Applied Energy 173 (2016) 578–588

Contents lists available at ScienceDirect

Applied Energy

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

Storage capacity assessment of liquid fuels production by solar gasification in a packed bed reactor using a dynamic process model

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HIGHLIGHTS

- First analysis to assess storage requirements of a stand-alone packed bed, batch process solar gasifier.
- 35 days of storage required for stand-alone solar system, whereas 8 h of storage required for hybrid system.
- Sensitivity of storage requirement to reactor operation, solar region and solar multiple evaluated.

ARTICLE INFO

Article history:
Received 26 December 2015
Received in revised form 14 March 2016
Accepted 10 April 2016
Available online 22 April 2016

Keywords:
Solar gasification
Stand-alone system
Fischer–Tropsch liquids production
Energy storage
System analysis

ABSTRACT

The first multi-day performance analysis of the feasibility of integrating a packed bed, indirectly irradiated solar gasification reactor with a downstream FT liquids production facility is reported. Two fuel-loading scenarios were assessed. In one, the residual unconverted fuel at the end of a day is reused, while in the second, the residual fuel is discarded. To estimate a full year time-series of operation, a simplified statistical model was developed from short-period simulations of the 1-D heat transfer, devolatilisation and gasification chemistry model of a 150 kW_{th} packed bed reactor (based on the authors' earlier work). The short time-series cover a variety of solar conditions to represent seasonal, diurnal and cloud-induced solar transience. Also assessed was the influence of increasing the solar flux incident at the emitter plate of the packed bed reactor on syngas production. The combination of the annual time-series and daily model of syngas production was found to represent reasonably the seasonal transience in syngas production. It was then used to estimate the minimum syngas storage volume required to maintain a stable flow-rate and composition of syngas to a FT reactor over a full year of operation. This found that, for an assumed heliostat field collection area of 1000 m^2, at least 64 days of storage is required, under both the Residual Fuel Re-Use and Discard scenarios. This figure was not sensitive to the two solar sites assessed, Farmington, New Mexico or Tonopah Airport, Nevada. Increasing the heliostat field collection area from 1000 to 1500 m^2, led to an increase in the calculated daily rate of syngas throughput that could be maintained over a full year by 74%, to 5.9 kmol/day. Importantly, a larger heliostat field collection area was calculated to reduce the required storage capacity to approximately halve 35 days, which in absolute terms corresponds to 3.0 tons of syngas. Nevertheless, a requirement for this capacity of storage suggests that the use of the packed bed solar gasification reactor for FT liquids production is unlikely to be viable without substantial changes to the design and operation of the reactor and/or downstream processing plant.

1. Introduction

Energy storage is essential to the high capacity factor operation of electricity generation or fuel production systems integrated with concentrated solar thermal (CST) power systems. Numerous studies have investigated the key drivers of the amount of energy storage required to integrate CST collectors with power generation [1–7] and fuel production cycles [8,9]. These analyses have largely been based on hybrid energy systems, where CST power is indirectly introduced through a secondary thermal loop [1–6] or the combustion of fossil fuels is either supplemented through the direct introduction of CST power into a thermochemical reactor [8], directly into a boiler volume to drive a power cycle [7]. These

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http://dx.doi.org/10.1016/j.apenergy.2016.04.067
0306-2619/

analyses further evaluate the sensitivity of the required storage volume to over capacity in the size of the heliostat field, the solar region and the capacity factor of the energy conversion (power) block [1–4]. It is well established that hybridizing conventional power systems to receive direct or indirect solar thermal input [1–7] requires a lower amount of energy storage but this is inevitably at the expense of reduced solar share. While there have been fewer assessments of standalone solar energy systems, Kueh et al. recently presented an important study assessing the storage requirements for a stand-alone solar thermal power generation cycle to have no unscheduled shut downs over a full year of operation [10]. However, there has been no study assessing the storage requirements of standalone CST systems designed to provide input to a chemical reactor. Indeed, no study has presented an evaluation of the minimum quantity of syngas storage required to enable the integration of a standalone solar thermochemical reactor with a downstream syngas upgrading system such that it has no shut-downs over a full solar year. The present assessment aims to meet this gap.

A recent full-year process modeling analysis of a system integrating an atmospheric pressure hybrid solar gasifier with a FT liquids production system, using an hourly averaged solar dataset, showed that as little as eight hours of syngas storage was required to enable steady state operation of the downstream syngas upgrading reactor over a full solar year [8]. This analysis proposed a hybrid, continuously operational solar, entrained flow gasifier based on the experimentally proven solar vortex reactor [11,12], assuming that CST power drives gasification in the reactor volume when it is available and autothermal reactions in pure O_2 drive gasification, within the same volume, when solar energy is not available [8]. Although this system required a modest quantum of syngas storage, it was estimated to contribute as much as 15% of the plant's total capital cost and between 10% and 15% of the levelised cost of fuel [13]. While the proposed hybrid solar vortex reactor enables a constant non-zero syngas output, there are several notable challenges to scaling this reactor to the same capacity as a pressurised, autothermal entrained flow gasifier [8,11,12]. These challenges include maintaining a clean window through which CST energy is introduced to the reactor volume, and because the window prevents the reactor from being operated above 1 bar-a [11,12]. In comparison, with this reactor concept, the indirectly irradiated packed bed reactor, has been proven to be operationally robust at a scale of 150 kW_{th} and could also feasibly operate in a pressurised environment (although this has not yet been experimentally demonstrated). However, in this system solar heat is transferred to the fuel bed via a SiC emitter plate [14–19], which makes the reactor less efficient than the solar vortex reactor where coal particles are directly irradiated [11,12]. Furthermore, because the packed bed reactor relies on solar energy alone to drive thermochemical reactions, it is far more susceptible to solar intermittency. Thus, it may require a much larger amount of storage than that estimated for the hypothetical hybrid solar gasification reactor [10]. The present study thus aims to assess the feasibility of integrating sufficient storage with a solar standalone packed bed gasifier, so as to enable the steady state of operation of a downstream syngas upgrading process over a full solar year.

