

Volumetric Combustion of Biomass for CO₂ and NO_x Reduction in Coal-fired Boilers

Jun Li^{*1}, Weihong Yang¹, Wlodzimierz Blasiak¹, Anna Ponzio²

¹*Division of Energy and Furnace Technology, Royal Institute of Technology (KTH)*

Brinellvägen 23, 10044 Stockholm, Sweden

Tele: +46 8 7908402; Email: jun2@kth.se

²Jernkontoret, Box 1721, 111 87 Stockholm

ABSTRACT:

To meet the urgent environmental targets, substituting coal with biomass has been considered to be an effective and promising method over the last decades. In this paper, **a new concept of volumetric combustion is proposed and further developed to achieve 100% fuel switching to biomass in large scale coal-fired boilers. Volumetric combustion not only changes the in-furnace flow but also affects the combustion reactions by the intensive mixing and internal recirculation of the flue gases.** Firstly, the volumetric combustion properties of the wood pellets were investigated experimentally. An Aspen model was then used to thermodynamically describe and study the volumetric combustion with three different types of fuel, and the emission properties of CO₂ and NO_x were compared. Finally, two applications of volumetric combustion were discussed. It is concluded that the wood pellets ignited and combusted much faster than the coal pellets and had a larger combustion volume when combusted under lower oxygen concentration conditions, and the ignition time was almost independent of the oxygen concentration when the oxidizer was preheated to 1000°C. In addition, the NO_x emissions decreased as the recirculation ratio of the flue gas increased, and as the percentage of biomass used in co-firing increased, the amount of flue gas that needs to be recycled for reduction of NO_x decreased. Thus, the volumetric combustion is beneficial as it reduces the operation cost of NO_x reduction. The volumetric combustion would be an attractive technology for co-firing a large proportion of biomass in coal-fired boilers with high boiler efficiency and effective emissions reduction.

Key words: *Volumetric combustion, Biomass, Co-firing, NO_x*

1 Introduction

In the year 2007, the EU adopted a far-reaching energy policy aimed at achieving a number of ambitious targets by the year 2020: reduce greenhouse gases by 20 % compared to 1990, raise the share of renewable energy in the EU to 20 % and improve energy efficiency by 20 %[1].

Compared with other techniques for biomass conversion, biomass and coal co-firing represents a near-term, low-cost and sustainable option that promises reductions in net CO₂, SO_x and NO_x emissions, and several societal benefits [2-4]. For example, a 5% of biomass co-firing in global co-fired power generation results in 40 GW of installed biomass capacity and reduces about 300 Mton of net CO₂ per year[4].

Over the past 5-10 years, there has been remarkably rapid progress in the development of co-firing. Several plants have been retrofitted for demonstration purposes, while another number of new plants are already being designed to co-utilize biomass with fossil fuels[3]. The approximately 40 pulverized coal-fired power plants worldwide that use co-firing of biomass on a commercial basis, average approximately 3% of biomass used in energy basis[5]. This leads to 3.5 Mton of coal substituted and results in approximately 10 Mton of reduction of net CO₂[4, 5]. Furthermore, co-firing potential is huge. According to Energy Technology Perspectives (IEA, 2006), global electricity production from biomass is projected to increase from its share of 1.3% to 3%-5% by 2050 [4].

Biomass is able to penetrate all energy sectarian markets, but economic constraints still limit its general deployment. Therefore, a progressive and efficient but sustainable biomass scheme is required. The economics of biomass co-firing are significantly impacted by the twin factors of deregulation and environmental requirements. Uncertainties in both

arenas make investment in most, or all, biomass co-firing technologies difficult to justify. Consequently, achieving the goal for the potential use large percentage of biomass in co-firing systems is challenging. Furthermore, new regulations force the power sector to use of large percentages (above 40 %) of biomass in co-firing by the power sector, such as, LCPD (Large Combustion Plant Directive), NECD (National Emission Ceilings Directive) and IPPCD (Integrated Pollution Prevention and Control Directive).

