard heat of reaction
t	Simulation time

Sub-index

g	Gas
s	Solid
f	Solid fuel
i	Inert solid

air, water-steam and/or a gaseous fuel-air mixture. This wave propagates reforming the solid fuel contained in the porous medium within a wide range of thermal power with high efficiency, high energy concentration per unit of volume [11] and stable combustion over a wide range of equivalence ratios [12]. Experimental hybrid filtration combustion has been studied for syngas production using several fuels, clearly showing that this technology represents a strong and feasible alternative for syngas production from solid and gaseous fuels, also glimpsing new opportunities for the development of new reactors [13]. Reports using carbon [14,15], coal [2,12], wood [1,16], eucalyptus nitens, pinus radiata, oat and wheat cane [17], avocado seeds [18], polyethylene [19] and algae [20], among other materials, are available. An interesting application of the technology has been developed by the Institute of Problems of Chemical Physics of the Russian Academy of Sciences, using the superadiabatic regime of filtration combustion to process combustible waste in two stages. The first stage considers a hybrid filtration combustion reactor where a steam-air flow is filtered through the waste and porous material, gasifying the solid fuel, and a second stage burns the produced gases in a steam generator; reporting efficiencies of the gasification process of up to 95% and the capacity to process materials with ash content of up to 90% and up to 60% of humidity [21].

On the other hand, some works presenting mathematical models based on mass and energy equilibrium have been presented by Salgansky et al. [14,15,22,23], Glazov and Polianczyk [24] and Toledo and Rosales [25]. More in detail, Salgansky et al. [14], presented a study of superadiabatic regimes, theoretically describing a steam-air wave filtered through a porous medium composed by carbon and an inert solid, with good agreement with experimental results. The numerical model considered was one-dimensional and unsteady, having two temperatures in an adiabatic reactor. Using the same model, Kislov et al. [15] presented a numerical -and experimental-study of the gasification of a coal with air and CO_2, comparing the results with coal gasified by steam and air in a porous medium finding that an equal volumetric replacement of steam by CO_2 in the gas flow produced a significant decrease of the temperature of combustion and that the calorific values of the gaseous products were similar in both cases. Salgansky et al. [26] modeled the filtration combustion of a pyrolyzing solid fuel in a porous medium at a steady-state through a theoretical analysis and numerical techniques, using a chemical scheme that included the formation of a coke residual and oxidation reactions; results showed that at a low content of porous material, pyrolysis occurs in a zone distant from the combustion zone, generating a pyrolysis front that moves as the combustion wave propagates in the domain. Amelin et al. [23] studied the dependence of temperature and rate of filtration combustion of carbon on the main operational parameters of the process through a model, being able to reveal the critical conditions to produce a stationary regime, finding that in such systems, the combustion wave velocity is determined by the rate of oxidant supply. Glazov and Polianczyk [24] present a model for the steady-state filtration of endothermic oxidizers through a carbon and inert solid mixture. The gaseous phase contained steam and/or carbon dioxide. Predictions of the simulations showed qualitative agreement with experimental data. Rabinovich et al. [27] presented the numerical results of the modeling of the combustion wave stability of the filtration combustion wave of a solid fuel, finding that the propagation of a plane combustion wave is unstable under certain conditions, presenting an inclination that is found to be related to the dimensionless gas flow rate and width of the reactor, determining these conditions.

Toledo and Rosales [25] presented a theoretical model for hybrid filtration combustion of a solid fuel which has not been tested. Therefore, such model is applied in this work for the analysis of hybrid filtration combustion of biomass. In this way, the study provides additional characterization of this new tool as well as it contributes to the description and understanding of the phenomena. This can lead to further developments and optimization of technologies that use this combustion technique.

Please cite this article in press as: Toledo M, et al., Numerical simulation of the hybrid filtration combustion of biomass, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.09.120