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ABSTRACT

Bio-oil, generated from fast pyrolysis of biomass, is emerging as an alternative energy carrier, complimentary to traditional fossil fuels. Fast pyrolysis requires certain reactor characteristics to be fulfilled in order to achieve a high biomass conversion and selectivity towards the desired compounds: i.e. high interfacial heat transfer; rapid removal and quenching of generated bio-oil vapours and precise temperature control. None of the currently employed reactor configurations simultaneously fulfill all of these criteria. A new reactor concept is presented called the Gas-Solid Vortex Reactor (GSVR), which can be beneficial for obtaining high yields of high-quality bio-oil [1] from lignocellulosic biomass. A detailed gas-flow analysis of the GSVR at various operating conditions desired for fast pyrolysis of biomass is presented in this work.


1 INTRODUCTION

Biomass fast pyrolysis has the potential to become one of the main contributors to renewable energy. The process can harvest energies in biomass and directly produce a fuel-grade liquid, commonly known as bio-oil. Additionally, commercially valuable chemicals such as 4-ethylguaiacol, furfural, creosol and catechol, are observed to be present in bio-oil fraction, making fast pyrolysis all the more valuable and attractive. Though bio-oil mass yields as high as 75% are reported, it is highly dependent on the vapour residence time inside the reactor, the heat transfer rate to the solid particles and the rapid cooling of the generated vapours.

The Gas-Solid Vortex Reactor (GSVR) can be considered as a fluidized bed reactor in which rotating particle beds are generated due to the actions of centrifugal and drag forces. Centrifugal force in these devices is typically generated by introducing the fluidization gas at high velocity via small, circumferentially distributed slots. One such vortex reactor, intended for generating bio-oil by fast pyrolysis of lignocellulosic biomass is being constructed at the Laboratory for Chemical Technology of Ghent University. As shown in Figure 1, this GSVR consists of two concentric cylinders in which the fluidization gas is distributed around the annulus and enters tangentially into the inner chamber via eight rectangular, 1 mm width slots, positioned at 10° with respect to the tangent. The axial length and the internal diameter of the reactor are 15 mm and 80 mm, respectively. Biomass is fed at one point next to the gas inlet slots through a circular conduit of 10 mm diameter connected to the top plate of the inner chamber, located at an 18° inclination with respect to the horizontal plane. Mass and energy balances show that the lower and upper limit for the biomass mass flow rate are 1.4 $10^{-4}$ and 8.3 $10^{-4}$ kg s$^{-1}$ respectively. The corresponding operating windows for the gas (N$_2$) mass flow rate and inlet temperature are 5.0 $10^{-3}$ - 1.0 $10^{-2}$ kg s$^{-1}$ and
800 - 923 K. As also indicated, the bottom wall and the outlet walls are profiled to minimize axial recirculation, which would unfavourably increase the residence time of unwanted particles and the pyrolysis vapours.

The GSVR exhibits fluidization in a centrifugal field and hence operates at inertial forces higher than the gravitational force. This results in a sustained, rotating, and moderately dense packed bed of biomass along the circumferential wall beyond the slots [2]. Such a solid bed is characterized by higher width-to-height ratios and by slip velocities much larger than those of a gravitational fluidized bed. Better heat transfer is thus achieved in this reactor configuration, allowing a more precise control of the reaction temperature compared to conventional fluidized bed reactors [3]. Also, using high velocity gas to maintain bed rotation reduces the space time of vapour phase in the GSVR. Owing to these properties, the GSVR becomes suitable for the fast pyrolysis of lignocellulosic biomass.

2 RESULTS AND DISCUSSIONS

2.1 Simulation Conditions

Computational fluid dynamic simulations were performed in order to get a better insight in the gas flow properties and fluid dynamics inside the GSVR. These simulations were performed in the commercial CFD software package ANSYS Fluent 15.0. The general simulation conditions are listed in Table 1.