The combustion behaviors of biomass are different from those of coal. Biomass yields a much higher fraction of its mass through devolatilization than that does coal. However, if the biomass particles are too large or dense, they may not be entrained into the flue gas and will enter the bottom ash stream with little or no conversion beyond drying if the biomass injection is not well organized. Additionally, the low densities of the biomass particles help the biomass particles become oxidized at rates much higher than coal. Furthermore, if the boilers do not mix the flue gases effectively in the furnace section, striated flows will form, which is a common feature of biomass-coal combustion[6]. Therefore, the research and development of an advanced combustion technology is a technical challenge for the use of biomass and/or a larger percentage of biomass co-fired with coal with the aims of maximum efficiency and minimum emissions in larger scale electricity generation.

In this paper, volumetric combustion, the idea for a new combustion concept for the 100% biomass combustion in a boiler is further developed. The initial concept of the volumetric combustion was proposed by Blasiak et al. in 2008[7]. Volumetric combustion can be characterized by a very intensive mixing and internal recirculation inside of the combustion chamber. In this way, combustion occurs in a very large volume with a relatively uniform distribution of the reacting species, temperature and heat fluxes.

To understand the volumetric combustion properties of biomass in combustion chamber, the flame phenomenon and ignition time of wood pellets were studied experimentally and compared with that of coal. Furthermore, the properties of volumetric combustion were systematically studied thermodynamically. The emissions reduction during volumetric combustion process was also investigated for three different types of fuel, namely, biomass only, co-firing and coal only. Finally, two applications for volumetric combustion were discussed. The aim of this work is not only to determine the probability for 100% biomass combustion in a boiler without the reduction of efficiency but also to ascertain the emissions reduction properties of the volumetric combustion technology.

2 Development Testing and Thermodynamic Analysis

2.1 Concept of volumetric combustion

Traditional air staging systems are not uncommon in utility and district heating boilers and are independent of the firing configuration or combustion technology. A typical organization of staged combustion is shown in Figure 1(a). To prevent the formation of nitrogen oxides from fuel-bound nitrogen, the primary combustion zone is operated under sub-stoichiometric conditions with an excess air ratio less than one. To complete the combustion, a secondary air is introduced into the upper furnace by means of an air supply system known as Over-Fire Air (OFA). The secondary combustion zone is operated with an excess air ratio above one. The interaction between the two separated combustion zones is difficult to control in large scale combustion chambers particularly when the boiler loads and operational parameters change.

The negative effects of such staged combustion are usually an excessively high content of carbon in the fly ash (known as Loss on Ignition, LOI) and the production of carbon monoxide. Furthermore, the NO_x reduction for traditional systems is limited. Other known negative effects include a drop of the main steam temperature and water wall wastage. The reason for all of the negative effects is poor mixing inside the combustion chamber. This often results in uncontrolled flow pattern that are typically characterized by a so-called “chimney” flow that transports part of the gases and fuel particles through the combustion chamber with an excessively high velocity and thus an insufficient residence time.

Flue gas recirculation is commonly used to design low-NO_x combustion processes [8, 9]. It is applied to the design of low-NO_x burners and low-NO_x combustion in large-scale combustion chambers. In the traditional approach, either external or internal flue gas recirculation is used. External recirculation has obvious drawbacks such as a drop in efficiency and high investment costs. Internal flue gas recirculation is usually very limited because the traditional secondary air systems are designed to only deliver the secondary air for complete combustion. Usually only 10-15 % of the total combustion air is supplied as a secondary air.

Volumetric combustion commonly combines an air-staging concept and internal flue gas recirculation, and has a very intensive mixing and internal recirculation inside of the combustion chamber and has been used as schematically shown in Figure 1(b).

