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Steam gasification of coal cokes by internally circulating fluidized-bed reactor by concentrated Xe-light radiation for solar syngas production

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ABSTRACT

A laboratory-scale prototype windowed reactor using a fluidized bed of coal coke particles was tested for thermochemical gasification using concentrated Xe light radiation as an energy source. The fluidized-bed reactor, designed to be combined with a solar reflective tower or beam-down optics, is evaluated for steam gasification of coal coke according to gasification performance: CO, H_2, and CO_2 production rates; carbon conversion; light-to-chemical efficiency. Internal circulation of coal coke particles inside the reactor increases gasification performance, which is further enhanced by higher steam partial pressure of the inlet gas.

1. Introduction

Thermochemical conversions such as combustion, gasification, and pyrolysis are a core technology that can be broadly utilized to generate clean energy. Solar gasification is a promising thermochemical conversion that can produce clean chemical fuels by utilizing high-temperature solar heat as an energy source and carbonaceous materials as a chemical source. Solar thermochemical gasification allows the high-temperature solar heat, produced via concentrated solar radiation, to be converted to a long-term storable energy carrier [1–3]. Coal gasification using CO_2 or steam as an oxidant, which is a highly endothermic process at high-temperatures, is a process available for the production of solar-hybrid syngas (solar-fuel) composed of a mixture of hydrogen and carbon monoxide [1–3].

$$CH_n(coal) + H_2O(l) = CO + (1 + n/2)H_2 \ \Delta H_{298K} = 175 \text{ kJ/mol} \quad (1)$$

$$CH_n(coal) + CO_2 = 2CO + n/2H_2 \ \Delta H_{298K} = 172 \text{ kJ/mol} \quad (2)$$

The calorific value of coal or carbon feed can theoretically be raised by about 45% when the process heat required to drive the reactions shown in Equations (1) and (2) is sourced from concentrated solar radiation. Syngas derived from solar energy can be used directly as a combustion fuel for power generation or be thermochemically converted into hydrogen via the water-gas shift reaction to liquid hydrocarbon fuels such as diesel, kerosene, and gasoline via the Fischer–Tropsch synthesis. Furthermore, ammonia can be produced from the hydrogen, by combining with a nitrogen source via Haber–Bosch process, while methanol and DME (dimethyl ether) can be converted from syngas. The production of transportable liquid fuel is an important step when importing solar energy to remote countries, such as Japan, from sunbelt countries (Australia, India, China, etc.) that have much higher solar radiation and abundant coal reserves.

The concepts of solar receiver-reactors, used for driving the solar gasification process, have been demonstrated for solar gasification reactors including direct-absorbing particle bed [4,5], molten salt pool [6], vortex-flow [7,8], particle-flow [9], and packed-bed [10] designs. Indirect-absorbing particle reactors have been scaled-up to pilot plant stage and experimentally tested for solar gasification of carbonaceous materials [9,10]. The indirect irradiated packed-bed reactor is characterized by its robustness, simplicity of

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operation, and independence from feedstock shape [10]. Alternatively, in a direct-absorbing particle design where solar radiation is focused directly onto a reacting particle bed through a transparent quartz window, the receiver-reactors are developed and tested for the solar gasification of coal and petroleum cokes [11–16]. A fluidized bed of coke particles is desirable for the development of a solar gasification reactor at an industrial scale, compared with the fixed-, packed-, and moving-bed reactors. A fluidized-bed reactor can essentially overcome the limitations of mass and heat transfer, long solid residence times, and ash buildup that slow the reaction. Taylor et al. [12] demonstrated the CO_2 gasification of charcoal in a fluidized-bed reactor under direct solar irradiation. The reactor, made of a vertical silica-glass tube, was placed and tested at the focus of a solar furnace. Epstein et al. [13] studied circulating or spouted fluidized-bed reactors as solar gasification reactors. A gas particle solar receiver-reactor was constructed and tried for the solar steam gasification of petroleum coke particles [14]. This windowed solar reactor consisted of a continuous vortex flow of steam loaded with petroleum coke particles confined to a cavity receiver. A 5 kW reactor was tested in the temperature range 1300–1800 K. In recent years, a solar gasification pilot plant designed for a power input of 500 kW was constructed and tested for steam gasification of petcoke under direct solar irradiation [15]. The 500 kW solar gasification plant was installed for gasifying heavy crude oil solid derivatives at the SSPS (small solar power system) tower located at the Plataforma Solar de Almería research site (Spain) [16].

