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Design and cold flow testing of a Gas-Solid Vortex Reactor demonstration unit for biomass fast pyrolysis

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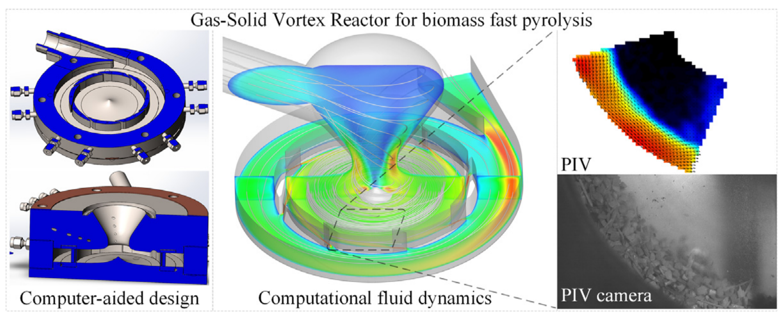
HIGHLIGHTS

- Design of a Gas-Solid Vortex Reactor or GSVR for biomass fast pyrolysis.
- New features: single main gas inlet, profiled bottom end wall and diverging exhaust.
- Sufficiently high centrifugal-to-drag force ratio for sustaining a rotating bed.
- Stable rotating fluidized bed with average solids azimuthal velocities of 6–7 m s^{-1}.

GRAPHICAL ABSTRACT



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ABSTRACT

Innovative gas-solid fluidized beds with process intensification capabilities are among the most promising alternatives for the current state of the art in the chemical industry. In the present work the advantages of such a reactor that sustains a rotating fluidized bed with gas-solid slip velocities much higher than those in conventional fluidized beds are illustrated computationally and experimentally. A Gas-Solid Vortex Reactor (GSVR) demonstration unit is designed to operate at typical biomass fast pyrolysis conditions targeting the production of chemicals and fuels from renewable feedstocks. For the demonstration unit preheated N_2 supplies the thermal energy required by the fast pyrolysis process but alternative sources can also be evaluated. A broad range of operation conditions in the 80 mm diameter and 15 mm height GSVR can be evaluated: N_2 mass flow rates of 5–10 g s^{-1} and biomass feed mass flow rates of 0.14–1.4 g s^{-1}. Particle-free and particulate flow experiments confirmed that the carrier gas is evenly distributed around the GSVR cylindrical chamber as anticipated by computational fluid dynamic simulations. The latter also supported the inclusion of a profiled bottom end wall and a diverging exhaust. Cold flow experiments with biomass confirmed that the GSVR sustains a rotating fluidized bed with average bed height of 10 mm and solids azimuthal velocities of 6–7 m s^{-1}.

1. Introduction

The diversification of natural resources for the sustainable production of chemicals and fuels and for the conversion of energy requires the development of innovative reactor technologies. Ideally, orders of magnitude reduction in size, improved control and enhanced heat, mass and momentum transfer are combined with a safe, cost-effective and energy-efficient operation. This has been generally referred to as process intensification [1]. Gas-solid fluidized beds (FBs), widely used for reactive and non-reactive processes in the chemical industry, are the focus in this work [2].

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Nomenclature

Bi	biot number – $(h_pL)/\lambda_s$
CFB	circulating fluidized beds
CFD	computational fluid dynamics
C_{ps}	biomass heat capacity (J kg^{-1} K^{-1})
d_p	particle diameter (mm)
Da_I	first Damköhler number – $(\rho_sC_{ps}L^2k)/\lambda_s$
Da_{II}	second Damköhler number – $(\rho_sC_{ps}Lk)/h_p$
D_E	exhaust diameter (mm)
D_J	jacket diameter (mm)
D_R	reactor diameter (mm)
FB	fluidized bed
FCC	fluid catalytic cracking
$F_{C,r}$	centrifugal force per unit volume (N m^{-3})
$F_{D,r}$	drag force per unit volume (N m^{-3})
GSVR	Gas-Solid Vortex Reactor
GSVU	gas-solid vortex unit
h	bed height (mm)
h_p	convective heat transfer coefficient (W m^{-2} K^{-1})
HCL	heat carrier loop
I_0	slot thickness (mm)
k	pyrolysis reaction rate coefficient (s^{-1})
L_R	reactor length (mm)
L	characteristic length scale (m)
$\dot{m}_g^{in}$	inlet gas mass flow rate (g s^{-1})
$\dot{m}_g^{out}$	outlet gas mass flow rate (g s^{-1})
$\dot{m}_s^{in}$	inlet solids mass flow rate (g s^{-1})
$\dot{m}_s^{out}$	outlet solids mass flow rate (g s^{-1})
n_I	number of reactor inlet-slots (–)
NREL	National Renewable Energy Laboratory
PIV	particle image velocimetry
Py^I	pyrolysis number I – $\lambda_s/(\rho_sC_{ps}L^2k)$
Py^{II}	pyrolysis number II – $h_p/(\rho_sC_{ps}Lk)$
QUICK	quadratic upstream interpolation for convective kinematics
F_V	gas volumetric flow rate (m^3 s^{-1})
r	radial position (mm)
RANS	Reynolds-averaged Navier-Stokes
RSM	Reynolds Stress Model
SFA	solids feeding accuracy
SFB	static fluidized beds
T_s^{in}	biomass inlet temperature (K)
T_s^{py}	solid phase pyrolysis temperature (K)
T_g^{in}	gas inlet temperature (K)
T_s^{out}	solid phase outlet temperature (K)
VOC	volatile organic compounds
ε	bed void fraction (–)
ΔH_r	enthalpy of reaction (kJ kg^{-1})
ρ_g	gas density (kg m^{-3})
ρ_s	solids density (kg m^{-3})
γ	gas injection angle (°)
λ_s	biomass thermal conductivity (W m^{-1} K^{-1})
μ_g	gas viscosity (kg m^{-1} s^{-1})
σ_{gs}	Azimuthal gas-solid slip factor (–)