Figure 1<insert>

Contrary to the traditional OFA system, volumetric combustion allows for an increase in the amount of secondary air up to approximately 30-40% without causing problems with

the combustion stability or incomplete combustion. The secondary air is injected downwardly with an angle of inclination, which carries and conveys a part of flue gas from the secondary combustion zone back down to the primary combustion zone, and thus promotes an intensive internal recirculation of the flue gases. The combination of air staging and internal flue gas recirculation in volumetric combustion not only changes the in-furnace flow but also affects the combustion. The air-staging technique reduces the formation of NO_x that originates mainly from fuel nitrogen, and internal flue gas recirculation is used with purpose of reduction of thermal NO_x. Due to the intensive recirculation and good mixing between the secondary air and the flue gas, the combustion volume is larger than with traditional staged combustion. Such combustion is termed “volumetric” combustion. The volumetric combustions of gas fuel and liquid fuel have been reported for conditions of High Temperature Air Combustion (HiTAC)[10-12], or flameless oxidation, the importance of extensive flue gas recirculation in the combustion and formation of so-called “flameless” combustion in industrial furnaces has been reported[13]. Volumetric combustion has also been used for oxygen enriched and oxy-fuel combustion air [14].

2.2 Test facility and experimental procedure

The scheme of the test facility is shown in Figure 2. The rig consists of a horizontal combustion chamber of an inner diameter about 0.1 m. During the heating stage, the fuel and air are fed from air nozzles (1) to the mixing chamber (12) and then burned in combustion propane chamber (2). The hot flue gas heats the ceramic honeycomb (3) and flows through the next part of the combustion chamber. Once the proper temperature was reached, the fuel feed was shut off and the experimental stage started. The proper oxidizer

composition was set by adjusting the flows of air and oxygen or nitrogen and the resulting oxidizer was fed through the air nozzles and was heated by the hot honeycomb. The oxidizer temperature was measured by a thermocouple (11). The pellet (10) was hung in the rig, with a small cooling chamber (5) where it was constantly cooled by nitrogen. Once the pellet was in the combustion chamber, it was visible through glass window (9). The process was recorded by a digital camera through the glass window, and the mass loss of pellet was measured by digital balance (7).

In this work, combustion experiments were performed using 5 g of 8 mm, 30 g of 8 mm wood pellets, and a single wood pellet of 15 mm diameter (5 g) inserted into a small basket. The pellets were separately hung to a certain piston inside the combustion chamber during the test processes, as (10) shown in Figure 2. The experiments were carried out for three different oxygen concentrations in the oxidizer (5%, 10% and 21%) and three different temperatures of the oxidizer (600, 800 and 1000°C). The total oxidizer flow was 10 Nm³/h in all 5 g experiments and 4 Nm³/h in both 30 g experiments. The proximate and ultimate analyses of wood pellets are presented in Table 1. The experimental cases are presented in Table 2.

Figure 2 <insert>

Table 1<insert>

Table 2<insert>

2.3 Model description

The volumetric combustion system process, including the processes of solid fuel decomposition, volatile and chars combustion, and internal flue gas recirculation, was modeled using Aspen plus as shown in Figure 3. In this model, the CO₂ and NO_x emissions

were determined when using three different types of fuel, namely, biomass only, co-firing and coal only. The main assumptions of the model are as follows: 1) steady state flow; 2) the potential and kinetic energies are negligible; 3) the environmental state at $T=298$ K and $P=1$ atm; 4) the gases obey the ideal gas relations.

Figure 3<insert>

During the devolatilization process, biomass and coal are separately converted into their constituting components, which include radicals (hydrogen, oxygen, and nitrogen), and residues of char and ash via two independent blocks, ‘BIOPYRO’ and ‘COALPYRO’, respectively. After devolatilization, the compositions of biomass and coal are mixed and fed into the next block, ‘PC-ZONE’, in which fuel rich combustion occurs with an excess air ratio less than one; this process is called the primary combustion in this study. After the primary combustion, the stream is fed into the next block, ‘SC-ZONE’, in which oxygen-rich combustion occurs with an excess air ratio above one; this process is called the secondary combustion. The stream after the secondary combustion is labeled as flue gas, some of which is recycled back into the bottom of furnace (internal recirculation), and the remainder is flowed into the backpass of the boiler to exchange heat in the economizer and air preheater. To conveniently compare the results with the reference data, and improve the validation of this model, the proximate and ultimate analysis of the used biomass and coal are selected from reference [15], as presented in Table 3. It is well known that fuel nitrogen is converted kinetically into volatiles-N and char-N during the devolatilization process. However, due to the complicated char-N conversion mechanism and the limitation of the thermodynamic analysis, the simulation assumed that all fuel-N was converted into

volatiles-N[15, 16]. In this work, all of the data for the predicted NO_x are based only on thermodynamics.

