

Optimizing Co-Firing Ratio of RDF MSW and Coal in a Fluidized Bed Reactor

I Made Agus Putrawan^{1,5,a}, I Nyoman Suprpta Winaya^{2,b*},
I Nengah Simpen^{3,c}, Ida Bagus Alit Swamardika^{4,d}, I Made Rajendra^{5,e},
Wayan Gede Ariastina^{4,f}, I Putu Angga Yuda Pratama^{2,g},
I Gusti Ngurah Putu Tenaya^{2,h}

¹Udayana University Engineering Science Doctoral Study Program, Jl. PB Sudirman, Denpasar-Bali, Indonesia

²Mechanical Engineering Udayana University, Jl. Kampus Bukit Jimbaran-Bali, Indonesia

³Chemical Engineering Udayana University, Jl. Kampus Bukit Jimbaran-Bali, Indonesia

⁴Electrical Engineering Udayana University, Jl. Kampus Bukit Jimbaran-Bali, Indonesia

⁵Mechanical Engineering, Bali State Polytechnic, Jl. Kampus Bukit Jimbaran-Bali, Indonesia

^aagusputrawan@pnb.ac.id, ^bins.winaya@unud.ac.id, ^cnengahsimpen@unud.ac.id,
^dgusalit@unud.ac.id, ^emaderajendra@pnb.ac.id, ^fw.ariastina@unud.ac.id,
^gipa.yudapratama@unud.ac.id, ^hngnrtenaya@unud.ac.id

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Abstract. Co-firing Refuse Derived Fuel (RDF) from Municipal Solid Waste (MSW) with coal presents a promising approach to urban waste management and reduction of fossil fuel dependency. This study primarily investigates the optimal co-firing ratio of RDF MSW and coal, alongside other operational parameters, in a laboratory-scale fluidized bed reactor. Experiments were conducted with variations in RDF MSW to coal ratio (5%, 10%, 15%), operating temperature (750°C, 850°C, 950°C), and excess air (15%, 20%, 25%, 30%) in a reactor with a combustion chamber volume of 1000 cm³. Results demonstrate that the co-firing ratio significantly influences combustion efficiency and overall performance. The optimal ratio was found to be 10% RDF MSW with 90% coal, yielding a peak combustion efficiency of 95.89% and a minimum Specific Fuel Consumption (SFC) of 0.19260 kg/kWh. This optimal ratio balances the benefits of RDF's higher volatile content with coal's stable combustion characteristics. Additionally, an operating temperature of 750°C and excess air of 20% complemented this optimal ratio, further enhancing stability and efficiency. SEM analysis and chemical composition studies of agglomerates revealed the role of Ca, K, Na, and Mg in deposit formation, providing insights into the interaction between RDF and coal during co-firing. This research offers valuable guidance for optimizing co-firing ratios in industrial applications, supporting the development of more efficient and environmentally friendly waste-to-energy solutions.

Introduction

Indonesia faces significant waste management challenges, generating approximately 29 million tons of waste annually, with only 65.02% being properly managed [1]. The conversion of Municipal Solid Waste (MSW) to Refuse Derived Fuel (RDF) presents a promising solution that aligns with Indonesia's renewable energy targets of 23% by 2025 and 31% by 2050 [2].

The implementation of RDF MSW co-firing with coal offers a cost-effective approach to reducing fossil fuel dependency while addressing waste management issues. Direct co-firing technology requires minimal modifications to existing power plants, making it an economically viable option for reducing CO₂, NO_x, and SO_x emissions [3]. Studies have shown that co-firing can reduce greenhouse gas emissions by up to 20% compared to coal-only combustion [4]. Moreover, the economic analysis of RDF co-firing implementation indicates potential cost savings of 15-30% in fuel expenses, depending on the mixing ratio and local waste availability [5]. The technical feasibility of co-firing

has been demonstrated across various scales, with successful implementations reporting minimal impact on boiler efficiency when proper pre-treatment and mixing procedures are followed [6].

