FFF Hybrid Conference on Solar Fuels and High Temperature Solar Applications
Johannesburg, South Africa, August 20-21, 2014

Solar-driven Gasification of Carbonaceous Feedstock

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Overview

Introduction

Solar gasification of petcoke – SYNPET
\[ \gamma 500 \text{ kW}_\text{th} \text{ solar pilot plant} \]

Solar gasification of coal, biomass, and C-waste materials – SOLSYN
\[ \gamma 150 \text{ kW}_\text{th} \text{ solar pilot plant} \]
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ŷ 500 kW\textsubscript{th} solar pilot plant

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ŷ 150 kW\textsubscript{th} solar pilot plant
H$_2$O/CO$_2$-splitting

Decarbonization

Concentrated Solar Energy

Solar Fuels (H$_2$, syngas, liquid fuels)

Long-term goal

Short/mid-term transition

Optional CO$_2$/C Sequestration

Fossil Fuels (NG, oil, coal)

H$_2$O

CO$_2$

Solar High-T Electrolysis

Solar Thermochemical Cycle

Solar Electricity + Electrolysis

Solar Reforming

Solar Cracking

Solar Gasification

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Solar Thermochemical Fuel Production

Solar pilot plants demonstrated in the power range of 150-500 kW_th

Solar steam reforming of natural gas / methane

Solar steam gasification of carbonaceous feedstock

SOLGAS (200 kW_th)  SOLREF (400 kW_th)  SYNPET (500 kW_th)  SOLSYN (150 kW_th)
Solar Thermochemical Gasification

Background

β Hybrid solar/fossil endothermic process:

- Fossil fuels as chemical source for syngas and H₂
- Concentrated solar radiation as energy source of process heat

β Solar-driven vis-à-vis autothermal gasification:

- Higher energetic value of the syngas produced
- Higher syngas output per unit of feedstock
- Higher quality of the syngas produced
- Elimination of air-separation unit

Solar Thermochemical Gasification

Solar-driven gasification vs. Autothermal gasification

\[
C + H_2O \xrightarrow{\Delta H} CO + H_2
\]

\[
C + H_2O + 0.78(C + O_2) \xrightarrow{\Delta H = 0} CO + H_2 + 0.78CO_2
\]
Solar Thermochemical Gasification

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

Beech charcoal \( C_{1H_{0.47}O_{0.055}} \) @ 1 bar

\( \frac{LHV_{\text{syngas}}}{LHV_{\text{C-feedstock}}} = 1.33 \)

\( T > 1500 \text{ K} \)

C-materials

Concentrated Solar Radiation

Solar Gasification

\( \text{H}_2\text{O} \)

\( \text{CO} \)

\( \text{H}_2 \)

Syngas

Liquid Fuels

\( LHV_{\text{syngas}} \)

\( LHV_{\text{C-feedstock}} \)

\[\begin{align*}
\text{Energy Environ. Sci.} & \quad 4, 73-82, 2011. \\
\text{AIChE Journal} & \quad 57, 3522-3533, 2011.
\end{align*}\]
Solar Thermochemical Gasification

Syngas for liquid fuels production

- Coal
- Concentrated Solar Radiation $T > 1500 \text{ K}$
- Solar Gasification
- $\text{H}_2\text{O}$
- $\text{CO}$
- $\text{H}_2$
- Syngas
- Liquid Fuels
Solar Thermochemical Gasification

Syngas for power production

Concentrated Solar Radiation $T > 1500$ K

Coal $\rightarrow$ Solar Gasification $\rightarrow$ CO $\rightarrow$ CC $\rightarrow$ Work $\rightarrow$ Optional Sequestration

$H_2O$ $\rightarrow$ CO $\rightarrow$ H$_2$ $\rightarrow$ Shift Reactor $\rightarrow$ CO$_2$ $\rightarrow$ Separation $\rightarrow$ H$_2$ $\rightarrow$ Fuel cell $\rightarrow$ Work

Solar Thermochemical Gasification

Syngas for power production

\[
\eta = \frac{\text{Work Output}}{Q_{\text{solar}} + \text{LHV}_{\text{coal}}}
\]

