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Design of a Circulating Fluidized Bed Combustor for Lignin-Rich Residue Derived From Second-Generation Bioethanol Production Plant

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The present paper reports on the design of a pilot circulating fluidized bed combustor (CFB) for the conversion of lignin-rich residue derived from a second-generation bioethanol production plant. The designed combustor aims to improve the combustion efficiency of the lignin-rich residue, therefore increasing the heat recovery to partially cover the biorefinery's heat consumption.
Among the existing technologies, the fluidized bed combustion shows several advantages, in particular the fuel flexibility and the higher combustion efficiency mainly due to the presence of an inert material that uniforms the temperature and enhance the reactants mixing. The CFB differs from the bubbling fluidized bed (BFB) for the higher velocity of the oxidizer in the reactor, resulting in a better gas-solid mixing and higher burning rate (Basu 2015). Hence, by providing enhanced fuel conversion rate is and reduced reaction time, the characteristics of this apparatus meet the requirements for a more efficient combustion of the lignin-rich residue.
The CFB combustor is mainly composed by a vertical combustion chamber (riser), a solid gas-particle separator (cyclone) and a solid particles recirculation system (recirculation valve or loop seal valve). The design process followed some consequential steps. The first step involved the theoretical 1D modeling of the reactor. Considering the project constraints of maximum plant capacity (5 kg h^{-1}) and the consequent maximum thermal power, the geometry was chosen correlating some literature data to obtain a riser diameter of DN100 and a riser height of 3500 mm. Besides, energy and mass balances were carried out to obtain air mass flowrate data, which has an impact on the hydrodynamic study of the fluidized bed. After the geometry selection and the stoichiometric calculation, a mono-dimensional empirical model was implemented to estimate the physical behavior of the bed particles (Basu 2015), (Kunii & Levenspiel 1991). The main output of the model is the voidage fraction profile along the riser. Further important outcomes of the model are the pressure drop along the riser and the solid recirculating rate. The latter is the main input parameter for the design of the cyclone and the loop seal valve. The second step was focused on the realization of the Piping and Instrumentation Diagram selecting the measurement instruments (thermocouples, pressure transducers and flowmeters) and the ancillary equipment (blower pumps, valves and pipes). In the third step, a three-dimensional CAD model was drawn for the design of the mechanical parts including the choice of the materials and the layout. The last step involved the project of the control logic and the hardware for the data acquisition system.
The results of combustion tests on the circulating fluidized bed prototype will be used to gain insights into the combustion process of the lignin-rich residue, in the perspective of an industrial scale up to increase the efficiency of the energy recovery.

1. Introduction

The lignin-rich residue is the main co-product of second-generation bioethanol in the conversion processes from lignocellulosic raw material. The high amount of lignin-rich residue produced, and its significant energy content, make its valorization essential, in order to further improve the economics of the overall ethanol

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production process (Öhman et al., 2006). Among many alternatives, the lignin valorization through direct combustion is the most straightforward, capable of supplying on one hand the internal thermal energy demand of the process and on the other hand, satisfying a part of the plant electricity needs in the context of a CHP application. The constitutive peculiarities of the co-product, which include a low softening temperature, a significant content of inorganic elements and a pronounced tendency to agglomeration, are an obstacle to a valorization in boilers and traditional furnaces (Miccio et al., 2016). Hence, the optimization of combustion systems, in particular the use of fluidized bed combustion technologies, can make the energy recovery much more efficient, mitigating technical problems related to the physico-chemical characteristics of lignin (Solimene et al., 2016b).

Fluidized bed combustion technology is characterized by ensuring a high mixing between the fuel particles and the combustion air reducing residence times and enhancing greater temperature uniformity due to the presence inside the bed of a high heat capacity inert material (i.e. alumina or silica sand). Fluidized beds are used in many processes of industrial interest ranging from energy conversion to chemical and petrochemical processes (catalytic cracking, Fischer-Tropsch synthesis). Their classification is based on the motion regime inside the bed. Therefore, increasing the fluidizing agent velocity, it is possible to distinguish three categories: boiling fluidized bed (BFB), circulating fluidized bed (CFB) and entrained flow reactor. Compared to other woody feedstock, the lignin-rich co-product requires higher reaction time to complete the conversion and it needs to be burned at higher reaction rate ambient. Thus, due to the higher combustion efficiency, the CFB was selected as the most appropriate combustion technology for this application (Koornneef et al., 2007). In a previous work (Solimene et al., 2016a), the authors experimentally studied the combustion mechanisms of the lignin solid residue in a pilot fluidized bed reactor. In particular, the mechanisms of devolatilization and fragmentation of the burnt particles and the characteristics of the combustion products have been investigated. Also (Ren et al., 2015) in their experimental work analyzed the combustion characteristics of a residue from ethanol production from corn stalks, mainly composed of lignin. The experimental campaign was performed in a circulating fluidized bed combustor and the characteristics of ignition of the fuel, the emissions and the phenomena of ash agglomeration were in detail evaluated.

