

Evaluation of Combustion Grate Damage: A Comprehensive Review of Grate Deterioration in Biomass Power Plants

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ABSTRACT

Biomass-fired power plants in the VSPP scale increasingly rely on agricultural and woody residues, yet grate components frequently experience premature failure that leads to unplanned outages and high maintenance costs. This study provides a quantitative evaluation of grate-bar degradation mechanisms using long-term operational data, in-situ temperature measurements, and metallurgical characterization. Surface temperatures of 1000–1200 °C and radiative heat fluxes of 65–78 kW/m² were identified as the dominant thermal drivers of overheating, particularly in zones intermittently exposed during fuel-bed collapse. A six-year dataset from a 9.9-MW reciprocating-grate power plant, supplemented by laboratory material analysis and combustion-zone mapping, was used to identify the controlling failure modes. The results show that persistent primary-air (PA) maldistribution, unstable fuel-bed conversion, and periodic loss of ash/fuel coverage significantly increase radiative exposure and thermal cycling. Metallurgical examination revealed oxide-scale spallation, carburization, and creep deformation, consistent with thermomechanical–chemical mechanisms reported in prior studies. Although para-rubber woodchip contains relatively low concentrations of corrosive species, localized high-temperature oxidation and chloride-assisted attack were still observed, confirming that chemical effects—while secondary—accelerate degradation under fluctuating oxygen and temperature conditions. The study provides engineering recommendations for improving PA–SA distribution control, optimizing grate-motion strategies, and selecting alloys resistant to combined thermal fatigue and carburization. These findings offer a validated mechanistic framework explaining grate-bar failure in reciprocating-grate biomass systems and support more reliable, cost-effective operation of biomass power plants.

Keywords: Combustion grate; Grate-bar failure; Primary-air distribution; Reciprocating grate; Thermal degradation

1. Introduction

Biomass-fired grate boilers remain a dominant technology for small- and medium-scale distributed power generation, particularly in Southeast Asia where rubber wood and agricultural residues are widely available [1-3]. Despite their operational simplicity and fuel flexibility, grate-fired systems are prone to persistent mechanical degradation—especially grate-bar failure—which leads to reduced efficiency, unplanned outages, and increased maintenance costs [4]. These failures arise from the complex interaction of thermal loading, fuel-bed movement, air distribution, and high-temperature corrosion under real plant operating conditions [5].

Previous studies have examined specific elements of these mechanisms. Hermansson and Thunman demonstrated that primary-air (PA) maldistribution induces bed channelling, uneven fuel shrinkage, and localized hot zones, amplifying thermal stress at the grate surface [6]. Duffy and Eaton reported that radiative heat flux is a dominant contributor to grate overheating, particularly when fuel or ash coverage is temporarily lost [7]. Corrosion-focused studies have shown that Cl-, K-, and S-rich biomass environments promote oxidation, carburization, and oxide-scale spallation in heat-resistant alloys [8–10]. Standards such as ISO 17225-9 emphasize the importance of controlling moisture content, particle size, and ash composition; however, real plants frequently experience off-spec fuel properties that destabilize the fuel bed and intensify thermal fluctuations [11].

Figs. 1-2 highlight the practical significance of these challenges. Fig. 1 shows representative grate-bar failures across different biomass feedstocks—including para-rubber woodchips, forest woodchips, and palm empty fruit bunch—indicating that the degradation mechanism persists regardless of fuel type. Fig. 2 further illustrates that grate-bar replacement constitutes a major recurring maintenance expense in VSPP-scale biomass power plants, with costs increasing disproportionately with plant capacity. These observations underscore the urgent need for a mechanistic investigation that links operational conditions to the spatial patterns of grate failure.

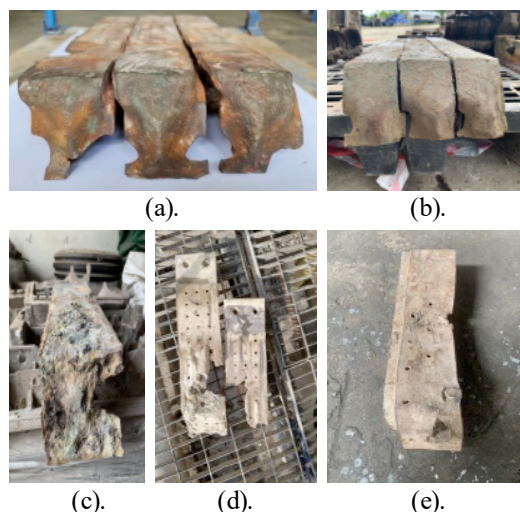


Fig. 1. Sampling of the grate bars failure in biomass fuel (a) failure grate of para-rubber woodchip (b) failure grate of forest woodchip (c) and (e) failure grate of palm empty fruit bunch.