- Concentrated Solar Radiation
  - T > 1500 K
  - Solar Gasification
    - Coal
    - H₂O
    - CO
    - H₂
    - CC
    - Work
    - CO₂
    - Separation
    - H₂
    - Fuel cell
    - Work

Coal

H₂O

H₂O

CO

H₂

CC

Work

CO₂

Optional Sequestration

- CC Work
- E = 3.5 kWhₑ/kg
- E = 6.1 kWhₑ/kg
- E = 6.6 kWhₑ/kg

- Rankine
  - \( \eta = 35 \% \)
  - \( E = 3.5 \text{ kWh}_e/\text{kg} \)

- Solar Gasification
  - \( \eta = 51 \% \)
  - \( E = 6.6 \text{ kWh}_e/\text{kg} \)

- Syngas
  - \( \eta = 46 \% \)
  - \( E = 6.1 \text{ kWh}_e/\text{kg} \)


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Solar Thermochemical Gasification

Syngas for power production

Coal $\rightarrow$ Water $\rightarrow$ Solar Gasification $\rightarrow$ Concentrated Solar Radiation $\rightarrow$ $T > 1500 \text{ K}$ $\rightarrow$ CO, H$_2$ $\rightarrow$ Shift Reactor $\rightarrow$ CO, H$_2$ $\rightarrow$ CO$_2$, H$_2$ $\rightarrow$ Separation $\rightarrow$ CO$_2$ $\rightarrow$ Optional Sequestration $\rightarrow$ H$_2$ $\rightarrow$ Fuel cell $\rightarrow$ Work


Specific CO$_2$ emissions

- Coal-gasification to syngas + 55%-η CC
- Coal-gasification to H$_2$ + 60%-η fuel cell
- Coal-combustion + 35%-η Rankine cycle
Solar Thermochemical Gasification

Syngas for power production

Advantages:

- Calorific value of feedstock is upgraded by solar power input
- Gaseous products are not contaminated by combustion by-products
- Discharge of pollutants to the environment is avoided

Coal → Solar Gasification → Shift Reactor → CO₂, H₂ → Separation → CO₂ → Fuel cell → Work

Advantages:

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Solar Thermochemical Reactor Concepts

Direct heating

Concentrated Solar Radiation

Indirect heating

Concentrated Solar Radiation

C + H₂O

syngas

H₂O

syngas
Solar Thermochemical Reactor Concepts

Direct heating

- Concentrated Solar Radiation
- C + H₂O
- syngas
- Convective heat transfer
- Conductive heat transfer
- Radiative heat transfer
- Chemical reaction

Indirect heating

- Concentrated Solar Radiation
- H₂O
- syngas
- upper cavity
- lower cavity
- packed bed
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\[ 150 \text{ kW}_{\text{th}} \] solar pilot plant
Solar Reactor Technology

**Vortex flow reactor:**
- Ø $5 \text{ kW}_{th}$ prototype tested at solar furnace, PSI

**Petcoke slurry:**
- Ø $T_{\text{reactor}} = 1200-1400\degree C$
- Ø $m_C = 0.6-3.6 \text{ g/min}$
- Ø Mean slurry stoichiometry (H$_2$O:C) = 1.5
- Ø Mean total stoichiometry (H$_2$O:C) = 4.0
- Ø Residence time $\tau = 1.0-2.5 \text{ s}$
- Ø $X_C = 87\%$
- Ø $\eta_{\text{thermal}} = 22\%$

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**Energy & Fuels 22, 2043-2052, 2008.**

**Int. J. Hydrogen Energy 33, 679-684, 2008.**
Solar Vortex Reactor (SYNPET)

Solar Reactor Modeling

- Radiation
  - absorption
  - emission
  - reflection/scattering
- Convection
- Fluid flow
- Conduction
- Chemical kinetics

![Diagram of Solar Vortex Reactor](image)

- Petcoke + H₂O slurry
- Concentrated Solar Radiation
- Ceramic cavity
- Vortex flow
- Quartz window
- Syngas (H₂ + CO)
- H₂O nozzle

Graph showing molar fraction vs. radius.