Fluidized bed technology has emerged as an efficient platform for RDF-coal co-firing, offering superior mixing characteristics and enhanced heat transfer. The technology's success relies heavily on operational parameters, including bed material properties and combustion conditions [7]. Silica sand, used as bed material, contributes to high combustion efficiency through its excellent heat transfer properties and thermal stability [8]. Recent studies have demonstrated that fluidized bed systems can achieve combustion efficiencies up to 95% when operating under optimized conditions [9]. Research by Chen et al. [10] has shown that proper bed material selection and management can reduce agglomeration tendencies and improve overall system stability. Furthermore, investigations into heat transfer mechanisms in fluidized beds have revealed that the technology can maintain stable combustion even with fuel moisture content variations of up to 30% [11].

Previous studies have investigated various RDF-coal mixing ratios, with results indicating significant effects on system performance. Research has shown that a 5% RDF mixture maintains stable furnace temperatures around 850°C [12], while a 10% ratio impacts thermal efficiency and Net Plant Heat Rate in large-scale applications [13]. These studies have highlighted the complexities of co-firing systems, particularly regarding combustion stability, emission characteristics, and operational challenges. However, comprehensive studies optimizing RDF-coal ratios alongside other operational parameters remain limited, particularly in laboratory-scale investigations. This research gap, combined with the need to balance environmental benefits, operational stability, and economic viability, underscores the importance of determining optimal co-firing conditions. This study primarily investigates the optimal co-firing ratio of RDF MSW and coal, alongside critical operational parameters such as temperature and excess air, in a laboratory-scale fluidized bed reactor.

The novelty of this research lies in its comprehensive approach to simultaneously optimizing multiple operational parameters while examining their interdependent effects on combustion efficiency and specific fuel consumption. Furthermore, this study provides valuable insights into deposit formation mechanisms through detailed SEM analysis and chemical composition studies of agglomerates, contributing to the fundamental understanding of RDF-coal co-firing behaviour in fluidized bed systems. The investigation of deposit formation is particularly crucial as it addresses one of the major operational challenges in co-firing systems – the potential for fouling and slagging that can impact long-term system performance and maintenance requirements. These findings bridge the gap between laboratory research and industrial application, offering practical guidelines for implementing efficient RDF-coal co-firing systems in waste-to-energy facilities, ultimately contributing to more sustainable waste management and energy production practices in developing countries.

Method

Fluidized bed combustion system. The direct co-firing of RDF MSW and coal was conducted using a laboratory-scale fluidized bed combustion system. The experimental apparatus for direct co-firing of MSW-derived RDF and coal utilized a Fluidized Bed Combustion (FBC) technology, as illustrated in Fig. 1. The combustion system consisted of several integrated components designed to ensure controlled and efficient combustion processes. The primary combustion chamber (1), equipped with an external heat source, featured a total volume of 1000 cm³. A specially designed distributor plate (2) was installed at the base of the combustion chamber to ensure uniform air distribution and proper fluidization of the bed material. The experimental procedure began with the introduction of silica sand as the bed material, followed by nitrogen gas purging (3) to create an inert environment within the reactor, preventing premature oxidation and ensuring controlled combustion conditions. The reactor was heated to the desired operational temperature (800°C) using external electric heaters (4) positioned strategically around the combustion chamber. To maintain thermal efficiency and minimize heat losses, the reactor walls were insulated with glass wool (6), providing effective thermal isolation of the combustion zone.

