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ScienceDirect

Solar Energy 129 (2016) 85–100

SOLAR ENERGY

www.elsevier.com/locate/solener

Heat transfer in directly irradiated fluidized beds

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Received 1 October 2015; received in revised form 27 January 2016; accepted 31 January 2016
Available online 13 February 2016

Communicated by: Associate Editor Michael Epstein

Abstract

Directly-irradiated fluidized bed solar reactors are very promising in the context of solar chemistry and concentrated solar power (CSP) applications. With proper choice of the bed solids, fluidized bed reactors can be operated at fairly high process temperatures that enable thermochemical storage with high energy density and production of solar chemicals and fuels. Bed surface overheating upon irradiation is one key to the efficiency of the fluidized bed as thermal receiver and may be responsible for sintering and/or degradation of the fluidized particles. Tailoring the hydrodynamics of the bed close to the region where the incident power is concentrated may disclose effective measures to improve the interaction between the incident radiative flux and the bed and mitigate bed surface overheating.

In the present study radiative heat transfer from a concentrated simulated solar radiation source to a fluidized bed is investigated by time-resolved infrared mapping of the bed surface temperature. A fluidized bed of silicon carbide particles (0.127 mm), whose cross-sectional area is 0.78 × 0.78 m, was directly irradiated by highly concentrated simulated solar radiation, emitted by a 4 kW_{el} short-arc Xe lamp coupled with an elliptical reflector. The experimental apparatus is also equipped with a movable nozzle coupled with a bubble generation system located coaxially to the concentrated simulated solar beam. The interaction of the concentrated radiative flux with the fluidized particles moving under the action of bubble bursting was assessed by characterizing the time-resolved bed surface temperature as the fluidization gas velocity was varied. The effect of localized generation of bubbles was also investigated by injecting chains of multiple bubbles from the nozzle located at variable distance from the bed surface.

Keywords: Fluidized bed; Solar reactor; Heat transfer; Bubble bursting

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1. Introduction

Development and deployment of Concentrated Solar Power (CSP) as a renewable energy resource in Countries with strong direct normal solar irradiance is gaining ever-increasing interest as it represents a key climate-change mitigation technological option. International Energy Agency (IEA) provides outlooks for CSP deployment from 2010 to 2050 predicting that, with appropriate support, CSP could supply 11.3% of global electricity demand by 2050, 9.6% directly derived from solar power and 1.7% from backup fuels. CSP plants coupled with thermodynamic cycles can be integrated with Thermal Energy Storage (TES) and hybridized with fuels to compensate for sunlight variability over the daytime scale and possible shift between peak solar irradiation and power demand. Three different mechanisms for energy storage are being

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http://dx.doi.org/10.1016/j.solener.2016.01.057
0038-092X/

considered, based on storage of sensible, latent and thermochemical heat (Herrmann and Kearney, 2002; Kato et al., 2009; Gil et al., 2010; Fernandes et al., 2012; Felderhoff et al., 2013; Pardo et al., 2014). Among them, storage of thermochemical heat offers larger storage density and virtually unlimited storage period and transport distance, though the technology is more complex and not yet readily deployable. An efficient path for thermochemical storage consists in the production of solar fuels. Several processes are currently under investigation worldwide, based on: (i) H_2O/CO_2 molecule splitting by solar two-step thermochemical cycles using metal oxide redox reactions (Kodama, 2003; Gokon et al., 2008, 2011; Furler et al., 2012); (ii) solar decarbonization of fossil fuels (petcoke and coal) by solar cracking, solar reforming and solar gasification (Gokon et al., 2012, 2015); (iii) solar biomass gasification for liquid bio-fuels production (Hertwich and Zhang, 2009; Nzihou et al., 2012).