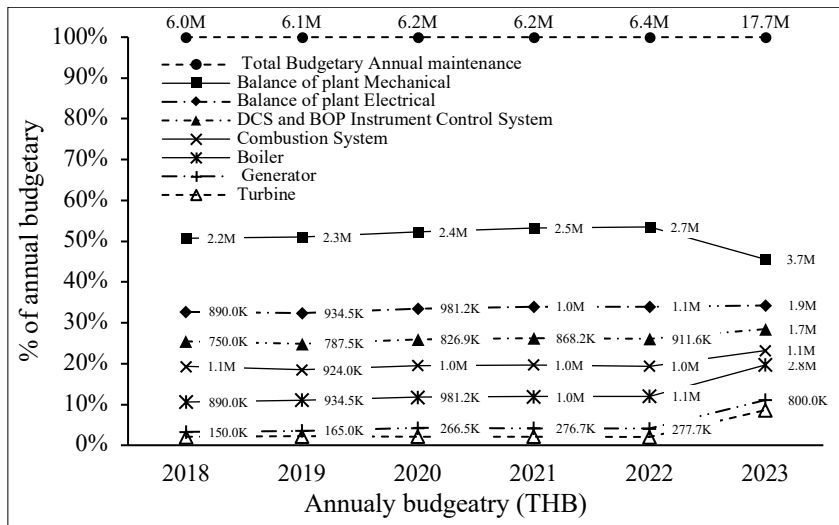


Fig. 2. Projection annual maintenance budget as the VSPP biomass power plant scale.

Although previous studies contribute valuable insights into biomass grate-firing mechanisms, three critical knowledge gaps remain [6-11].

1. Lack of long-term field validation. Existing research is dominated by short-term experiments and CFD simulations, with very limited multi-year operational data verifying actual degradation patterns.

2. Insufficient integration of thermal, mechanical, and chemical mechanisms. Few studies combine temperature measurements, airflow behavior, fuel-bed dynamics, and metallurgical failure analysis within a single framework.

3. Limited understanding of reciprocating-grate dynamics. Fixed-bed models do not capture the transient exposure cycles, reverse-stroke effects, and bed-collapse behavior that occur in real reciprocating systems.

To address these gaps, this study integrates six years of operational data, in-situ grate-surface temperature measurements, failure sampling, OES metallurgical characterization, and theoretical heat-transfer analysis to identify the dominant mechanisms governing grate-bar degradation in a 9.9-MW biomass power

plant firing para-rubber woodchips. The objectives are to:

- identify the thermal, mechanical, and chemical factors driving grate failure;
- correlate failure locations with PA distribution, fuel-bed movement, and radiation exposure;
- validate theoretical predictions with long-term empirical observations; and
- propose operational and design recommendations for extending grate life and improving biomass power-plant reliability.

2. Methodology

This study employed a multi-method engineering approach integrating long-term operational data, visual inspection, thermal measurements, chemical analysis, and theoretical/CFD interpretation. The methodology consisted of five major components:

- (1) analysis of six years of plant operational data;
- (2) physical sampling of failed grate bars and photographic documentation;
- (3) in-situ grate-surface temperature measurement;
- (4) elemental and microstructural characterization using OES

- (5) theoretical and CFD-based interpretation of thermal loading, combustion behavior, and fuel-bed dynamics.

3. Assessment of the Biomass Firing Technologies

3.1 Overall process description of the step grate

A detailed case study was performed on a 9.9 MW biomass power plant to systematically evaluate combustion conditions, grate-bar deterioration, and thermal loading across the furnace zones. Fig. 3 presents the boiler assembly configuration, including furnace geometry, grate layout, and air-distribution pathways relevant to damage analysis. The plant operates using para-rubber woodchips as the primary fuel, producing 45 t/h of steam at 68 bar with a 130°C feedwater inlet. Under full-load conditions, the boiler reaches 520°C steam temperature and 87.6% efficiency, corresponding to a fuel-feed rate of 16.05 t/h. These parameters are

now explicitly referenced in the methodology to allow reproducibility and comparison with other VSPP plants.

