Fuel 211 (2018) 331–340

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Design and demonstration of a prototype 1.5 kW_{th} hybrid solar/autothermal steam gasifier

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ARTICLE INFO

Keywords:
Solar gasification
Synthesis gas
Autothermal gasification
Fluidized bed

ABSTRACT

A 1.5 kW_{th} hybrid solar/autothermal steam gasifier was designed and tested for continuously producing synthesis gas. Time-averaged responses to a series of inlet flow conditions were examined in a high-flux solar simulator. The gasifier consisted of a SiC absorbing/emitting tube inside of a windowless Al_2O_3-SiC cavity containing a fluidized bed indirectly irradiated by concentrated irradiation. Monte Carlo ray-tracing was performed to examine heat flux distributions and determine optimal prototype geometry and lamp settings. An experimental design with replicates was used to examine the effects of H_2O:C, O_2:C, and feedstock with two-way analyses of variance. Carbon conversions of up to 0.79 were achieved, and maximum cold gas ratio and solar-to-fuel efficiency were 1.16 and 22%, respectively. Introduction of O_2 led to a significant increase in bed temperature. Higher performance was observed using activated charcoal compared with lignite coal. The gasifier results indicate that a hybrid solar/autothermal gasification process may be used to overcome disturbances due to solar transients.

1. Introduction

Utilizing concentrated solar irradiation to drive thermochemical processes affords a wide range of paths for producing sustainable fuels. Previous work has examined the concept of coupling together autothermal and solar-driven gasification processes within a single gasifier, allowing for continuous, 24-h production of H_2- and CO-rich synthesis gas (syngas) for downstream fuel or chemical synthesis [1–4]. Fischer-Tropsch (F-T) synthesis allows for the production of drop-in liquid hydrocarbons for the transportation sector. Three modes of operation were realized: (1) solar-driven allothermal gasification during periods with abundant sunlight; (2) autothermal gasification at night or during cloudy periods with the sun obscured; and (3) combined gasification during periods of low to moderate sunlight. Kinetic analyses for the relevant combustion and gasification reactions were performed with activated charcoal, bituminous coal char, and *miscanthus x giganteus* char as the carbonaceous feedstocks [2].

Solar-driven allothermal gasifiers transfer heat to the reactants using two different configurations: (1) directly and (2) indirectly irradiated [5]. Indirectly-irradiated gasifiers avoid use of a quartz glass window, which is prone to fouling at the expense of irreversibilities resulting from conducting heat through an opaque absorber [6]. Previous indirectly-irradiated designs have implemented absorbing/emitting tubes [7–12], plates [13–15], or cylindrical cavities [16,17] to transfer heat to reactants. SiC is commonly used as an absorbing material due to its favorable properties: high emissivity, high thermal conductivity, inertness at high temperatures, and low coefficient of thermal expansion.

Prominent solar-driven gasifier designs that have been examined in literature have employed entrained flow [11,16,18], drop tubes [7,8,10], packed beds [15,19,20], and fluidized beds [12,21–28]. Entrained-flow and drop-tube gasifiers generally have very short residence times while benefiting from enhanced heat and mass transfer. A few studies have been able to achieve high carbon conversions despite these limitations [7,16,18]. Packed beds are able to handle a wide variety of feedstocks and particle sizes with long residence times, but face challenges with heat and mass transport. In addition, all previous packed-bed investigations have operated in a batch-mode. An additional design has explored the use of molten salt as a reaction and heat transfer medium for gasification [17,29,30].

Fluidized beds are used in combustion and gasification applications, as they allow for continuous operation, rapid adjustment of the reactant inputs, high particle residence times, and high gas-solid contact with efficient heat and mass transport. Directly-irradiated fluidized beds for

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http://dx.doi.org/10.1016/j.fuel.2017.09.059
Received 20 July 2017; Received in revised form 5 September 2017; Accepted 13 September 2017

Nomenclature

D	distance traveled by ray
$\hat{e}$	unit vector
h	height
i	surface indices
n	moles
$\hat{n}$	unit normal vector
P	P-value
Q	heat
$\bar{r}$	energy bundle vector
$\bar{r}_0$	starting point vector
$\bar{r}_s$	surface vector
R	cold gas ratio
Re	Reynolds number
$\hat{s}$	unit vector along the path of the energy bundle
t	time
T	temperature
u	velocity
V	volume
x	distance (Cartesian)
X	carbon conversion
y	distance (Cartesian)
z	distance (Cartesian)

Greek

ε	emissivity, void fraction
η	efficiency
λ	wavelength
ρ	density
υ	surface parameter

solar gasification of coal, cokes, and cellulose have been explored in literature [12,21–28]. One drawback of fluidized-bed designs compared to packed beds is that small, relatively uniform feedstock particles are required, translating to costlier feedstock preparation. The continuous nature of fluidized beds where inputs can be adjusted in response to disturbances (*e.g.*, solar irradiance) makes the design applicable for a hybrid solar/autothermal system. Experimental investigations of indirectly-irradiated fluidized beds are lacking in literature [31], with only one study that used steel for the emitter tube material [12].