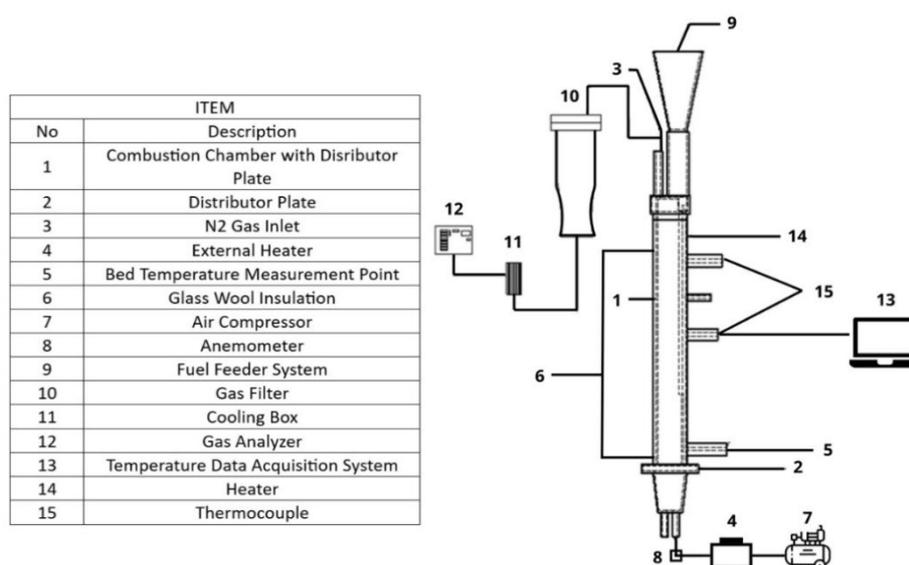


Fig. 1. Schematic diagram of the experimental setup

The fluidization and combustion air was supplied via a compressor (7), with the minimum fluidization velocity maintained at 9 m/s, precisely monitored using an anemometer (8). The fuel feeding system consisted of a calibrated fuel feeder (9) designed to deliver consistent mixtures of RDF MSW and coal at predetermined ratios. The exhaust gas treatment system incorporated a series of components: a gas filtration unit (10) for particulate removal, a cooling box (11) for temperature reduction of the exhaust gases, and a gas analyser (12) for continuous monitoring of emission products. Temperature measurements throughout the combustion process were recorded using K-type thermocouples (13) connected to a data acquisition system, enabling real-time monitoring and analysis of the combustion characteristics. The residual ash was collected and weighed post-combustion to determine the specific fuel consumption rate and combustion efficiency.

Materials and experimental setup. Prior to each experimental run, silica sand (mean particle size: 250 μm , bulk density: 2.6 g/cm^3) was introduced into the reactor as bed material. The system was initially purged with nitrogen gas to create an inert environment and prevent premature oxidation. Since this work was conducted at laboratory scale, an external heating source was required to initiate and stabilize combustion. However, during steady-state operation, the combustion process was sustained primarily by the fuel mixture (RDF and coal). To minimize heat loss and maintain thermal stability, the reactor walls were insulated with glass wool with a thermal conductivity of 0.04 $\text{W}/\text{m}\cdot\text{K}$. Compressed air was supplied through a compressor and regulated to maintain a minimum fluidization velocity of 9 m/s, monitored using a calibrated flow meter. The RDF MSW and coal mixture was continuously fed through a calibrated fuel feeder to ensure consistent fuel supply during the combustion process. The exhaust gases passed through a filtration system and were cooled in a cooling box before analysis. A gas analyzer was employed to measure the concentration of various combustion products (CO , CO_2 , NO_x , and SO_x). Throughout the incineration process, combustion temperatures were continuously monitored using K-type thermocouples with an accuracy of $\pm 1.5^\circ\text{C}$.

The experiments were conducted under systematically varied conditions to investigate the effects of key operational parameters. These parameters included RDF MSW to coal ratios of 5%, 10%, and 15% (by weight), operating temperatures of 750°C, 850°C, and 950°C ($\pm 5^\circ\text{C}$), and excess air ratios of 15%, 20%, 25%, and 30% ($\pm 1\%$). Temperature profiles and combustion duration were recorded at 1-second intervals using a data acquisition system. The ash residue was collected and weighed after each experimental run to determine the specific fuel consumption rate. The combustion efficiency was calculated based on the carbon conversion rate and heat loss analysis. Each experimental condition was repeated three times to ensure reproducibility, with the average values used for analysis.

Throughout the experiments, several key performance indicators were measured and analyzed, including combustion temperature profiles, specific fuel consumption rate, emission concentrations (CO, CO₂, NO_x, SO_x), ash characteristics and composition, carbon conversion efficiency, and heat transfer effectiveness. This comprehensive experimental approach enabled detailed investigation of the relationship between operational parameters and system performance, particularly focusing on the effects of varying RDF-to-coal ratios on combustion efficiency and emissions characteristics. The systematic variation of parameters allowed for the identification of optimal operating conditions that maximize combustion efficiency while minimizing environmental impact.

Results and Discussion

RDF-MSW composition ratio. As seen from Fig. 2, the experimental results demonstrated that increasing the RDF percentage up to 10% in the fuel mixture enhanced combustion efficiency, a finding consistent with previous studies on RDF-coal co-firing systems [4]. However, further increases in the RDF-to-coal ratio led to decreased efficiency, aligning with the observations reported by [5] in their large-scale co-firing trials. The optimal performance was achieved with a mixture of 90% coal and 10% RDF, yielding the highest efficiency of 95.89% with the specific fuel consumption of 0.19260 kg/kWh. These results demonstrate comparable or superior performance to conventional coal combustion systems, as documented in similar studies [14].