The indirectly irradiated, packed bed solar gasifier has been proven, at a scale of 150 kW_{th}, to be operationally robust [14–19]. Concentrated solar thermal radiation is introduced into this reactor through a compound parabolic concentrator (CPC) at the top to irradiate a SiC-coated metal emitter plate (see Fig. 1). This emitter plate then re-radiates the thermal energy to the fuel bed that is batched into the reactor before the start of each solar day. The emitter plate reaches temperatures of up to 1400 K after only one hour from the start of the solar day. However, the top of the fuel bed can take 2–3 h to reach steady-state temperatures [14,19]. As the temperature

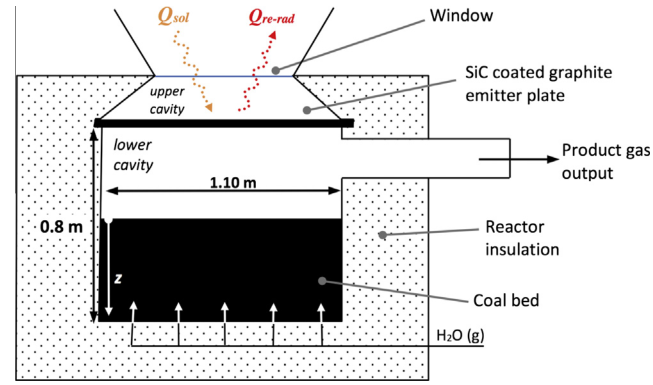

Fig. 1. Schematic diagram of the solar packed bed gasifier, based on the experimental configuration reported by Wieckert et al. [19].

at the top of the bed rises, the fuel is dried, undergoes thermal decomposition (devolatilisation) to release volatile gases and is then slowly gasified at temperatures above 1000 K in the presence of steam. The reacting layer then descends through the bed, causing the bed to shrink at a rate that is approximately linear with time. Although, this leads to acceleration in the rate of heat conduction through the bed [14,20], the accumulation of ash on top of the fuel bed insulates the more active char layers underneath. In practice, this has meant that the bed surface temperature has been more than 500 K hotter than the base by the end of a solar day, on a day with consistent solar irradiation [14,19]. This temperature gradient through the fuel bed leads to a large variance in the rate at which devolatilisation and gasification reactions proceed through the bed. It has also meant that only 50–60% of the fuel that is batched into the reactor at the start of a solar day is converted to syngas and the average composition of the residual fuel at the end of the day is vastly different to that of the original feedstock [20]. Building on previous work [14–19], Kaniyal et al. [20] developed a simplified model of the packed bed gasification reactor using one-dimensional heat transfer, functional group devolatilisation and gasification reaction kinetics to compare syngas production and composition for a range of fuels with varying volatile content [21,22]. While the Kaniyal et al. model broadly represented the fuel conversion rate that the packed bed reactor was measured to achieve experimentally, no study has presented a multi-day analysis of the packed bed reactor's gasification performance. Hence, to assess the impact of the potential operational impacts of variations in solar energy over a full year, on syngas production and composition, the present assessment aims to estimate these performance parameters for two scenarios, one where residual fuel that is left ungasified from each day is reused and a scenario, and second where fuel at the end of each solar day is discarded.

Two options to upgrade the syngas produced with the packed bed solar gasifier are, electricity generation (typically in a combined cycle gas turbine system) [23–25] and/or the production of synthetic crude oil by a Fischer-Tropsch process [23,26–30] (see Fig. 2). Typically the FT option is likely to be more desirable due to the higher value of liquid fuels over electricity [13,31]. However, a prerequisite to FT liquids production with currently available FT reactors is the need to propose a method with which to achieve a steady-state output in both the flow-rate and composition of the upgraded syngas over a full solar year despite variable output from the packed bed gasifier. The preferred type of FT reactor for solar thermal operations is likely to be a micro-channel reactor, since these can reduce by an order of magnitude the throughput needed to achieve viability over a conventional fixed bed FT reactor [32,33]. However, it is necessary to maintain a precise temperature of 210 ± 2 °C within a microchannel FT reactor to achieve high syngas conversion rates of ~70–75% and enable >90% C5+ (i.e. C_nH_{2n+2}