Characterization of Bed Agglomeration in Circulating Fluidized Bed Boilers: Influence of Coal Quality and Bed Material Interactions

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Abstract

The global use of coal for energy generation is highly prevalent due to its affordability. Alternatively, the quality of coal significantly contributes to various potential issues. This study assessed the characteristics of agglomeration in circulating fluidized bed (CFB) coal-fired power plants to identify the primary components of agglomeration and to offer recommendations for mitigating future occurrences of agglomeration processes. The methodologies employed in the study were categorized into four phases: visual observation, Scanning Electron Microscopy (SEM) utilizing the Tabletop Microscope TM3030+, Energy Dispersive Spectroscopy (EDX) with the Bruker EDS Quantax 75, and X-ray Diffraction (XRD) conducted with the XRD Terra. The results indicate that most agglomeration samples were granular and predominantly exhibited round shapes, as visually observed. The EDX analysis indicates that the three predominant elements in the agglomeration sample are oxygen, silica, and calcium. XRD analysis indicates that the most reactive products were muscovite, albite, and dolomite compounds. The composition included natrium at 1.95–2.84%, silicon at 20.2–21.16%, aluminium at 13.05–15.46%, calcium at 1.05–3.11%, among other elements. Consequently, various potential alternatives may be the most effective means to mitigate the risk of agglomeration in a boiler. Incorporating additives such as china clay and soils, particularly those rich in kaolin, and employing alternative bedding materials. A viable alternative to mitigate this issue is to lower the combustion temperature and periodically substitute the bed material.

Keywords**:** *agglomeration, clinker, boiler, lignite, coal, SEM, EDX*

Abstract

Penggunaan batu bara secara global untuk produksi energi sangat umum digunakan karena keterjangkauannya. Kualitas batubara secara signifikan berkontribusi terhadap berbagai potensi masalah. Studi ini membahas karakteristik aglomerasi pada pembangkit listrik tenaga uap tipe boiler circulating fluidized bed (CFB) untuk mengidentifikasi komponen utama aglomerasi dan memberikan rekomendasi untuk mengurangi terjadinya proses aglomerasi di masa depan. Metodologi yang digunakan dalam penelitian ini dikategorikan menjadi empat fase: observasi visual, uji Scanning Electron Microscopy (SEM) menggunakan Mikroskop Meja TM3030+, uji Energy Dispersive Spectroscopy (EDX) dengan Bruker EDS Quantax 75, dan uji X-ray Diffraction (XRD) yang dilakukan dengan XRD Terra. Hasil penelitian menunjukkan bahwa sebagian besar sampel aglomerasi bersifat granular dan sebagian besar berbentuk bulat, seperti yang diamati secara visual. Analisis EDX menunjukkan bahwa tiga unsur dominan dalam sampel aglomerasi adalah oksigen, silika, dan kalsium. Analisis XRD menunjukkan bahwa produk yang paling reaktif adalah senyawa muskovit, albit, dan dolomit. Komposisinya meliputi natrium pada 1,95–2,84%, silikon pada 20,2–21,16%, aluminium pada 13,05–15,46%, kalsium pada 1,05–3,11%, di antara unsur-unsur lainnya. Untuk mengurangi risiko aglomerasi dalam boiler, diperlukan cara alternatif potensial yang paling efektif seperti penggunaan aditif tanah liat cina dan tanah, terutama yang kaya akan kaolin, serta menggunakan bahan alternatif untuk bed material. Alternatif lain yang layak untuk mengatasi masalah ini adalah menurunkan suhu pembakaran dan secara berkala mengganti material bed.

Keywords**:** *aglomerasi, clinker, boiler, lignite, batu bara, SEM, EDX*

1. Introduction

Currently, a coal-fired steam power plant is the main priority of the power plant that should be replaced with a new renewable power plant type according to the Paris Agreement in 2015. One method of complying with the Paris Agreement without shutting down the power plant is to reduce needless coal usage at the power plant. In the coal-fired steam power plant, reducing unnecessary consumption of coal can be caused by vacuum drops, tube leaks, instrument protection, agglomeration, slagging, and others. For example, the formation of slagging will increase the temperature of the exhaust gas coming out of the furnace, affect inefficiency at the boiler, and increase fuel consumption. Therefore, optimizing coal combustion in the power plant will improve its efficiency and lead to a reduction of greenhouse gases [1]. Approximately a 1% increase in coal power plant efficiency leads to a 2.7% reduction in CO_2 emissions.

