Solar Energy 141 (2017) 25–37

Contents lists available at ScienceDirect

Solar Energy

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

Experimental and numerical investigation of the flow characteristics within a Solar Expanding-Vortex Particle Receiver-Reactor

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ARTICLE INFO

Article history:
Received 23 May 2016
Received in revised form 24 October 2016
Accepted 10 November 2016

Keywords:
Solar reactor
Vortex flow
Particle deposition
Precessing Vortex Core
CFD
Particle image velocimetry

ABSTRACT

The iso-thermal flow field within several configurations of a Solar Expanding-Vortex Particle Receiver-Reactor (SEVR) was investigated, using a combination of multi-plane particle image velocimetry (PIV) and Reynolds-Averaged Navier-Stokes (RANS) computational modeling, at a constant inlet Reynolds number of 12,300. The experimental and numerical results confirmed that the SEVR generates a well-established vortex flow pattern, which approaches a forced vortex near to the injection plane and a combined (free and forced) vortex in the main body of the cavity. The SEVR also features a reversed flow in the vortex core region and a complex precessing vortex core (PVC) structure, which is stronger in both the inlet and outlet regions of the cavity. The primary mechanism for particle deposition was identified as a primary recirculation zone near to the aperture that transports fluid from the main cavity through the aperture. The presence or absence of this recirculation zone was associated with the relative size of the vortex core dimension at the aperture plane and the aperture size. It was also found that the presence of a PVC at the aperture plane further increases the potential for the particle deposition onto the receiver-reactor window by generating a secondary recirculation zone in the vortex core region that transports fluid through the aperture. The use of a sufficiently long cavity or a sufficiently large cone angle can assist both in stabilising the PVC and increasing the size of the vortex core at the aperture plane. These two effects are postulated to reduce the potential for particle deposition onto the receiver-reactor window.

1. Introduction

There is growing interest in directly-irradiated particle receivers-reactors for concentrated solar thermal (CST) applications due to their potential to achieve higher temperatures and efficiencies than indirectly-irradiated receivers-reactors (Piatkowski et al., 2011; Steinfeld, 2005; Ho and Iverson, 2014). Current high temperature CST receivers/reactors typically adopt a cavity-type configuration to limit heat losses, together with an opening, or aperture, to transmit the incident concentrated solar radiation into the device (Steinfeld, 2005). One of the most promising directly-irradiated solar reactors is the solar vortex reactor (SVR), which has been applied successfully to gasification of carbonaceous materials, methane decomposition as well as co-production of zinc and syngas (Hirsch and Steinfeld, 2004; Kräupl and Steinfeld, 2001; Lay, 1959; Trommer et al., 2004). The SVR consists of a transparent window, a secondary concentrator (SC), an aperture and a cylindrical cavity. Fluid is used to convey solid particles (typically reacting), which are injected tangentially into the reactor to generate a vortex flow within the cavity. This vortex transports the particles through the reactor and increases the effective absorption of the concentrated solar radiation by increasing the particle residence time within the reactor. Importantly, the SVR has also been found to have the highest energy conversion efficiency among several directly irradiated solar reactors, achieving a maximum solar to chemical conversion efficiency of 26% in a laboratory scale solar-gasification application (Piatkowski et al., 2011). Although these values depend strongly on the reactor scale, this is a significant improvement over the particular packed-bed and fluidized-bed solar receivers-reactors of comparable scale which typically achieve energy conversion efficiencies in the range of 8–16% (Steinfeld, 2005; Taylor et al., 1983; Z'Graggen et al., 2006; Kodama et al., 2008). Therefore, the overall objective of the present paper is to provide an increased

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http://dx.doi.org/10.1016/j.solener.2016.11.020
0038-092X/

Nomenclature

D_c	receiver-reactor diameter (mm)
d_p	particle diameter (μm)
$d_{v,\max}$	vortex core dimension (m)
f	frequency (Hz)
L	receiver-reactor Length (mm)
r	radial location (mm)
Re	Reynolds number
R_{cy}	radius of the cylindrical section of the receiver-reactor (mm)
Sk	Stokes number
Sr	Strouhal number
t	time (s)
U_{in}	inlet gas velocity (m/s)
u_θ	tangential velocity (m/s)
u_r	radial velocity (m/s)
u_x	axial velocity (m/s)
$\dot{V}$	total inlet volumetric flow rate (m^3/s)
x	axial coordinate

Greek symbols

α	cone angle (°)
γ	specific gravity
μ	dynamic viscosity
Δr	displacement between the geometric centre and the vortex core

Subscripts

ap	aperture
con	conical region
cy	cylindrical region
in	inlet
jet	Jet
p	seeding particle
SC	secondary concentrator

Acronyms

CST	Concentrated Solar Thermal
PVC	Precessing Vortex Core
SEVR	Solar Expanding-Vortex Particle Receiver-Reactor
SVR	Solar Vortex Reactor

understanding of the aerodynamics within these devices and thereby to support the further development of the directly-irradiated solar vortex receiver-reactor technology.

