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Design of the air reactor for a chemical looping combustion plant coupled with a turbo expander[#]

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ABSTRACT

Carbon Capture and Storage is a technology of paramount importance for Sustainable Development Goal 7 (Affordable and Clean Energy) and Sustainable Development Goal 5 (Climate Action). The European Union is moving rapidly towards low carbon technologies, see the Energy Union Strategy. Coupling biofuels and carbon capture and storage to decarbonize the power and the industrial sector can be done through the development of BECCS (Bioenergy with Carbon Capture and Storage). However there are some technical barriers to the development of this technology. If a Chemical Looping Combustion (CLC) plant has to be coupled with a gas turbine, it has to work in pressurized conditions. The effect of pressure on chemical reactions and fluidized bed hydrodynamics, at the moment, is not clear. The aim of this paper is to present a model for the dimensioning of an air reactor to be coupled to a gas turbine of the power of about 14 MW. Based on the air mass flow requirements to produce such a power. The fluidized bed is designed choosing geometry parameters and making a sensitivity analysis of the influence of the turbine inlet temperature on final plant efficiency. It can be seen from the analysis presented in this paper that the diameter of the fluidized bed is mainly influenced by the mass flow of the air in the reactor, while the height of the reactor is mainly influenced by elutriation and transport disengaging height calculations.

Keywords: BECCS, Chemical Looping, Combustion, ASPEN, Air reactor, Iron based Oxygen Carrier (Max. 6)

NOMENCLATURE

Abbreviations	
CLC	Chemical Looping combustion
Symbols	
ρ_G	Gas Density (kg/m^3)
A	Parameter A (-)
B	Parameter B (-)
C	Parameter C (-)
dCv	Concentration of particles in volume (-)
h	Bed height (m)
$k_{i,\infty}$	Component elutriation rate constant (kg/(m^{2}s))
TIT	Turbine Inlet Temperature (°C)
u	Fluidizing velocity (m/s)
u_{ti}	Particle terminal velocity (m/s)

1. INTRODUCTION

In both AR5 and Shared Socioeconomic Pathways (SSP), the ICPP identifies Bioenergy with Carbon Capture and Storage as a key technology to meet the goal of the increase of the earth temperature below 2°C, see [1]. BECCS is still under development nevertheless and a big help can be given by coupling bioenergy with chemical looping combustion, see for example the recent work of Mendiara et al [2] or the work of Ryden et al [3]. Many reviews have already dealt with several aspects of chemical looping, see for example [4-9]. There is also a recent interest on pressurized chemical looping as reported in [10]. Nevertheless, the work on the coupling of PCLC reactors with gas turbines is still not complete, given the many barriers that this process is facing and also the relative novelty of CLC technology.

In this context a Marie Curie project has been funded in the Spanish National Research Council (CSIC), Instituto de Carboquimica (ICB) named GTCLC-NEG which objective is to promote a Carbon Negative Technology, able to burn multiple biofuels derived from biomass (eg, pyrolysis oil, biogas and syngas) and to capture the CO2 emissions at a very low cost. In this way there will be negative GHG emissions due to the use of BECCS (Bioenergy with Carbon Capture and Storage), a technology which is going to be developed within 2050,

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according to the IPCC. The proposed plant is based on the coupling of a Chemical Looping Combustor to a gas turbine, as proposed in figure 1.

As it can be seen in the proposed plant the compressed air used to oxidize the oxygen carrier is then expanded in a gas turbine to produce electricity. In the fuel reactor biofuels (in this case pyrolysis oils) are used to reduce the oxygen carrier. The plant is based on the coupling of a Pressurized Chemical Looping Combustor (PCLC) with a gas turbine.

