Hydrogen and Syngas production by Hybrid Filtration Combustion: Progress and Challenges

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Introduction

Climate change, as a result of excessive consumption of fossil fuels, as well as other greenhouse gases sources, has put a herculean task in the shoulders of the global scientific community. Continuously rising global temperature levels, and the Paris Agreement to keep it below 2°C, limits directly the use of fossil fuels stressing out the necessity of finding alternative energy sources, capable of being both sustainable and techno-economically feasible. In this context, hydrogen (H_2) and syngas (a mixture of H_2 and carbon monoxide, CO) production technologies development has gained traction in the efforts towards more efficient and responsible use of solid carbonaceous feedstocks, with a special focus on renewable and carbon neutral alternatives. As a matter of fact, H_2 is the simplest element on earth, and it has the highest energy content per unit mass (141.9 MJ/kg). As an excellent alternative to fossil fuels, H_2 is considered the fuel for the future. Due to the ever-growing demand for energy-efficient and eco-friendly alternatives and the uncertainty on the availability of fossil fuel as the primary feedstock for H_2 production, the need for novel and carbon-neutral H_2 production methods is quite obvious.

Hydrogen and syngas (mixture of H_2 and carbon monoxide) can be thermochemically produced from various sources such as fossil fuels, biomass, water, and solid wastes, via steam reforming, dry reforming, and partial oxidation. Porous medium combustion (PMC), a variant of conventional filtration combustion (FC), is well-known as a viable approach for producing H_2 and syngas by partial thermal oxidation of mainly gaseous and liquid fuels. However, with modifications to PMC, hybrid filtration combustion (HFC) has been introduced for producing H_2/syngas by gasification of solid fuels or by simultaneous reforming of gaseous and solid fuels. The various solid feedstocks studied include coal, biomass, polyethylene, among others, and the gasifying agents used are air, steam, carbon dioxide, and premixed air/fuel flows. The heat recirculation inside the HFC reactor enables the presence of high temperatures in the reaction wave, thus sustaining simultaneous homogeneous and heterogeneous reactions. This article presents a comprehensive review of H_2 and syngas production using HFC by covering fundamentals of gasification, FC, PMC, and HFC; HFC modeling; development of HFC reactors; industrial applications; and future directions. The prospects and challenges to replace fossil fuel sources by renewable sources such as solar energy and biomass are also highlighted. The present research has revealed the promising potential of this technology as an energy-efficient and sustainable alternative to produce H_2 and syngas from a variety of solid and gaseous feedstocks.

Methodology

Mathematical Modeling

A crucial component of the proposed research is the computational simulations of the gasification of several renewable carbonaceous feedstocks inside a rotary porous media reactor, that will be performed considering that this phenomenon is a multiphase, multiscale, and multiphysics challenge, thus requires a proper analysis on the problem to ensure that its most relevant characteristics are well recognized, such as the complex chemical kinetics (homogeneous, devolatilization, and heterogeneous reactions), enhancement of the heat transfer mechanisms (thermal radiation, heat convection and conduction), the thermal, structural and hydrodynamic properties, and the coupling of simultaneous reactions involving different phases. Governing equations are:

Conservation of mass for gaseous species equation of the *j-th* component of the gas:

$$\frac{\partial \theta \rho_g Y_j}{\partial t} = \nabla \cdot \left(\theta \rho_g D_j \nabla Y_j\right) - \nabla \cdot \left(\rho_g Y_j \vec{u}\right) + S_j$$

Conservation of mass for solid fuel species equation:

$$\frac{\partial [\rho_f (1-\theta)]}{\partial t} + \nabla \cdot [\rho_f (1-\theta)] \vec{v} = -B_f$$

Conservation of energy for the gas phase equation:

$$\frac{\partial \theta \rho_g C_{p_g} T_g}{\partial t} + \nabla \cdot \left(\rho_g C_{p_g} T_g \vec{u}\right) = \nabla \cdot \left(\theta \lambda_g \nabla T_g\right) + \nabla \cdot \left(\theta \rho_g \sum_{j=1}^{N_{SP}} C_{p_j} T_g D_j \nabla Y_j\right) + H_V$$

Conservation of energy for the solid equation:

$$\frac{\partial [(\rho_f C_f + \rho_i C_i)(1-\theta) T_s]}{\partial t} + \nabla \cdot [(\rho_f C_f + \rho_i C_i)(1-\theta) \vec{v} T_s] = \nabla \cdot [(1-\theta) \lambda_s \nabla T_s] - \frac{\varepsilon}{W_s} \sum_{\gamma=1}^{N_{HE}} r_\gamma^H Q_{R\gamma} - \xi F (T_s - T_g)$$

This research aims to improve the heat transfer within the particle bed of an allothermal gasifier exposed to concentrated solar energy (See Figure 1). These challenges will be addressed through mixing chemically inert bur thermally active solid particles with the carbonaceous feedstock, in addition to incorporate rotation to the process. This will enhance the effective thermal conductivity of the packed bed, ensure an homogeneous supply of reactants to the reaction zone, and effectively storage solar energy as part of the chemical energy from the produced syngas.