Despite its advantages, the original configuration of the SVR has one major limitation for stable continuous operation, namely, the propensity of particles to deposit onto the receiver-reactor window (Jaya Krishna and Ozalp, 2013; Ozalp and Kanjirakat, 2010a, 2010b; Ozalp et al., 2013). This leads not only to a reduction in efficiency through attenuation of the input radiation, but also to a greater risk of structural failure of the receiver-reactor window due to the overheating of localised particle deposits. One approach to mitigate this challenge is to employ an array of auxiliary gas jets over the receiver-reactor window to minimize the particle deposition (Hirsch and Steinfeld, 2004; Jaya Krishna and Ozalp, 2013; Kogan and Kogan, 2002). However, the introduction of purging gas dilutes the products and decreases the energy conversion efficiency because a portion of the incoming solar energy is absorbed by the purging gas, whose flow-rate is large. Furthermore, the optimal purging flow configuration is sensitive to the operating conditions. An alternative approach to mitigate these challenges has been recently proposed by Chinnici et al. (2015a, 2015b, 2015c, 2016). They developed a novel configuration of SVR, termed the Solar Expanding-Vortex Particle Receiver-Reactor, SEVR, that can be configured to greatly mitigate the particle deposition onto the receiver-reactor window (without the use of purging gas flows) by modifying the fluid-dynamic structure of the vortex within the receiver-reactor cavity in comparison with current SVR configurations. However, only limited measurements are presently available of the performance of this device, particularly of the flow-field. Therefore, the present paper aims to meet this need.

Previous investigations of the SEVR technology (Chinnici et al., 2015b, 2016), identified a partially validated aerodynamic mechanism that offers potential to substantially mitigate the particle deposition through an experimental and numerical investigation of the iso-thermal flow-patterns within the SEVR and particle deposition onto the window. However, the available measurements of the flow patterns within the SEVR are limited to the outer part of the vortex region in the main cavity and were also performed with single-point techniques (Chinnici et al., 2015c, 2016). Therefore, a more detailed characterisation of the flow patterns within the SEVR is needed to advance current understanding of the mechanisms controlling the particle deposition onto the receiver-reactor window in a SEVR.

Furthermore, the use of single-point techniques in previous investigations prevented the assessment of the possible influence of large-scale coherent and time-dependent structures such as the Precessing Vortex Core, PVC, (Syred, 2006; Valera-Medina et al., 2009; Martinelli et al., 2007) within the SEVR. The PVC is a fluid-dynamic instability that has been observed in several vortex devices (Syred, 2006, 2011) that appears to be a mechanism for the rapid transport of fluid, caused by the unsteady precession of an internal vortex in the vicinity of a central recirculation zone, CRZ (Valera-Medina et al., 2009). It significantly influences the flow characteristics, the mixing process and the overall performance of a vortex device (Syred, 2006). A key flow feature of the SEVR is the CRZ (Chinnici et al., 2015b), so that the PVC is likely to be present in some configurations of the SEVR. Hence, an assessment of the presence of the PVC within the SEVR and its potential impact on the particle deposition is also needed.

To meet these needs, the present paper reports an experimental and numerical investigation of the iso-thermal flow patterns within a SEVR with the following specific aims: (a) to provide a detailed characterisation of the flow-field within a SEVR, (b) to advance current understanding of the previously proposed aerodynamic mechanism and (c) to identify and characterise any large coherent structures (e.g. PVC) within a SEVR and assess their role in the mechanism controlling transport of particle-laden fluid into the chamber supporting the window.

2. Research approach

2.1. SEVR configuration selected in the present study

The SEVR configuration is shown schematically in Fig. 1. Its design principles have been reported previously (Chinnici et al., 2015b), so only the key features are described here. The cavity of the receiver-reactor consists of a cylindrical chamber with a coni-