

Industrial Design of New Generation of Power Plants Based on Oxy-Fuel Technology

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Abstract

This work presents the design of large utility-scale oxy-fuel boilers based on two industrial pathways of *constant thermal power scenario* and *constant furnace size scenario*. The work is based on a comprehensive test campaign in 100 kW_{th} and 4 MW_{th} oxy-fuel test units which led to a comprehensive modeling tool developed by the author. The results suggest that the major strategy for increasing the heat extraction outside the furnace is to use cyclones with high efficiency leading to a higher share of fine particles and nanoparticles in the boiler loop while the amount of aerosols is reduced. The furnace wall heat flux maxima is in *constant furnace size scenario* is around double of the corresponding values in *constant thermal power scenario*. Thus the combustion is more intense *constant furnace size scenario* which increases the rate of NO_x generation in addition to tube damage risks. It is also concluded that the operation of the oxy-fired boilers at high O₂ concentrations is much safer in *constant thermal power scenario* is compared to *constant furnace size scenario*. It is also concluded that the aspect ratio of new oxy-fuel CFB furnaces are to bigger than the typical furnaces and consequently approaching the fluid catalytic cracking fluidized beds.

Keyword: Oxy-fuel, Fluidized Bed, Combustion, Carbon Capture and Storage, Nanoparticles

1. Introduction

Oxy-fuel combustion is a technology applicable to thermal power plants like circulating fluidized bed (CFB) boilers in a move to reduce greenhouse gases *via* carbon capture and storage (CCS). One of the main drivers for developing oxy-fuel CFB boiler technology is its dependence on the mature technology of fluidized beds (see Koorneef et al. [1]

for historical development of fluidized bed combustion) . Even though introduction of gas turbines to the energy market slowed down the CFB penetration to the energy market [2], there are merits in fluidized bed technology which ensures its niche market. The major merit in fluidized bed boilers is the fuel flexibility [3] in addition to in-furnace emission reduction which reduces the costs for flue gas aftertreatment [4].

While the major energy penalty associated with oxy-fuel CFB boilers is the work required to separate oxygen from air in air separation units (ASU) [5, 6], operation of the boiler at high O₂ concentration can be of great economic and technical advantage. From technical point of view, operation at high O₂ concentration leads to improved combustion efficiency [7], lower boiler emission [5, 7, 8], higher boiler efficiency [9] and most importantly higher thermal output [10]. From economic point of view, the oxy-fuel combustion boilers have the potential of being a major profitable solution for clean coal power generation, particularly at high O₂ concentration, though it is still a developing technology which is still far from commercial diffusion [11-14].

For building new oxy-fuel CFB boilers, two major scenarios, which are both studied in this work, can be evaluated: 1) *constant furnace size scenario* and 2) *constant thermal power scenario*. In first scenario operation at elevated O₂ concentration results in increased power generation from the same size furnace which is economically favorable. In the latter scenario, i.e. *constant thermal power scenario*, higher O₂ concentration gives the economic advantage of furnace size reduction for the same thermal output leading to a lower cost of generated electricity compared to the cases with typical O₂ concentrations.

There have been major theoretical and experimental research activities in the field of oxy-fuel CFB. Anthony [15], Kuivalainen et al. [16], Stewart et al. [17], Tan et al. [18], Wang et al. [19] and Wu et al. [20] studied different aspects of oxy-fuel CFB for

vast range of fuels using experimental data from Canmet Energy 0.8 MW_{th} and 100 kW_{th} oxy-CFB boilers. Myöhänen et al. [21] and Rahiala et al. [22] developed modeling tools for oxy-fuel CFB focusing on combustion and heat transfer in air- and oxy-fired flexible boilers. Czakiert et al. [23-25] and Krzywanski et al. [26, 27] developed modeling tools mainly focusing on combustion and emission using experimental data from their 100 kW_{th} oxy-fuel CFB boiler. Scala and Chirone [28, 29] and Scala and Salatino [30] studied oxy-fuel CFB mainly focusing on fundamental aspects of combustion in the oxy-fired furnace. Zhou et al. [7, 31] and Duan et al. [32-34] studied fluid dynamics and combustion using data from a 50 kW_{th} oxy-fuel CFB boiler. Author of this work performed his PhD thesis [35] on model development for combustion, heat transfer and fluid dynamics under oxy-fuel CFB conditions using own data from a 4 MW_{th} and a 100 kW_{th} oxy- and air-fired CFB boilers (see also [5, 8, 10, 36] for journal and conference publications on his thesis).