A newly developed solar reflective tower or beam-down optics is proposed for the production of solar fuel [17–20]. The optical path of a beam-down system consists of a heliostat field that illuminates a hyperboloidal reflector placed on a tower, and directs the beams downward. In principle, this beam-down arrangement has some advantages over standard tower-top reactor arrangements, as it allows a large-scale reactor to be built closer to the ground. The solar radiation enters the reactor housing through a transparent quartz window in the ceiling of the reactor. Both the upper and downward focal points of the concentrated solar radiation are essentially fixed, irrespective of the Sun's trajectory over time. A solar gasification reactor utilizing a beam-down arrangement, therefore, enables a large heliostat field compared with that of a conventional tower system and subsequently a much higher concentration of solar energy can be achieved in one receiver.

The previous studies examined a fluidized-bed reactor of reacting particles for the purposes of combining it with beam-down optics for the solar gasification of coal coke particles. Two designs of fluidized-bed reactor—internally circulating type and conventional type without a draft tube—were evaluated for CO_2 gasification of coal coke, using Xe-light concentrated via a beam-down-type sun simulator as an energy source [21–23]. The purposes of this study are to demonstrate the validity of the internal circulation of coke particles within a solar reactor for steam gasification, and to further enhance the steam gasification performance of an internally circulating fluidized-bed reactor. This was achieved by using concentrated Xe-light from a 3 kW_{th} beam-down type

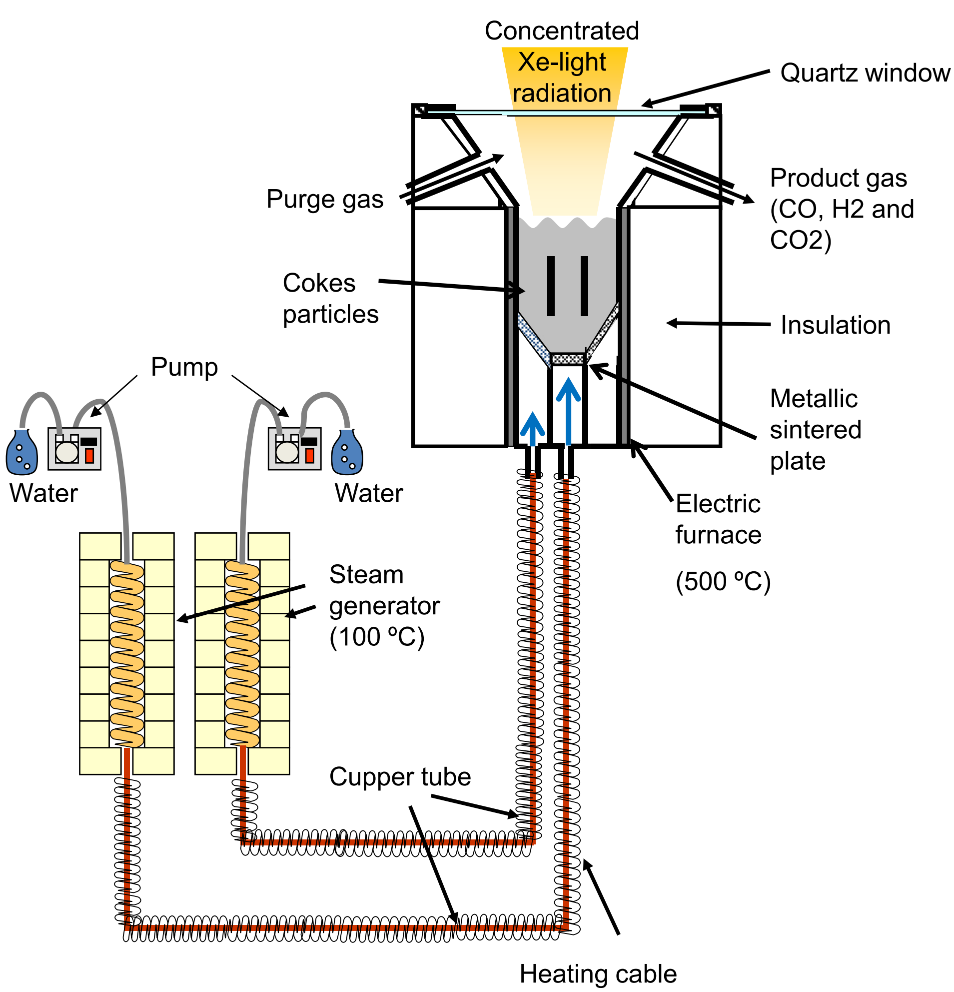

Fig. 1. Experimental setup for gasification in an internally circulating fluidized-bed reactor using coal coke particles.

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