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# Performance Modelling of Biomass/Ammonia/Coal Co-firing in Pulverized Coal-fired Boiler using Process Simulation

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Global pledges to reduce greenhouse gases (GHGs) emission have induced gradual reduction of coal utilization as fuel in power generation. Co-firing coal with carbon-neutral and carbon-free fuel such as biomass and ammonia offer an economically viable way to reduce carbon emissions. This study presents a thermodynamic analysis of biomass/ammonia/coal co-firing in 1,500 $MW_{th}$ pulverized coal-fired boiler. The studied boiler is modelled using process simulation where equilibrium reactor is coupled with heat transfer equipment inside the boiler to approximate temperature and composition of flue gas. Base simulation case using pure coal as fuel is validated by comparing temperature and gas mass flow rate obtained from simulation with values reported in the datasheet of studied boiler. Fuel blends are varied while maintaining constant heat input and constant adiabatic flame temperature (AFT). The effect of co-firing ratio on flue gas temperature profile and GHGs reduction are visualized and discussed. Further analysis explores various fuel composition and identifies operating condition that exhibit lowest GHGs emissions. This study highlights the potential of biomass/ammonia/coal co-firing to reduce GHGs emission.

## 1. Introduction

Countries around the world have pledged to reduce greenhouse gases (GHGs) emissions as part of wider effort to combat climate change. As mentioned in a report by global climate agency, energy sector contributes significant amounts of GHGs through utilization of unabated coal in power generation (International Energy Agency, 2022). Therefore, introduction of alternative fuel into existing coal-fired power generation facilities carries great potential in achieving GHGs emission target.

Ammonia and biomass appear as promising candidate as energy carrier to help phasing out coal. In recent years, ammonia is gaining attention as promising energy carrier with carbon-free value chain (Spatolisano and Restelli, 2024). The entire molecular structure of ammonia is free of carbon which enable immediate reduction in GHGs emission. On the other hand, biomass offers carbon-neutral alternatives which does not contribute to the net increase of GHGs content in the atmosphere. However, the challenges in adopting co-combustion scheme lies in the emission control of non-carbon GHGs (NO, $N_2O$, and $SO_x$).

Partial introduction of biomass and ammonia have been attempted in coal-fired boiler in several works. Experimental investigation of ammonia/coal co-combustion in lab scale furnace reveals feasible operating point can be achieved by controlling $NO_x$ emission through air staging scheme (Tamura et al., 2020). Other study employs numerical simulation to find the optimal position of ammonia injection in coal-fired boiler based on $NO_x$ emission relative to pure coal combustion (Ahmad et al., 2024). Meanwhile, scientific literatures on coal/biomass co-combustion were dominated by lab scale experiments. Characterization attempt of biomass/coal co-combustion using circulating fluidized bed (CFB) reports that measured combustion temperature increases along with the increasing biomass ratio in the fuel stream (Q. Liu et al., 2021).

Despite its apparent feasibility, simultaneous introduction of biomass and ammonia to coal-fired furnace is still rarely researched in the literature. Experimental investigation using small scale CFB elaborate the influence of ammonia injection location on pollutant and GHGs emission of biomass/ammonia/coal co-combustion (Kim et al., 2025). Due to its complexity, numerical approach is seldom pursued to explore operating conditions for multi fuel combustion. A study proposed model for ammonia/coal co-combustion using reactor network managed to

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elaborate the chemical pathways for different ammonia firing ratio (Ishihara et al., 2020). Similar approach using process simulation illustrate the influence of increasing ammonia thermal input ratio (Xu et al., 2022) on coal-fired power plant. Although process simulation is usually limited to equilibrium reactor to model combustion, the relatively simple approach enables thermodynamic analysis as basis for more rigorous studies.

To the best of author knowledge, there is no comprehensive thermodynamic analysis using process simulation to model pulverized coal-fired boiler with biomass/ammonia/coal as fuel for power plant scale application. Previous research is limited to analysis of coal/ammonia co-firing in power plant scale using process simulation (Xu et al., 2022) or biomass/ammonia/coal co-firing in laboratory scale experiment (Kim et al., 2025). Accordingly, the present study aims to: (1) Assess accuracy of process simulation to predict performance of coal-fired boiler and (2) Explore feasibility of biomass/ammonia/coal boiler under various operating conditions.