The oxy-fuel CFB boilers are also studied vastly by major boiler manufacturers since 2000 like by Foster Wheeler [37, 38], Alstom [39] and Metso [5, 40]. These efforts have been accompanied by ambitious experimental campaigns including Foster Wheeler 30 MW_{th} oxy-fuel CFB with minor technical results published in [37, 41], Alstom 3 MW_{th} oxy-fuel CFB with some results published in [42] and Metso 4 MW_{th} and 100 kW_{th} oxy-fuel CFB with major results published by author of this paper in [5, 35, 36, 43].

Since the scale-up process imposes considerable risks to the investor and manufacturer, the design of new oxy-fuel CFB boilers requires studies in which the effect of operations with high O₂ concentrations on the boiler operation are investigated. So far most oxy-fuel CFB studies focused on retrofit scenarios. This work addresses the major remaining step in commercialization of oxy-fuel CFB boilers which is the scale-up of this technology from pilot-scale to large-scale. Thus the aim of this work is to 1) evaluate the major design scenarios for building new large-scale oxy-fuel CFB boilers in addition to retrofitting the current CFB designs, 2) compare the suggested design scenarios based on their technical merits and challenges, and 3) suggest the optimum design pathway for new generation of CFB boilers capable of operation at high O₂ concentrations. This work presents the first-of-kind studies on comparing the design scenarios for the design and scale-up of large-scale oxy-fuel-fired boilers based on the models validated with 100 kW_{th} and 4 MW_{th} oxy-fuel boilers.

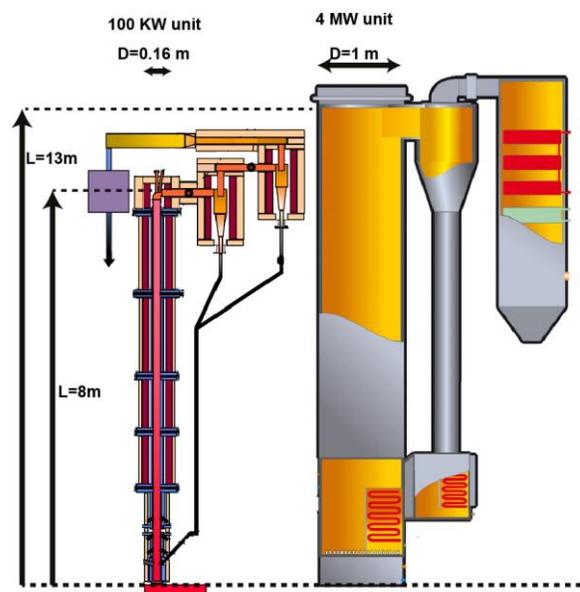


Figure 1: Schematic of the 100-kW [43] and 4-MW [44] oxy-fired CFB units used in the experiments for this work