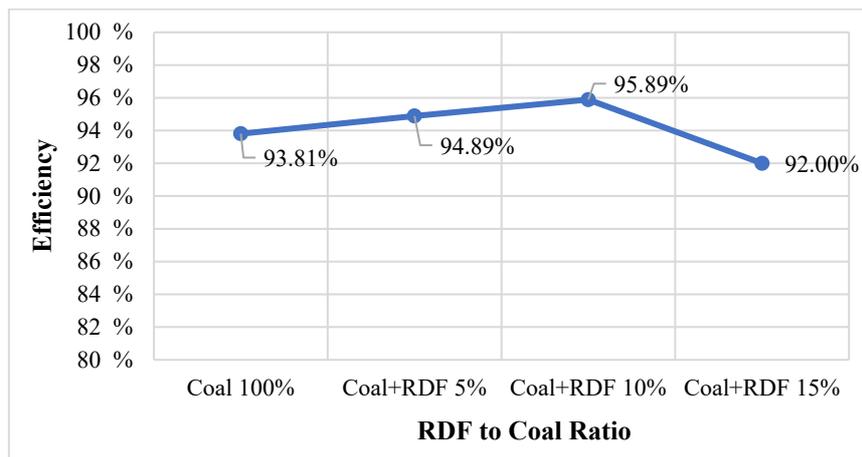


Fig. 2. Variation of RDF Coal Ratio to Efficiency of FBC system

Temperature variation experiments conducted at 750°C demonstrated stable temperature distribution immediately after fuel feeding, as illustrated in Fig. 3.

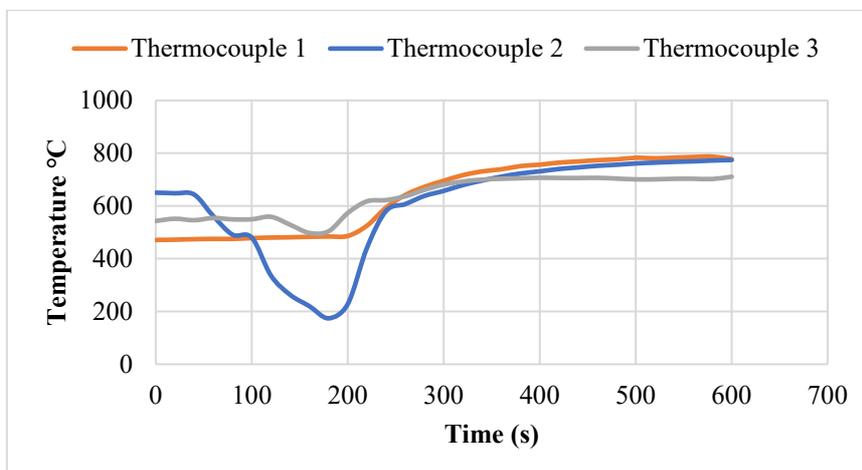


Fig. 3. The temperature profile along the bed at temperature of 750°C

Three thermocouples were strategically installed at different heights along the reactor to monitor temperature profiles. The temperature measurements in the bed region, represented by the blue line in Fig. 3, indicate stable operational conditions throughout the combustion process. This operational temperature resulted in minimal agglomeration formation with more compact structures, suggesting optimal combustion conditions. The temperature stability at this operating condition can be attributed to effective heat distribution within the bed material and proper mixing between the fuel and fluidizing air. This observation aligns with findings by [15] regarding optimal temperature ranges for RDF-coal co-firing. In contrast, at higher temperatures of 850°C and 950°C, temperature distribution became unstable, and larger agglomerates formed.

SEM investigation of agglomerates. Microscopic analysis of the agglomerates revealed structures characteristic of melted and re-solidified ash, consistent with previous research on ash behavior in fluidized bed systems [16]. The formation of larger agglomerates at elevated temperatures can be attributed to the lower melting points of certain mineral constituents, as demonstrated by [17] through detailed compositional analysis. SEM-EDX analysis revealed increased concentrations of alkali metals and other low-melting-point compounds in these agglomerates, supporting the mechanism of ash fusion and subsequent agglomeration at higher temperatures [18].

