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# Dry redox reforming hybrid power cycle: Performance analysis and comparison to steam redox reforming

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ABSTRACT

There has been much interest in the use of renewable resources for power generation as the world's energy demand and the concern over the rise in emissions increases. In the near term, however, renewable sources such as solar energy are expected to provide a small fraction of the world's energy demand due to intermittancy and storage problems. A potential solution is the use of hybrid solar-fossil fuel power generation. Previous work has shown the potential of steam redox reforming for hybridization. However, this type of reforming requires some water consumption (which may be infeasible in certain locations) as not all the water can be recovered through recycling. An alternative is to utilize dry (or $CO_2$) redox reforming. In this paper, a system analysis for a $CO_2$ redox reforming hybrid cycle and comparison of cycle and reformer performance between a $CO_2$ redox reformer and steam redox reformer hybrid cycle are presented. The effect of important operating parameters such as pressure, amount of reforming $CO_2$, and the oxidation temperature on the reformer and cycle performance are discussed. Simulation results show that increasing the oxidation temperature or the amount of reforming $CO_2$ leads to higher reformer and cycle efficiencies. In addition, the comparison between the $CO_2$ and steam redox reformer hybrid cycles shows that the $CO_2$ cycle has the potential to have better overall performance.

## Introduction

With concern regarding emissions due to fossil fuel power production growing, there is an increased interest in using renewable resources such as solar for power production. However in the near term, due to intermittency and storage issues, renewable resources like solar are expected to provide minimal contribution to the world's energy demand [1]. One potential solution for these problems is hybrid solar-fossil fuel power generation. With the hybrid operation, intermittency concerns are eliminated as fuel can be used when solar is not

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**Nomenclature**

*Latin letters*

| | |
|---|---|
| HRSG | heat recovery steam generator |
| $\Delta H^\circ$ | standard enthalpy of reaction, kJ/mol |
| $X_{input,solar}$ | input solar share |
| Q | heat input, W |
| I | solar irradiance, W/m$^2$ |
| A | solar collector area, m$^2$ |
| T | temperature, K |
| $\tilde{C}$ | mean flux concentration ratio, suns |
| $\dot{n}$ | molar flow rate, mol/s |

*Greek letters*

| | |
|---|---|
| $\sigma$ | Stefan–Boltzmann Constant, W/m$^2$/K$^4$ |
| $\eta$ | efficiency |

*Subscripts*

| | |
|---|---|
| *red* | reduction |
| *oxd* | oxidation |
| *solar* | solar field input |
| *fuel* | fuel input |
| *ref* | reformer |
| *rec* | solar receiver |
| *chem* | chemical |

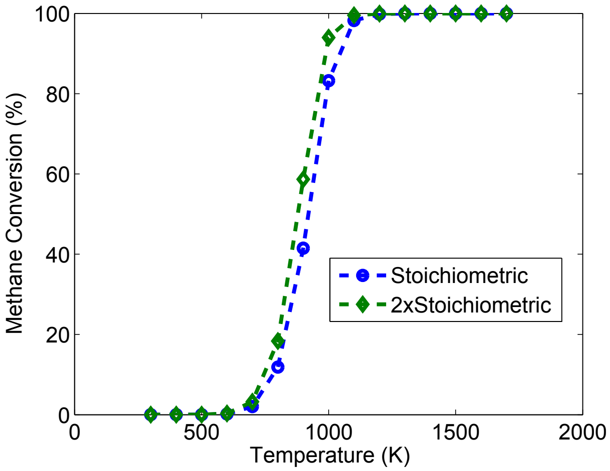

**Fig. 1 – Equilibrium methane conversion for $Fe_3O_4$ reduction at different temperatures (stoichiometric and 2 x stoichiometric metal oxide to fuel ratio).**

available, and in particular, when solar reforming is used as the hybridization method, a viable storage option is obtained through the use of solar fuels [2]. Moreover, analysis of solar reforming hybrid cycles has shown that the hybridization can improve the solar energy system performance [3].

When solar reforming is used as the hybridization technique, fuel (natural gas) is reformed into syngas (which has a higher heating value) using the solar energy. The produced syngas is then used as the fuel for a gas turbine system. Many different reforming processes can be used to convert the natural gas into syngas. These processes include steam reforming, $CO_2$ (dry) reforming, and to a lesser extent, metal redox reforming.

There has been much previous work on solar steam and dry reformers [4–11] as well as redox reformers [12–17]. System level studies have also been performed for steam and redox reformer hybrid cycles [2,3,18]. Specifically for the redox reformer hybrid cycle, the previous analysis done was for a reformer utilizing steam in the oxidation step [18]. The system analysis of the steam redox reformer cycle identified important parameters, such as amount of reforming water and oxidation temperature, and their effect on both reformer and cycle performance.

A hybrid cycle that utilizes this steam redox reforming requires consumption of steam since not enough water can be obtained through just recycling. Another option is to use $CO_2$ instead of steam within the redox reformer. If $CO_2$ is used as the oxidizing agent, the main reactions for the reformer are

$$MO + CH_4 \rightarrow M + CO + 2H_2 \ (\text{Endothermic})$$

$$M + CO_2 \rightarrow MO + CO \ (\text{Exothermic or Endothermic})$$

where M/MO represents the metal/metal oxide pair chosen for the redox reactions.

Geographic locations that have large solar energy resources usually also have water scarcity and may not have the water needed to operate a steam redox reforming hybrid cycle that requires some water consumption. Therefore, it would be useful to determine what conditions would be needed for a redox reformer hybrid cycle that utilizes $CO_2$ and how its performance compares to that of the steam redox reformer hybrid cycle. In this paper, a system level analysis of a $CO_2$ based redox reformer hybrid power cycle is presented. The effect of pressure, amount of reforming $CO_2$ used, reformer temperature, and solar energy fraction on the redox reformer and hybrid cycle performance is discussed. In addition, the performance of this type of hybrid cycle is compared to that of the redox reformer hybrid cycle that utilizes steam. The performance is compared on the basis of both reformer and cycle performance. Moreover, the operating conditions for the metal redox reforming processes (using either steam or $CO_2$ for oxidation) are discussed.

## Metal redox reforming conditions

Before going into the detail regarding the system analysis, the operating conditions for the redox reforming process will be presented. As shown previously, metal redox reforming involves a two step process. First, a fuel (methane) is used to reduce a metal oxide, forming metal (or a reduced state of a metal oxide) and syngas. Next, the reduced metal is oxidized using an oxidizing agent (air, steam, or $CO_2$). Basically, a chemical looping process is created. From previous system analysis of a redox reforming hybrid cycle, iron/magnetite was shown to be a promising metal/metal oxide pair for solar redox reforming due to its required temperatures for the reactions, oxygen carrying capacity, and material costs [18]. The iron/magnetite pair will be used for the redox reformer cycle