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A Novel Solar Expanding-Vortex Particle Reactor: Experimental and Numerical Investigation of the Iso-thermal Flow Field and Particle Deposition

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Abstract

The paper reports an experimental and numerical analysis of the iso-thermal flow field within a solar vortex receiver–reactor, termed the Solar Expanding-Vortex particle Reactor, SEVR, together with an assessment of its propensity to mitigate particle deposition onto the receiver–reactor window, with the aim to assess the validity of an aerodynamic mechanism previously proposed. The influence of the dominant reactor geometrical parameters, particle size and load on the vortex structure and particle deposition onto the receiver–reactor window was investigated. It was found that the SEVR can be configured to substantially mitigate the particle deposition in comparison with the previous state-of-the-art of solar vortex receiver–reactor. Furthermore, the experimental results confirmed the aerodynamic mechanism previously proposed, in which two critical parameters controlling the propensity of particles to penetrate into the secondary concentrator chamber are the intensity of the vortex at the plane of the aperture and the diameter of the vortex core at the aperture plane relative to the aperture diameter.

Keywords: Solar receiver–reactor; Vortex flow; Cobra probe; CFD; Particle deposition

1. Introduction

Directly-irradiated particle receivers for Concentrated Solar Thermal energy (CST) applications are attracting growing attention because their potential to achieve higher temperatures and higher efficiency than is possible with tubular receivers (Ho and Iverson, 2014). Compared with other solar receivers, particle receivers have many favourable characteristics such as the potential to achieve direct heat transfer, through absorption of the concentrated solar radiation by the particles, without the exergetic losses and the flux limitations associated with heating a fluid through tubes (Piatkowski and Steinfeld, 2008, 2011; Piatkowski et al., 2011). Particle receivers can potentially be employed for industrial process heat applications, solar energy (including fuels and chemicals production) or for heating the working fluid in a power cycle for electricity generation. In power cycles, particles also provide potential for sensible and/or chemical heat storage, offering a thermal energy storage capability in a larger temperature range, at a cheaper cost in comparison with current state-of-the-art of nitrate salt thermal energy storage systems (Behar et al., 2013). In chemical processes such as gasification and mineral processing, the benefits of employing particle

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Nomenclature

d_{ap}	aperture diameter (m)
D_c	receiver–reactor diameter (m)
d_{in}	inlet diameter (m)
d_p	particle diameter, (μm)
$d_{v,max}$	vortex core dimension (m)
I	turbulence intensity (see Eq. (3))
L	receiver–reactor length (m)
$\dot{m}_{p,win}/\dot{m}_{p,in}$	particle deposition rate
S	Swirl number (see Eq. (2))
Sk	Stokes number (see Eqs. (1) and (4))
u	axial velocity (m/s)
U_{in}	inlet gas velocity (m/s)
V	receiver–reactor volume (m^3)
$\dot{V}$	total inlet gas volumetric flow rate (m^3/s)
v	tangential velocity (m/s)

Greek symbols

α	cone angle (°)
μ	gas viscosity (Pa s)
ρ_p	particle density (kg/m^3)
τ	nominal receiver–reactor residence time (s)
ϕ	volume fraction of particles

Subscripts

ap	aperture plane
out	outlet plane
p	particle
SC	secondary concentrator
win	receiver–reactor window

Abbreviations

CSR	Concentrated Solar Radiation
CST	Concentrated Solar Thermal
SC	Secondary Concentrator
SEVR	Solar Expanding-Vortex particle Reactor
SVR	Solar Vortex Reactor

receivers include CO_2 emission reduction and prevention of gaseous products contamination due to the use of concentrated solar radiation as the source of process heat, rather than internal combustion (Taylor, 1983; Trommer and Steinfeld, 2006; Z'Graggen and Steinfeld, 2008; Puig-Arnavat et al., 2013; Jafarian et al., 2014). However, further development is required to develop particle receivers that are both energetically efficient and technologically robust.

A wide range of directly-irradiated particle receivers have been proposed to date, such as fluidised bed and falling particle receivers. One of the most promising particle receiver–reactor concepts is the Solar Vortex Reactor, SVR, which has been found to have a comparatively high energy conversion efficiency among several directly-irradiated solar receiver–reactors and it has been applied successfully at laboratory scale to several applications, e.g. gasification of carbonaceous materials (Steinfeld, 2005; Piatkowski and Steinfeld, 2011; Z'Graggen et al., 2006, 2007; Z'Graggen and Steinfeld, 2008; Z'Graggen, 2008; Jafarian et al., 2013). Similarly to other previous high temperature CST receivers, the SVR features a cylindrical cavity together with an aperture, sealed with a transparent window through which the incident Concentrated Solar Radiation, CSR, enters into the cavity. The reactor also employs a Secondary Concentrator (SC). Transport fluid and solid particles are injected tangentially into the SVR, together with any gaseous reactants and purge streams, to generate a vortex flow within it. The tangentially injected fluid transports the particles through the cavity, resulting in an efficient absorption of the CSR and mixing. However, despite its advantages, present SVR design has an important limitation that poses a significant challenge to the robust operation of this receiver, namely the propensity to deposit particles onto the receiver–reactor window (Ozalp et al., 2013; Steinfeld, 2005). In particular, this adversely affects the energy efficiency and the chemical conversion, while also generating the risk of failure of the window. Means to avoid window damage due to particle deposition have thus far proved prohibitive to implement (Steinfeld, 2005) or less than 100% effective (Tian et al., 2015). Therefore, the overall objective of the present study is to support the development of an alternative configuration of directly-irradiated solar receiver–reactors, which aims to allow both direct heat transfer and continuous operation by addressing particular limitations of concepts that have previously been proposed.

Several studies (Steinfeld et al., 1998; Hirsch and Steinfeld, 2004; Shilapuram et al., 2011; Kogan and Kogan, 2002; Kogan et al., 2004, 2007; Kodama et al., 2002, 2008) have shown that the fluid-dynamic vortex structure within the SVR strongly influences the particle deposition onto the window. However, only limited relevant experimental measurements of the flow-patterns within the SVR and qualitative analysis of the particle deposition and window state are available in literature (Meier et al., 1996; Kogan and Kogan, 2002; Ozalp and Kanjirakat, 2010; Ozalp et al., 2013), so that the mechanisms that control the propensity of the particles to deposit onto the receiver–reactor window are still poorly understood. Furthermore, a comprehensive study that correlates key parameters (particle size, particle load, vortex structure, geometrical reactor parameters) with the window state is currently not available in literature. A full