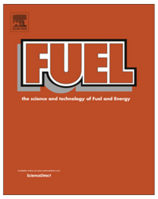
Fuel 193 (2017) 432–443

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel



Full Length Article

# A pressurized high-flux solar reactor for the efficient thermochemical gasification of carbonaceous feedstock

F. Müller [a,b], P. Poživil [a], P.J. van Eyk [c], A. Villarrazo [d], P. Haueter [a], C. Wieckert [b], G.J. Nathan [e], A. Steinfeld [a,*]

[a] *Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland*
[b] *Solar Technology Laboratory, Paul Scherrer Institute, 5232 Villigen, Switzerland*
[c] *School of Chemical Engineering, Centre for Energy Technology, University of Adelaide, Adelaide, South Australia 5005, Australia*
[d] *Universidad Tecnologica Nacional, C1041AAJ Buenos Aires, Argentina*
[e] *School of Mechanical Engineering, Centre for Energy Technology, University of Adelaide, Adelaide, South Australia 5005, Australia*

## HIGHLIGHTS

- 3-kW solar reactor was experimentally demonstrated with concentrated radiation.
- Charcoal-water slurry was converted to high-quality pressurized syngas.
- Reaction extent of 94% was obtained in less than 5 s.
- The solar-to-fuel energy conversion efficiency reached 20%.
- The calorific value of the feedstock was solar upgraded by 35%.

## ARTICLE INFO

*Article history:*
Received 30 September 2016
Received in revised form 12 December 2016
Accepted 14 December 2016
Available online 3 January 2017

*Keywords:*
Gasification
Solar
Concentrated
Radiation
Thermochemical
Syngas

## ABSTRACT

We report on the design and first-ever experimental demonstration of a 3 kW pressurized solar reactor for thermochemically converting carbonaceous feedstocks into gaseous fuels. It uses a windowless SiC cavity to efficiently absorb and transfer concentrated solar radiation to an annular gas-particle vortex flow created by injecting tangentially a charcoal/water slurry at high pressures. Experiments were carried out in a high-flux solar simulator under a solar concentration ratio equivalent to 3718 suns. For slurry feeding rates in the range 0.42–1.26 g/min, $H_2O$:C molar ratios in the range 1.48–1.98, and absolute reactor pressures in the range 1–6 bar, the nominal reactor temperature was between 1009 and 1273 °C yielding high-quality syngas with a carbon conversion up to 94% within residence times of less than 5 s. The peak solar-to-fuel energy conversion efficiency, defined as the ratio of the heating value of the syngas produced to the solar radiative energy input plus the heating value of the slurry converted, reached 20%. The calorific value of the feedstock was solar upgraded by 35%, thus outperforming autothermal gasification in addition to delivering higher syngas output per unit of feedstock and eliminating the need for upstream air separation. The performance of this robust windowless design also was compared with that of an equivalent windowed configuration in which the gas-particle vortex flow was directly exposed to high-flux solar irradiation.

## 1. Introduction

Solar gasification thermochemically converts carbonaceous feedstocks into energy-rich and high-quality syngas – a mixture of CO and $H_2$ – using concentrated solar energy [1]. The thermochemical conversion involves principally two sequential processes: pyrolysis and steam-based char gasification, both of which are critical in the handling of carbonaceous fuels over a wide temperature range, with the former occurring typically in the range 200–600 °C and the latter becoming dominant at above 1000 °C. The simplified net reaction for stoichiometric water delivery can be represented by:

---

*Abbreviations:* CCD, charged coupled device; D-I, directly-irradiated; FT, Fischer-Tropsch; IR, infrared; GC, gas chromatograph; HFSS, high-flux solar simulator; I-I, indirectly-irradiated.

[*] Corresponding author.
*E-mail address:* aldo.steinfeld@ethz.ch (A. Steinfeld).

http://dx.doi.org/10.1016/j.fuel.2016.12.036
0016-2361/

**Nomenclature**

*Latin symbols*

| | |
|---|---|
| $C$ | solar concentration ratio [kW/m$^2$] |
| $d$ | particle size [μm] |
| $LHV$ | lower heating value [MJ/kg] |
| $\dot{m}$ | mass flow rate [g/min], [$L_N$/min] |
| $\dot{n}$ | molar flow rate [mmol/min] |
| $p$ | pressure [bar] |
| $\dot{Q}$ | power [W] |
| $R$ | universal gas constant: 8.314 J/(K mol) |
| $r$ | radial coordinate [mm] |
| $T$ | temperature [°C], [K] |
| $t$ | time [min] |
| $U$ | energetic upgrade factor |
| $u$ | gas velocity [m/s] |
| $V$ | volume [m$^3$], [L] |
| $X_C$ | reaction extent [%] |
| $x$ | H:C molar ratio |
| $y$ | O:C molar ratio |
| $z$ | horizontal coordinate [mm] |

*Greek symbols*

| | |
|---|---|
| $\eta_{\text{solar-to-fuel}}$ | solar-to-fuel energy conversion efficiency [%] |
| $\tau$ | nominal residence time [s] |
| $\varphi$ | angular coordinate [°] |

