

Receiver reactor concept and model development for a solar steam redox reformer

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Abstract

As concern over the CO₂ emissions associated with power production from traditional fossil fuels grows, there has been more interest in using renewable energy sources such as solar energy. However, there are many issues with using solar energy on a large scale including dispatchability and economically viable storage methods. A potential solution to these problems is using a hybrid solar-fossil fuel power generation system. Within such systems, solar reforming has been shown to be a promising integration method with steam redox reforming as an effective reforming process. In this article, a receiver reactor concept for a solar steam redox reformer is presented. The receiver-reactor consists of a dumbbell shape absorber system that has two distinct absorbers. This absorber system setup allows for the switching between reduction and oxidation steps without having to constantly change inlet streams to the reactor and is designed such that the inlet connections do not interfere with the solar window. In addition, at any point in time only one solar absorber is irradiated by the solar energy (during the reduction step). A computational model is developed to assess its performance. Simulations show that the receiver-reactor strongly absorbs the solar radiation and most of the radiative heat transfer occurs in the front half of the reactor. Moreover, results show that higher conductivity absorber materials yield smaller temperature variations not only within the reactor but also with time, and therefore are more suitable for long term reactor operation.

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1. Introduction

There has been much interest in the use of renewable energy resources such as solar energy for power generation as means for limiting CO₂ emissions associated with power production from fossil fuels. However, currently and for near term projections, only a small percentage of the world's power production comes from non-hydropower renewables ([International Energy Outlook, 2013](#)). The reasons for this small percentage include the lack of

economically viable methods of storage as well as intermittency and dispatchability problems with renewable power sources like solar energy. One potential solution to this problem is the use of hybrid solar fossil fuel power generation. In this hybrid operation, there is the potential to reduce emissions as compared to fossil fuel only power production while avoiding the intermittency problems associated with solar only power production. Within this scope of hybrid solar fossil fuel power generation, there are a number of ways in which the solar energy can be incorporated into a fossil fuel power cycle ([Sheu et al., 2012](#)), and previous work has shown that solar reforming is a promising integration method ([Sheu and Mitsos, 2013](#)).

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Nomenclature

Latin letters

u	velocity (m/s)
T	temperature (K)
k_s	thermal conductivity (W/m/K)
K_{ext}	extinction coefficient (m^{-1})
d	channel size (m)
L	channel length (m)

Greek symbols

ϵ	porosity
σ_s	scattering coefficient (m^{-1})
σ_a	absorption coefficient (m^{-1})
δ	thickness (m)
η_{CH4}	methane conversion
η_{su}	solar utilization efficiency

The solar reforming integration method involves reforming the fuel (natural gas) into syngas (which has a higher heating value) using solar energy. The syngas is then used as a fuel for the gas turbine to produce power in a combined cycle. Solar reformers can be categorized into two main categories: directly irradiated and indirectly irradiated. In this work, the focus will be on directly irradiated solar reformers as higher temperatures can be reached in these reformers which leads to higher methane conversion. However, it should be noted that indirectly irradiated reformers can also be of great interest due to cost considerations. For a directly irradiated solar reformer, the solar receiver and reactor are one integrated unit. In traditional solar receivers used in solar only power production, a solar absorber (usually a porous ceramic disk or wire mesh) is placed inside a solar receiver and irradiated by the solar energy. A heat transfer fluid is then sent through the solar absorber and heated by convection. To apply this concept to solar reforming, the solar absorber merely becomes the reaction site. Most often in these solar reformers, the solar absorber is a porous ceramic disk or ceramic honeycomb with any catalyst needed for the reforming process coated onto the porous surface or channels. The most commonly used solar reforming processes are steam reforming, dry reforming, and redox reforming. There has been much experimental work with steam and dry solar reformers (Anikeev et al., 1998; Berman et al., 2007; Buck et al., 1991; Maria et al., 1986; Dahl et al., 2004; Levy et al., 1992; Wörner and Tamm, 1998), and to a less extent on redox solar reformers as well (Kodama et al., 2000; Steinfeld et al., 1998; Steinfeld et al., 1993). Meanwhile there has been much less computational work, with only a few numerical studies on steam and dry solar reformers (Ben-Zvi and Karni, 2007; Petrasch and Steinfeld, 2007; Skocypec et al., 1994). Development of computational models for solar reformers in conjunction with experimental studies can aid in the design and operation of the solar reformer for use in hybrid solar fossil fuel power production.

Previous system analysis has shown that steam redox reforming has some advantages for use in hybrid power cycles (Sheu and Ghoniem, 2014) and will be the focus in this work. Moreover, since a number of different oxygen

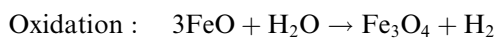
carriers can be used, redox reforming does not require the use of expensive noble metal catalysts (as is usually the case with solar dry and steam reformers). Steam redox reforming can also yield product compositions with more desirable H_2/CO ratios than direct steam reforming. In this article, a design for a receiver-reactor that can be used for the steam redox process is discussed. In addition, a computational model that can aid in the design of the solar reactor is presented. Finally, a set of base case results from the reactor model is shown and the validity of the results discussed.

2. Receiver–reactor design

As mentioned previously, the solar reformer studied herein uses steam redox reforming which consists of two main reactions: a (metal) reduction reaction and an oxidation reaction. In previous work, iron oxide has been shown to be a promising option as an oxygen carrier for a steam redox reformer and hence is utilized in this analysis (Sheu and Ghoniem, 2014). For this reformer, the two states for the oxygen carrier are magnetite (Fe_3O_4) and wustite (FeO). Thus, the two main reactions for the reformer studied herein are



$$\Delta H^o = 266.60 \text{ kJ/mol}$$



$$\Delta H^o = -60.44 \text{ kJ/mol}$$

Note that CO_2 can also be used as the oxidizing agent. However, steam is used in this analysis due to the faster oxidation rates (Stehle et al., 2011).

In chemical looping applications, often times two separate reactors are used (one for oxidation and one for reduction) with a fluidized bed circulating the oxygen carrier between the two reactors (Adanez et al., 2012). However, the energy required for the circulating bed as well as the associated pressure drop can be detrimental to reformer performance (Adanez et al., 2012). Moreover, there are other complexities associated with maintaining the fluidized bed, separating the particles, and particle agglomeration at high temperatures (Adanez et al., 2012). Therefore, the reactor

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