2. Theory

Simulations in this work are performed using a comprehensive mathematical model including fluid dynamics, combustion and heat transfer. An earlier version of this mathematical model is previously validated by the author, using data from a 100 kW_{th} and 4 MW_{th} oxy-fuel and air-fired CFB boilers (see details in [5, 35, 36, 43]). It should be noted that there is no large-scale oxy-fuel CFB boiler built so far and the 4 MW_{th} oxy-fuel CFB boiler used for development and verification of the model used in this work is the second largest oxy-fuel CFB boiler in the world right after the 30 MW_{th} oxy-fuel CFB in CIUDEN which so far has published very little technical data. Thus, the model used in this work offers a unique opportunity for the oxy-fuel CFB research and development in relation to scale-up of the oxy-fuel CFB technology. More information on the design and scale-up of oxy-fuel CFB technology and the 4 MW_{th} oxy-fuel CFB boiler can be seen in [35, 36] and details on 30 MW_{th} oxy-fuel CFB in CIUDEN project can be seen in [37]. The computer code is totally re-written in MATLAB in order to generate a faster and more efficient code while adding new features to the model. While the successful application of MATLAB for modeling in engineering applications is common (see examples in [45-49]), MATLAB is also being widely used for comprehensive modeling of fluidized bed boilers such as those performed by Myöhänen et al. [21, 50, 51],

Werther et al. [52] and Seddighi et al. [5, 8, 10, 35, 36]. An intrinsic source of uncertainty in CFB mathematical models is their dependence on semi-empirical equations which can be improved for oxy-fuel CFB furnaces when measurements from larger oxy-fired CFB boilers become available.

Combustion

The combustion model takes into account both kinetics and mixing and utilizes a global reaction mechanism to calculate the gas field in the CFB loop and consists of heterogeneous and homogeneous reaction modules. Previous work by the author [5, 8, 35] found CO to be the marker and indicator for the progress of combustion and shows to what extent the combustion in the furnace is complete. CO which is monitored in almost all thermal power plants in developed countries as a general emission monitoring measure [53] can also be as a benchmark of combustion efficiency and incomplete combustion [54, 55]. Thus in-furnace profiles of CO are used in this work to investigate the combustion in large-scale oxy-fuel fired CFB boilers.

Another source of CO is from fuel devolatilization. This work calculates the volatile composition by solving a system of equations consisting of conservation of mass and heat. The major assumption is the type of light and heavy hydrocarbons which are assumed to be $C_{1.16}H_4$, $C_6H_{6.2}O_{0.2}$ respectively [56]. Other products of devolatilization are H_2 , CO, CO_2 , H_2O , SO_2 and NH_3 .

The reaction rate for CO oxidation reaction is calculated by the model described in Seddighi et al. [43] developed and validated for oxy-fuel and air-fired CFB combustion. The CO oxidation kinetics is enhanced by increase in temperature (T), activation energy (E) and concentrations of CO, O_2 and H_2O while CO_2 retards the reaction as described below.

$$\frac{dC_{CO}}{dt} = K_{0,CO} \exp\left(\frac{-E}{RT}\right) C_{CO} c_{O_2}^{0.25} c_{H_2O}^{0.5} c_{CO_2}^{-0.32} \quad (1)$$

Heat transfer

While heat transfer in CFB furnaces are governed by both radiation and convection [57, 58], radiation is the source for around 70% of furnace heat extraction under both oxy-fuel and air-fired CFB conditions [36]. This work models both convective and radiative heat transfer between the following parts in the furnace:

- 1- Gas-solids suspension in core region
- 2- Gas-solids suspension in wall layer

- 3- Water walls
- 4- Wing and/or division walls

For modeling convection, the contributions from solids convection and gas convection are taken together in a single semi-empirical correlation found by author in a 4 MWth oxy-fuel and air-fired CFB furnace as below [36].

$$h_{conv} = 3.69\rho_s^{0.58} \quad (2)$$

where ρ_s is concentration of solids in the wall layer.

The radiation is modeled using the net radiation approach where emitted heat is found from sum of gray gas radiation and solids radiation. The emissivity of gas-solids suspension is calculated by using the emissivity of gas and particles as a function of gas emissivity and composition, solid particle emissivity, path length, temperature, particle diameter and solids concentration

The emissivity of a solid particle is taken as 0.6 [59, 60] and the emissivity of steel surfaces is assumed to be 0.8 [36, 61, 62].