The production of deposits on solid surfaces as a result of molten or softened ash is known as slagging. On the other hand, clinkering happens within the body of the bed material as a result of the melting or fusion of bed solids [2]. A temporary or permanent combination of tiny particles to create larger lumps is called agglomeration [3]. If the bed temperature rises above the fusion temperature recommended by normal testing, any of these problems could develop in the CFB boiler. Clinkering can be seen in the furnace during start-up when local hot areas occur, even when CFB boilers run at low temperatures. Slagging may also result from inadequate airflow, uneven grid air distribution, insufficient heating surfaces in a lower furnace, or ineffective oil gun startup atomization.

When smaller bed particles stick together to generate larger particles, bed agglomeration may take place as shown in Figure 1. It has been known that problems with bed agglomeration in CFB boilers are caused by the fuel's high alkali metal content [4]. The alkali metal combines with phosphorus, chlorine, silica, and sulfur to create eutectics, which are compounds with low melting points. The bed particles are coated with these eutectics, which cause them to aggregate into sizable agglomerates. The ratio of kalium and calcium in the fuel and bed has a significant impact on how function as fluxing agents, the likelihood of agglomeration rises [5]. Even in the presence of insufficient amounts of alkali metal to form agglomerates, alkali metals tend to encourage the formation of agglomerates because of the fluxing agent's function. The likelihood of experiencing ash-related issues such as fouling, agglomeration, slagging, etc. increases as the amount of reactive alkali in the fuel increases [6]. Agglomeration in the bed furnace and loop seal is especially harmful since it causes the boiler to stop working [7], [8]. Because fluidization velocity is lower in the loop seal and external heat exchanger than in the combustor, aggregation is more likely to happen there. Agglomeration may result in de-fluidization in the external heat exchanger and loop seal, even obstructing the recirculation system.

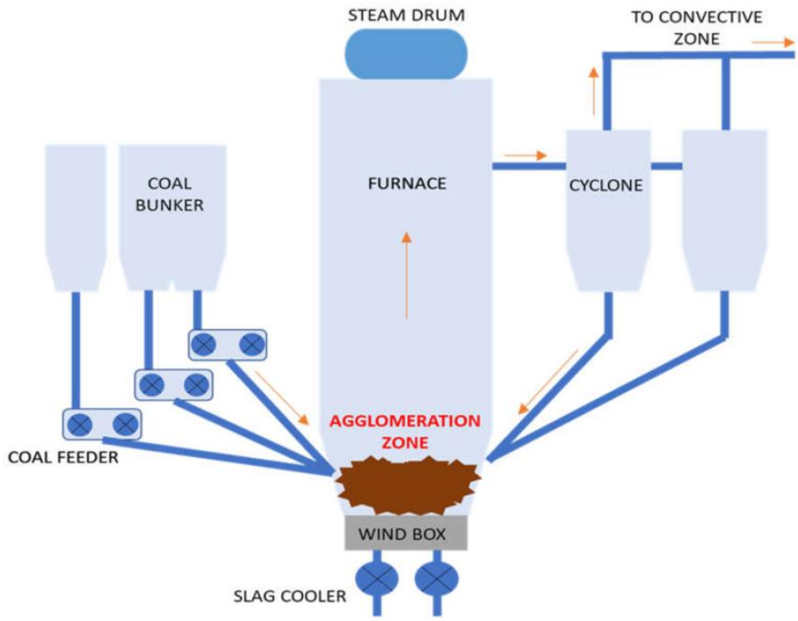


Fig. 1. Agglomeration Zone in CFB Boiler coal-fired steam power plants in East Nusa Tenggara

The phenomenon of bed agglomeration should allow engineers to propose inexpensive and effective countermeasures. Several countermeasures, such as biomass treatment, alternative bed materials [9], co-combustion, and additive addition, have already been proposed [10]. Unfortunately, it seems that they cannot eliminate agglomeration problems during combustion. This effort endeavors to identify and characterize agglomeration formation samples. In this study, the characteristic of agglomeration in CFB boiler coal-fired power plants was evaluated. It attempts to know the main composition of an agglomeration and provides suggestions and information to reduce the occurrence of agglomeration processes in the future. At the outset of the introduction, the previous studies are described. The material and methods section describes the sampling process and tools used during the test. The results and discussion sections show the details of the findings. The recommendation section describes the follow-up evaluation of the findings from the result discussion. The conclusion section of this study summarizes the findings.