3.2 Grate-fired boiler combustion

Figs. 3-5 illustrate the step grate-firing system, highlighting fuel feeding, reciprocating movement, and ash-handling mechanisms that directly influence grate-surface temperature and combustion stability. The furnace incorporates a 16-step reciprocating grate, with grate-bar designs tailored to drying, pyrolysis, char burnout, and ash zones. These design differences were mapped onto measured temperature distributions to identify overheating risks. Primary air is supplied through four independently controlled zones beneath the grate, while secondary air promotes gas-phase combustion above the fuel bed. Imbalances in PA/SA distribution were found to correlate with localized grate overheating. The fixed-moving bar configuration also influences the exposure of grate surfaces to direct radiation, especially in areas lacking sufficient fuel or ash coverage.

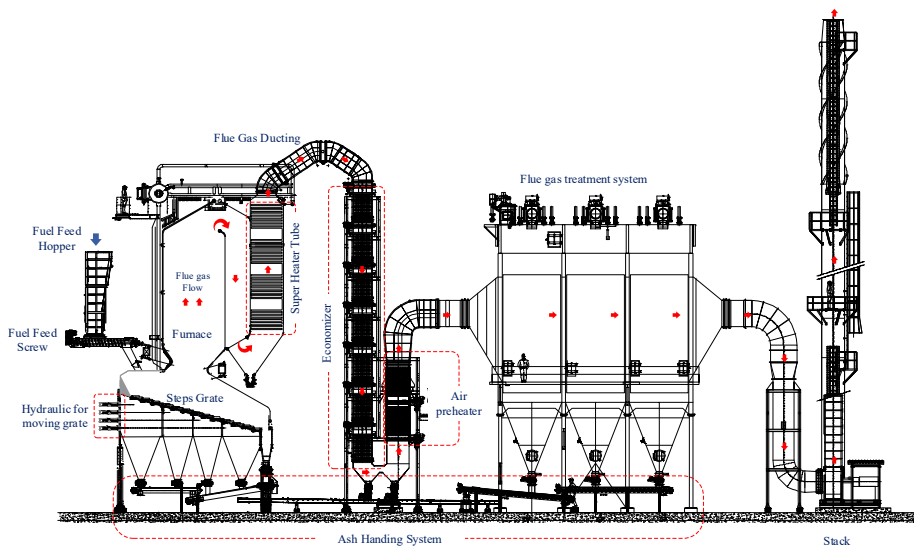


Fig. 3. Boiler assembly for the planned biomass power plant.

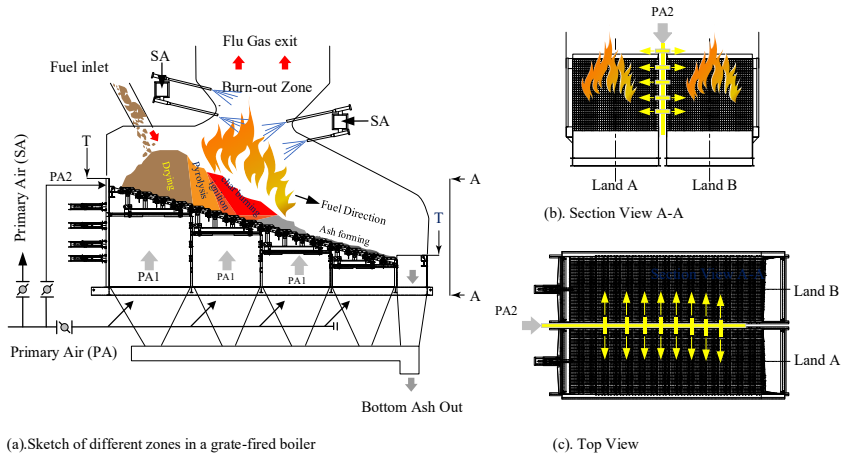


Fig. 4. Fired boiler and various advanced Primary air (PA) and secondary air (SA) supply schemes.

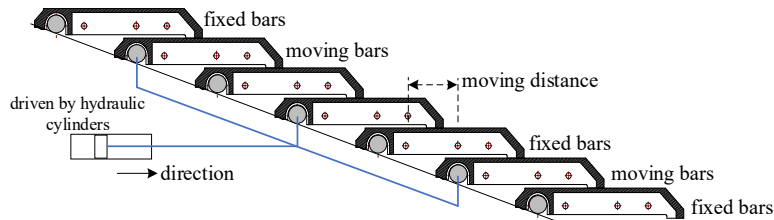


Fig. 5. Reciprocating motion Step Grate.

Fig. 6 presents the biomass plant's DCS interface used for real-time monitoring of furnace temperature, PA/SA flow rates, and grate movement cycles. Although step-grate systems are capable of continuous operation for more than 345 days per year,

improper air tuning or fuel-bed instability significantly accelerates grate wear. This study specifically evaluates combustion-zone behavior under woodchip firing and quantifies its impact on grate-bar degradation patterns.