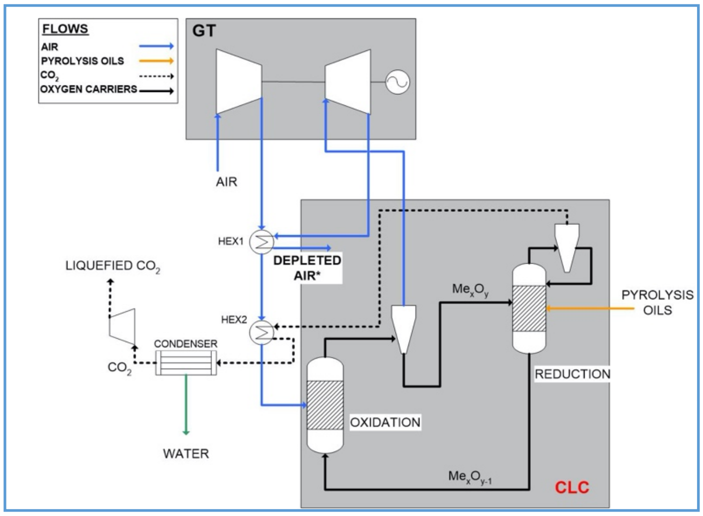

Fig. 1. The GTCLC-NEG concept

2. METHODOLOGY

The air reactor, which consist of a riser has been modeled with Aspen Plus, V11.

This version of the software has already a model to implement a fluidized bed which is available in the section “solids” with the reactor “Fluidbed”. The input parameters used to model the fluidized bed are reported in table 1.

The equation used to model the elutriation process is the following:

$$k_{i,\infty} = A * \rho_G * u^B * \text{expo}\,(C - u_{t,i}/u) \qquad (1)$$

The parameters reported in the equation (1) can be seen in table 1. Other assumptions for the model are:

- the air does not react with the oxygen carrier;
- the oxygen carrier is Fe_3O4;
- the inlet temperature of the turbine is regulated with an heat exchanger to perform a sensitivity analysis on the influence of TIT on plant efficiency.
- The circulation rate of the solids in the air reactor is not taken into account. We have indicated a fixed bed mass of 1200 kg but we did not indicate the rate at which the mass of the oxygen carrier is changed during time (expressed in kg/h or kg/s). Obviously this has to be proportional to the mass flow of air which is inserted in the air reactor, but this will be object of further calculation;
- The reactions happening in the air reactor are not considered as well as also the heat which is generated by exothermic reactions;
- Heat exchangers to be placed inside the air reactor are also neglected.

The final Aspen model is shown in figure 2.

Tab. 1. Fluidized bed model input parameters

Parameter	*Value*	*Unit of Measure*
Bed Mass	2200	kg
*V*oidage at minimum fluidization	*0*.5	-
Geldart classification	B	-
Minimum fluidization velocity calculation method	Ergun [11]	-
Transport disengagement Height Model	George and Grace [12]	-
Maximum dCv/dh	1e-05	-
Elutriation model	Tasirin & Geldart [13]	-
Decay constant	3	-
TG parameter A1	23.7	-
TG parameter A2	14.5	-
TG parameter B1	2.5	-
TG parameter B2	2.5	-
TG parameter C1	-5.4	-
TG parameter C2	-5.4	-
Fluidized bed height	9.5	m
Fluidized bed diameter	2.5	m
Constant diameter	-	-
Cross section	circular	-
Solids discharge location	95% of total height	-
Gas distribution	perforated plate	-
Distributor pressure drop	0.05	bar

3. RESULTS

The results of the model are shown in table 2. As it can be seen by the data shown in the table, the air reactor, is interested by a fast fluidization regime with a very small height of the bed bottom zone while the height of the freeboard is important.