2. Materials and Methods

All materials were sampled in low temperatures from different spots at one of the coal-fired steam power plants in East Nusa Tenggara that experimented with the agglomeration issue in January 2020 as shown in Figure 2. The samples used in this study were coal from Kalimantan Indonesia with an average caloric value of 17,841 kJ/kg (see Table 1). The methods that used in the work were divided into four steps, namely visual observation, Scanning Electron Microscope (SEM) with Tabletop Microscope TM3030+, Energy Dispersive Spectroscopy (EDX) with Bruker EDS Quantax 75, and X-ray Diffraction (XRD) using XRD Terra.

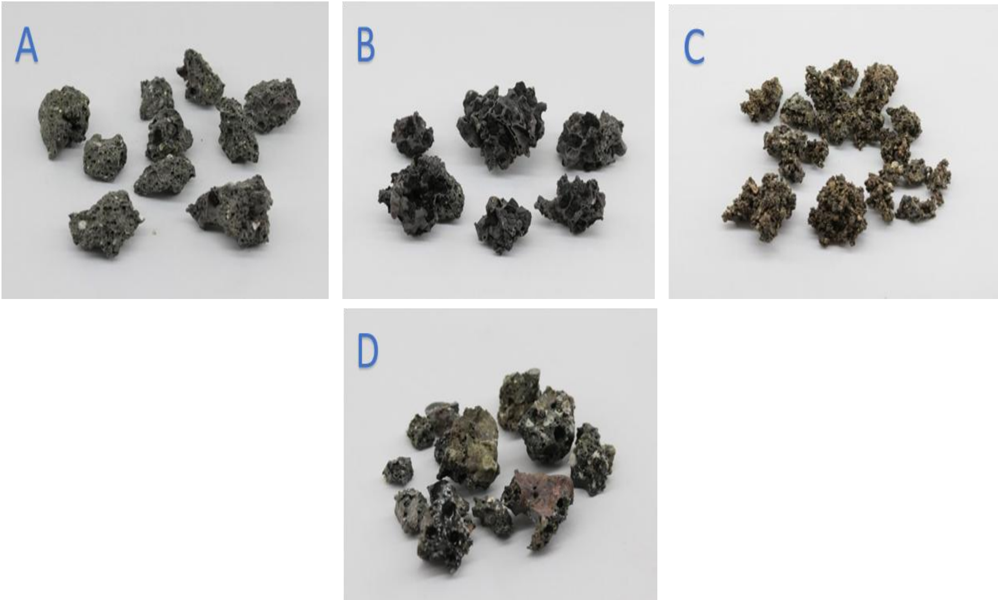


Fig. 2. Slagging Sample

3. Result and Discussion

3.1. Visual Observation

Agglomeration of bed materials could cause the cyclone to flood among other issues. This might occur if clumped particles prevent solids from freely flowing through the loop seal, causing them to build up in the standpipe and the cyclone and eventually completely suffocate the system. Agglomeration's precise mechanism is still not fully understood. Designing the loop seal freely without leaving a potential dead spot in the loop seal where particle movement may be impeded will help to some extent avoid this issue. At a specific height in the furnace, some commercial CFB boilers recorded extraordinarily high temperatures of more than 1,273K. Another instance revealed a significant rise in the temperature of the materials across the cyclone, indicating intense combustion in hot cyclones. Both circumstances could result in the bed solids in the circulating solids congregating, which could clog the loop seal and the furnace. Figure 3 shows samples of the slagging after plugging the bed furnace from fluidization.

Visual observation from figure 2 and figure 3 shows that most agglomeration samples were granular. The spot point in figure 3D shows melted elements. Referring to Table 1, the initial deformation of the coal starts at 1,413K, and the operating temperature in the boiler combustion is below 1,273K suggesting that bed material and coal should not melt. On the other hand, the presence of vanadium during combustion could lead to an agglomeration problem because of low melting temperature. Furthermore, the silica in the common bed material (sand) will react preferentially with the alkali salts to generate a low-melting eutectic combination [11]. At 1,147K, the eutectic mixture created by the aforementioned reaction melts. Even below 1,027K, the eutectic mixture of kalium salt will melt. These cause the fluidization that leads to agglomeration to become disturbed, causing the particle in the furnace to form local hot patches and sticks. The presence of agglomeration changes the fluid dynamics of the fluidized bed due to its larger size and finally secondary pollutants increase [12].