A critical point in CSP systems is the development of the receiver, which must accomplish the crucial task of collecting and transferring the incident solar energy. A good receiver should ensure the lowest possible heat losses and minimize local overheating, so as to limit the thermomechanical stresses that could deteriorate process materials. The global efficiency of a CSP plant is highly dependent on the receiver performance which affects all the subsequent steps of the process. Gas–solid fluidized beds have been proposed as convenient tools for the development of solar receivers. They are characterized by large heat transfer coefficients and thermal diffusivities (Bachovchin et al., 1983; Solimene et al., 2014) which make them a fairly convenient environment for solar-driven thermochemical processes (Angrisani et al., 2013). The potential of such reactors has already been recognized and discussed by several research groups (Flamant et al., 1980; Flamant, 1982; Bachovchin et al., 1983; Flamant and Olalde, 1983; Koenigsdorff and Kienzle, 1991). Fluidized beds have been positively tested at the laboratory scale for generation of solar fuels and materials (Steinfeld et al., 1997; von Zedtwitz and Steinfeld, 2005; von Zedtwitz et al., 2007; Gokon et al., 2008, 2011, 2015) and they have also been proposed for the integration of CSP with calcium looping for post-combustion CO_2 capture and storage (Tregambi et al., 2015).

Different configurations can be considered as regards the interaction between the incident radiative flux and the fluidized bed. Indirect heating is accomplished by focusing solar radiation onto a cavity or an exposed surface whence heat is transferred to the fluidized bed. Indirect heating is inherently simple, but possible uneven irradiation on temperature-sensitive surfaces may lead to exceedingly large local radiative fluxes, overheating and unacceptable thermomechanical stresses acting on the solar irradiated wall of the reactor. Different concepts of indirectly-heated dense gas–solid fluidized bed receivers have been recently proposed. Chirone et al. (2013) and Salatino et al. (2016) documented the use of unevenly and unsteadily fluidized beds accomplishing three basic tasks: (1) collection of concentrated solar radiation; (2) thermal energy transfer to end-use; (3) thermal energy storage. This concept led to the successful demonstration of a 150 kW_{th} (peak) solar receiver. An external-circulating dense dual fluidized bed rated at about 150 kW_{th} maximum power has been developed and demonstrated by Flamant et al. (2013) and Benoit et al. (2015).

An alternative option can be represented by direct irradiation of the fluidized bed through transparent walls or windows (direct heating). Direct absorption of solar energy permits higher operating temperatures (Alonso and Romero, 2015), hence availability of high-grade thermal energy. Directly-irradiated fluidized bed reactors are very promising in the context of solar chemistry and CSP applications, as they can be operated at process temperatures high enough to perform thermochemical storage with high energy density and production of solar fuels. Several studies (Flamant et al., 1980; Flamant, 1982; Bachovchin et al., 1983; Flamant and Olalde, 1983; Gokon et al., 2012; Matsubara et al., 2014) investigated direct heating of the surface of fluidized beds by high-density radiative flux generated by concentrated solar radiation. Typically, bed temperature and axial temperature profiles along the bed were measured for different bed materials and gas superficial velocities. Bed surface overheating is a critical issue because it determines the efficiency of fluidized beds as thermal receivers and possible sintering and/or degradation of the fluidized particles, hence the reduction of the efficiency of thermochemical cycles. The key drawback of direct heating across transparent media is the need to keep the medium clean and scratch-free, as any deterioration of the medium transmittance drastically reduces the efficiency of the system and increases the medium temperature (Koenigsdorff and Kienzle, 1991; Werther et al., 1994).

The present study aims at deeper characterization of the direct interaction between concentrated simulated solar radiation and a fluidized bed. Radiative heat transfer and lateral dispersion of the incoming radiative flux are characterized by time-resolved infrared mapping of the surface of a directly-irradiated gas–solid dense fluidized bed. Possible improvements of the interaction between radiative flux and fluidized particles induced by tailoring the hydrodynamics of the bed have been assessed. To this end the effect of localized injection of chains of bubbles from a nozzle located in the proximity of the radiation focal point has been investigated.

2. Experimental

2.1. Experimental apparatus and materials

The experimental apparatus is represented in Fig. 1. Its main components are:

(i) A fluidized bed reactor with a gas preheater and a mass flow control system;