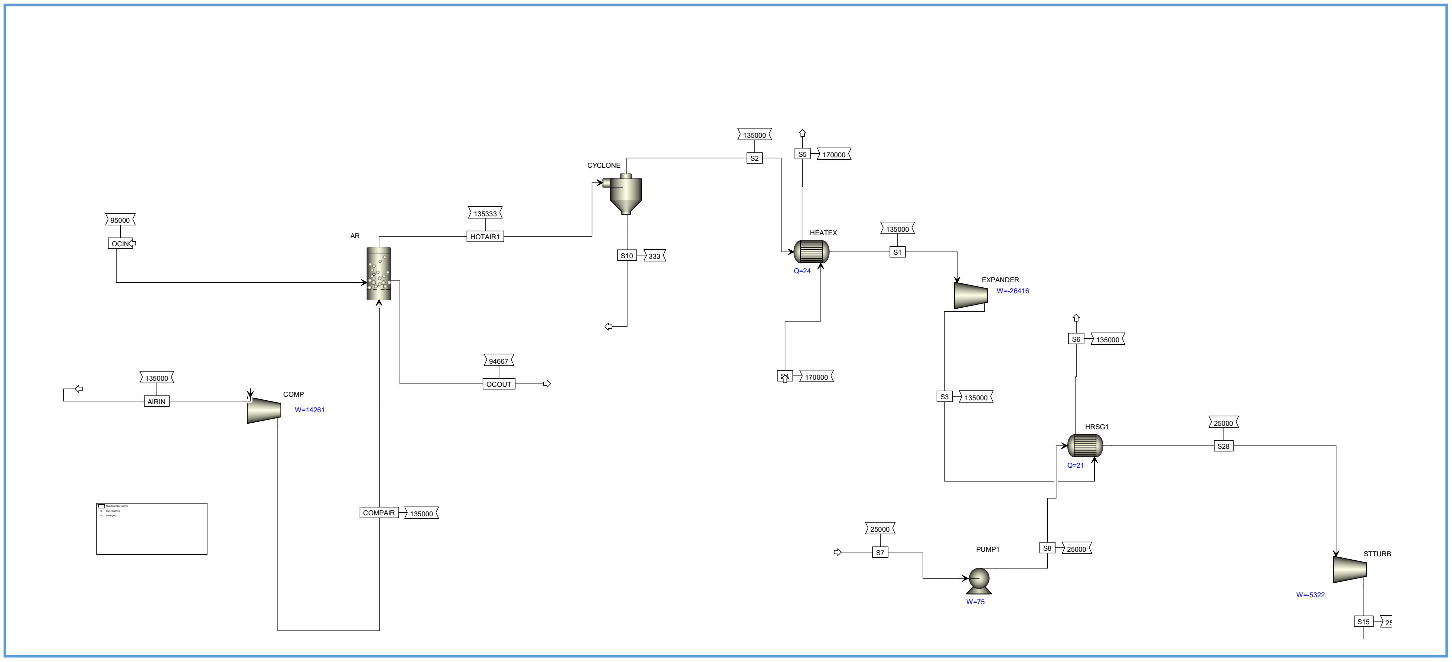

Fig. 2 Aspen Plus model

Tab. 2. Air reactor model results

Parameter	*Value*	*Unit of Measure*
Height of bottom zone	0.31	m
Height of freeboard	9.2	m
Transport Disengaging Height calculated by correlation	9.0	m
Transport Disengaging Height based on solids volume fraction profile	3.9	m
Solids hold up	2200	m
Number of particles in bed	4.9e+08	-
Surface area	1543	sqm
Distribution pressure drop	0.5	bar
Bottom zone pressure drop	0.023	bar
Freeboard pressure drop	0.025	bar
Fluidized bed pressure drop	0.048	bar
Overall pressure drop	0.055	bar
Heat duty	0	Gcal/hr
Minimum fluidization velocity	0.65	m/sec
Calculated temperature	746	°C

The transport disengaging height is the one which determines the total length of the reactor, while the diameter is adjusted based on the mass flow of air. This is done in a way to have a reasonable velocity inside the air reactor which falls into the range of the fast fluidization regime. Given the high mass flow of air the velocity is also high and this increase the elutriation index and the transport disengaging height (which has to be lower than the total height of the reactor). The pressure drop is not so high, this is confirmed also by published literature in the topic, see [14]. This means that the influence of the pressure drop on the final plant performance is quite limited, while much more important is the influence of the inlet temperature of the air expanding in the turbo expander. This is assumed to be about 1200°C at a pressure similar to 11 bars. This temperature (1200°C) can be regarded as the maximum which can be achieved on a fluidized bed reactor without having agglomeration of the oxygen carrier.

To complete the analysis done on the turboexpansor optimization it has to be clear that the net power production should take into account also the power consumed to compress the air which is fed this means that the dimensioning at the moment is based on the gross power of the. Gas turbine.

The cyclone has been modelled based on the following assumptions:

- Leith-Licht method for simulation of cyclone working behavior [15];
- Type of cyclone: Barth 3 type with round inlet;
- Diameter: 1 meter
- Number of cyclones: 2.

The results of the modeling of the cyclone are proposed in table 3.