500 kW\textsubscript{th} solar vortex reactor tested at PSA, Spain

- Industrial project SYNPET (2003-2012)
- Material flows:
  - \( \dot{m}_{\text{petcoke}} = 30-50 \text{ kg/h} \)
  - \( \dot{m}_{\text{water}} = 60-100 \text{ kg/h} \)
- Syngas production:
  - \( \dot{m}_{\text{syngas}} = 100-180 \text{ Nm}^3/\text{h} \)

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Solar Reactor Technology

**Two-cavity batch reactor:**
- 5 kW\textsubscript{th} prototype tested at solar simulator, PSI

**Beech charcoal:**
- Reacted mass: measured: 0.29 kg ; simulated: 0.28 kg
- Thermal efficiency: measured: 29% ; simulated: 26%

**Fuel 89, 1133–1140, 2010.**
**AIChE Journal 57, 3522-3533, 2011.**
Solar Gasification Pilot Plant (SOLSYN)

150 kW

Torch
Syngas pipe
Platform with pilot plant
Solar Gasification Pilot Plant (SOLSYN)

Carbonaceous feedstock used

- Beech charcoal
- Low Rank Coal
- Tire chips
- Industrial sludge 1
- Fluff 1
- Dried sewage sludge
- Industrial sludge 2
- Fluff 2
- Bagasse

Energy & Fuels 2013, 27, 4770–4776.
Proximate analyses of feedstock used

- Beech charcoal
- Low rank coal
- Ind. sludge I
- Ind. sludge II
- Fluff I
- Fluff II
- Tire chips
- Dried sewage sludge
- Bagasse

- Energy & Fuels 2013, 27, 4770–4776.
Solar Gasification Pilot Plant (SOLSYN)

Typical solar experiment

Sugar cane bagasse

before test, 138.0 kg, ~20 cm

after test, 8.8 kg, 2-4 cm

Energy & Fuels 2013, 27, 4770-4776.
Solar Gasification Pilot Plant (SOLSYN)

Syngas composition averaged over entire tests

- Beech charcoal
- Low rank coal
- Ind. Sludge I
- Ind. Sludge II
- Fluff I
- Fluff II
- DSS-M
- Bagasse
- Tire chips

Components:
- C3H6 (GC)
- C2H6 (GC)
- C2H4 (GC)
- CO2 (GC)
- CO (GC)
- CH4 (GC)
- H2 (GC)
Energy & Fuels 2013, 27, 4770–4776.

\[ U = \frac{m_{\text{syngas}} \cdot LHV_{\text{syngas}}}{m_{\text{feedstock}} \cdot LHV_{\text{feedstock}}} \]

\[ \eta_{\text{solar-to-fuel}} = \frac{m_{\text{syngas}} \cdot LHV_{\text{syngas}}}{Q_{\text{solar}} + m_{\text{feedstock}} \cdot LHV_{\text{feedstock}}} \]
Solar Gasification Pilot Plant (SOLSYN)

150 kW\textsubscript{th} solar reactor tested at PSA, Spain

- Industrial project SOLSYN (2007-2012)
- Steam gasification of carbonaceous feedstock:

\[
C_1H_xO_y + zH_2O + Ash + (1 - y - z)H_2O \rightarrow CO + (1 - y + x/2)H_2 + Ash
\]

- Two-cavity batch reactor for “beam-down” optics:
  - Temperature range 1000-1200°C
  - Variety of feedstock (coal, sludge, fluff, bagasse) converted to syngas for use in cement manufacturing
  - Calorific value of solar-produced syngas upgraded by 30%
  - Thermal efficiency 30-50%

Energy & Fuels 2013, 27, 4770–4776.
Solar Gasification Industrial Plant

30 MW<sub>th</sub> Industrial Solar Plant Concept

- 1144 heliostats; Reflective area: 61,876 m<sup>2</sup>
- Aim-point at 140 m height

Artist’s view of 50 MW<sub>th</sub> solar gasification plant to produce syngas for use in cement kiln
Gemasolar (Spain): 300 MW$_{th}$, 20 MW$_{e}$ solar power plant with 15 hours molten salt storage
Contact

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