We present the design and cold flow testing of a Gas-Solid Vortex Reactor (GSVR) demonstration unit that enables fluidization in a centrifugal field [3–5]. A dense fluidized bed with bed width-to-height ratio and gas-solid slip velocity much higher than those in gravitational fluidized beds can be sustained [6–9]. Higher gas-solid slip velocity leads to intensified interfacial transfer of heat, mass and momentum. Many industrial processes that rely on gas-solid contact can be implemented in the GSVR; in this work, the transformation of biomass via fast pyrolysis is addressed. The latter is regarded as one of the key potential technologies for biomass valorization [10]. The fast pyrolysis bio-oil is an extremely complex mixture of aromatic and nonaromatic oxygenates, *e.g.*, alcohols, carboxylic acids, aldehydes, esters, ketones, furans, pyrans, carbohydrates as well as large molecular oligomers and nitrogen containing compounds [11,12]. The GSVR technology can potentially benefit the biomass fast pyrolysis process in terms of both bio-oil yield and bio-oil quality.

Conventional FBs are limited to gas-solid slip velocities that do not exceed the terminal velocity of the solid particles in the earth gravitational field [13]. Additional drawbacks of gravitational FBs are the decrease in bed density with increasing gas velocity and the non-uniformity of the bed [2]. In the GSVR, gas is injected at high velocity via tangentially oriented inlet slots in a cylindrical chamber in which solids are continuously fed [4,5,13]. Momentum transfers from the gas to the solids, causing the latter to rotate, thus generating a large radially outward centrifugal force which opposes the radially inward gas-solid drag force. A sufficiently high centrifugal-to-drag force ratio in the GSVR removes the limitation in gas-solid slip velocity and provides the opportunity for significantly increasing the efficiency. Moreover, both the drag and the counteracting centrifugal force increase roughly equally with increasing gas flow rate within a wide gas flow range [13]. Therefore, a GSVR of given design offers a high flexibility with respect to the gas flow rate. Both experimental and numerical studies point out the process intensification potential of the GSVR. Several industrially relevant processes have been suggested for implementation in the GSVR: fluid catalytic cracking (FCC) [14], coating of cohesive particles [15], gas adsorption [16], drying [17], gasification [18], combustion [19] and pyrolysis [18,20,21]. However, to the best of the authors' knowledge the current unit is the first reactive GSVR actually being constructed.

Several fast pyrolysis reactor configurations have been developed and some technologies have been scaled up to demonstration scale. The most relevant are spouted bed [22], static and circulating fluidized beds (SFB and CFB, respectively) [23,24], rotating cone [25,26], auger [27], and ablative [28] reactors. The latter category also includes the so-called vortex pyrolysis reactor [29] developed in the 90's at the National Renewable Energy Laboratory (NREL) which, apart from the name, differs substantially from the GSVR studied in this work. With the currently established reactor technologies it has not been possible to reconcile the actual and the ideal operation conditions, *i.e.*, high interfacial heat transfer, rapid removal of the pyrolysis vapors, and precise temperature control [30,31]. In the GSVR, convective heat transfer coefficients that are three to five times higher than those in conventional FBs can be reached [20]. The estimated residence time of the pyrolysis vapors before reaching the quenching section ranges from 50 to 110 ms. These residence times are substantially lower than those in the other fast pyrolysis reactors mentioned above in which they vary from 0.5 to 2 s. The enhanced heat transfer and bed uniformity allows to gain improved control on the pyrolysis temperature. Computational fluid dynamics (CFD) simulations of biomass fast pyrolysis in a GSVR show that the gas and solid phases rapidly reach thermal equilibrium after entering the reactor chamber, approaching a final temperature that can be adjusted via the gas-to-biomass mass flow ratio [20]. As a consequence of the improved temperature control and bed uniformity, it is possible to produce bio-oils with a higher selectivity towards targeted components.