Table 3 <insert>

3 Results and Discussions

3.1 Flame phenomena of the combustion of wood pellets

Figure 4 shows the typical flame appearances for three different oxygen concentrations oxidizers when the oxidizers were preheated to 1000°C. The photos are ordered from left to right by increasing oxygen concentration, 5%, 10% and 21%. When the oxygen concentration is 5%, 4 s and 640 ms after the experiments ignition started smoothly, a long flame developed that wrapped the pellet and persisted to the end of the 3-minute experiment; when the oxygen concentration is 10%, ignition started at 1 s and 760 ms, and the ignition started at the front of the pellet and a long flame appeared that wrapped the pellet. The flame was extinguished at 2 min and 11 s. When the air (21%) preheated to 1000°C was used to combust the wood pellets, ignition occurred at 2 s and 640 ms after the start of the experiment, the flame was shorter than that of the more dilute oxidizer cases, and the flame was extinguished at 2 min 8 s and 800 ms.

Figure 4<insert>

From the flame phenomenon of Figure 4, it is clear that the lower the oxygen concentration, the larger the combustion volume, and the longer combustion time. These results agree well with the desired features of volumetric combustion, which is a large volume process with relatively uniform distribution of reacting species, temperature and heat fluxes.

3.2 Ignition time of wood pellets

In this work, two different approaches were used to determine the ignition time: 1) using a stop-watch and video recording the experiments and 2) equalizing the ignition time to the time of a temperature increase in the gases downstream from the sample. The latter method was used as a compliment of the stop-watch method due to the difficulty of determining exactly when the flame appeared in the diluted cases because of its weak color. The results of both of the two methods are shown separately in Figure 5(a) and 5(b). It can be noted that the two methods differ significantly only for the 5% oxygen conditions in which the stop-watch method indicated a longer ignition time; presumably, the flame was there for some time before it was actually visible. The tendency of the ignition time was almost independent of the oxygen concentration at high temperatures (1000°C) and highly dependent on the oxygen concentration at low temperatures (600°C). Particularly, at a 5% oxygen concentration of the oxidizer and 600°C, the wood pellets did not ignite in five minutes. The similar trends have been observed during the combustion of coal pellets [17].

Figure 5a and 5b <insert>

3.3 Mass loss properties of wood pellets

The combustion experiments for the wood pellets were performed at a higher flow-rate of the oxidizer and with smaller samples both in weight and size, so a direct comparison should be avoided. However, one cannot but note the striking difference in the reactivity between biomass and coal. In Figure 6(a) and 6(b), the wood showed a large difference between the mass loss rate in the “devolatilization-zone” and the mass loss rate in the “char-zone”, and the mass loss rate in the “devolatilization-zone” is much larger than that in the “char-zone”. According to the combustion results of coal pellets reported by A.

Ponzio [17], there was little difference in the mass loss rate between these two zones for coal pellets for 5-21% oxygen and almost no visible difference for 30-100% oxygen. This finding would suggest that the devolatilization of wood is much faster than the devolatilization of coal.

Figure 6a and 6b <insert>

There may be several explanations for these results. First and foremost, there were much higher oxygen-to-fuel ratios in the wood experiments due to higher flow-rate of the oxidizer and the lower mass of the sample. However, when 30 g wood samples were used, the five-minute conversions ranged from 84 to 89% for 800-1000°C and 5-21% oxygen concentration, as shown in Table 4. The lower density and higher porosity of wood when compared to coal seem to be another explanation for the faster mass loss rate. Moreover, the high volatile content of the biomass particle leaves a more accessible char that could be readily contacted by reactants and products of all types.