Once the modeled values of cell temperatures in the furnace converge during the simulations, the outgoing solids and gas leave the furnace toward the cyclone and loop seal carrying certain amount of heat depending on the mass flow, gas and solids composition and temperature. The loop seal heat transfer is modeled considering both heat source from combustion of solids and heat sink of heat exchangers. The solids leaving the loop seals toward the furnace with considerably lower temperature due to the heat extractions in the loop seal. Thus in order to obtain accurate temperature field in the furnace and loop seal, an iterative procedure is used in this model covering the interdependence of the furnace and loop seal heat balance.

Fluid dynamics

For modeling fluid dynamics, the furnace is divided to four regions of dense bed, splash zone, transport zone and exit zone. Dense bed is critical in CFB furnaces since it carries the major share of boiler solids inventory including fuel particles [63, 64]. In addition, CFB operation requires constant monitoring the existence of the bed in order to avoid sudden temperature variations and operational difficulties. The injection of primary air causes the formation and eruption of bubbles dividing the bed to fuel-rich emulsion phase and O_2 -rich bubble phase with very limited mixing between these two phases [8]. Eruption of bubbles in either single bubble or multiple bubble regimes (depending on gas velocity

[63]) leads to net upward motion of solids and have a decisive role in furnace hydrodynamics. Bubble eruption forms the splash zone which is characterized by strong solids back-mixing and solid clusters ballistic motion [65]. The bubble eruptions and cluster formations gives the CFB furnace flow a pulsating and fluctuating nature which makes both modeling and measurements very difficult in splash zone [5]. The transport zone is located above the splash zone with core-annulus structure where the solids wall layer is formed by solids back mixing. Thus, the concentration of solids profile in the furnace to include two exponential decay from splash zone and transport

Size segregation, which is modeled accurately in this work, is an important feature of CFB furnaces in which large particles with diameters up to several centimeters can be found only in lower parts of the furnace close to dense bed and small particles up to nanoparticles are going up from furnace toward the cyclone. The large particles are mainly fuel particles close to fuel feed location and rapidly undergoes attrition and fragmentation leading to the size reduction. The particle size distribution (PSD) of aerosols which are nanoparticles ranges from 3 to 422 nm with two modes. The peak size of the first mode is around 20 nm where the particles mainly made from potassium, sulfur and sodium. The second-mode particles which are mostly lead and zinc peaks around 100 nm [66].

For the gas mixing, the model by the author [5, 8] is used where the oxy-fuel furnace is divided to three mixing zones: 1) limited mixing in dense bed due to limited contact between O₂-rich bubble phase and fuel-rich emulsion phase, 2) improved mixing due to bubble eruptions and secondary gas injections, 3) limited mixing in dispersed phase governed by dispersion.

3. Design Scenarios

The scale up of the oxy-fuel CFB technology can be performed through two roadmaps of Constant Furnace Size Scenario and Constant Thermal Power Scenario. The Constant Furnace Size Scenario relies on retrofitting the conventional CFB boiler technology imposing relatively low investment risk which is great advantage for the short term development of oxy-fuel CFB technology. In this scenario the design takes departure from the mature and reliable available CFB boiler technology keeping the furnace geometry constant to minimize the investment risks such as what proposed by Alstom Power [67]. The second option which is the Constant

Thermal Power Scenario relies on reduced furnace size due to the reduced exhaust gases from the furnace at elevated O₂ concentration. Alstom Power estimates the potential for size and cost reduction in oxy-fuel CFB to be around 44% and 32% respectively leading to considerable cost reduction for such designs in the long term [7]. Thus both scenarios can be selected by the industry for further development and scale-up of oxy-fuel CFB technology due to their financial and technical criteria. Given the merits in both scenarios, this work investigates the design of large scale oxy-fuel CFB boilers based on these two scenarios as described below.