In the present work, the design of a CFB for the combustion of a lignin-rich residue is presented, reporting the criteria and the methods adopted for the theoretical calculations, for the sizing and for the selection of the auxiliary components as well as the mechanical design of the main parts of the plant.

2. Calculation methods and sizing criteria

The design of the pilot CFB combustor is based on the development of a calculation model derived from the state of the art of fluid bed technology (Basu 2015). The model includes a sizing procedure consisting in thermal energy balances and calculations related to fluidization parameters. The basic geometry of the designed reactor was compared with data available in the literature. The results of the model include the required air flow for the complete combustion of the lignin and the distribution of inert material along the riser. Afterwards, the sizing and selection of auxiliary components, such as the fluidizing and combustion air blowers and the measuring instrumentation, were carried out. The mechanical design of the parts of the plant and the layout was realized in a native 3D modelling environment (i.e. Solidworks©).

The calculation model was developed following an algorithm that provides, for a set of input parameters, the data output of the process parameters necessary for the definition of the auxiliaries and the geometry of the plant parts. It includes several steps of calculation, from thermal and mass balance to empirical model of solid distribution along the riser.

The basic riser geometry was obtained comparing characteristic literature parameters (Basu 2015). The riser inner diameter was derived from the grate heat release rate (ratio between the thermal power and the riser cross section). Typical values of this parameter range between 3.6 and 4.4 $MW \cdot m^{-2}$. The theoretical height of the riser was evaluated from the volumetric heat release rate (ratio between the thermal power of the bed and the internal volume of the riser). Typical values range between 0.08 and 0.15 $MW \cdot m^{-3}$. The thermal power was set to 25 kW as a design constraint. Depending on several design conditions, the riser inner temperature reached during the combustion could vary (e.g. the presence of heat exchanger on the riser walls). A temperature of 850˚C was found reasonable for calculating the air/gas properties during the fluidization (Solimene et al., 2016b). The lignin-rich feedstock was characterized in terms of lower heating value, proximate and ultimate analysis, as well as bulk density, moisture and ash content. Alumina sand (Al_2O_3) with an average particle size of 125μm and a bulk density of 3920 $kg \cdot m^{-3}$ was selected as inert material of the bed.

Thermal and mass balances were carried out to calculate fuel and air mass flow rate. For the airflow calculation, a 20% of oxygen excess was considered and it was chosen to split the flow in the primary and secondary line to increase the conversion efficiency. The secondary is about the 40 % of the primary air, according to the selected reference model (Basu 2015). Moreover, a small percentage of primary air is supplied to the loop seal valve as fluidization air to ensure the circulation of the solids.

2.1 Riser fluidization model

Implementing an empirical mono-dimensional model, the riser fluidization parameters were estimated to obtain the voidage (or solid) fraction distribution along the reactor and consequently, to calculate the riser pressure drop (Δp_r). First, the superficial velocity u_o was calculated for the primary and secondary section at the riser pressure and temperature conditions. Then, the inert particle terminal velocity u_t was fixed through a balance of forces. The reactor was ideally divided in two zones located respectively below and above the dilution point (secondary air injection point): dense zone and a transport zone. For each section, different correlations to calculate the voidage fraction distribution ($\boldsymbol{\varepsilon_z}$) were used. The voidage fraction of the dense zone ($\boldsymbol{\varepsilon_{dz}}$) was considered constant along the vertical axis even though this approximation tends to overestimate the amount of solid entrained. The dense layer can be analyzed as a bubbling fluidized bed since the particles tend to be more packed and the correlation given by Loffler (Loffler et al., 2003) was used to calculate the voidage fraction as function of the bubble density:

$$\varepsilon_{dz} = \delta_b + (1 - \delta_b) \cdot \varepsilon_{mf}$$

Where:

- δ_b is the bubble density calculated from the correlation given by (Loffler et al., 2003).
- ε_{mf} is the voidage fraction at minimum fluidization condition calculated assuming the bed bulk and solid particles densities, $\varepsilon_{mf} = (1 - \rho_{bulk}/\rho_s)$.