## 2. Methods

### 2.1 Composition and properties of fuel

This study analyses the performance of typical 1,500 $MW_{th}$ supercritical coal-fired boiler system under co-firing with biomass and ammonia. The simulation employs Aspen Plus® v14 software to model equilibrium reaction and heat transfer inside the studied boiler. In Aspen Plus, heterogenous solid fuels such as coal and biomass are classified as non-conventional components which consist of identifiable constituents obtained from proximate and ultimate analysis (Aspen Technology, 2003). Table 1 summarizes the relevant compositions and physical properties of coal (Xu et al., 2022), biomass (L. Liu et al., 2022), and ammonia (Kim et al., 2025) in this study. Elemental composition of combustible matter from ultimate analysis in coal and biomass are reported in total mass percentage including ash and moisture content.

*Table 1: Fuel properties of coal, biomass, and ammonia in this study*

| Properties | Coal (ar) | Biomass (ad) | Ammonia |
|---|---|---|---|
| **Proximate analysis (%wt)** | | | |
| Moisture | 8.14 | 6.55 | - |
| Ash | 24.48 | 8.54 | - |
| Volatile Matter | 29.51 | 73.49 | - |
| Fixed Carbon | 37.87 | 11.42 | - |
| **Ultimate analysis (%wt)** | | | |
| C | 54.37 | 41.02 | - |
| H | 3.75 | 3.83 | 17.65 |
| N | 0.81 | 1.72 | 82.35 |
| S | 0.18 | 0.28 | - |
| O* | 8.27 | 38.06 | - |
| Lower Heating Value (MJ/kg) | 21.23 | 16.20 | 22.4 |

ar: as received basis, ad: air dried basis, *by difference

### 2.2 Combustion cases being considered

The boiler operation using pure coal will be employed as a base case for comparison with other combustion cases. The feasibility of coal co-firing with biomass and ammonia will be explored by comparing fuel blends individually i.e. coal/biomass or coal/ammonia and simultaneously with coal/biomass/ammonia blends. The fuel mixing is quantified in terms of co-firing ratio which represents heat input percentage of specific fuel components. Co-firing ratio ($R_i$) of fuel component i is defined as follows.

$$R_i = \frac{HV_i \times m_i}{\sum_j HV_j \times m_j} \times 100\ \% \tag{1}$$

where $HV_i$ and $m_i$ represent heating value and mass flow of component *i* in the fuel stream, respectively. The composition of fuel will be specified by combination of fuel name and co-firing ratio, e.g. C70/B20/A10 denotes fuel mixture that consists of 70 %, 20 %, and 10 % heat input from coal, biomass and ammonia, respectively.

To ensure comparability between combustion cases, constant heat input and constant adiabatic flame temperature (AFT) are maintained among different cases. AFT is maintained at same value attained in the base case by varying the amount of air feed rate as presented in Table 2. The references in Table 2 represent previous research on fuel with same co-firing ratio and not necessarily utilized identical composition of coal and biomass in the present study (Table 1). The AFT is taken from the temperature of flue gas from decomposition and burner block in Figure 1 without external heat transfer following procedure adopted by Xu et al. (2022). For cases with fuel co-firing, total air feed rate will be varied until AFT achieves the same value as the base case. Total air feed rate is changed by configuring the value of heated primary air (HPA) and heated secondary air (HSA), each of which is supplied at 294 °C and 311 °C, respectively. Combustion of non-conventional components is modeled using RYield and RGibbs reactor block of Aspen Plus, which has been adopted by previous research (Xu et al., 2022). Coal, biomass, air, and feedwater are supplied at ambient temperature of 20 °C while air and ammonia inlet pressure are 101.3 kPa and 200 kPa, respectively. Feedwater (FW) and reheater steam (RS1) are supplied at 279 °C, 28.97 MPa and 311 °C, 4.17 MPa, respectively. Mass flow rate of FW and RS1 are 1,560.0 t/h and 1, 326.0 t/h which are within 10 % of value reported in the thermal calculation datasheet of the studied boiler (1,623.4 t/h and 1,375.7 t/h, respectively). Around 18.8 t/h of ambient air leaks into the boiler (LA). All parameters of input streams that just mentioned could be referred to thermal calculation datasheet of the studied boiler (Harbin power plant, n.d.).