Table 4<insert>

In Figure 7, the mass-time curves for the wood experiments performed with a single wood pellet (15 mm) are shown. As observed, the mass loss rate was slightly lower than in the cases for the wood pellets presented above. The differences in the ratio between the surface area and mass may be the explanation. Furthermore, with respect to coal[17], the results in Figure 7 confirm that wood pellets were combusted much faster than the coal pellets. The differences in density between the wood pellets and the coal pellets were significant.

Figure 7<insert>

The devolatilization rate appeared to be independent of the oxygen concentration when oxidizer was preheated to 1000°C, whereas when the oxidizer was at 800°C, the devolatilization rate seemed to be determined by the oxygen concentration. In fact, the mass loss rate in the “devolatilization zone” was significantly increased, mainly between 10 and 21%, as shown in Figure 8(a). This was also evidenced by an inclined 1 min curve in Figure 8(b). A plausible interpretation is that, at 800°C, the heat of combustion is indeed an important promoting factor for the devolatilization process. As was noted above, there is a similar but less significant tendency toward the increased importance of the oxygen concentration for low oxygen concentrations, which was also reported in the initial part for the experiment for the coal pellets[17]. The behavior of the mass loss of wood had little dependence on the temperature of the oxidizer, at least in the very initial part of the experiment.

Figure 8(a) and 8(b) <insert>

The mass loss showed very little dependence on the oxygen concentration at 600°C, as shown in Figure 9(a). This is no surprise, a look at the ignition times reported above confirms that merely devolatilization occurred without significant combustion in the longer time of the experiment procedure. Flaming ignition occurs only from 1 min 30 s to 2 min 30 s during the process, depending on the oxygen concentration, and if only 5% oxygen is used, there is no ignition at all. No or little combustion results in no or little release of heat, thus there is no influence of the oxygen concentration on the mass lost; this finding is confirmed by the almost flat curves in Figure 9(b).

Figure 9a and 9b<insert>

3.4 Model validation of the volumetric combustion system

The model was validated against the power plant boiler, and the operating data from Higgins et al. [15], which is a pulverized coal boiler with a maximum 55 MWe of electricity output and 179 MWt of heating output. The input data for both coal only and co-firing was used in this paper, as shown in Table 5 [15]. And the operating data for pure biomass was calculated based on pure coal case with same boiler load and block efficiency.

Table 5 <insert>

According to the predicted results, the NO_x emission for pure coal combustion without flue gas recirculation was 227 mg/Nm³ at 6% O₂ content, and the measured value of NO_x under the same conditions was 275 mg/Nm³. The predicted NO_x was smaller than the measured value, but it was in reasonable range of NO_x emission. The reason might be the simplified conversion mechanism of fuel nitrogen. Moreover, the under- or over-operation result is a common problem for Aspen plus, because it is a steady state model of the combustion process that does not consider the kinetics, and there are many other factors affect the real operation results[18]. Finally, the main purpose of this work is to compare the CO₂ and NO_x emissions under different operating conditions.

3.5 Emissions reduction of volumetric combustion

Biomass is a renewable resource and the CO₂ released during biomass combustion will be re-captured by the re-growth of the biomass through photosynthesis[19]. The neutrality of biomass CO₂ has been recognized for many years by an abundance of studies and is universally accepted by agencies, institutions, regulations and legislation. The CO₂ emissions from combustion of biomass fuel sources are not assumed to increase the net

atmospheric CO₂ levels[20]. Therefore, biomass is widely accepted as a potential solid fuel to reduce the net emission of CO₂.

In this work, three portions of biomass in the total feed fuel were used in volumetric combustion system: 0%, 45%, and 100%, as shown in Table 5. The properties of the CO₂ net emission in the combustion processes of the three different types of fuel are compared, as shown in Table 6.