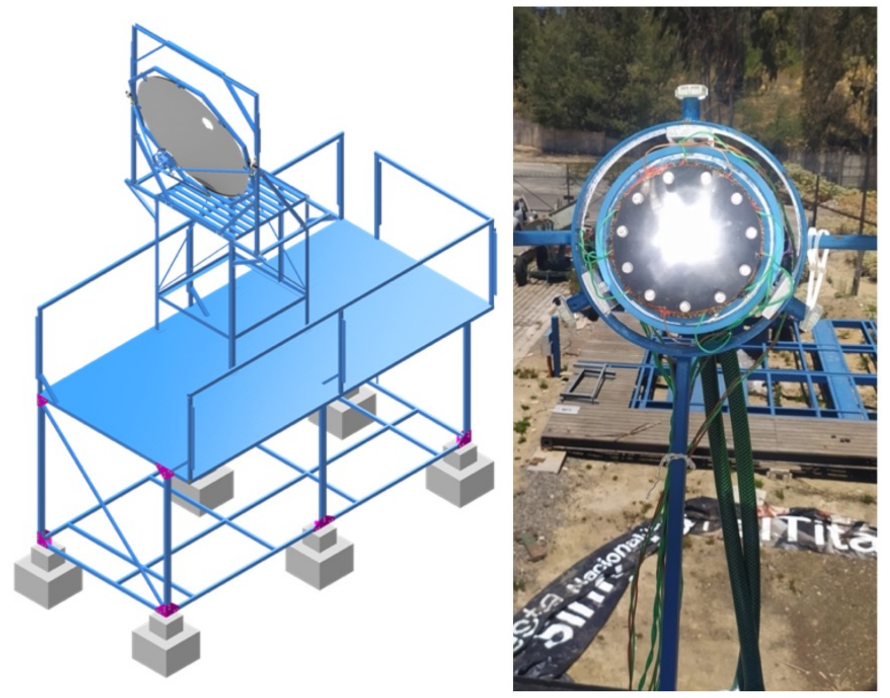
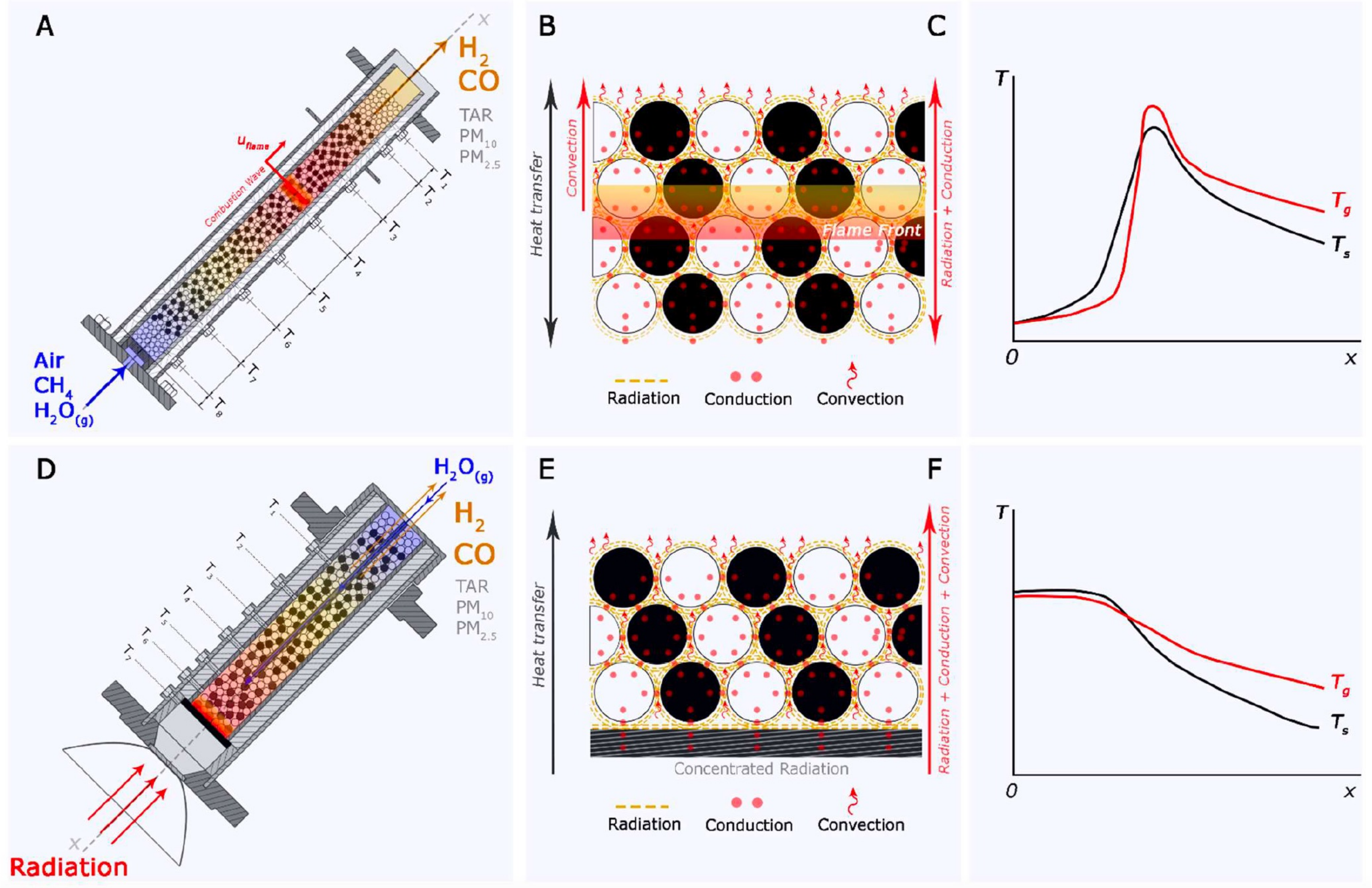