*Table 2: Combustion cases being considered in this study*

| Cases No. | Fuel composition | Total fuel feed rate (t/h) | Air feed rate (AIR) (t/h) | AFT (°C) | Total heat input (MW) | Reference |
|---|---|---|---|---|---|---|
| 1 | C100 | 219.5 | 1,781.1 | 1,941 | 1,294 | (Xu et al., 2022) |
| 2 | C90/B10 | 226.3 | 1,767.7 | 1,941 | 1,294 | (Tamura et al., 2020) |
| 3 | C80/B20 | 233.1 | 1,755.3 | 1,941 | 1,294 | (Tamura et al., 2020) |
| 4 | C70/B30 | 239.9 | 1,743.0 | 1,941 | 1,294 | (Tamura et al., 2020) |
| 5 | C90/A10 | 222.6 | 1,753.1 | 1,941 | 1,294 | (Xu et al., 2022) |
| 6 | C80/A20 | 225.7 | 1,726.1 | 1,941 | 1,294 | (Xu et al., 2022) |
| 7 | C70/A30 | 228.8 | 1,699.2 | 1,941 | 1,294 | (Xu et al., 2022) |
| 8 | C71/B8/A21 | 231.5 | 1,713.8 | 1,941 | 1,294 | (Kim et al., 2025) |
| 9 | C56/B22/A22 | 241.3 | 1,693.6 | 1,941 | 1,294 | (Kim et al., 2025) |

### 2.3 Flow diagram of process simulation

Figure 1 illustrates the proposed model of boiler system with biomass/ammonia/coal co-firing. In general, the boiler system can be divided into 3 modules: 1) fuel gasification and combustion, 2) heat transfer, and 3) flue gas treatment.

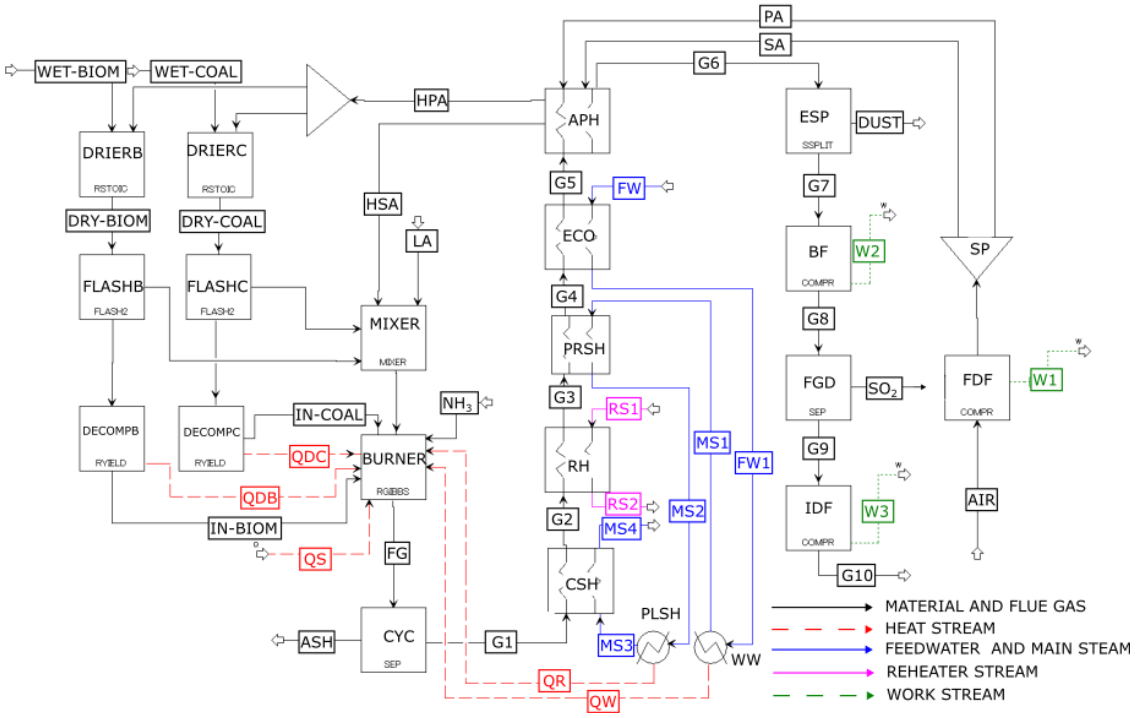

*Figure 1: Schematic of process simulation for biomass/ammonia/coal co-firing of boiler system*