Table 6 <insert>

As mentioned above, the recirculation of the internal flue gas in the volumetric combustion not only contributes to intense in-furnace flow, it is also beneficial to form lower oxygen concentrations for reduction of the NO_x emissions. Therefore, the recirculation ratio R is an important factor in volumetric combustion. Here, R represents the recycled fraction of total gas products. For example, $R=0$ means that there is no flue gas is recycled back to the furnace chamber, $R=0.1$ means that 10% flue gas is recycled back into the primary combustion zone.

Figure 10 shows the effect of the recirculation ratio on NO_x emissions at different combustion conditions. One of the conditions is an un-staging combustion, in which both primary air and secondary air were introduced form the port for the primary air (see Figure 1). The other condition is an air-staging combustion, in which the combustion air was divided into primary air and secondary air. Therefore, the combustion zone was divided into two combustion zones, where the feed was combusted with a deficiency of air in the primary zone and with an excess of air in the second burnout zone. In this case, the solid fuel consists of 55% coal and 45% biomass, the combustion air temperature was kept at 498

K in both the un-staging combustion and air staging combustion conditions, and the primary air ratio (λ) was kept as 0.7 in the air-staging combustion.

Figure 10<insert>

Figure 10 shows that the amount of NO_x emission in the un-staging combustion process was linear and decreased slightly with the increasing R . The total amount of NO_x decreased from 359 mg/Nm³ to 337 mg/Nm³ with R range from 0 to 10%. The similar decreasing trend was obtained by Baltasar J. et al by experimental methods[9]. Compared to the un-staging combustion, the amount of the NO_x emission was significantly reduced in the air-staging combustion, and the same mechanistic pathways for the formation and reduction of nitrogen oxides during air-staging combustion were reported by Beer[21]. More interestingly, the NO_x emission first rapidly increased then decreased sharply with the increasing R during the air-staging combustion, and the NO_x approached 0 mg/Nm³ when $R=4\%$ **when only thermodynamics were considered**. This means that, in this case, all of the formed NO_x can be deoxidized to N₂ under a reducing atmosphere. A possible explanation for the initial increase of NO_x emission is as follows: when the small proportion of the high temperature flue gas is recycled into the boiler furnace, it mainly contributed to the furnace temperature but had a small influence on the formation of low-oxygen concentration zone. The thermal NO_x formation is highly dependent on the temperature and oxygen concentrations, whereby a higher temperature promotes thermal NO_x formation. As recirculation ratio increased, more flue gas contributed to further decrease the oxygen concentration and the maximum flame temperature, and thus lowers the thermal NO_x formation. Furthermore, it was assumed that all fuel nitrogen released as volatile-N, which subsequently reacted to form NO_x in an oxidizing environment and N₂ in

a reducing environment[2]. Therefore, the more flue gas that is recycled, the lower the oxygen concentration formed inside furnace, and thus a good reducing environment is formed for the reduction of NO_x. Flue gas recirculation plays a particularly important role for the reducing of NO_x emissions during the air-staging combustion process, as there is almost no NO_x emission when the recirculation ratio approached 4% **when only thermodynamics were considered**.

The effects of the recirculation ratio on the NO_x emissions in the three different types of fuel, namely, biomass only, co-firing and coal only, are shown in Figure 11. From Figure 11, the similar trends were observed: the NO_x emission first increased and then sharply decreased, and there was almost no NO_x emission when recirculation ratio reached 10% in all three fuel conditions. More importantly, the level of the NO_x emission during the biomass combustion process is strikingly lower than that of the coal combustion process, and the level of the NO_x emission in co-firing is lower than that of coal combustion, but higher than biomass combustion. The first and obvious reason is the nitrogen content in biomass is lower than that of coal (see Table 4). Munir (2010) has analyzed the mechanism of the reduction NO_x in biomass co-firing[2]. According to Munir, there are two additional explanations. First, the volatile matter in biomass is higher than that in coal, and thus, for higher percentages of biomass that replaced coal as fuel, more volatile matter was released, so the predominant combustion consisted of gas-phase reactions. Second, as biomass contains less carbon and is high in oxygen compared coal (see Table 4), the amount of stoichiometric air required is less than for coal combustion, and a stronger local reducing environment can be created with the addition of biomass without changing the air supply conditions.