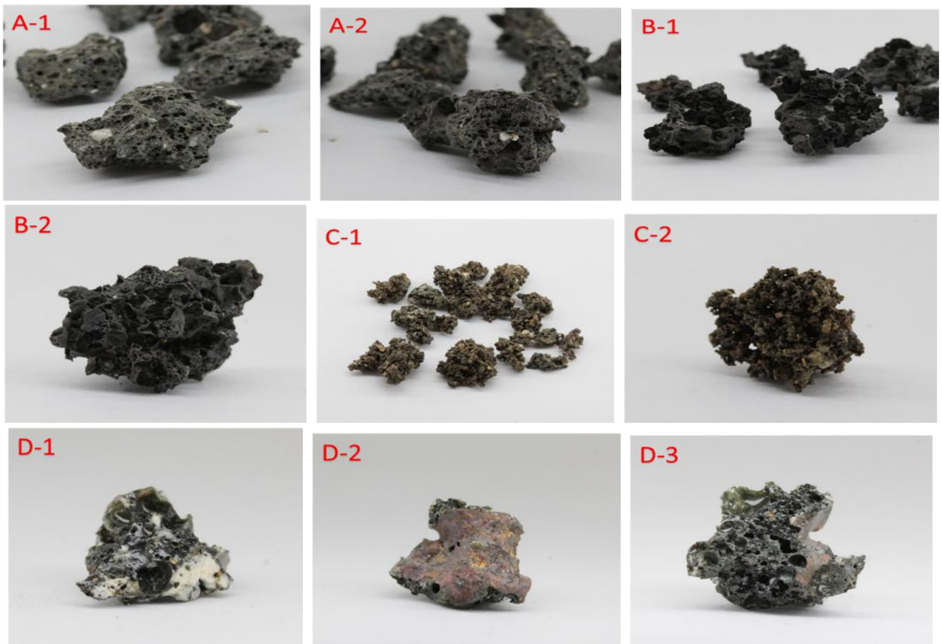


Fig. 3. Visual Observation (A) Sample A (B) Sample B (C) Sample C (D) Sample D

Table 1. Coal Analysis

Sample	Slagging Factor	Fouling Factor	Calorivic Value (kCal/kg)	IDT (^{0}C)
Coal 1	0.14	0.35	4,253	1,160
Coal 2	0.85	0.24	4,267	1,140
Coal 3	1.12	2.59	4,264	1,260
Coal 4	3.98	1.03	4,267	1,290
Coal 5	3.89	0.51	4,281	1,370
Coal 6	1.36	0.81	4,254	1,250

Furthermore, Table 1 showed that coal analysis from the last six shipments of the coal supply for combusting in the CFB boiler before the issue is dominant of a medium also high and severe classification of slagging factor [13]. It means to have a big impact on the generation of agglomeration formation during combustion. In more detail, the slagging index is divided into 4 classifications among them below 0.5 are low; between 0.5 and 1.0 is called medium; high values above 1.0 to 2.0 also severe are above 2.0. Meanwhile, the fouling index in lignitic ash has 2 classifications with 20% of more weight for $CaO + MgO + Fe_2O_3$ or otherwise. For weight less than 20%, the range of low to medium is below 1.2, the high value between 1.2 to 3.0 also the severe is above 3.0.

3.2. SEM EDX Analysis

Materials in the fluidized bed become less mobile as they soften. The combustion heat produced by fuel particles burning cannot be dispersed because there is no free mixing with inert particles. Therefore, as the temperature increases around them, particles begin to soften and sinter. Agglomerates are created when particles become immobile and soften. The agglomeration temperature could increase and lead to defluidization [14]. Clinkers are created if the temperature ultimately rises above the bed materials' melting point. By accelerating or lowering the temperature, one can fluidize the bed of freshly sintered particles. However, as soon as clinkers form, the bed becomes defluidized and cannot be revived. Compared to a CFB's fast fluidized furnace, this issue is more severe in a bubbling fluidized bed combustor.