Coal and biomass were fed into the first module through drying process in DRIERC and DRIERB by using heated primary air (HPA) from air preheater (APH). Mass flow of drying air is supplied in proportion to coal and biomass flow. Solid fuels are being separated from the moisture content in FLASHC and FLASHB blocks. After that coal and biomass are gasified in DECOMPC and DECOMPB into constituent components (C, $O_2$, $H_2$, $N_2$, S, Ash, $H_2O$) at 25 °C and 101.3 kPa. Here gas composition is specified following ultimate analysis result in Table 1. Subsequently, fuel gas flows into the BURNER block where the main combustion reaction occurs at atmospheric pressure. Heated secondary air (HSA) is mixed with moist HPA and air leakage stream (LA) in MIXER and flows to BURNER. Composition of flue gas is calculated by assuming equilibrium conditions where total Gibbs energy is minimized while fulfilling heat requirement of steam generation and heating at water wall (WW) and platen superheater (PLSH). Combustion heat from BURNER block is radiated to WW and PLSH until supercritical steam at 26.81 MPa attain 438 °C and 542 °C, respectively. The first module ends at separator (CYC) where hot flue gas is separated from incombustible ash before being transferred to heat transfer module. Subsequently, both steam and flue gas flow into the convective superheater (CSH) where steam is heated to 571 °C at 25.2 MPa before being expanded in a steam turbine outside the boiler system. Further heat recovery from flue gas occurs in reheater (RH), primary superheater (PRSH), economizer (ECO), and APH where RS1, main steam (MS1), FW, primary air (PA), and secondary air (SA) are heated to 569 °C, 468 °C, 317 °C, 294 °C, and 311 °C, respectively. After the temperature has been sufficiently lowered, flue gas is fed into flue gas treatment module. Here pollutant such as particulate matter and $SO_2$ are removed using electrostatic precipitator (ESP) and flue gas desulfurization (FGD), respectively. In addition, flow of flue gas within this module is maintained using boost fan (BF) and induced draft fan (IDF). Parameters of blocks presented in Figure 1 are summarised in Table 4. All parameters of operation blocks that just mentioned could be referred to thermal calculation datasheet of the studied boiler (Harbin power plant LLC, n.d.) Several assumptions were adopted in the proposed boiler system: (1) Combustible mixture attain equilibrium composition at PLSH outlet (2) Negligible pressure loss for flue gas flow between and within blocks, (3) 1.92 % of heat generated in BURNER is lost to environment (QS), (4) Ambient air leakage (LA) into the system only occurs in BURNER (5) PA constitutes 19.2 % of total air.

## 3. Results and discussion

### 3.1 Process simulation validation using pure coal combustion

The process simulation is validated with design valued from thermal calculation datasheet of the studied boiler (Harbin power plant LLC, n.d.). Table 5 presents the comparison between design and simulated values obtained from process simulation using pure coal as fuel (Case 1, C100). Simulation results show relatively low deviation (below 10 %) for air feed rate, flue gas flow rate, and flue gas temperature. These findings suggest that the proposed process simulation is adequate to model boiler system.