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<th>Table 1 : General simulation conditions</th>
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<td>Gas</td>
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<td>Near-Wall Treatment</td>
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2.2 Computational domain size

Due to the design of the tangential inlet, the rotational symmetry of the GSVR is broken. However, to reduce the computational domain for the simulations, the effect of omitting the tangential inlet is investigated, thus restoring rotational symmetry and allowing to reduce the computational domain to 1/8\textsuperscript{th} of its original size. A comparative study on the three obtained reactor geometries was performed, see Figure 2: full geometry with the tangential gas inlet (~2.3 \(10^6\) cells); full geometry with circumferential gas inlet (~1.7 \(10^6\) cells) and 1/8\textsuperscript{th} pie section with circumferential inlet (~0.25 \(10^6\) cells). In case of the pie-shape domain, periodic boundary conditions were used on the tangential domain boundaries. These steady-state gas-only simulations were performed with the realizable k-\(\varepsilon\) turbulence model at equivalent boundary conditions.

![Figure 2: Three Geometries of the reactive GSVR studied](image)

![Figure 3: Pressure and Velocity comparisons in various reactor geometries](image)
As can be seen in Figure 3, both the pressure and velocity show very similar trends in all three configurations. Noticeable differences in these profiles are visible only in the jacket and in the slots as the velocity, in particular the tangential velocity, there is much lower in case of a circumferential inlet. The radial component on the other hand behaves quite similar for all geometries, also in the slots. Nevertheless, since the differences in the inner chamber are negligible, it was deemed acceptable to reduce the computational domain to 1/8th of its original size to decrease the computational cost.

2.3 Turbulence Model Comparisons

The realizable k-ε (rk-ε) model and Reynolds Stress Model (RSM) were compared for a constant gas flow of $10^2$ kg s$^{-1}$ under the hot flow inlet conditions. Based on the pressure and velocity profiles for both these cases, the results obtained with both turbulence models are very similar, as shown in Figure 4. The anisotropy of stresses inside these reactors can be captured to a satisfying level with an inherently isotropic model such as the realizable k-ε model. However, as the simulations with the rk-ε model are faster and more stable than those with the RSM model, this model is selected.

![Figure 4: Comparison of realizable-k-ε and RSM turbulence model for gas-only simulations in GSVR.](image)

2.4 Gas-only simulations

These simulations are performed with realizable k-ε turbulence model for gas flow $10^2$ kg s$^{-1}$ and inlet temperature of 842 K. The pressure profiles at $z=10$ mm plane for hot flow is displayed in Figure 5. The pressure drop across the slots and between the slots & the outlet of the reactor is 12 kPa and 40 kPa respectively. These values are in agreement to the order of magnitude with similar works published in the literature [1].

As seen in the velocity field in Figure 6, a strongly swirling flow is developed inside the reactor. As is characteristic of a swirling flow, the velocity increases as the radius decreases. Towards the centre of the reactor, an axial recirculation zone is created which reduces the velocity to near-zero values.
As can be seen in Figure 7, the tangential velocity component is the dominant contribution to the total gas velocity. The radial velocity is low compared to the tangential velocity, except for in the slots. This confirms that the flow inside the reactor is swirl-dominated. The relative maximum in radial velocity near the reactor outlet will result in a maximum of radial drag force and will be important for particle entrainment in gas-solid operation.
3 CONCLUSION

Gas-only simulations of the GSVR display promising trends in terms of using this reactor for the fast pyrolysis of biomass. The comparisons between various turbulence models revealed there is not much difference in the calculated parameters in the reactor. The pressure drop values across the slots and in the reactor are reasonable and coherent with the published literature in similar areas. Detailed gas-only simulations indicate that the tangential velocity is the dominant velocity component in the inner chamber of the reactor. However, the high tangential velocities induce an axial recirculation zone close to the central axis of the reactor. In a next phase, gas-solid simulations will be carried out to confirm the operating window of the geometry and to assess the bed stability at various operating conditions. Ultimately, the full pyrolysis process will be simulated, including chemical reactions.

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