



# A two-zone solar-driven gasifier concept: Reactor design and experimental evaluation with bagasse particles



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## HIGHLIGHTS

- Two-zone solar-driven gasifier offers high conversion and favorable syngas quality.
- A drop-tube zone provides efficient radiative heat transfer for rapid pyrolysis.
- A trickle-bed increases solids residence time and enhances the overall heat transfer.
- The two-zone reactor prototype demonstrated improved performance over the drop-tube.
- Solar energy was stored in the syngas and the biomass was energetically upgraded.

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## ABSTRACT

A two-zone solar reactor concept for the steam-based gasification of biomass particles using concentrated solar energy has been developed and experimentally evaluated with particles of sugarcane bagasse at a 1.5 kW solar input scale. The gasifier has been designed with the objective to provide pyrolysis and gasification conditions yielding high carbon conversion into syngas and suppressing the formation of tars and gaseous hydrocarbons. It consists of two zones. In the upper drop-tube zone, a high radiative heat flux to the dispersed particles induces their fast pyrolysis. In the lower trickle bed zone, a structured packing provides the residence time and temperature required for the char gasification and the decomposition of the other pyrolysis products.

A series of 20 min gasification experiments comparing the two-zone reactor vs. a drop-tube reactor were performed in a high-flux solar simulator with a maximum particle flux of 16 g/s m<sup>2</sup>. It has been demonstrated that the former allows for more efficient decomposition of CH<sub>4</sub> and C<sub>2</sub> hydrocarbons at comparable reactor temperatures. The LHV of the product gas leaving the two-zone gasifier was significantly higher than those typically obtained in conventional autothermal gasifiers. Solar energy was chemically stored in the product gas, resulting in energetic upgrade of the biomass by 5% and a maximum energy conversion efficiency of 21%.

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## 1. Introduction

Solar-driven steam-based gasification of biomass is a promising route for producing precursors for valuable chemicals and low-carbon footprint transportation fuels from a renewable resource [1,2]. The highly endothermic thermochemical conversion of biomass with steam to syngas (a mixture composed of H<sub>2</sub> and CO) comprises two main steps: (1) pyrolysis, producing tars, gases and char, and (2) steam-based gasification of the tars and the char to form syngas [3]. The produced syngas can then be processed into H<sub>2</sub> (water–gas shift reaction), diesel or kerosene (Fischer–Tropsch process), or methanol and then gasoline (MTG, Mobil). Alternatively,

the syngas may be used directly as a combustion fuel for power generation.

Previous investigations of solar-driven allothermal gasification of Brazilian sugarcane bagasse have revealed potential benefits over the conventional autothermal gasification such as a higher heating value and a more favorable quality of the produced syngas, i.e. a higher H<sub>2</sub>/CO ratio and less CO<sub>2</sub> contamination [4]. Moreover, a higher utilization of the feedstock can be achieved: instead of combusting 25–40% of the feed biomass to provide the heat necessary to drive the endothermic gasification reactions, the solar-driven gasification uses concentrated solar radiation as the source of high-temperature process heat [1,2,4]. Thus, as the solar energy is chemically stored in an amount equal to the enthalpy change of the endothermic reactions, the calorific value of the syngas produced per unit of feedstock is higher.

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### Nomenclature

$\Delta H_R$	reaction enthalpy (J/mol)	$T$	temperature (K)
ID	inner diameter (mm)	$t$	time (s)
$L$	length (mm)	$U$	upgrade factor (-)
LHV	lower heating value (MJ/kg)/(MJ/Nm <sup>3</sup> )	$x$	elemental molar ratios of H/C (-)
$M$	molar mass (kg/mol)	$X_C$	carbon conversion (-)
$m$	mass(kg)	$y$	elemental molar ratios of O/C, mole fraction (-)/(-)
$\dot{n}$	molar flow rate (mol/s)	$\eta$	energy conversion efficiency (-)
OD	outer diameter (mm)		
$\dot{Q}$	heat flow (W)		

Oxygen- and air-blown downdraft gasifiers are the preferred concepts for the autothermal conversion of a highly volatile feedstock such as biomass into a high-quality syngas. They feature a turbulent oxidation zone maintained at temperatures in the range of 1000–1200 °C. While passing through this high-temperature zone, tars and gaseous hydrocarbons released during pyrolysis are cracked and reformed so that the resulting product gas contains low amounts of tars, dust, and CH<sub>4</sub> (~1–2%). However, it is also diluted by a substantial amount of CO<sub>2</sub> and N<sub>2</sub> if air is used as the combustion gas [3] and contaminated by combustion byproducts (SO<sub>x</sub> and NO<sub>x</sub>) that deactivate catalysts used in the subsequent liquid fuel production step. Therefore, purifying the final product (syngas) and eliminating its dilution imposes additional capital and operating costs for gas scrubbing, CO<sub>2</sub> removal, and on-site O<sub>2</sub> generation.