Tab. 3. Cyclone design and behavior

Parameter	*Value*	*Unit of Measure*
Type of cyclone	Bart 3 – Round inlet	-
Number of cyclones	2	-
Efficiency	1	-
Pressure drop	0.16	bar
Diameter of cylinder	1	m
Length of vortex	1.6	m
Length of cylinder	2.4	m
Length of cone section	0.6	m
Diameter of overflow	0.4	m
Diameter of gas inlet	0.47	m
Length of vortex finder	0.6	m
Diameter of underflow	0.4	m
Number of gas turns	4	-
Inlet saltation / velocity ratio	1.43	-
Axial inlet gas velocity	22	m/s

The ratio of inlet to saltation velocity is 1.43 and is greater than 1.36 so solids entrainment can occur. This is particularly dangerous for the gas turbine life and so the cyclone systems has to be improved in the future also foreseeing magnetic separation systems for the oxygen carrier which is represented by iron oxide.

Dealing with the turbo expander this is modelled based on the following assumptions:

- calculations are based on turbine isentropic efficiency;
- discharge pressure is set to 101 kPa.

The final profiles of the following quantities inside the air reactor are proposed in figures 3,4,5,6, respectively:

- superficial velocity (m/s)
-
- interstitial velocity (m/s)
-
- solids volume fraction (-)
-
- Pressure (bar).

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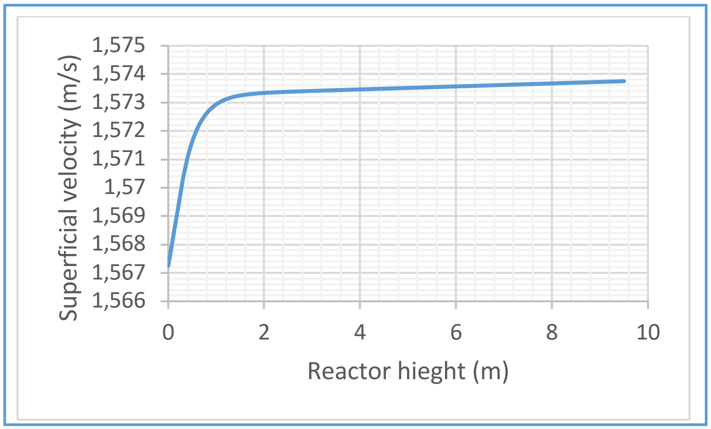

Fig. 3 Superficial velocity (m/s)

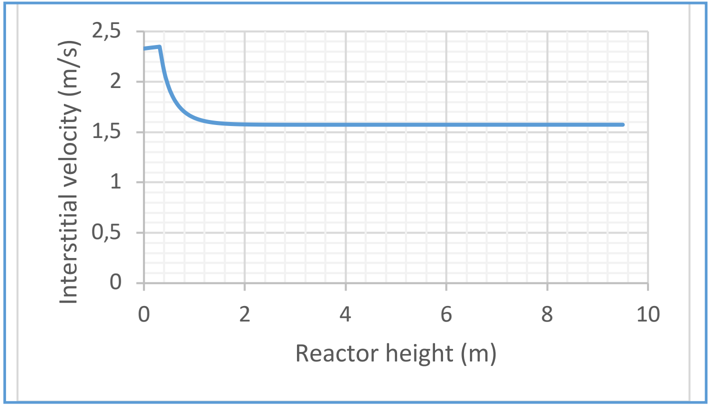

Fig. 4 Interstitial velocity (m/s)

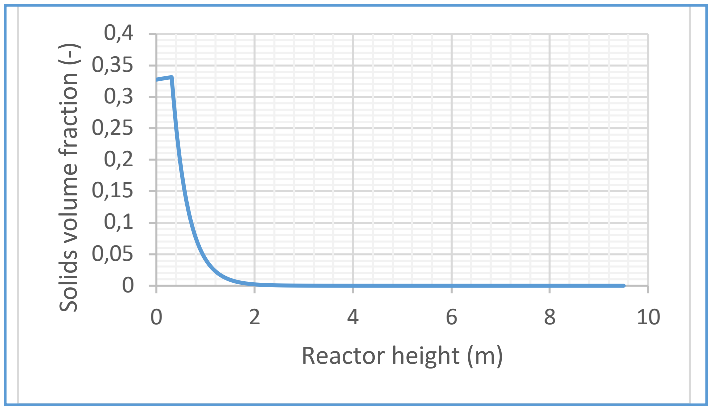

Fig. 5 Solids volume fraction (m/s)