Constant Furnace Size Scenario

In this scenario the size of the furnace is kept constant and therefore, the increase in furnace O₂ concentration leads to increase in the boiler thermal power. At certain concentration of O₂, adiabatic flame temperature in the furnace becomes like the one in air-fired boilers. When O₂ concentration elevated to higher values, the boiler thermal power increases respectively. Since the furnace heat extraction area is limited, the increase in boiler thermal power is compensated by enhanced heat extraction in the loop seals. Also the increase in O₂ concentration leads to increase in furnace temperature. Thus the circulating solids flux is elevated to a level that these two constraints are satisfied: 1) total heat extraction matches the thermal power, and 2) furnace temperature maxima is kept in below ash melting temperature, i.e. below 1000 °C.

Constant Thermal Power Scenario

In this scenario, the boiler thermal power is kept constant while increase in O₂ concentration corresponds to smaller size furnace. In this scenario also the circulating solids flux is increased to maintain the boiler heat balance in addition to keep the furnace temperature maxima below ash melting temperature, i.e. below 1000 °C.

The operation of oxy-fuel CFB at high O₂ concentrations, i.e. above 60%, is an emerging research field due to the economic advantages (see for example Leckner and Gómez-Barea [68], Zhao et al. [69] and Seddighi et al. [10, 35, 36]). The main driver for academic and industrial research on oxy-fuel CFB operation at high O₂ concentrations is the potential for heat extraction outside the furnace using the circulating solids flux. The impact of change from air-firing mode to oxy-fuel mode on the boiler in relation to thermal and radiative properties and the fluidization velocity can be compensated by adapting the flow rate of recycled flue gas [67]. Thus the

furnace temperature and the fluidization velocity can be kept in the ranges applicable in the typical commercial air-fired CFB while avoiding slagging and fouling and corrosion of the furnace surfaces. It is noteworthy that the fluidization and convective heat transfer in the furnace at high O_2 concentrations can be easily maintained by recirculating the flue gases to the furnace as a substitution to the air N_2 flow (for further information see for example Leckner and Gómez-Barea [68], Seddighi et al. [36]).

For all cases studied, the height of the furnace is assumed to be 44 m which lies in the cost effective height range for bituminous coal as fuel [70]. The furnace height is optimized by careful consideration of combustion efficiency and furnace heat extraction area. For the reference case and for the constant furnace size case, the furnace cross section is 130 m^2 . The choice of the furnace cross section is also in the cross section range for currently available large scale CFB boilers which is limited by the penetration length of the fuel injection and secondary gas injection [70]. The dense bed temperature is taken around $890 \text{ }^\circ\text{C}$ which lies in the operational temperature range of CFB furnaces and enables in-bed emission reduction. The water temperature in the heat extraction panels for all cases is set to be around $60 \text{ }^\circ\text{C}$ which is also in the range for industrial-scale CFB furnaces. The furnace heat extraction in all cases are performed by water walls starting from 5m above air distributors up through the roof in addition to wing walls.

Heat extraction is performed through 1) water walls and wing walls in the furnace, 2) heat exchangers in the flue gas pass, and 3) external heat exchangers located in the loop seal of the return leg. The flow in furnace and loop seals are assumed to contain heterogeneous and homogenous reactions as heat source and heat extraction as major heat sinks. The gas and solids leaving furnace toward the loop seal are assumed to have the same temperature. By means of heat extraction, solids in the loop seal and flue gases can be cooled down to $400 \text{ }^\circ\text{C}$ and $200 \text{ }^\circ\text{C}$ respectively which are assumed due to heat extraction efficiency and environmental limitations for exhaust gas temperatures. The O_2 concentration in the furnace exhaust gases is assumed to be 3.5% for all cases.

4. Results and Discussion

The effect of increased O_2 concentration on different parameters are studied in both scenarios. The 29% value for O_2 concentration for achieving the same bed temperature as the air-fired case is in agreement with the findings of Leckner and Gómez-Barea [68] and

Seddighi et al. [36]. It should be noted that the usage of adiabatic flame temperature is an unreliable design criterion in pulverized coal (PC) boilers due to differences in gas radiation properties of N_2 and CO_2 dominated atmospheres [68]. However, the adiabatic flame temperature is a valid design criterion in oxy-fuel CFB furnaces due to that the radiation in the oxy-fuel CFB furnace is dominated by the solids and change from N_2 gas atmosphere to CO_2 gas atmosphere leads to the marginal change of only 1% in the radiative heat extraction in the furnace [71].