*Table 3: Comparisons of predicted variables of boiler system using process simulation with design values*

| Parameters | Design value | Simulated value | Relative deviation (%) |
|---|---|---|---|
| Total air feed rate (including air leakage) (t/h) | 1,879.8 | 1,882.2 | 0.123 |
| Flow rate of flue gas inlet to APH (t/h) | 2,044.2 | 2,051.9 | 0.377 |
| Temperature of flue gas at CSH inlet (˚C) | 1,088 | 1,020 | 6.066 |
| Temperature of flue gas at APH inlet (˚C) | 349 | 368 | 5.444 |
| Temperature of flue gas at APH outlet (˚C) | 124 | 125 | 0.807 |

### 3.2 Effect of co-firing on temperature profile of boiler system

Introduction of ammonia and biomass on existing coal-fired boilers leads to different flue gas behavior. Figure 2 illustrates the temperature of flue gas at various locations for different coal co-firing ratio using biomass and ammonia. The difference in trend of temperature profile over different co-firing cases is emphasized by temperature value at CSH inlet (G1) where coal/biomass co-firing decreases flue gas temperature at G1 by about 0.3 % in contrast to coal/ammonia co-firing which increases flue gas temperature at same location up to 0.2 % for each 10 % of substituted thermal input. The observed temperature trend for coal/ammonia co-firing is opposite to temperature trend reported in previous process simulation research (Xu et al., 2022) where increase in ammonia co-firing ratio was accompanied by decrease in temperature. Previous research adopted equilibrium flue gas composition at high temperature (1,390 ˚C) which effectively fixes the chemical composition of flue gas at that temperature. On the other hand, the current study adopts direct heat transfer from BURNER to PLSH and WW which enables flue gas to achieve equilibrium at lower temperatures. Although the newer approach yields a different temperature trend, this study manages to provide more accurate value for flue gas temperature at CSH inlet as shown in Table 3. Equilibrium composition of coal/ammonia flue gas at lower temperature yields higher water content which increases the flue gas' specific heat capacity. High specific heat capacity causes reduced temperature change for the same amount of heat. Consequently, the downstream flue gas temperature increases with rising ammonia co-firing ratio as observed in different research (Wang and Sheng, 2023).

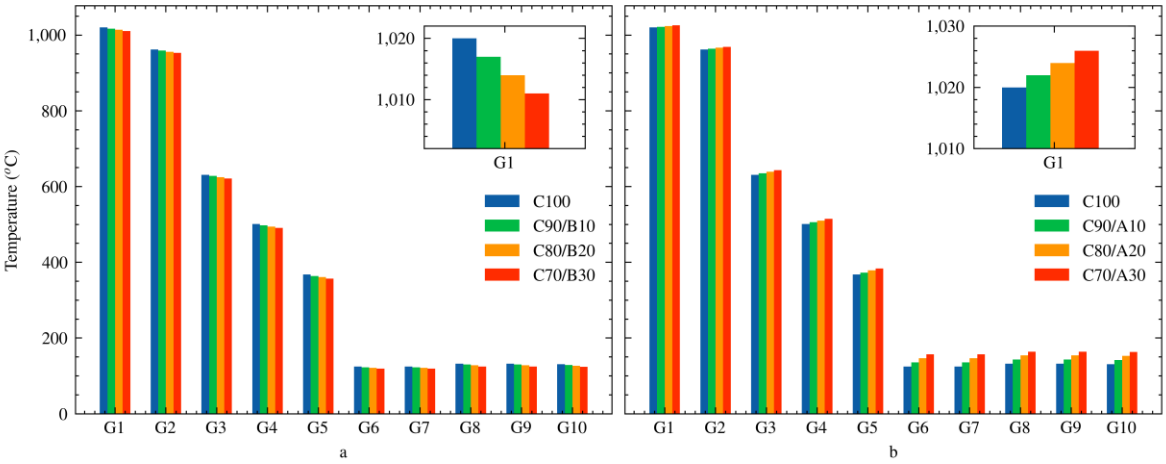

*Figure 2: Temperature profile of flue gas at various location in the boiler system during co-firing (a) coal/biomass (b) coal/ammonia. Fuel composition and stream tags refer to Table 2 and Figure 2, respectively.*

### 3.3 Effect of co-firing on GHG emission of boiler system

Further assessment of coal-fired boiler operation under co-firing with biomass and ammonia is illustrated in Figure 3. Figure 3a shows the emission profile of flue gas outside the furnace in terms of molar fraction of major components.