According to the SEM morphology in Table 3, the agglomeration is dominated by round shapes. The spherical shape of agglomeration formation was also noticed, and it most likely represents a heavy atom like Fe. Furthermore, lignite ash combustion has a higher slagging and fouling index and also impacts agglomeration formation than bituminous ash combustion [15]. A CFB boiler's loop seal operates in the regime of bubbling fluidization. Agglomeration can lead to defluidization in loop seals, which can block the solid recirculation system, in addition to the bed furnace region. Agglomeration has occurred in loop seals and external fluidized bed heat exchangers, but because there is not any fuel present to burn it, the issue is not as severe as it is in bubble fluidized bed combustors. Biomass-fired boilers are more prone to agglomeration than coal-fired boilers because of the alkali in the feedstock, particularly if it is agricultural biomass.

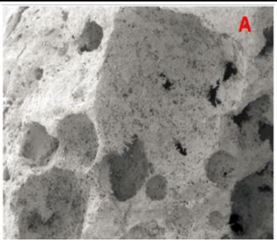
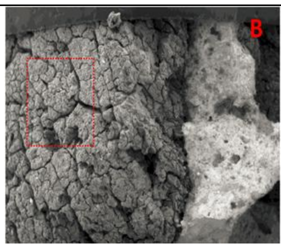
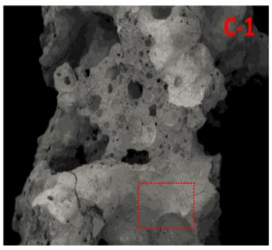
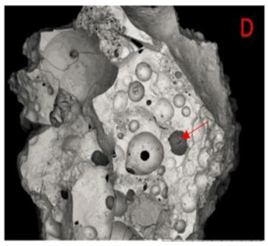
The eutectic mixture created by the aforementioned process melts at 1,147 K, although silicon dioxide, a common bed material (sand), has a high melting point. The eutectic combination for kalium salt will melt even at a lower temperature of 1,027 K. As a result, fluidization is disrupted and local hot spots are created, which cause agglomeration and sintering. Compared to natrium, kalium is a stronger alkali in the formation of eutectic. As a result, biomass with higher kalium content, like straw, has a greater chance of agglomerating. China clay and soils, particularly those containing kaoline could be used as additives to lessen the likelihood of agglomeration in a biomassfired boiler to lower temperature [16], [17]; reduced vaporization of alkali salts and the subsequent agglomeration or hot corrosion could occur from reduced combustion temperature. Alternative bed materials instead, like iron oxide, as iron oxide will react with alkali salt preferentially to generate $X_2Fe_2O_4$, which melts at a higher temperature of 1,408 K, other materials like feldspar, magnesite, and alumina. Another promising option such as preprocessing of fuel to reduce alkali [18], and also replace with fresh bed material continuously during combustion [19] could avoid agglomeration. Because the coal must match the boiler's requirement for particle size to stay at the optimum fluidization limit and avoid agglomeration due to operating a boiler at a high temperature for an extended period of time [20].

In the EDX analysis, slagging sample A, C1 and D is dominated by oxygen followed by silicon, calcium, aluminium, and other elements with their contents below 6% of the mass. Other EDX results also show that the five biggest elements are formed by silica and oxygen. Even, the bed material analysis reveals that fusion temperature should reach 1,579 K but silica and oxygen are the most dominant element in forming agglomeration formation. In addition, referring to bed material analysis in Table 2, it is seen that slagging factor reaches medium class in October and November 2019 which most likely will be burned in the combustion whilst the agglomeration is formed in January 2020.

Table 2. Bed Material Analysis

Compound	Mass (%)
Al_2O_3	8.41
SiO_2	35.13
Fe_2O_3	18.01
K_2O	2.25
CaO	31.79
MnO	0.94
SO_3	1.24
RuO_2	0.79
TiO_2	1.45

Table 3. SEM-EDX Analysis Result

Sample / Parameter								
Unit	**Mass (%)**	**Atomic (%)**	**Mass (%)**	**Atomic (%)**	**Mass (%)**	**Atomic (%)**	**Mass (%)**	**Atomic (%)**
Oxygen	50.27	62.24	25.64	25.2	50.99	64.54	52.88	64.36
Silicon	16.84	11.88	2.53	1.41	17.64	12.72	14.24	9.87
Calcium	10.52	5.2	9.33	3.66	10.98	5.55	10.19	4.95
Aluminium	7.61	5.59	-	-	4.12	3.09	5.68	4.1
Carbon	5.87	9.68	50.76	66.43	4.35	7.33	6.62	10.74
Ferrous	3.42	1.21	11.75	3.31	6.87	2.49	4.81	1.68
Natrium	2.42	2.09	-	-	1.62	1.42	2.3	1.94
Magnesium	1.84	1.5	-	-	3.42	2.85	2.4	1.93
Kalium	1.22	0.62	-	-	-	-	0.88	0.44