While, for the transport zone, the correlation given by Kunii (Kunii and Levenspiel, 1991) was chosen, where the voidage fraction ($\boldsymbol{\varepsilon}$) is estimated as an exponential function:

$$\frac{\varepsilon - \varepsilon_\infty}{\varepsilon'_{dz} - \varepsilon_\infty} = exp[-a_d(H - H_{dz})]$$

Where:

- ε_∞ is the is the voidage at an infinite height calculated using the equation $\varepsilon_\infty = 1 - K_\infty/[\rho_s \cdot (u_o - u_t)]$ where K_∞ is the elutriation rate at an infinite height and it is obtained applying the Tanaka correlation contained in (Kunii and Levenspiel, 1991)
- ε'_{dz} is the voidage at the dilution section obtained from a volume flow rates balance.
- a_d is ad is the decay constant that accounts for the interchange of solids between upward and downward flowing solids evaluated applying a correlation given in (Kunii and Levenspiel, 1991).
- H_{dz} is the height of secondary air injection

The voidage value at the riser outlet section was further used to calculate the solid recirculation rate G_s, the solid particles mass flow rate, the riser inventory (mass of inert in the riser). The pressure drop along the riser was estimated considering only the pressure drop due to the local solids holdup (Loffler et al., 2003):

$$\Delta p_r = \int_0^H [1 - \varepsilon(z)] \cdot \rho_s dz$$

2.2 CFB mechanical parts design

The main parts of the CFB that needs to be carefully designed for proper plant operation are the distributor plate, the cyclone and the loop seal.

The primary air distributor, placed at the base of the riser, ensures the expansion of the bed and the solid particles transport as well as uniformly distributes the oxygen inside the reactor. The distributor was designed calculating the number and the diameter of the holes according to semi-empirical criteria (Kunii and Levenspiel, 1991). The primary cyclone separates the solids from the gas exiting the riser and it was designed following literature suggestions (Basu 2015), using the Stairmand sizing criteria for high efficiency cyclones. The loop seal valve is a non-mechanical valve that performs a double function: it allows the reintegration in the riser of the inert solid coming from the cyclone and realizes a seal that acts as a non-return valve in the loop. The valve is composed of two fluidized chambers. The *supply chamber* collects the solid coming from the cyclone and a minimum airflow is sent to guarantee the reduction of the friction between the particles and allow the particles vertical sliding. The *recycle chamber* is fluidized at a higher speed it realizes an expansion of the sand bed in order to overcome the weir allowing it to fall into the delivery pipe close the solid recirculation loop. The design followed the criteria proposed in (Basu 2015).

2.3 Feeding line

The feeding line has to be carefully designed due to the tricky thermoplastic behavior of the lignin material along the channels. The relatively low softening temperature in the range 90-150 ˚C (Tejado et al., 2007), implies that the material tends to agglomerate on the hot wall of the feeding pipe leading to clogging problems and consequent shut down of the plant. Different solutions can be used to partially avoid these effects, acting on the feedstock pretreatment or modifying the feeding technology. Zhou et al. (Zhou et al., 2015) propose a treatment with calcium hydroxide that modifies the chemical bonds between the lignin molecules, raising the melting temperature of the material. Similarly, Howe et al. (Howe et al., 2016) propose a thermal treatment at temperatures between 250-350 ˚C in an inert environment. Another system was proposed by Berruti (Berruti & Briens 2013) with an intermittent air pulsating feeding technology that reduce the contact time between the feedstock and the pipe walls.

2.4 Criteria for auxiliaries equipment selection

The primary and secondary blowers have been selected to guarantee the airflow rate of oxygen needed for the combustion reactions and for the fluidization of the bed. Besides, every blower must give the prevalence necessary to overcome the pressure losses of the pipelines, the riser, the cyclone and the loop seal valve. Electrical heaters on the primary and secondary air lines were adopted to bring the riser bed temperature to the fuel ignition minimum temperature and to preheat the air up to 500 °C increasing the combustion efficiency. In addition, a pilot GPL burner was selected to accelerate the plant starting. A water cooling system was designed to recovery the thermal energy of the flue gas and it consists of a closed circuit that removes the heat from the fumes.