Figure 11<insert>

When considering the flue gas recirculation in the volumetric combustion system, the recirculation ratios corresponding to NO_x emissions approaching to 0 mg/Nm³ are different: 10%, 4% and less than 3% in coal only, co-firing and biomass only, respectively. Clearly, for higher percentage of biomass in co-firing, less flue gas must be recycled to realize lower NO_x emissions. In other words, to achieve lower NO_x emissions in volumetric combustion, more drive power for recirculation is needed during coal combustion, and less drive power for recirculation is needed during biomass combustion. This is very interesting result because the volumetric combustion of biomass makes it possible to achieve lower NO_x emissions with lower investment costs and operating costs and is more reliable.

4 Applications of volumetric combustion

4.1 Application concepts

Generally, in volumetric combustion, solid fuels are combusted under a high temperature and oxygen deficient atmosphere caused by a strong internal flue gas recirculation. As analyzed above, volumetric combustion system has several benefits as described below:

- Lower NO_x emissions (both Fuel-NO_x and Thermal-NO_x),
- Lower particle matter emissions,
- A higher uniform temperature profile, thus, a higher heat transfer and a higher exergy efficiency,
- The possibility to apply a large portion of biomass in co-firing system due to better control of combustion,
- Maintaining the maximum parameters of main steam.

Based on those benefits, 100% biomass as the combustion fuel in a power plant boiler is more realizable. There may be several methods to achieve the intensive internal recirculation and mixing of gases inside furnace. In this work, two application concepts of volumetric combustion in a real boiler are presented. One application uses rotating secondary air supplied via high velocity air nozzles in the upper furnace. The higher momentum of the secondary air promotes the intensive internal recirculation of flue gases from the secondary combustion zone to the primary combustion zone. In this way, the cold secondary air swirls down along the furnace wall, and the hot flue gas from the primary combustion zone swirls up inside furnace, as shown in Figure 12(a). Another application concept uses an Ecotube inside furnace, a high injection velocity results in a higher momentum of the secondary air, which also promotes intensive internal recirculation. In contrast to the first application, the colder secondary air swirls down from the middle-upper of the furnace, and the hot flue gas swirls up along furnace wall, as shown in Figure 12(b). The same Ecotube application for gas sinking in a great boiler has been verified by Dong et al[22]. In both the mentioned applications, the biomass is designed to be grinded by a separate mill system, and then combusted separately in the upper burners. The bottom burners can be used either for coal in co-firing cases, or can be switched to use biomass in pure biomass combustion cases, as shown in Figure 12.

Figure 12<insert>

4.2 Application example

An example of the first application concept of volumetric combustion is Rotating Opposed Fired Air (ROFA) system with a boosted over-fire air that includes a patented rotation process[23]. In a typical ROFA System installation, 25-40% of the total combustion air is

injected into the upper furnace through special asymmetrically placed air nozzles, creating a sub-stoichiometric condition at the burner area, and significantly decreasing the NO_x formation by both air-staging and internal flue gas recirculation technologies. Several different biomass fuels were combusted with/without ROFA and tested in a real boiler; the alternative biomass fuels were straw pellets, willow pellets and wood pellets[15].

The measured results showed a dramatic reduction of NO_x emissions when applying the ROFA system, as shown in Figure 13. In Figure 13, the NO_x emissions and LOI change with varying burner stoichiometric ratio (BSR). LNB-NO_x represents the coal combustion using lower NO_x burner without flue gas recirculation; ROFA-NO_x represents the coal combustion with flue gas recirculation; Biomass-NO_x represents 45% biomass and 55% coal co-fired with flue gas recirculation. All of the operating conditions are the same with those shown in Table 5. The NO_x emissions for the co-firing of varying biomass fuels are significantly decreased when compared to coal-only combustion.