Figure 2 shows the boiler thermal power for the cases studied. In *constant furnace size scenario*, increased O_2 concentration while keeping the furnace geometry constant leads to elevated thermal power which is economically favorable since it is associated with considerably higher electricity production with the same furnace geometry. However, for the *constant thermal power scenario* the increased O_2 concentration does not affect the thermal power and only can give a considerable size reduction in exchange for keeping the thermal power constant which also economically favorable since it reduces the capital costs.

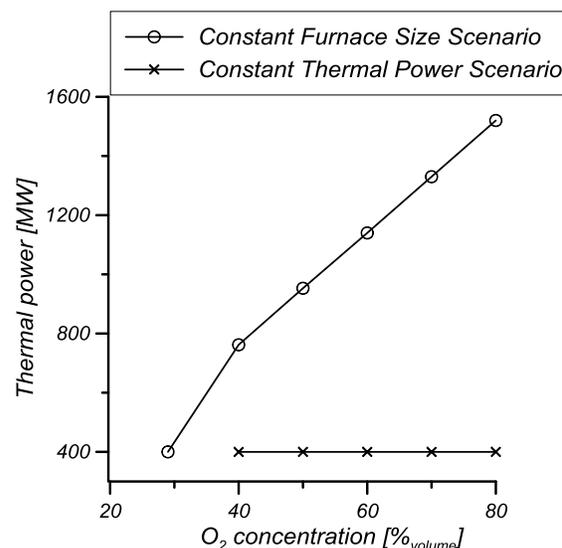


Figure 2: Boiler thermal powers obtained from the modeling for the cases investigated

Figure 3 shows the circulating solids flux for the cases studied. As seen, the circulating solids flux increases more in *constant furnace size scenario* compared to *constant thermal power scenario* due to that the absolute thermal power is considerably higher in the first scenario. Since the absolute value for the boiler thermal power increases dramatically with the increase in the O_2 concentration in *constant furnace*

size scenario, the circulating solids flux must be increased respectively in order to transfer the heat from furnace toward the loop seals. In addition, heat extraction from the loop seals become necessary in order to close the heat balance over CFB loop and to keep the bed temperature in the designed level, i.e. 890 °C. A major method for increasing solids flux is improving the efficiency of the cyclones capturing finer particles up to nanoparticles sending them to the loop seal and then to the furnace. Increased rate of fly ash recirculation is known to have positive impacts on furnace combustion, boiler thermal efficiency reduction in unburnt carbon emission [72]. In all, the increased circulating solids flux is associated with higher cyclone efficiency compared to typical CFB boilers and leads to changes in the PSD in different locations in the boiler and increased share of fine particles including micro particles and nanoparticles in the furnace.

