



Sensitivity analysis for a solar steam redox reformer



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ABSTRACT

Interest in using renewable energy sources like solar energy for power production has grown because of the concern over CO₂ emissions. One method of implementing solar energy for large scale power production is using hybrid solar fossil fuel power generation systems. Solar reforming has been shown to be a promising integration method with steam redox reforming to raise the chemical energy of the fuel. In this article, a sensitivity analysis for a solar steam redox reformer (proposed in Sheu and Ghoniem, 2016) with respect to different performance metrics is presented. Results show that the channel cross section, inlet gas temperature, and reformer pressure have the largest effect on the reactor performance. Furthermore, the analysis shows that the reduction kinetics can have a large effect on the calculated reactor performance and should be considered carefully. A reactor sizing analysis was also performed and results show that complete conversion can be achieved with a reasonable reactor size and that there is a tradeoff between conversion and cost/solar utilization efficiency. Moreover, a strategy for reactor design based on maximizing stand-alone performance as well as integration with a power cycle is discussed.

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1. Introduction

Interest has grown in using solar energy as a source for power production because of the potential for reducing CO₂ emissions. One method of utilizing solar energy on a large scale is to implement hybrid solar fossil fuel power generation. The hybrid operation avoids intermittency associated with traditional solar only power production. Under the umbrella of hybrid solar fossil fuel power generation, solar reforming has been shown to be a promising method of integrating solar heat and chemical energy (Sheu and Mitsos, 2013).

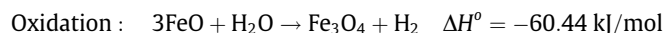
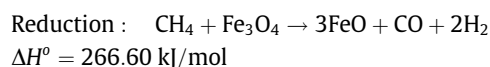
Solar reforming involves “upgrading” the input fuel using heat collected from solar concentrators. The upgraded solar fuel, mostly synthetic gas consisting of hydrogen and carbon monoxide, can have a heating value 25–30% higher than input fuel (methane/natural gas) (Sheu et al., 2015). Thus, syngas combustion can have up to a 22% reduction in CO₂ emissions when compared to methane combustion (Wagar et al., 2011). The “upgraded” solar fuel can then be used in a gas turbine to produce more power than what could be produced with the original fuel (Fig. 1). Moreover, in hybrid operation and in the absence of solar energy, no reforming occurs and the fuel is sent directly to the gas turbine. This operation allows for the hybrid system to operate continuously without

the need for storage. The most commonly used solar reforming processes are steam reforming (Berman et al., 2007; Maria et al., 1986; Epstein, 2010), dry reforming (Anikeev et al., 1998; Buck et al., 1991; Dahl et al., 2004; Levy et al., 1992; Tamme et al., 2001; Wörner and Tamme, 1998), and redox reforming using steam or CO₂ (Kodama et al., 2000; Steinfeld et al., 1998; Steinfeld et al., 1993). Previous system analysis has shown that steam redox reforming has some advantages when used in hybrid power cycles (Sheu and Ghoniem, 2014) and will be the focus in this work.

In this article, sensitivity analysis is performed for the solar steam redox reformer (proposed in Sheu and Ghoniem, 2016) with respect to different reactor performance metrics. Important parameters are identified based on how they affect the reactor performance and a discussion of how the reactor should be designed as well as its integration with a power cycle are presented.

2. Receiver–reactor design and computational model

The solar reformer studied herein uses steam redox reforming which consists of two main reactions – the reduction reaction and the oxidation reaction:



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Nomenclature

Latin letters

u	velocity (m/s)
T	temperature (K)
k_s	thermal conductivity (W/m/K)
d	channel size (m)
L	channel length (m)

Greek letters

ϵ	porosity
σ_s	scattering coefficient (m^{-1})
σ_a	absorption coefficient (m^{-1})
δ	thickness (m)
η_{CH_4}	methane conversion
η_{su}	solar utilization efficiency

The receiver reactor consists of a dumbbell shape solar absorber system. For a certain cycle time τ_{cyc} , the dumbbell system will rotate 180° every $\tau_{\text{cyc}}/2$. This rotation allows for the switching of the absorber between the reduction and oxidation steps without having to switch inlet streams. The rotation also allows the absorber to switch between being irradiated (during reduction) to not being irradiated (during oxidation). The rotor in between the two absorbers is insulated to ensure that it is not damaged by the high operating temperatures and to minimize heat transfer between the two absorbers. The absorber itself is a honeycomb disk with the oxygen carrier coated on its channel walls. Schematics of the receiver reactor are shown in Figs. 2 and 3. Previous work on systems that utilize rotating reactors and/or honeycombs for thermochemical water-splitting is described in (Diver et al., 2008; Roeb et al., 2011; Lange et al., 2015).