Figure 13<insert>

5 Conclusions

A new concept of volumetric combustion was proposed in this paper, which takes advantage of intensive internal recirculation and good mixing between the secondary air and the flue gas, and where the combustion volume is larger than with traditional staged combustion. Volumetric combustion could be a suitable technology for combusting a high percentage of biomass with higher boiler efficiency and higher reduction of CO₂ and NO_x emissions. Several benefits were shown in the volumetric combustion system, and those benefits contribute to the possibility of using higher percentages of biomass in co-firing boilers; even the use of 100% biomass is possible.

Based on the concept of volumetric combustion, experimental and modelling research was performed. It is concluded that wood pellet was ignited and combusted much faster than coal pellet with a large combustion volume, and the ignition time was almost independent from the oxygen concentration when the oxidizer was preheated to 1000°C. In addition, the NO_x emissions decreased with the increasing recirculation ratio of the flue gas and the higher percentages of biomass used in co-firing decreased the amount of flue gas recycling needed to lower NO_x emissions; thus, a benefit of volumetric combustion is to reduce the operating cost of NO_x reduction. In the future, the volumetric combustion would be an attractive technology for co-firing a large proportion of biomass in coal-fired boilers with high boiler efficiency and effective emissions reduction.

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Table captions

Table 1. Properties of the wood pellets (received basis)

Table 2. Experimental conditions for the combustion of the wood pellets

Table 3. Fuel parameters of coal and biomass used in modelling

Table 4. Five-minute conversion of the wood pellet (8 mm, 30 g)

Table 5. The operating conditions used in modeling

Table 6. CO₂ net emission with different fuel types

Figure captions

Figure 1. Scheme of two combustion concepts (a. traditional combustion; b. volumetric combustion)

Figure 2. Schematic picture of the batch type HiTAC/G facility at KTH(1-gases nozzles; 2-combustion chamber; 3-honeycomb; 4-heat insulation; 5-cooling chamber; 6-tiny wire; 7-digital balance; 8-exhaust; 9-glass window; 10-wood pellets; 11-thermocouple; 12- mixing chamber)

Figure 3. Aspen plus flow sheet of the volumetric combustion with biomass and (or) coal

Figure 4. Typical flame appearances with three different oxygen concentrations (oxidizers were preheated to 1000°C)

Figure 5. The effect of the oxidizer temperature on the ignition time of wood pellets (a. video recording method; b temperature increase recording method.)

Figure 6. Influence of the oxygen concentration on the wood pellet combustion for $T_{\text{oxidizer}}=1000^{\circ}\text{C}$ (a. Mass as function of time for different oxygen concentrations in the oxidizer; b. Mass as function of oxygen concentration in the oxidizer for different durations of the experiment)

Figure 7. Influence of the oxygen concentration on the single wood pellet combustion for $T_{\text{oxidizer}}=1000^{\circ}\text{C}$

Figure 8. Influence of the oxygen concentration on the wood pellet combustion for $T_{\text{oxidizer}}=800^{\circ}\text{C}$ (a. Mass as function of time for different oxygen concentrations in the oxidizer; b. Mass as function of oxygen concentration in the oxidizer for different durations of the experiment)

Figure 9. Influence of the oxygen concentration on the wood pellet combustion for $T_{\text{oxidizer}}=600^{\circ}\text{C}$ (a. Mass as function of time for different oxygen concentrations in the oxidizer; b. Mass as function of oxygen concentration in the oxidizer for different durations of the experiment)

Figure 10. Effects of the recirculation ratio on NO_x emissions at different combustion conditions

Figure 11. The effect of the recirculation ratio on NO_x emissions under different fuel conditions

Figure 12. Two application concepts of the volumetric combustion in boilers (a. Rotating secondary air supplied from upper furnace wall; b. Rotating secondary air supplied inside the upper furnace)

Figure 13. NO_x and LOI as a function of the BCR for varying biomass fuel tests [15]