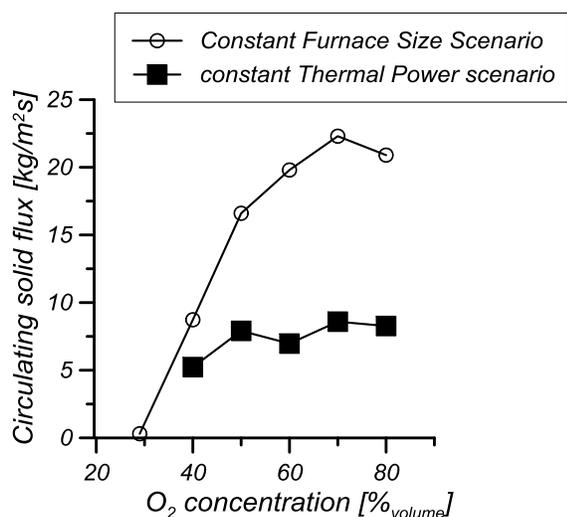


Figure 3: Circulating solids flux from the modeling of the different cases

Figure 4 shows the heat extraction duty from the furnace, seal, and flue gas normalized with boiler thermal power for different O₂ concentrations. In Figure 4 both scenarios show reduction in normalized furnace heat extraction duty when O₂ concentration increase. The share of seal heat extraction at 80% O₂ concentration is around 30% and 50% for *constant thermal power scenario* and *constant furnace size scenario* respectively which shows that the latter scenario is more dependent on the external heat exchangers located in the loop seal. Given the low heat extraction efficiency and high rate of erosion in loop seal heat exchangers, the *constant furnace size scenario* faces higher maintenance and operational costs.

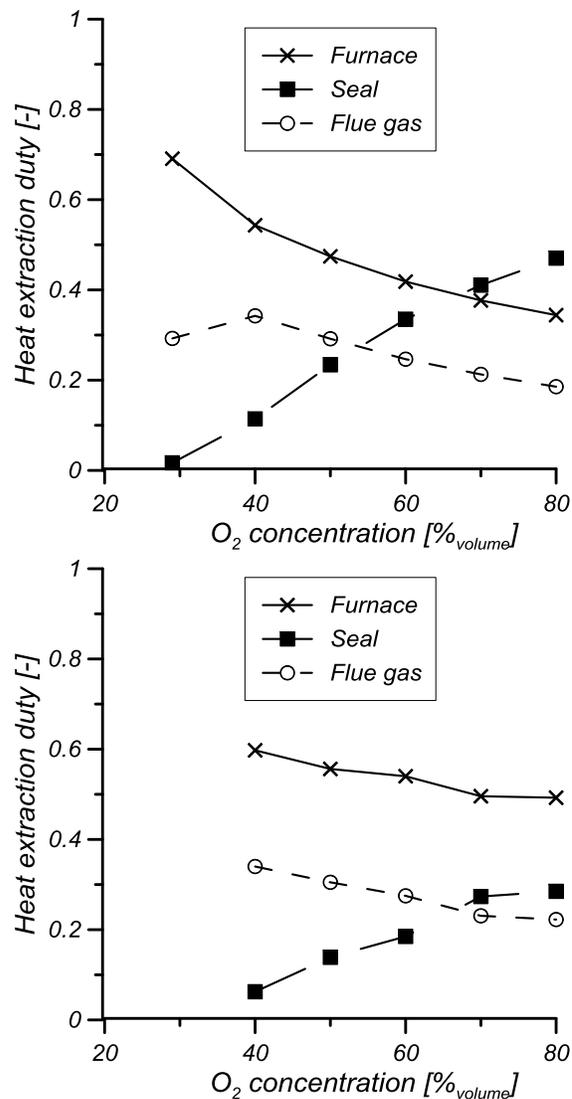


Figure 4: Heat extraction duty from the furnace, seal, and flue gas normalized with boiler thermal power for different O₂ concentrations in a) Constant furnace size scenario, b) Constant thermal power scenario

Figure 5 shows the profiles of heat flux from furnace water walls, which are critical design parameters [35, 73, 74] for different O₂ concentrations. As seen, the heat flux from furnace water walls is considerably higher in *constant thermal power scenario* compared to *constant furnace size scenario* due to that the furnace net heat extraction duty is considerably higher in the latter scenario when O₂ concentration increases. Even though increase in thermal power in *constant furnace size scenario* is associated with reduced share of heat extraction from furnace, the net amount of heat that should be extracted from furnace at high O₂

concentrations in *constant furnace size scenario* also increases. This considerable increase in the furnace heat extraction capacity in *constant furnace size scenario* leads to increase in the furnace heat flux. Thus the material selection for oxy-fuel CFB heat extraction panels is more challenging in *constant furnace size scenario* compared *constant thermal power scenario*. The higher heat flux maxima accompanied with more intense combustion increases the risk of tube damage in *constant furnace size scenario*.