In the present study, a novel 1.5 kW_{th} hybrid solar/autothermal gasifier was designed, fabricated, and tested in a 6 kW_{th} high-flux solar simulator (HFSS) [32]. The HFSS provides an external source of intense thermal radiation, mostly in the visible and IR spectra, closely approximating the heat transfer characteristics of high solar concentrating facilities. Monte Carlo (MC) ray-tracing analysis was performed to optimize the geometry of the gasifier for maximum absorption of concentrated irradiation. During testing, factors were varied at two levels: (1) H_2O:C ratio (1.1–2.32), feedstock type (activated charcoal and lignite coal), and O_2:C ratio (0–0.33). Time-averaged responses were evaluated in terms of average bed temperature, carbon conversion, cold gas (upgrade) ratio, solar-to-fuel efficiency, H_2:CO ratio, and CO_2 production. Statistical analyses were performed using analysis of variance (ANOVA) to identify significant effects and interactions on response variables.

2. Experimental setup

Experimentation was performed in a novel hybrid solar/autothermal gasifier designed to run continuously in both solar and combined solar/autothermal gasification modes. A fluidized-bed design was implemented, as it allowed for both modulation of feedstock inputs and increased residence times for high conversions of feedstock to syngas. An indirectly-irradiated gasifier was used to avoid the use of a window, eliminating the possibility of failure or fouling during operation in combined solar/autothermal gasification.

A schematic of the gasifier is given in Fig. 1a. The gasifier consisted of a cavity that was constructed from Buster M-35 (Zircar Zirconia) blocks, composed of Al_2O_3-SiO_2 insulation with low thermal conductivity, high operating temperature, and high reflectivity [33]. The cavity was used to capture multiple reflections and emissions while minimizing re-radiation losses to the environment and was held together with a stainless steel casing with dimensions of 210 × 215 × 275 mm^3. The front block contained a 40-mm diameter conical aperture with an acceptance angle of 45°. An absorber tube made of pressureless sintered SiC (Saint-Gobain Ceramics, Hexoloy SA) was positioned inside the cavity and had inner and outer diameters of 42 mm and 52 mm, respectively, and length of 300 mm. SiC was used due to durability at high temperatures, low coefficient of thermal expansion, and high thermal conductivity. Its high strength and chemical inertness

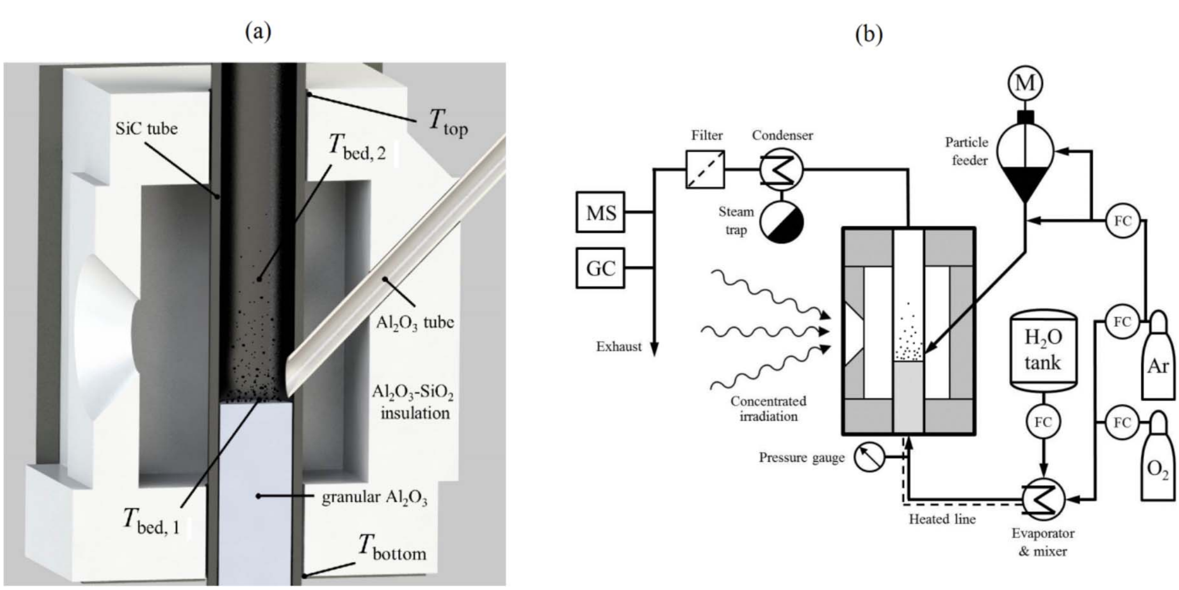

Fig. 1. Hybrid solar/autothermal gasifier (a) schematic and (b) process flow diagram.