



Analytical assessment of a novel rotating fluidized bed solar reactor for steam gasification of char particles



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ABSTRACT

A novel rotating fluidised bed solar reactor for the gasification of carbonaceous materials is presented. A simplified single particle model, in which the particle gasification is coupled with three dimensional equations of motion, is developed and used to study the particle residence time and gasification conversion within the proposed reactor, together with their sensitivity to changes in key operating parameters, namely reactor rotational speed, initial feedstock particle radius, radiation intensity, and particle release position. The proposed reactor is shown to offer potential for increased particle residence time and conversion relative to conventional fluidised beds through adjustments of the operating parameters other than the particle release position. The results presented assist in developing an understanding of the operation of the proposed reactor and optimising its performance.

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1. Introduction

Solar energy is becoming an increasingly attractive renewable energy source due to its abundance and low environmental impacts (Desideri and Campana, 2014). Concentrated Solar Thermal (CST) systems for application in electrical power generation are being applied in increasing numbers and scale due to their low cost for energy storage (Ho and Iverson, 2014). An alternative application of CST is for the solar thermal gasification of carbon rich materials which converts solid carbonaceous feedstocks into calorifically upgraded synthesis gas for use in power generation cycles or the Fischer Tropsch process for the production of liquid fuels (Piatkowski and Steinfeld, 2008). Solar thermal gasification has two distinct advantages over auto-thermal gasification; the net carbon emission is reduced, and the quality of syngas is improved due to the lack of combustion and associated by-products (von Zedtwitz and Steinfeld, 2005). Through life cycle analysis, Z'Graggen and Steinfeld (2008) estimated that solar energy could upgrade the calorific value of carbonaceous feedstock by up to 34% and lower the production cost of syngas by up to 14% per unit compared to auto-thermal gasification. However, a number of technical and economic challenges remain to be overcome before this technology can become commercially viable. Among these is the need for more efficient and reliable gasification reactors.

Solar thermal gasification of carbonaceous materials derived from biomass and fossil origins has been studied in a variety of solar reactors to determine their suitability for various feedstocks and operating conditions (Taylor et al., 1983; Trommer, 2006; Kodama et al., 2008; Z'Graggen et al., 2006; Piatkowski and Steinfeld, 2008; Melchior et al., 2009). The directly irradiated configuration has received a lot of attention because it directly delivers high flux solar heat to the reaction site, resulting in relatively high temperature and fast reaction rate. The Solar Vortex Reactor (SVR) developed by Z'Graggen et al. (2006) was found to be one of the most promising concepts and currently has the highest lab scale solar to chemical energy conversion efficiency (Piatkowski et al., 2011). However, it suffers from the inability to preferentially control particle residence time based on particle size which could result in the premature conversion of small particles and incomplete conversion of large particles. Chinnici et al. (2015) modified the solar vortex reactor and proposed a new vortex reactor concept, referred to as the Solar Expanding Vortex Reactor (SEVR), which utilises an expansion cone in the vicinity of the tangential inlets to alter the vortex structure responsible for particle entrainment. Their CFD analysis showed that the altered vortex structure could significantly increase the sensitivity of particle residence time to particle size and reduce the number of particles depositing on the reactor window. Later, Chinnici et al. (2016) performed PIV experimental measurements in a lab scale SEVR to verify the findings of the CFD analysis. The SEVR's ability to preferentially extend particle residence time greatly improves the conversion of feed-