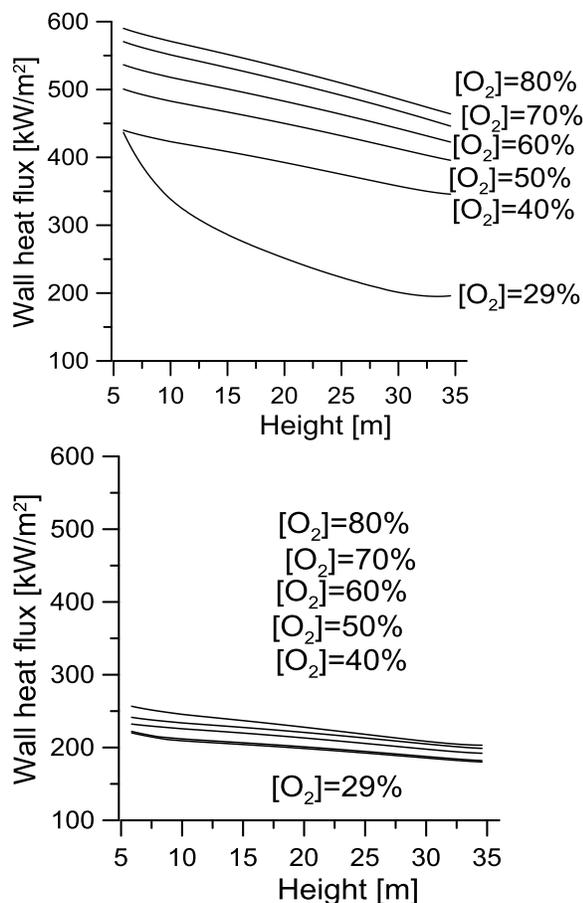


Figure 5: Profiles of heat flux from furnace water walls for different O_2 concentrations in a) Constant furnace size scenario, b) Constant thermal power scenario

5. Conclusions

A mathematical model is developed based on a model previously validated with a 100 kW_{th} and 4 MW_{th} oxy-fuel CFB boilers and is used to evaluate the design of large scale oxy-fuel CFB boilers in two scenarios of 1) *constant thermal power scenario* and 2) *constant furnace size scenario*. In *constant thermal*

power scenario, the increase in boiler O_2 concentration is associated with reduced furnace size while thermal power is kept constant. In *constant furnace size scenario*, the increase in boiler O_2 concentration is associated with increase in boiler thermal power while the furnace size is kept constant.

The results show that, in order to keep the furnace temperature maxima below ash melting temperature, the heat extraction duty of the seal must be increased considerably in *constant furnace size scenario* while it decreases in *constant thermal power scenario*. Such increase in seal heat extraction duty for high O_2 concentrations requires considerable increase circulating solids flux in *constant furnace size scenario*. The increased circulating solids flux can be maintained by using cyclones with better efficiency and leads to higher share of fine particles and nanoparticles in the CFB loop.

At high O_2 concentrations, the level of CO concentration which is an indicator for the progress of the combustion is considerably higher for the *constant furnace size scenario* due to higher thermal power and consequently higher fuel input in this scenario. This high levels of CO concentration may lead to more intense combustion and potentially hot spots. The heat flux from furnace water walls is also considerably higher in *constant furnace size scenario* compared to *constant thermal power scenario* which shows the need for higher grades of materials in *constant furnace size scenario*. In all, this work suggests that the utilization of the *constant thermal power scenario* imposes considerably less challenges to the industry compared to *constant furnace size scenario* when designing new boilers aiming for high O_2 concentrations. The results and outputs of this study imply a change in the design of the current conventional CFB boilers in a way that the aspect ratio of future large-scale oxy-fuel CFB boilers are larger than the current air-fired CFB boilers and approaches the fluid catalytic cracking fluidized bed applications.

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