To evaluate the reactor performance, a computational model is used that describes the processes along individual channels within the solar absorber (Fig. 4). The model describes the chemical reactions between the gas phase and the solid surface and accounts for heat and mass transfer between the solid and gas phases as well as radiative transport and conductive heat transfer within the solid phase (Fig. 5).

The reactor operation is modeled as cyclical with two separate steps: (1) while the reactor is being irradiated with solar energy, methane (along with a carrier gas – in the case presented here it is 50% CO_2) is fed into the channel to reduce the metal oxides and (2) the reactor is rotated 180° and the input stream is switched from methane to steam and metal oxidation occurs while the reactor is shielded from the solar irradiation. During the oxidation step, no solar energy is provided to the reactor. The carrier gas chosen here is CO_2 to prevent coking that may occur during the methane partial oxidation process. CO_2 has the potential to react at the surface with the methane to produce more syngas through dry reforming. Experimental work with dry reforming and FeO as the catalyst was done in (Gokon et al., 2002). The study shows that

Fe_3O_4 is not a catalyst for the dry reforming reaction and that any dry reforming with FeO occurs much slower than the main reduction reaction. More detailed discussion can be found in (Sheu and Ghoniem, 2016).

To initialize the model, the solid temperature is set to the steady state solid temperature calculated assuming no gas flow. For every subsequent cycle, the initial condition for the appropriate variables (i.e., temperature) are set to the values obtained at the end of the previous cycle. The model is considered converged when the reformer has reached a cyclic stationary state. The reformer has reached a cyclic stationary state when the temperature profile of the solid is the same (< 1 K difference) at the end of the cycle as it was at the beginning of the cycle. Note that as the solid

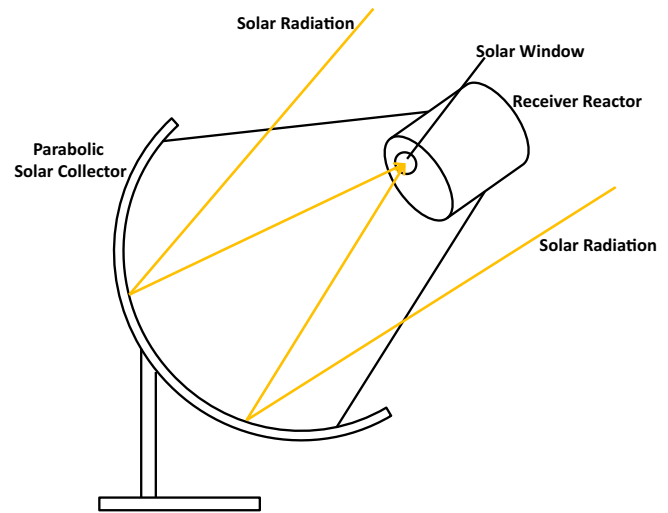


Fig. 2. Schematic of receiver reactor with solar collector (Sheu and Ghoniem, 2016).

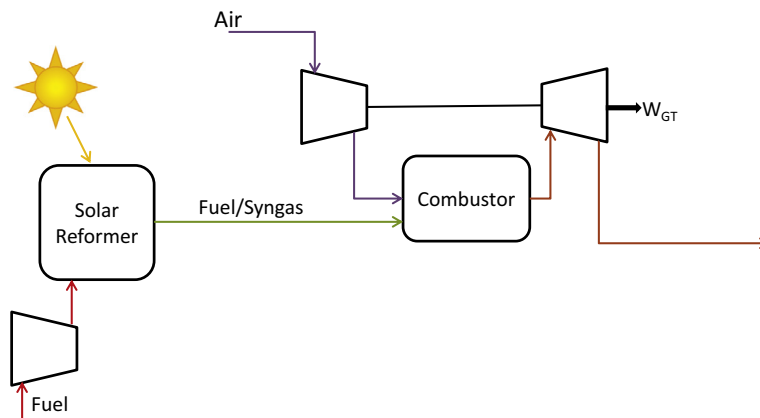


Fig. 1. Schematic of solar reformer integrated with power cycle.

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