*Subscripts*

| | |
|---|---|
| cavity | cavity |
| chemical | chemical |
| conduction | heat conduction |
| convection | free convection |
| feedstock | feedstock, charcoal |
| gi | gradually increasing |
| i | inlet |
| N | normal conditions: 273.15 K and 1 atm |
| offgas | off gas stream |
| radiation | radiation |
| reactor | reactor |
| reflection | reflection |
| reradiation | re-radiation |
| sensible | sensible heat |
| shell | metallic shell |
| solar | solar |
| solar-to-fuel | solar-to-fuel |
| syngas | syngas |
| v10,50,90 | upper threshold particle size in μm |

$$C_1H_xO_y + (1-y)H_2O = \left[\frac{x}{2} + 1 - y\right]H_2 + CO \qquad (1)$$

where $x$ and $y$ are the elemental molar ratios of H:C and O:C in the feedstock, respectively. Nitrogen, sulfur, mineral matter, and other impurities contained in the feedstock are omitted from consideration in Eq. (1). Both pyrolysis and gasification are highly endothermic. The advantages of the solar-driven process vis-à-vis the conventional autothermal process are four-fold: (1) it delivers higher syngas output per unit of feedstock, as no portion of the feedstock is combusted for process heat; (2) it produces syngas with higher calorific value and lower $CO_2$ intensity, as the energy content of the feedstock is upgraded through the solar energy input; (3) it allows for higher gasification temperatures (>1200 °C), resulting in faster reaction kinetics and superior quality of the syngas produced with low – or without – tar content, resulting in better exploitation of the available resources; and (4) it eliminates the need for upstream air separation for oxy-combustion. Ultimately, solar gasification offers an efficient means of storing intermittent solar energy in a transportable and dispatchable chemical form. To overcome the intermittency of solar radiation, hybrid solar gasification concepts are proposed for around-the-clock process operation [2–5].

The measure of how well the solar energy input is converted into chemical energy contained in the syngas produced is given by the solar-to-fuel energy conversion efficiency $\eta_{\text{solar-to-fuel}}$, defined as:

$$\eta_{\text{solar-to-fuel}} = \frac{\dot{m}_{\text{syngas}} \cdot LHV_{\text{syngas}}}{\dot{Q}_{\text{solar}} + \dot{m}_{\text{feedstock}} \cdot LHV_{\text{feedstock}}} \qquad (2)$$

where $\dot{Q}_{\text{solar}}$ is the solar energy delivered through the solar reactor's aperture, $\dot{m}_{\text{feedstock}}$ and $\dot{m}_{\text{syngas}}$ are the gasified feedstock and the evolved syngas mass rates, respectively, and $LHV$ is the low heating value of the feedstock converted. Another important performance indicator is the energetic upgrade factor $U$, defined as the ratio of the heating value of the syngas produced to that of the feedstock processed:

$$U = \frac{\dot{m}_{\text{syngas}} \cdot LHV_{\text{syngas}}}{\dot{m}_{\text{feedstock}} \cdot LHV_{\text{feedstock}}} \qquad (3)$$

For the stoichiometric system $C + H_2O$, the equilibrium composition at 1300 K consists of an equimolar mixture of $H_2$ and CO, yielding $U = 1.33$ for solar gasification [6]. Obviously, for autothermal gasification, $U < 1$, and typically $U = 0.75–0.85$ depending on the feedstock [7,8].

Solar gasification reactors may be classified [1] into: (1) directly-irradiated reactors, where the solid carbonaceous reactants are directly exposed to concentrated solar irradiation; and (2) indirectly-irradiated reactors, where heat is transferred to the reaction site through an opaque wall. While directly-irradiated gasification reactors provide efficient heat transfer directly to the reaction site, they require a transparent window for the access of concentrated solar radiation, which becomes a critical and troublesome component at large scales and, particularly, under industrially-preferred high pressures. On the other hand, indirectly-irradiated reactors eliminate the need for a window at the expense of having less efficient heat transfer by conduction through the walls of an opaque absorber. Thus, the disadvantages are linked to the limitations imposed by the materials of the absorber with regard to maximum operating temperature, inertness to the chemical reaction, thermal conductivity, radiative absorptance, and resistance to thermal shocks. Previous experimental studies have used solar reactor concepts based on packed-beds [9–12], fluidized-beds [13–17], drop-tubes [18,19], and entrained flows [20,21]. Of particular interest is the directly-irradiated vortex flow reactor [20], which was successfully applied for the solar conversion of petcoke particles. However, its window became critical component during scale-up and pressurized operation because of the structural and thermal stresses [22]. This prompted us to consider converting the directly-irradiated configuration to an indirectly-irradiated one by replacing the window with a SiC cavity, since this configuration was recently applied successfully for heating pressurized air to 1200 °C at 6 bar using a 250 mm-inner diameter SiC cavity for a solar radiative power input of 50 kW [23].