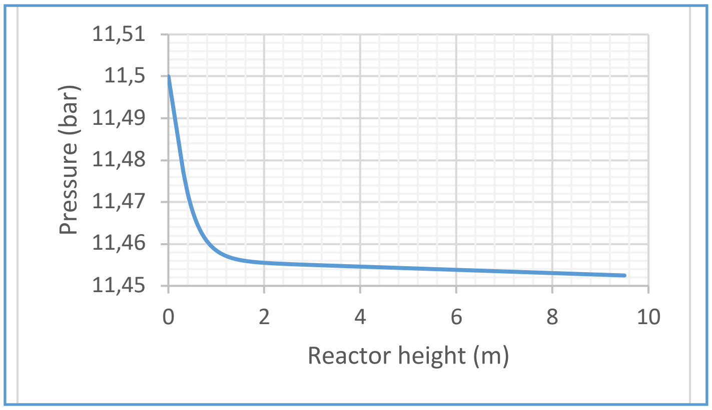

Fig. 6 Pressure (bar)

4. DISCUSSION AND NOVELTY OF THE WORK

The current methodology to design an air reactor and then couple it with a gas turbine, even though it is a preliminary one, it can be used to design Bioenergy coupled with Carbon Capture and Storage (BECCS) plants. We propose here the preliminary guidelines identified in the framework of the GTCLC-NEG Marie Curie project. These represent a new way to design chemical looping combustors, based on the specification of the gas turbine which will be coupled with the combustor.

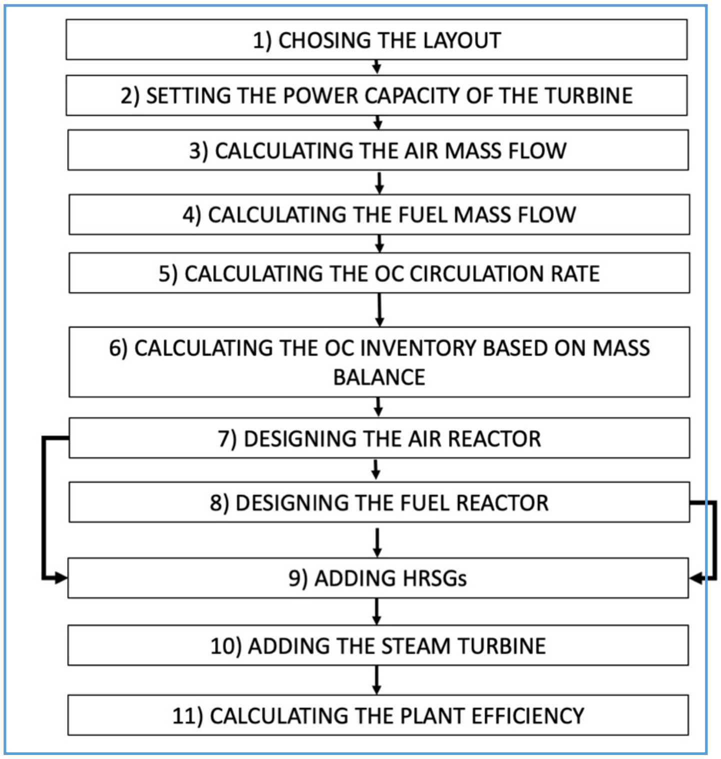

Fig. 7 Methodology to design chemical looping combustion plants when coupled with a turbo expander

We see from figure 7 that first of all the turbine capacity is selected, then from this the air mass flow is identified. This has to be done also considering the mass flow of the exhaust combustion gases which normally evolve in the turbine when used with natural gas. From the air mass flow the fuel mass flow is determined based on stoichiometric calculations. Once the fuel mass flow is clear the circulation rate and the solids inventory has to be determined. Finally the geometry of the reactors is calculated and the excess air is optimized based on enthalpy balance performed at the air reactor and at the fuel reactor.

The methodology proposed is iterative and so the plant is optimized with a cyclic iteration trying each cycle to decrease the fuel input and maximize air to fuel ratio. The more air evolves into the turbine the more the power with the fuel being constant.

5. CONCLUSIONS

The paper has presented a model for the dimensioning of an air reactor to be coupled to a gas turbine of the power of about 14 MW. Based on the air mass flow requirements to produce such a power. The fluidized bed is designed choosing geometry parameters and making a sensitivity analysis of the influence of the turbine inlet temperature on final plant efficiency. It can be seen from the analysis presented in this paper that the diameter of the fluidized bed is mainly influenced by the mass flow of the air in the reactor, while the height of the reactor is mainly influenced by elutriation and transport disengaging height calculations.

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