For solar-driven gasification, where no heat is generated within the reactor, efficient transfer of the concentrated solar radiation to the reaction site is critical for high productivity and favorable gas-phase selectivity. Directly-irradiated solar gasifiers, where the solar radiation is absorbed by the feedstock at the reaction site, enable high heat transfer rates. Yet, those also require a transparent window that not only has to be kept clean during operation which impairs operability in case of highly volatile feedstocks, but also introduces limitations in the scale-up [5–13]. In indirectly-irradiated reactors the incident solar radiation impinges on the outer wall of an opaque absorber which confines feedstock. The heat is transferred to the inner absorber wall by conduction and from there to the feedstock by convection and radiation. Therefore, the need for a window is eliminated at the expense of having less efficient heat transfer. This imposes even more stringent constraints on the materials of the absorber with regards to its operating temperature, chemical stability, thermal conductivity, radiative absorptance, and resistance to thermal shock [2,12,14–20].

A commonly suggested method to achieve the required heat transfer rates in an indirectly-irradiated gasifier is the drop-tube concept. Solar radiation is concentrated through an aperture into either a specularly reflecting [14,19] or absorbing [15,18–20] cavity-receiver housing one or more vertical reactor tubes. The reactor tubes absorb the high-flux irradiation and re-radiate the heat to the particles flowing through. Scalability is straightforward as it is based on a modular multi-tube design [15,21]. However, this reactor concept is suitable only for particles of up to a couple of hundred microns in size for which the radiative heat transfer mode is dominant [22] and the residence time of the order of a second is long enough [4]. Grinding raw biomass to this size range imposes high capital and operating costs that often justify a partial low temperature pyrolysis of the biomass (torrefaction) in order to improve its grindability [23]. At the same time, as the gas is mainly convectively heated by the surface area of the particles that are in a rather dilute flow, this kind of reactor generally does not pro-

vide gas temperatures high enough for effective tar and methane cracking and reforming. Alternative reactor concepts such as packed or moving beds allow the use of coarser biomass particles by providing reaction time that is sufficiently long for high carbon conversion. Unfortunately, these concepts suffer from significantly impaired overall heat transfer due to high extinction of radiation by the densely packed bed of feedstock and ash [13,17].

This work introduces a two-zone solar-driven gasifier designed to retain the advantage of the efficient radiative heat transfer inherent to drop-tube reactors while, however, overcoming their residence time and particle size limitations that constrain cracking and reforming of hydrocarbons. The gasifier consists of a drop-tube zone for fast pyrolysis and a trickle bed for the char gasification. The trickle bed utilizes a structured packing to control the overall porosity of the gasification zone in order to increase the residence time of the char particles while still allowing the radiation to penetrate through. The performance of the two-zone reactor was experimentally tested with Brazilian sugarcane bagasse particles and compared to the performance of the drop-tube configuration.

## 2. Experimental

### 2.1. Feedstock

The feedstock considered was Brazilian sugarcane bagasse. It was dried (105 °C, >4 h) and sieved (sieve size 0.5 mm) to a mean particle size of 455 μm (LA-950 analyzer, HORIBA). The elemental analysis of the particles presented in Table 1 implies CH<sub>1.665</sub>O<sub>0.663</sub> as the overall chemical formula after neglecting the presence of ash, N and S. Calorimetric measurements of the particles after drying (C7000, IKA-Werke) showed a lower heating value (LHV) of 16.50 MJ/kg.

### 2.2. Solar reactor concept

The biomass pyrolysis conditions such as heating rate, gas temperature, and residence time have a strong influence on the release

**Table 1**  
Elemental analysis of bagasse particles (dry basis); C, H, N determined with CHN-900, O with RO-478 and S with CHNS-932 (all LECO Corporation, St. Joseph, MI).

Bagasse		
Carbon (C)	(%wt)	42.51
Hydrogen (H)	(%wt)	5.94
Oxygen (O)	(%wt)	37.54
Nitrogen (N)	(%wt)	0.41
Sulfur (S)	(%wt)	0.09
Ash	(%wt)	13.5
H/C = $x$	(mol/mol)	1.665
O/C = $y$	(mol/mol)	0.663

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