3. Results and discussion

3.1 Riser geometry

A stainless steel commercial pipe with nominal diameter of 4 inches (DN100), outer diameter 114.3 mm and thickness 8.56 mm was chosen for the riser and the net design height calculated was 3500 mm.

3.2 Air and fuel mass flow

The fuel and air mass flow rates resulting from thermal and mass balances are summarized in Table 1 below.

Table 1: CFB mass flow results

Fluid flow	Mass flow rate	Unit
Fuel	5	$kg{\cdot}h^{-1}$
Primary air	27.1	$kg{\cdot}h^{-1}$
Secondary air	10.8	$kg{\cdot}h^{-1}$
Loop seal valve air	1.38	$kg{\cdot}h^{-1}$

3.3 Fluidization model results

The theoretical voidage distribution along the riser axis (Figure 1) was obtained by evaluating the empirical functions at different heights (every 10mm). The position of the secondary air injection point was set to 1000mm from the primary air distributor. Finally, the output parameters of the model are summarized in Table 2.

Table 2: fluidization model output parameters

Parameter	Value	Unit
Solid mass flow rate	1476	$kg{\cdot}h^{-1}$
Solid recirculation rate	56	$kg{\cdot}s^{-1}{\cdot}m^{-2}$
Riser Inventory	7	kg
Riser Pressure Drop	9000	Pa

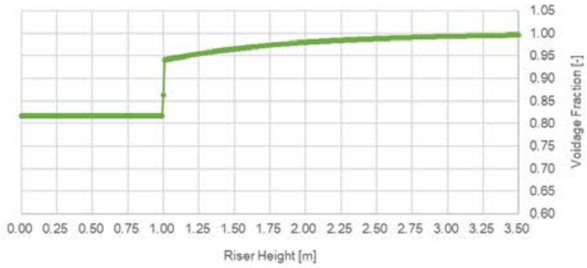

Figure 1: Estimation of voidage fraction distribution along the riser

3.4 Feeding line

In the present work a double screw conveyor feeding system, composed by a micro-batch feeder and a cooled screw conveyor was selected. The feeder allows the control of the fuel mass flow while the second conveyor is installed into a cooled channel composed by two coaxial pipes in order to maintain the temperature below the critical softening point and partially avoid the line clogging.

3.5 Auxiliaries equipment

For the primary air line, a centrifugal blower with 25 $Nm^3 \cdot h^{-1}$ and a prevalence of 13000 Pa at the design point. Besides, it is coupled with an inverter able to vary the frequency and therefore the number of revolutions to control the airflow. Similarly, the secondary controlled centrifugal blower discharge 9 $Nm^3 \cdot h^{-1}$ with a prevalence of 6000 Pa. The electrical heaters absorb an electric power 5 kW and 2.5 kW to preheat primary and secondary air respectively. Regarding the flue gas cooling section, a commercial tube bundle heat exchanger was selected to recover 25 kW of thermal energy using water as coolant.

3.6 Mechanical components design

The CFB reactor has been designed in its entirety, and a 3D CAD frontal view is shown in Figure 3a. While, a frontal view of the CFB plant assembled on a support structure is given in Figure 3b.