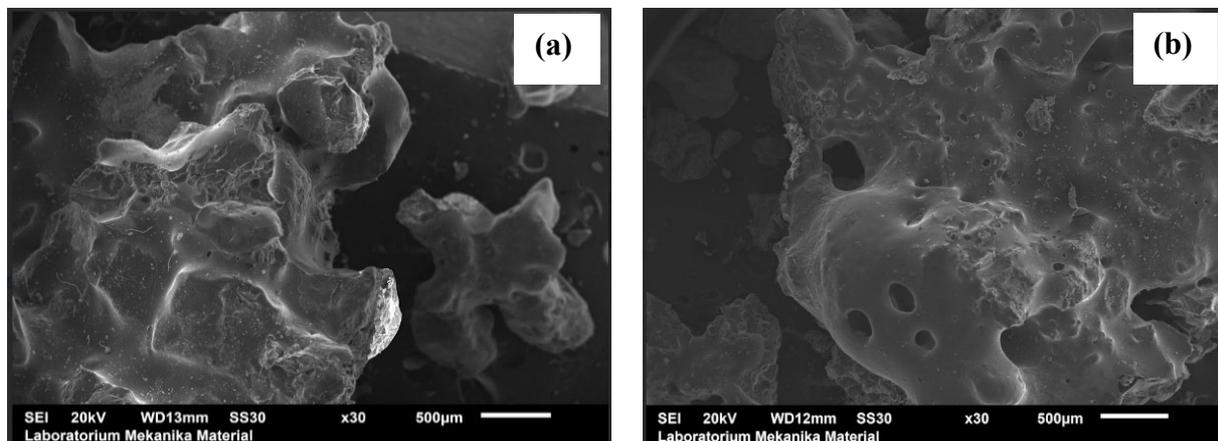


Fig. 4. SEM agglomeration at different temperatures (a) 750 °C, (b) 950 °C

The SEM analysis of agglomerates as seen in Fig. 4 formed at different temperatures revealed distinct morphological characteristics. At 750°C, the agglomerates exhibited relatively loose inter-particle spacing and moderately smooth surface structures. Similar morphological characteristics at this temperature range were reported by [18] in their study of ash behavior during RDF-coal co-firing. As the temperature increased to 850°C, the particles became more densely packed, and the agglomerate surface structure developed increased roughness. At 950°C, the inter-particle spacing became highly compact, and the agglomerate structure displayed characteristics of molten material, consistent with findings by [19], who observed similar phase transitions in their high-temperature co-firing experiments.

The variations in agglomerate structure can be attributed to the different melting points of ash constituents. Operational control of bed temperature is essential to mitigate agglomeration in RDF-coal co-firing. As temperature increases, certain ash components undergo melting, leading to changes in particle morphology and size distribution. This phenomenon was extensively documented by [20] in their investigation of ash transformation mechanisms during co-firing processes. Their research demonstrated that the presence of alkali metals (Na, K) and alkaline earth metals (Ca, Mg) significantly influenced the agglomeration behavior, particularly at temperatures above 800°C.

Chemical composition of agglomerate formation. Chemical composition analysis revealed distinctive patterns of agglomerate formation across different combustion temperatures as seen in Fig. 5. At 750°C, the agglomerates primarily contained Na, K, and Mg. As temperature increased to 850°C, Ca was detected in addition to the previous elements, while at 950°C, Mn was also present

alongside Na, K, Mg, and Ca. This temperature-dependent variation in elemental composition can be attributed to the different melting points of these constituents, explaining why Ca and Mn were only detected in agglomerates formed at higher temperatures. The LIBS analysis verified the presence of consistent elemental species across both spectra, except for Mg, which displayed distinct emission wavelengths attributable to differences in electronic transition pathways induced by the varying combustion temperatures and plasma excitation conditions. These findings align with research by [21] who observed similar patterns in elemental distribution across temperature ranges in RDF-coal co-firing systems.