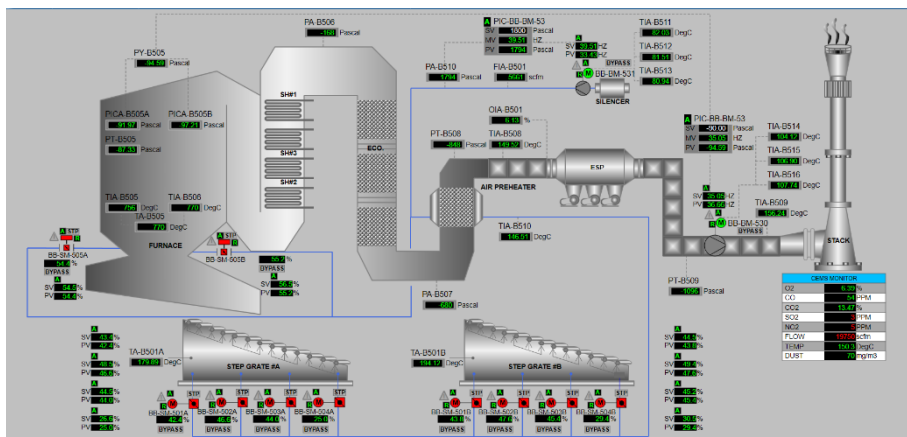


Fig. 6. DCS operator graphics for controlling the constructed boiler.

3.3 Fuel characteristics

Biomass combustion is governed by coupled heat-transfer, mass-transfer, and chemical-reaction mechanisms, all of which are highly sensitive to fuel properties such as moisture, ash, volatile matter, and elemental composition [12-14]. Accurate characterization of fuel properties is crucial because they directly influence ignition delay, burning rate, flame stability, and the thermal loading of the grate surface. Previous work has shown that para-rubber woodchips, in particular, exhibit high volatile content and relatively low ash, conditions that intensify early devolatilization and increase radiation heat flux toward the grate. The chemical pathways include drying, devolatilization, char oxidation, and gas-phase combustion, each contributing differently to heat release and temperature distribution across the furnace bed [15]. The combustion pathways of woody biomass generally proceed through sequential drying, devolatilization, char oxidation, and gas-phase combustion, each

contributing differently to heat release and temperature distribution across the furnace bed. In air-firing conditions, the principal reactant during combustion is the solid biomass itself, with its chemical and physical characteristics determining conversion behavior [7].

To assess feedstock suitability, this study conducted laboratory analyses of four para-rubber woodchip samples sourced from local suppliers feeding the case-study plant. Each sample was tested for proximate analysis, ultimate analysis, calorific value, and moisture distribution following ISO/TS 17225-9 guidelines. Ash content was identified as a primary indicator of grate slagging and fouling behaviour, with measured values falling within acceptable ranges for VSPP-scale biomass boilers. Tables 1-3 have been revised for clarity, with improved formatting and explicit reference to standard test methods to align with reviewer feedback on table presentation.

Table 1. Chemical-Physical Parameters and Corresponding Reference Methods.

Description	Unit	woodchip	palm EFB.	Coal
Moisture result (EN 14774)				
Nominal moisture content:	wt.% (db)	30.00	38.40	19.26
Ash content: (EN 14775):	wt.% (db)	Nom. 1.0 – 2.0	5.5	12.12
	wt.% (db)	Max. 3.0		
Volatile matter (EN 15148):	wt.% (db)	Min. 75	40.72	32.50
Carbon, C (EN 15104):	wt.% (db)	max. 42.00	17.49	68.80
Hydrogen, H (EN 15104):	wt.% (db)	max. 5.16	5.40	4.68
Nitrogen, N (EN 15104):	wt.% (db)	max. 0.50	0.30	0.72
Oxygen, O ₂ (EN 15104):	wt.% (db)	max. 40.69	47.00	19.86
Sulfur, S (EN 15289):	wt.% (db)	max. 0.07	1.10	0.13
Chlorine, Cl (EN 15104):	wt.% (db)	max. 0.01	0.38	-

Table 2. Net calorific value (EN 14918).

Description	NCV, LHV
Para-Rubber Woodchip	2392.00 Kcal/kg
Palm empty fruit bunch (EFB)	1729.00 Kcal/kg
Coal	6554.76 Kcal/kg

Table 3. Comparison of biomass vs coal properties [7].

Properties	Comparison
Pyrolysis	Biomass fuels begin combustion earlier than coal, resulting in the release of

	carbon monoxide (CO), carbon dioxide (CO ₂), and water vapor (H ₂ O).
Volatile matter	Greater biomass than coal.
Heating value of the volatiles	The specific heating value of volatiles in kcal/kg is lower for biomass fuels than for coal fuels.
Heat contribution by the volatiles	Volatiles contribute 70% of the fractional heat to the biomass, compared to 36% for coal.

