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Research paper

Efficiency potential of indirectly heated solar reforming with open volumetric solar receiver

Henrik von Storch [a,*], Hannes Stadler [a], Martin Roeb [b], Bernhard Hoffschmidt [b]

[a] Deutsches Zentrum für Luft-und Raumfahrt, Solar Research, Karl-Heinz-Beckurts-Str.13, 52428 Jülich, Germany
[b] Deutsches Zentrum für Luft-und Raumfahrt, Solar Research, Linder Höhe, 51147 Köln, Germany

HIGHLIGHTS

- A process for solar reforming of natural gas is proposed.
- A process model is developed to determine process efficiency.
- Several process parameters are investigated and the process is optimized to reach high efficiencies.
- The process achieves promising efficiencies.
- The solar receiver is the crucial process unit for further improvement of process performance.

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ABSTRACT

In solar reforming, the heating value of natural gas is increased by utilization of concentrated solar radiation. Hence, it is a process for storing solar energy in a stable and transportable form that also permits further conversion into liquid fuels like methanol. The feasibility of solar reforming is proved. However, its overall process efficiency potential has not been studied systematically. In this work, an indirectly heated solar reforming process with air as heat transfer fluid is designed and modelled to produce syngas suitable for subsequent methanol synthesis. For provision of solar high temperature heat, an open volumetric receiver is implemented into the process model and the overall performance is investigated. Results show the paramount significance of the air return ratio of the receiver and its ability to achieve high efficiencies at temperatures above 850 °C. For realistic air return ratios, design point process efficiencies of 19% can be achieved, for an increased air return ratio, values up to 23% are feasible. The determined corresponding annual efficiencies are 12% and 14% respectively. Considering its relative technical simplicity this makes indirectly heated solar reforming a promising technology to overcome the current limitations of solar energy in the medium term.

1. Introduction

Solar energy is the most abundant of the renewable energy sources. However, the fluctuating and spatially unbalanced nature of its supply limits its utilization to daytime and areas with large solar resources. While thermal storage enables concentrated solar power (CSP) plants to operate some hours beyond sunset, storage for several days is not feasible yet. Even though this drawback could be solved with hybrid-solar fossil combined cycle fossil fuel power plants, as investigated by Rovira et al. [1], there are no processes established that allow the utilization of solar energy as a fuel for transportation. Transport of solar energy from sunny regions in the world into regions with high energy demand is possible via high voltage direct current. However, this possibility is usually limited to a few hundred kilometres, whereas the international energy market relies on transport of fuels over several thousand kilometres at low cost. Solar reforming of natural gas or other methane rich gases represents a process with the potential to tackle those drawbacks of solar energy utilization. Solar reforming can achieve this by converting solar energy into chemical energy. As stated by Kodama [2], solar reforming increases the heating value of the reactant gases by 28%. This represents the amount of stored solar energy in the product.

* Corresponding author. Tel.: +49 2203 601 4173.
E-mail address: henrik.vonstorch@dlr.de (H. von Storch).

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Nomenclature

ARR	Air return ratio of the receiver –
ΔH_{Gas}	Change of enthalpy of reactant gas kWh
ΔHGas	Change of enthalpy of reactant gas flow kW
E	Direct normal solar irradiation kW
$E_{el,net}$	Net electricity energy output kWh
H	Specific enthalpy kJ kg^{-1}
I	Insolation (radiative flux) kW m^2
M	Quantity for description of syngas quality –
$\dot{m}$	Mass flow kg s^{-1}
n	Amount of substance Gmol
$P_{el,net}$	Net electric power output of the process kW
$\dot{Q}_{ARR}$	Heat loss due to incomplete air return kW
$\dot{Q}_{Convective}$	Convective heat losses of the receiver kW
$\dot{Q}_{\alpha}$	Absorbed power kW
$\dot{Q}_{Compr}$	Heat loss due to cooling at compression
$\dot{Q}_{Compr}$	Heat loss in Condenser of Water steam cycle
$\dot{Q}_{\varepsilon}$	Re-emitted power kW
$\dot{Q}_{Intercept}$	Intercept radiation onto receiver kW
$\dot{Q}_{Refl}$	Reflective power loss kW
$\dot{Q}_{Use}$	Useful part of the power absorbed by the receiver kW
T	Temperature K (or °C)
z_i	molar fraction of component i in syngas –