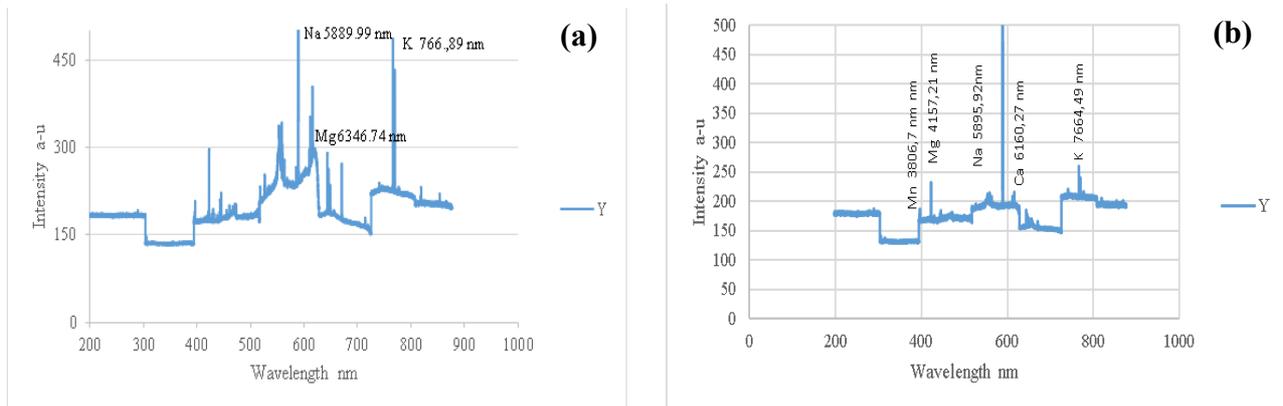


Fig. 5. LIBS of agglomeration (a) 750 °C, (b) 950 °C

Similar results were reported by [22] regarding temperature influence on agglomeration formation, particularly noting unstable temperature patterns during combustion and increased elemental diversity in agglomerates at higher temperatures. This phenomenon was further explored by [23], who documented the progressive transformation of ash compounds and their role in agglomerate formation.

The structural analysis revealed significant differences in particle spacing between agglomerates formed at 750 °C versus 950 °C, supporting the observations of [24]. These findings were complemented by recent research from [25], who provided detailed microscopic analysis of temperature-dependent agglomerate morphology in fluidized bed systems.

Combustion efficiency and gas formation. As shown in Fig. 6, the experimental results also demonstrated a decrease in combustion efficiency at excess air ratios of 25% and 30%. Optimal performance was achieved at 20% excess air, these results correspond with findings by [9], who identified similar optimal excess air ratios for RDF-coal co-firing systems.

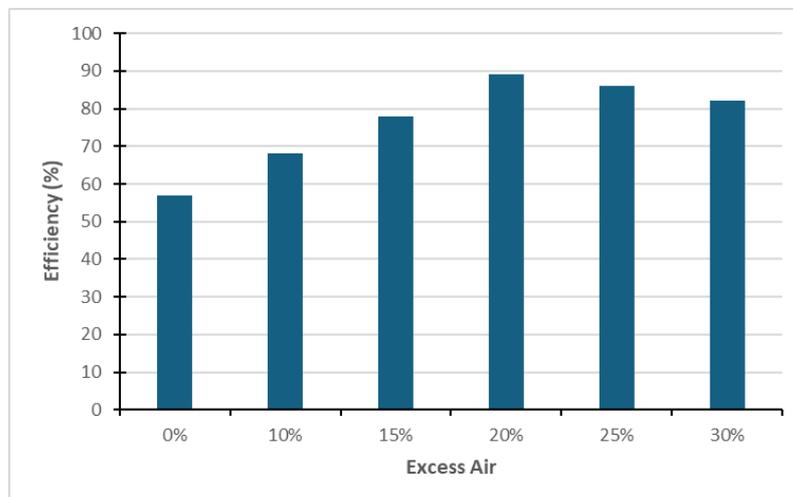


Fig. 6. Excess air effect to the combustion efficiency

Although the optimum efficiency was observed at 20% excess air, this condition was also associated with relatively high concentrations of flue gas emissions, as presented in Fig. 7. This apparent discrepancy indicates that optimum efficiency does not necessarily coincide with minimum emissions, since efficiency and pollutant formation are influenced by combined influence of excess air, incomplete combustion, volatile release, and mixing efficiency [30]. The trendline indicates a consistent decrease in CO emissions with increasing excess air ratios. This phenomenon can be attributed to improved combustion completeness through enhanced oxygen availability. Without sufficient excess air, many carbon particles and gaseous carbon compounds fail to achieve complete oxidation, resulting in partial combustion and increased CO formation [26]. Similar findings were reported by [27] in their comprehensive study of emission control in RDF-coal co-firing systems, where they observed a 35% reduction in CO emissions when excess air was optimally regulated.