Fig. 1. Concentrated solar energy (CSE) structure for allothermal experiments.

Results



Full description of a process for improving the difficulties and disadvantages of autothermal gasification (mainly tars) and synthesis gas production from solid fuels, preventing the formation of highly polluting VOC's via solar steam gasification.

Temperature profile for both solid and gaseous phases, but also identify/quantify the dominance of a heat transfer mechanism in both HFC and Solar gasification processes (See Figure 2).

Fig. 2. Autothermal hybrid porous media reactor basic schematic (A). Heat transfer mechanism in the reaction zone (B). Typical temperature profile inside the reactor of the solid (Ts) and gaseous phase (Tg) (C). Allothermal hybrid porous media reactor basic schematic (D). Heat transfer mechanism between the emitter plate and the reaction zone (E). Typical temperature profile inside the reactor of the solid (Ts) and gaseous phase (Tg) (F).

Summary

It is crucial to produce H_2 for reducing the carbon footprint and greenhouse gas emissions, shifting the current production of H_2 mainly from fossil fuels towards a green alternative. As analyzed in this study, there are some important parameters to be considered to evaluate which is the best way to optimize the HFC process: the temperature along the reactor, combustion wave velocities, and hydrogen and syngas yield. It is remarkable that H_2 and CO production is totally related to the thermal behavior of the reactor and the type of gasifying agent used. In the field of hydrogen production using HFC, it can be concluded that when using a mixture of air with steam as an oxidizer, the maximum hydrogen content in gaseous products can be 25% by volume. Catalysts and/or an oxygen-enriched oxidant can be used to increase the hydrogen content of the products. For filtration regimes, when the front velocity is limited by the supply of an oxidizer to the combustion zone, gas-dynamic instability of a flat front is possible. The development of instability should lead to an alternative combustion mode in the form of the propagation of a separate channel or inclined front. To prevent the development of gas-dynamic instability during HFC and the formation of a burnout channel, it is sufficient to introduce the factor of mixing of the solid phase. One of the possible solutions to this problem can be the implementation of the process in a rotating cylindrical reactor, with a certain angle of inclination, where a changing gravity enables mixing the solid material. Lateral feeding of powdered solid fuel mixed with the secondary oxidant stream and replacing the fixed bed by a moving one are also among the improvements explored in the reactor design and operation.
Extended research is needed in the characterization of HFC reactors, modeling and simulation of different systems and operational conditions, economic analysis, and environmental impact assessment, before materializing a complex matrix for hydrogen production.

Ongoing Work

3D Simulations will be carried out using the commercial software Ansys Fluent, in order to validate experimental data: HFC and Solar gasification. Transition from Hybrid Filtration Combustion to Solar Gasification (2022-2024).
Use of different carbon char particles, and different Chilean biomass species particles as feedstocks. (Native and exotic forest species).

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