Greek symbols

α	absorptivity
ε	emissivity
η	efficiency
σ	Stefan–Boltzmann constant: $5.67 \cdot 10^{-11}$ kW m^2 K^{-4}
Σ	sum of hourly values of operational year

Subscripts

Ap	aperture
Abs	absorber
air, hot	hot air flow produced by receiver
air, return	air returned to receiver for recirculation
air, amb	Ambient air
air	total air flow in air circuit
process	overall process
a	annual (throughout operational year of process)
Heliostat	heliostat field
Syngas	synthesis gas
J	in hour j

Solar reforming has been a topic of research for over twenty years now. Due to the high temperatures that are desirable for the reforming reaction (>650 °C), point focusing systems are most suitable to provide the necessary energy. In large scale, this makes solar power towers the most promising CSP-technology for solar reforming. In the past, a number of different research projects have dealt with the technical feasibility of solar reforming. These projects can be divided into two main groups, regarding the way of providing the heat for the reaction:

1. Indirectly heated solar reformers with utilization of a heat transfer fluid (investigated by Böhmer et al. [3] in the early 1990's; currently investigated at by McNaughton [4]).
2. Directly irradiated receiver reactors, where the absorbing surface is also the reaction surface (demonstrated in the CAESAR project in 1991 by Buck et al. [5] and in 2011 by Rubin and Karni [6]).

Furthermore, solar reformers have been demonstrated where the reforming reactor (i.e. a reforming tube) is directly irradiated and the heat is transferred into the reaction volume conductively. This concept was most recently studied by Liovic et al. [7].

Agrafiotis et al. [8] give a comprehensive overview of past and present activities related to solar reforming. When doing a literature review of the topic, it becomes clear, that more effort has been made in the investigation of directly irradiated solar reformers. To the best of the authors' knowledge, the only investigations of indirectly heated solar reformers were conducted by Böhmer et al. [3] within the ASTERIX project in 1989 and since 2012 by McNaughton [4] at CSIRO. However, both investigations focused on the technical feasibility of the concept, not on annual or overall process efficiency of the reforming process. Furthermore, subsequent syngas utilization and related syngas quality requirements were not taken into account in those projects. An example of an activity that focused on the overall annual efficiency of a directly irradiated solar reforming process including subsequent syngas utilization (in a gas turbine) is by Sheu and Mitsos [9]. In their work they come to the conclusion, that the investigated process has the potential of converting solar energy into electricity more efficiently than other hybrid solar-gas concepts.

Reforming of natural gas is well understood and has been applied broadly in the production of hydrogen, ammonia and methanol for several decades [10]. However, there are a number of differences between solar reforming and conventional reforming regarding the heat transfer into the reaction volume. In conventional steam reforming reactors, additional natural gas is burned outside of the reactor tubes in order to provide the necessary heat of reaction [11]. Due to the combustion in proximity to the reactor tubes, a large part of the heat is transferred radiatively. In solar reforming this is not the case, as the heat transfer fluid (HTF) will mainly transfer the heat convectively (assuming that the HTF either has a low absorptivity or a low transmissivity). However, Wesenberg [12] investigated the behaviour of a gas heated reformer intensively. A gas heated reformer is very similar to the air heated reformer that is investigated in this work. Therefore, as presented in sub-chapter 2.2, it was used for validation of the model used in the present investigation.

As the reforming product syngas features a very low volumetric energy density and high hydrogen content, storage and transport are difficult and cost intensive. Therefore, it is usually considered an intermediate product. It is commonly directly processed into purified hydrogen, ammonia, methanol or Fischer-Tropsch-products in the production plant [13]. However, further applications were proposed for solar syngas: combustion of the solar upgraded gas in a gas turbine, as investigated by Refs. [9,14–16] and transportation and/or storage for subsequent re-methanation, hence constituting a solar chemical heat pipe, as investigated by Fraenkel et al. [17]. When comparing the primary locations suitable for solar reforming (MENA, Australia and parts of the USA) and the main fuel importing countries (Europe, Japan and south Korea) it becomes clear, that a solar reforming product should be easily transportable over distances of several thousand kilometers in order to reach large markets. This requires a high volumetric energy density in order to fit the product into reasonable sized storage/transport tanks without additional compression or liquefaction work. Hence, combustion of solar syngas in a gas turbine or utilization in a solar