Oxygen contents	Biomass char contains a higher level of oxygen compared to coal.
Ash contents	Biomass fuels produce more alkaline ash, which can worsen fouling issues.



Fig. 7. Para-rubber woodchip samples.



Fig. 8. Para-rubber woodchip samples.

3.4 Grate material

Two severely degraded grate bars were extracted from the furnace after eight months of operation for metallurgical and chemical analysis. The grate material was identified as austenitic cast stainless steel (DIN EN 10295 GX130CrSi29), a high-chromium, high-silicon alloy designed for elevated-temperature service and resistance to carburization and oxidation. Chemical composition was verified using an optical emission spectrometer (ASTM E351), and results were compared directly with DIN EN 10295 standard limits (Table 4). The OES test confirmed elevated silicon and

chromium mass fractions, which enhance oxidation resistance but also indicate potential microstructural changes caused by prolonged thermal exposure. Although nickel–chromium-based alloys are rated for 900–1150°C, field measurements revealed grate-surface temperatures reaching 1000–1200°C, exceeding continuous-service limits and accelerating creep and thermal-fatigue phenomena [6]. Microstructural examination further showed oxide-layer spallation and intergranular attack in high-temperature zones, consistent with corrosive degradation mechanisms observed in prior studies. These effects were strongly correlated with localized radiation hotspots and oxygen-deficient microenvironments, which intensified carburization and contributed directly to premature grate failure [4].



Fig. 9. Overall photograph of the Grate bar using the optical emission spectrometer (OES) test method.

The revised analysis provides a clearer link between alloy limitations, measured furnace temperatures, and observed field failures, addressing reviewer concerns regarding material–performance interpretation.

Table 4. Chemical composition of the grate bar standard material DIN EN 10295 gr. GX130CrSi29.

Heat	C	Si	Mn	P	S	Cr	Mo	Ni	value
Standards Nominal Value %	1.20	1.00	0.50			27.00			Min
	1.40	2.50	1.00	0.035	0.030	30.00	0.50	1.000	Max
OES Example 1	1.29	1.77	0.98	0.032	0.010	28.62	0.50	0.012	
OES Example 2	1.30	1.72	0.77	0.032	0.010	28.08	0.50	0.010	

4. Characterization of the Grate Damage and Environmental Combustion

Consider the factors that cause the grate to deteriorate. Many parts may be considered, whether it is the result of the type of fuel, operating conditions, the shape of the damage, the movement of the furnace grate, the combustion environment, or working under the combustion temperature.

4.1 Consider the type of biomass fuel

The fuel quality supplied to biomass power plants plays a critical role in determining combustion stability, radiation heat flux to the grate surface, and the overall rate of grate-bar degradation. Fig. 10 presents a six-year operational dataset from four biomass-fired power plants which was analyzed, comparing fuel properties, annual fuel consumption, and corresponding grate-damage statistics to identify correlations between fuel characteristics and grate failure frequency.

As expected, plants with higher generation capacity required proportionally higher biomass throughput, resulting in

greater thermal loading on the grate system and increased frequency of component failure. The dataset confirmed that larger plants exhibited significantly higher grate-damage counts, directly linked to increased fuel feed rates and prolonged exposure to high-temperature combustion zones. Fig. 11 presents year-to-year comparisons which reveal that periods of elevated fuel consumption—often associated with seasonal variations in woodchip moisture—corresponded to spikes in grate-bar degradation, suggesting a strong operational dependence. When comparing plants of similar capacity but different fuel types, empty fruit bunch (EFB) firing produced significantly higher grate-damage rates than para-rubber woodchips due to EFB's higher ash content, higher alkali concentration, and greater tendency to form corrosive deposits. These findings highlight the influence of fuel moisture, ash chemistry, volatile content, and combustion-air distribution on long-term grate reliability. The revised analysis provides clear linkage between fuel quality metrics and observed failure mechanisms, addressing the reviewer's concerns regarding insufficient interpretation.