3.3. X-Ray Diffraction Analysis

In XRD analysis, the compound is dominated by muscovite. In detail, sample A presents a 48.1% muscovite compound group, albite compound with 32.1%, dolomite compound with 10.2%, and magnesioferrite with 9.7%. Similar to the result in sample A, sample B has differentiation on magnesioferrite which have a bigger percentage than dolomite compound in the amount of 12.6% compared to 6.7%. Examination of sample C, found magnetite compound as big 7.4% of the total compound. Most of the forming elements of this magnetite compound are from oxygen and Ferrous. Sample C and sample D showed that the muscovite compound is dominant with more than 63% of the total compound. On the other hand, sample D is formed by aragonite with 7.8%, muscovite, albite, and magnessioferrite. The aragonite compound is formed by oxygen, calcium, and carbon. In terms of slagging, aluminium generally has a favorable impact on coal ash, but sulfate has a negative impact [21]. Alkali metals have revealed that kalium, aluminium, and silica are impactful in agglomeration problems referring to this observation.

3.4. Discussion

Atakul et al. [22] have discovered that agglomeration began at 1,133-1,333K, which is roughly 398-473K lower than their initial ash deformation and 573-673K lower than the temperature of ash fusion. Considering that a fluidized bed's burning particles are 423-473K hotter than the bed itself, a second possibility for reduced agglomeration is the addition of lime to raise the calcium content which results in the creation of high temperature melting. The addition of lime stops the reaction between silica and kalium phosphate by covering silica particles and removing silica from the reactive solution [23].

According to Park et. al., [24] it was predicted to adhere to molten or sintered phases in the high-temperature areas of the CFB boiler. As the size of the particle reduced, the composition of the ash altered, exhibiting an enrichment of Fe_2O_3. The concentration of Fe and Ca in the smaller fractions of ashes has been observed, this justification suggests that the Fe and Cabearing minerals operate as a flux which is essential for the development of agglomerates. The smaller ash fractions had a major impact on the development of aluminosilicate linkages in clinker because they had low initial deformation temperatures and were less than 150 μm in size.

Operating factors including gas velocity, temperature, fuel size, sand size, and others have an impact on how much the bed agglomerates and defluidizes [25], [26]. Due to improved bed mixing that prevents the creation of hot patches and bed segregation, a higher gas velocity lessens the potential for defluidization. Higher gas velocity also boosts the kinetic energy needed to break agglomeration. Because the coating layer forms more quickly and there are more molten ash particles present, the bed agglomeration is frequently more pronounced at higher temperatures. Additionally, when temperatures rise, the coating layer's stickiness increases, encouraging viscous flow sintering.

Defluidization process is aided by larger sand and fuel particles while burning wheat straw and eucalyptus bark. Two factors can be used to explain how a larger bed material size affects agglomeration: total sand particle surface area and the ratio of gas velocity to the minimum fluidization velocity. Because the overall surface area of larger sand particles is lower, the coating layer's thickness is greater, which results in poorer mixing and, as a result, a greater tendency for defluidization. However, because the kinetic energy of larger sand particles is lower, it is more challenging to break up formed agglomerates. In addition, larger sand particles tend to have smaller porosities in the produced agglomerates, which tends to promote defluidization.

4. Conclusion

Evaluation of the characteristics of the agglomeration process has been carried out by taking samples at the coal-fired power plant with a CFB boiler type and performing laboratory testing on these samples. The majority of agglomeration samples were granular and dominated by round shapes, as observed visually. The EDX analysis shows that the three biggest elements in the agglomeration sample are oxygen, silica, and calcium. Even though the bed material analysis reveals that the fusion temperature should reach 1,579K, silica and oxygen are the most dominant elements in forming agglomeration. Alkali metals have revealed that kalium, aluminium, and silica are impactful in agglomeration problems, referring to this observation. Furthermore, to reduce this problem by replacing combustion material with fresh bed material continuously during boiler combustion to avoid partial agglomeration at the bottom of the furnace.

Acknowledgement

This study is supported by PT PLN (Persero) for research funds and collaboration in technical discussion with PT PLN Nusantara Power.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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