The relationship between excess air and CO emission reduction can be explained through the combustion stoichiometry and mixing dynamics. [28] demonstrated that increasing excess air promotes better fuel-air mixing in the combustion zone, leading to more complete carbon oxidation. The research showed that the optimal excess air ratio typically ranges between 20-25% for RDF-coal co-firing systems, beyond which diminishing returns and potential efficiency losses occur. Furthermore, [29] found that proper excess air management not only reduces CO emissions but also influences the formation of other pollutants such as NO_x and unburned hydrocarbons.

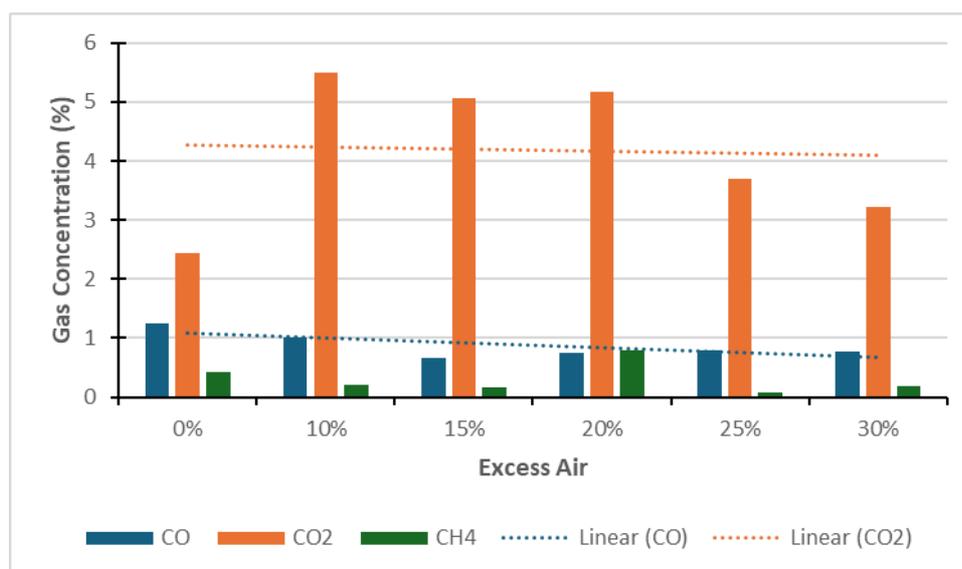


Fig. 7. Gas Emission Formation

The reduction in CO emissions with increased excess air can also be correlated with improved combustion zone temperature distribution and residence time. [11] observed that adequate excess air helps maintain optimal combustion temperatures while ensuring sufficient oxygen availability for complete carbon oxidation. Their study revealed that a well-controlled excess air ratio can reduce CO emissions by up to 40% compared to stoichiometric conditions.

Conclusion

This comprehensive study demonstrates the technical feasibility and optimization potential of co-firing RDF derived from MSW with coal in a laboratory-scale fluidized bed reactor. Through systematic investigation of operational parameters, several key findings have emerged that contribute to the advancement of waste-to-energy technologies.

The experimental results conclusively established that a 10% RDF MSW to 90% coal ratio represents the optimal mixing proportion, achieving a remarkable combustion efficiency of 95.89% and minimal Specific Fuel Consumption of 0.19260 kg/kWh. This optimization successfully balances the higher volatile content of RDF with the inherent stability of coal combustion. Furthermore, the study identified that operating temperatures of 750°C and 20% excess air provide the most favorable conditions for stable and efficient co-firing operations.

Microscopic and chemical analyses revealed critical insights into deposit formation mechanisms, particularly the role of alkali and alkaline earth metals (Ca, K, Na, and Mg) in agglomerate development. This understanding is crucial for predicting and mitigating potential operational challenges in industrial-scale applications. The findings regarding temperature effects on agglomeration behavior and chemical composition provide valuable guidance for managing deposit formation in commercial operations.

Particular attention should be given to the unique behavior observed at 20% excess air, where optimum efficiency coincided with relatively high emissions, through studies on RDF homogenization, combustion dynamics, and advanced emission monitoring to support industrial-scale applications.

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