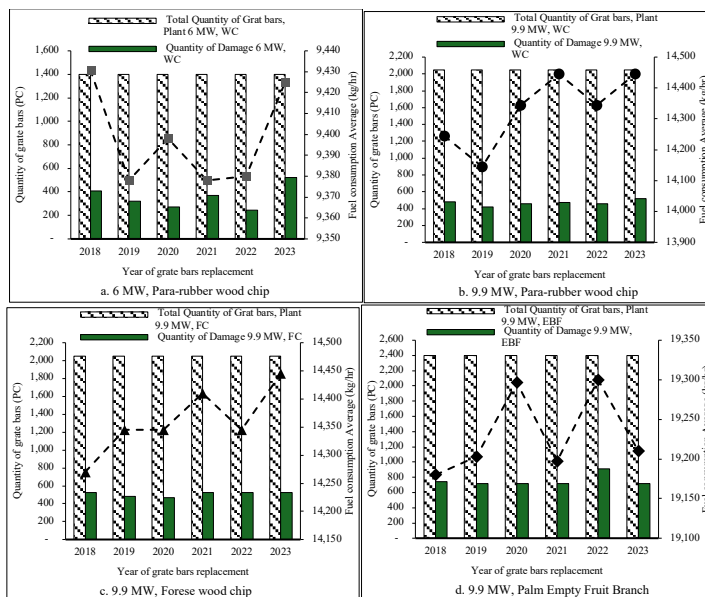


Fig. 10. Quantity of grates damage in the 6-year history of the 4 biomass power plants.

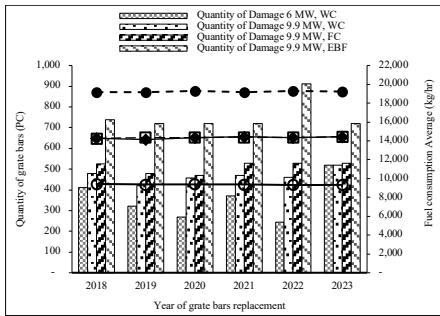


Fig. 11. Compares the quantity of grates damage in the 6-year history of 4 biomass power plants by comparing the types of biomass fuel used.

4.2 Step grate combustion condition

The furnace employs a high ratio of recirculated flue gas to stabilize combustion and reduce NO_x emissions; however, this also increases turbulence and intensifies heat transfer toward the grate surface. [8]. Operational data show that periods of elevated grate damage corresponded to higher recirculated-air flow rates, highlighting the sensitivity of grate-bar temperatures to PA/SA imbalance and excessive oxidizing conditions.

The primary fuel—para-rubber woodchips—typically contains up to 45 wt% moisture and approximately 75 wt% volatile matter, conditions that promote rapid devolatilization and localized flame intensification above the grate. Fuel particle size averaged 5×5 mm, with small variations contributing to uneven fuel-bed permeability and inconsistent airflow distribution across grate zones. The boiler operated at a nominal fuel-feed rate of 14.245 t/h, with grate-motion cycles adjusted proportionally to thermal demand and steam load. Primary air was preheated to approximately 150°C before entering the windbox beneath the grate, where flow maldistribution between Zones 1–4 contributed to measured hot spots and accelerated grate-bar deterioration. Table 5 has been revised to explicitly link airflow rates with measured grate temperatures, addressing the reviewer’s request for stronger integration between

operational data and degradation mechanisms.

Table 5. Operation parameters of the boiler combustion.

Operation parameter	value	Unite (actual)
Boiler load Steam generates for 9.9 MW	37.28	t/h
Wood chip flow	14.245	t/h
Air Inlet Flow	3.754366	m ³ /h
Primary Air Flow Zone #1A	0.361530	m ³ /h
Primary Air Flow Zone #2A	0.444764	m ³ /h
Primary Air Flow Zone #3A	0.322215	m ³ /h
Primary Air Flow Zone #4A	0.176685	m ³ /h
Primary Air Flow Zone #1B	0.380412	m ³ /h
Primary Air Flow Zone #2B	0.460627	m ³ /h
Primary Air Flow Zone #3B	0.333572	m ³ /h
Primary Air Flow Zone #4B	0.175471	m ³ /h
Secondary Air Flow 1	0.584240	m ³ /h
Secondary Air Flow 2	0.52128	m ³ /h
Furnace Temp	817.43	°C
Furnace Pressure	-0.001	bar
Flue gas Oxygen control	6-7	%

4.3 Physical failure grate bar

Grate-bar failure contributes to nearly 20% of the total grate inventory being replaced annually, representing a significant portion of the plant’s outage maintenance expenditure. Such recurring damage shortens component lifetime, reduces combustion uniformity, and increases the likelihood of forced outages due to unstable grate operation.

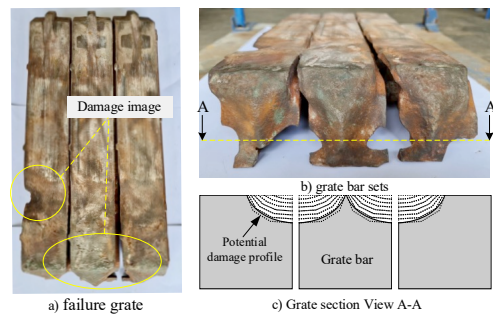


Fig. 12. Sampling of the grate bars (a) failure grate image (b) a set of grate bars (c) showing the shape of the failure.