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Nomenclature

A_j	frequency factor	r_{bed}	fluidised bed radius (m)
A_{dis}	area of the gas distributor (m)	r_{exit}	exit port radius (m)
A_p	particle cross sectional area (m ²)	$r_{distributor}$	gas distributor plate radius (m)
B_o	gas permeability of the porous char particle	$r_{aperture}$	reactor aperture radius (m)
C_d	particle drag coefficient	r_m	location of the boundary between forced and free vortices (m)
C_i	<i>i</i> th component concentration (mol m ⁻³)	S_r	internal reactive surface area (m ²)
C_t	total concentration of gas components (mol m ⁻³)	S_r^0	initial internal reactive surface area (m ²)
$C_{i,bulk}$	<i>i</i> th component concentration in the bulk gas (mol m ⁻³)	Sh	Sherwood number
$c_{p,s}$	specific heat capacity solid (J kg ⁻¹)	T	particle temperature (K)
$c_{p,g}$	specific heat capacity gas (J kg ⁻¹)	T_{srn}	reactor wall temperature (K)
$\mathcal{D}_{i,eff}$	effective diffusion coefficient of the <i>i</i> th gas component (m ² s ⁻¹)	T_g	bulk gas temperature (K)
$\mathcal{D}_{i,K}$	<i>i</i> th component Knudsen diffusion coefficient (m ² s ⁻¹)	T_{feed}	temperature of particles entering the reactor (K)
\mathcal{D}_{ij}	molecular diffusion coefficient (m ² s ⁻¹)	u_0	tangential component of the gas velocity in the freeboard (m s ⁻¹)
$D_{Aperture}$	diameter of the aperture (m)	u_r	radial component of the gas velocity in the freeboard (m s ⁻¹)
D_{Bed}	diameter of the bed surface (m)	u_z	axial component of the gas velocity in the freeboard (m s ⁻¹)
$D_{Distributor}$	diameter of the gas distributor (m)	v_f	fluidizing gas velocity at the distributor (m s ⁻¹)
d_{pore}	particle pore diameter (m)	ν	stoichiometric coefficient
g	gravitational acceleration (m s ⁻²)	$Y_{i,bulk}$	mole fraction of <i>i</i> th component in the bulk gas
$H_{release}$	height of release (fraction of cavity length)	Y_i	mole fraction of <i>i</i> th component in the particle
h	height of the gas distributor (m)	z	particle axial position (m)
k_i	gasification kinetic parameter	\dot{z}	particle axial velocity (m s ⁻¹)
k_c	mass transfer coefficient (mol m ⁻² s ⁻¹)	\ddot{z}	particle axial acceleration (m s ⁻²)
L	reactor cavity length (m)	ΔH_R	enthalpy change due to steam gasification reaction (J mol ⁻¹)
m_{init}	initial mass of particle (kg)	α	effective absorptivity
M_c	molecular weight of carbon (mol kg ⁻¹)	ε	effective emissivity
M	molecular weight (mol kg ⁻¹)	σ	Stefan-Boltzmann constant (W m ⁻² K ⁻⁴)
N_i	<i>i</i> th component net flux (m ³ mol ⁻¹ s ⁻¹)	σ_{ij}	collision diameter (Å)
Nu	Nusselt number	Ω_D	collision integral
P	pressure (Pa)	μ	viscosity (N s m ⁻²)
P_t	total pressure (Pa)	$\dot{\theta}$	particle angular velocity (rad/s)
p_i	<i>i</i> th component partial pressure (Pa)	$\ddot{\theta}$	particle angular acceleration (rad s ⁻²)
Q_{abs}	absorbed radiative heat (W)	φ	porosity
$Q_{convection}$	convective heat on the particle surface (W)	φ_{cr}	critical porosity
$Q_{conduction}$	conductive heat on the particle surface (W)	τ	tortuosity of the pores
$Q_{re-radiation}$	re-radiative heat on the particle surface (W)	λ_{eff}	effective thermal conductivity (W m ⁻¹ K ⁻¹)
Q_{solar}	solar radiation heat incident on the particle surface (W)	λ_s	thermal conductivity of solid char (W m ⁻¹ K ⁻¹)
q_{solar}	solar heat flux (MW m ⁻²)	λ_g	thermal conductivity of gas mixture (W m ⁻¹ K ⁻¹)
\mathcal{R}	universal gas constant (m ³ Pa kmol)	$\rho_{particle}$	apparent density of the particle (kg m ⁻³)
Re	Reynolds number	ρ_{char}	density of solid phase char (kg m ⁻³)
R_{char}	rate of char gasification (mol m ⁻³ s ⁻¹)	ρ_{gas}	density of the gas mixture in the particle (kg m ⁻³)
$R_{intrinsic}$	intrinsic rate of char gasification (mol m ⁻³ s ⁻¹)	ρ_{fluid}	density of the gas mixture in the freeboard (kg m ⁻³)
$R_{solar,char}$	rate of char gasification corrected for high solar flux (mol m ⁻³ s ⁻¹)	ω	rotational speed of the reactor (rad/s)
r	particle radial position (m)		
\dot{r}	particle radial acceleration velocity (m s ⁻¹)		
\ddot{r}	particle radial acceleration (m s ⁻²)		
r_p	particle radius (μm)		
$r_{p,0}$	initial particle radius (μm)		

stock particles at the reactor exit and the commercial viability of the reactor concept.

An alternative approach with increased particle residence time is the internally circulating bubbling fluidised bed solar reactor proposed by Kodama et al. (2008). In this reactor, feedstock particles are re-circulated in the fluidised bed under the influence of gravity and particle drag until they are reduced to sufficiently small sizes to be entrained by the fluidising gas. One key drawback of using a conventional fluidised bed for solar gasification is the limited bed surface area through which solar heat can be introduced to the bed. Conventional bubbling fluidised beds are typically tall and narrow in diameter which leads to a small top surface relative to the volume of the bed. The high flux solar heat

required to adequately heat the entire bed volume has a high risk of overheating the particles at the top bed surface and creating undesirable melted lumps that were reported in the work of Kodama et al. (2008). A different configuration that increases the relative surface area for radiation absorption is the laterally irradiated fluidised bed confined by transparent silica glass or quartz tube (Taylor et al., 1983; Kodama et al., 2002). However, Taylor et al. (1983) reported that using a transparent tube exposes the hot bed to the external environment, leading to increased re-radiation heat loss and reduced solar to chemical energy conversion efficiency. Both Taylor et al. (1983) and Kodama et al. (2002) found that the use of either silica glass or quartz tube imposed a maximum temperature limit on the fluidised bed. At temperatures

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