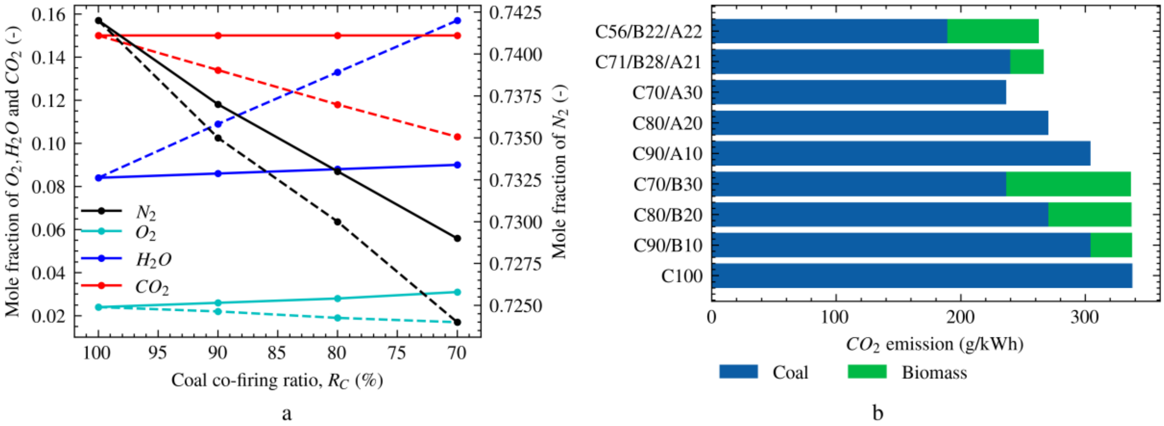

*Figure 3: Emission profile of coal co-firing cases in term of (a) flue gas composition in G1 stream for (straight) coal/biomass and (dashed) coal/ammonia co-firing and (b) GHGs emission per thermal power input*

Flue gas composition is dominated by nitrogen due to high air flow requirement to maintain slight excess air above stoichiometric value. Decreasing coal co-firing ratio using either biomass or ammonia decreases nitrogen in the flue gas which indicates decrease of the required oxidizer. Coal co-firing with ammonia yields significant increase (decrease) in water (carbon dioxide) contents of flue gas, which could explain the high temperature of flue gas in the previous section. In addition to flue gas composition, Figure 3b illustrates GHGs reduction achieved by implementing coal co-firing. The result of process simulations shows that coal/biomass co-firing increases total carbon dioxide ($CO_2$) emissions. However, carbon-neutral properties of biomass negate $CO_2$ emission from that fuel, hence the unabated $CO_2$ emission is reduced. Co-firing coal with ammonia shows direct reduction in total $CO_2$ emissions with negligible presence of other GHGs such as $N_2O$. The process simulation result also suggests that $CO_2$ emission is directly proportional to coal co-firing ratio e.g. C70/B30 emits 70 % unabated $CO_2$ relative to C100 case. These results contrast with experimental investigation where co-firing coal with biomass and ammonia exhibit higher $CO_2$ emission accompanied by measurable increase in $N_2O$ (Kim et al., 2025). The observed difference with literature highlights the inaccuracy of an equilibrium reactor approach which is adopted in the current studies for predicting GHGs emissions. Lack of information regarding kinetics modelling, residence time, and flow pattern inside combustion reactors contributes to low accuracy of equilibrium reactor approach. A network of chemical reactors which consists of perfectly stirred reactors (Ishihara et al., 2020) that could handle multiphase coal/biomass/ammonia co-firing could be proposed to improve temperature and emission modelling accuracy and reveal ways to reduce $CO_2$ and $N_2O$ emission.

## 4. Conclusions

Process simulation using an equilibrium reactor to model biomass/ammonia/coal co-firing has been performed to explore emission profile of various co-firing ratio. Temperatures of flue gas and GHGs emissions were discussed. Several conclusions were made:

1. Process simulation could be utilized to predict performance of coal-fired boilers using coal as fuel with deviation of temperature modelling less than 10 % at design point.
2. Unabated $CO_2$ emission obtained from process simulation is proportional to the coal co-firing ratio where fuel substitution with biomass (ammonia) leads to indirect (direct) reduction of $CO_2$ emission.

Future research will be attempted to increase accuracy of emission modelling relative to experiment by utilizing chemical reactor networks and detailed chemical mechanisms for multiphase biomass/ammonia/coal combustion.

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