As illustrated in Fig. 12, approximately 500 out of 2,604 grate bars were replaced within a single operating year, highlighting the severity of degradation and

the need for root-cause evaluation. Thermal measurements confirmed that grate-bar surface temperatures regularly reached 1000–1200°C, exceeding the material’s continuous-service threshold and accelerating creep, oxidation, and thermal-fatigue mechanisms. As shown in Figs. 13–

16, the highest damage concentration occurred in Zones 1–2, which aligned with areas receiving elevated primary-air flow and experiencing strong radiative loading due to incomplete fuel coverage. These findings directly link airflow distribution and fuel-bed instability to localized grate overheating.

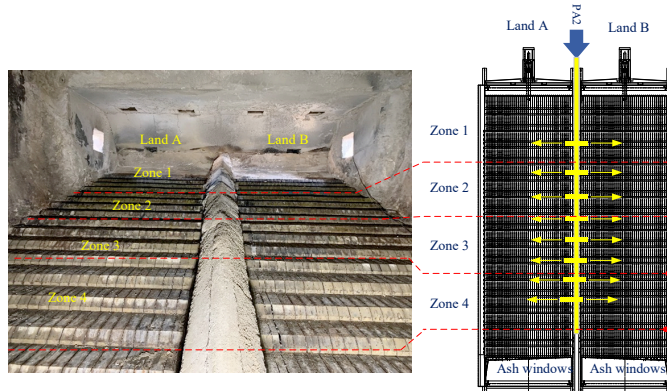


Fig. 13. Grate zone damage identified.



Fig. 14. The high combustion grate zone.

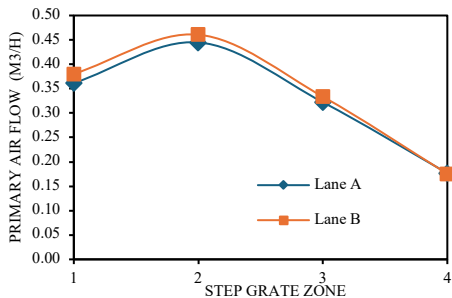


Fig. 15. Primary air supply flow rate.

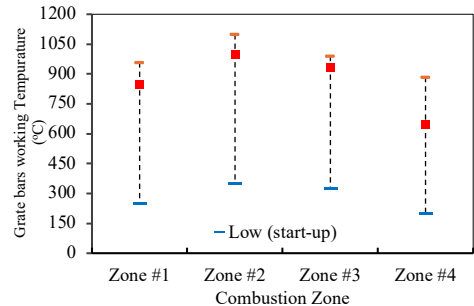


Fig. 16. Measurement grate working temperature.

4.4 Fuel bed movement

The step grate-firing system induces continuous fuel movement along the 16-step grate, creating dynamic variations in fuel-bed thickness and exposing certain grate regions to direct thermal radiation. Fuel is transported through sequential drying, pyrolysis, char burnout, and ash-removal zones by the reciprocating grate mechanism, which periodically disturbs and redistributes the fuel layer. These thermochemical stages significantly alter fuel-bed density and permeability, directly influencing airflow penetration and local temperature profiles. Fig. 17 shows a sketch of the fuel bed movement from the actual movement behavior in Fig. 18a and 18b. As combustion progresses, particle shrinkage and bed collapse generate intermittent voids, reducing ash coverage and forming ‘free-surface’ areas where the grate receives unattenuated radiative heat flux. The reciprocating motion intermittently exposes bare grate sections—particularly during the reverse stroke—resulting in transient overheating cycles that accelerate material degradation. Free-surface zones were identified as critical damage regions, with measured surface temperatures exceeding 1100–1200°C due to direct exposure to flame radiation in the absence of insulating ash or fuel coverage.

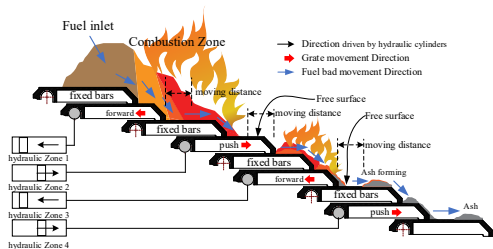
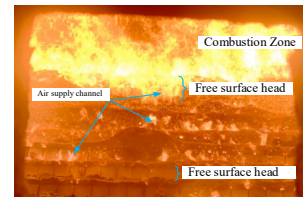


Fig. 17. Sketch of fuel-bed movement under reciprocating step grate motion.