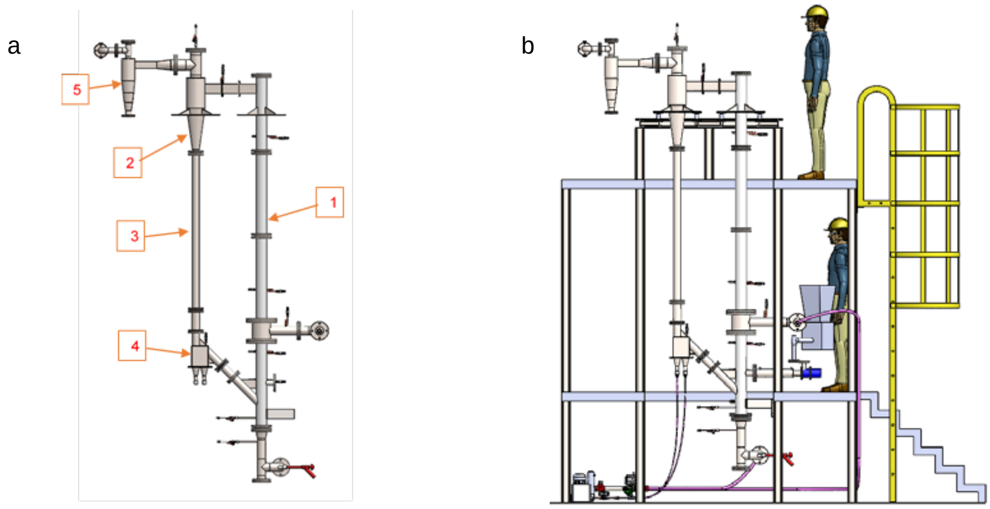

Figure 3: 3D Solidworks© CAD frontal view of the CFB combustor (a): modular riser (1), primary cyclone (2) the gas-solids separator (sand and char), standpipe (3), recirculation valve (4), secondary cyclone for ash recovery (5). Frontal Solidworks© view of the overall CFB plant (b).

The riser overall height has been divided into six modular sections connected with flanged couplings. In addition, an optical access on the top of the riser was provided to observe the proper combustion during operation. Regarding the main mechanical CFB components, Figure 4 shows the 3D CAD drawings of the grate (a), the cyclone (b) and the loop seal valve (c).

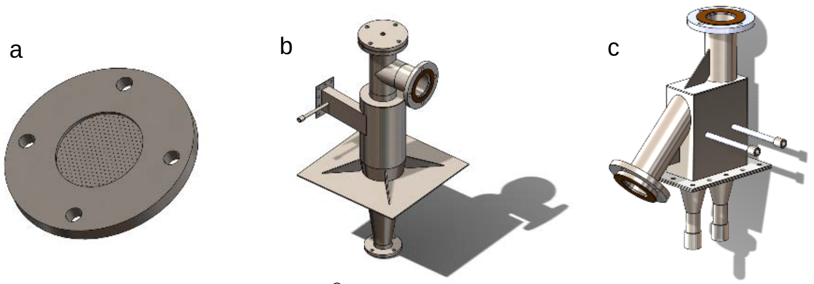

Figure 4: 3D CAD views from Solidworks© of: distributor plate (a), cyclone (b) and loop seal valve (c)

The distributor plate design were carried out imposing a pressure drop equal to the 30 % of the overall riser pressure drop and calculating 66 $m \cdot s^{-1}$ as jet velocity through the holes. Fixing the holes diameter to 1 mm, the calculation gives as output a plate with 302 holes. The cyclone works with a gas-solid inlet velocity of 10 $m \cdot s^{-1}$ and has 191 mm external diameter, 764 mm height and 65 mm as nominal diameter of the discharge standpipe. The loop seal valve maximum solid recirculation rate was set at 100 $kg \cdot s^{-1} \cdot m^{-2}$. The resulting valve is 217 mm height, 172 mm length and 86 mm width. Moreover, the two inner chambers have a length of 86 mm and the passage between them is 53 mm height.

For the construction materials, given the absence of mechanical stresses, the main requirement is the resistance to high temperatures. The combustor section is expected to operate up to 850-900°C of internal temperature, so special steel AISI 310S was selected for this application. The other mechanical parts are made of AISI 316/316L steel, including the flanges.

4. Conclusion

A pilot circulating fluidized bed combustor for the conversion of lignin-rich residue derived from second-generation bioethanol was designed. Thermal and mass balances were carried out to calculate the fuel and air mass flow rates, while an empirical model was implemented to predict fluidization behavior in the riser. The fluidization mono-dimensional model was realized using empirical correlations for the calculation of the voidage profile along the reactor and consequently the solid recirculation rate, the mass inventory and the pressure drop. Afterwards, the controlled air blowers were selected to insufflate the right airflow with the estimated prevalence value. Two electrical heaters were chosen for the plant starting and for the air preheating during operation. Considering the lignin thermoplastic behavior due to low softening temperature the feeding line was realized with a screw conveyor inserted in a water-cooled channel to reduce the possibility of agglomeration and clogging. Once the CFB plant will be built, it will give useful data in terms of technical feasibility and combustion efficiency, useful for a possible industrial scale up. The implementation of a higher efficiency fluidized combustion technology will improve the economy of the overall ethanol production process recovering and converting the energy contained in the lignin-rich co-product.

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