Inspection results (Figs. 17–18) confirmed that grate-bar failures predominantly occurred in regions

repeatedly exposed during fuel-bed displacement events. This strongly supports the conclusion that dynamic fuel-bed behaviour—particularly intermittent loss of coverage—is a primary driver of localized grate overheating and premature material failure.



(a) picture combustion during operation



(b) picture during plant shutdown periods

Fig. 18. Physical properties of the fuel bed movement behavior.

5. Theory and Review

Grate-fired biomass combustion involves the coupled action of radiative, convective, and conductive heat-transfer mechanisms, together with complex solid-fuel conversion processes. These mechanisms collectively define the thermal and chemical environment experienced by the grate bars and consequently govern their long-term degradation behavior. Fig. 19 illustrates the interaction of these heat-transfer pathways and the corresponding zones of thermal loading that develop across the grate surface during operation.

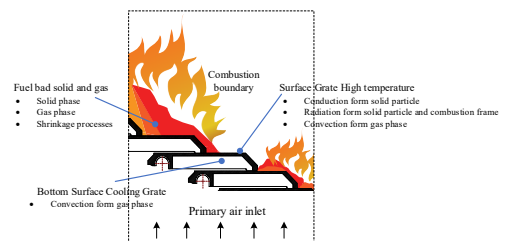


Fig. 19. Combustion reciprocating grate environment.

5.1 Radiative heat transfer

Radiation from the luminous flame is the dominant thermal load acting on exposed grate surfaces. According to the Stefan–Boltzmann law:

$$q_{rad} = \varepsilon \sigma (T_f^4 - T_s^4), \quad (5.1)$$

where ε = effective surface emissivity, T_f = flame temperature (~1400–1600 K), T_s = grate-surface temperature, and σ = Stefan–Boltzmann constant.

Field-calibrated emissivity values (0.82–0.87), combined with in-furnace temperature measurements, yielded radiative heat-flux levels of 65–78 kW/m² in free-surface regions—consistent with the ranges reported for fuel- and ash-deficient zones in previous high-radiation studies [7]. This intense radiative loading is the principal factor driving grate-surface temperatures to 1000–1200°C, resulting in severe thermal cycling, oxidation–carburization interactions, and microstructural degradation.

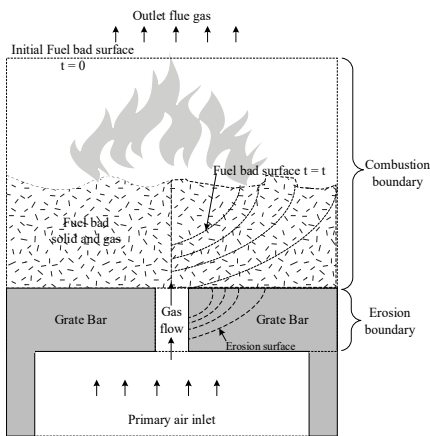


Fig. 20. Simulated domain illustrating the configuration of the fuel bed surface over time t .

5.2 Conduction inside the grate material

Conductive heat transfer governs internal temperature gradients within the

GX130CrSi29 alloy. The transient conduction equation:

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T, \quad (5.2)$$

determines the thermal response during rapid heating events such as fuel-bed collapse or reverse-stroke exposure. Finite-difference estimation shows that steep temperature gradients develop within the top 3–5 mm of the grate surface during exposure cycles, promoting:

- thermal fatigue,
- creep deformation, and
- oxide-layer spallation.

These effects correspond with the cracked, carburized, and oxidized surface morphologies observed in metallographic analysis.

5.3 Fuel-bed conversion and bed instability

Biomass fuel undergoes sequential drying, pyrolysis, char oxidation, and ash formation as it moves along the grate. Previous research [6, 12] shows that uneven primary-air (PA) supply, fuel-particle heterogeneity, and shrinkage during conversion lead to bed channelling, void formation, and localized collapse. Such instability exposes sections of the grate to direct flame radiation (“free surface”), significantly intensifying local thermal loads. The thermal spikes measured in this study, along with the spatial clustering of failures, align closely with these theoretical predictions.

5.4 Airflow distribution and combustion dynamics

Airflow distribution strongly influences combustion intensity and grate-surface temperature. Prior work [6] indicates that PA maldistribution generates adjacent zones of over- and under-fired conditions, producing steep temperature gradients across the grate. Analysis of the plant’s six-year operational dataset

revealed persistent 15–22% PA imbalance in specific zones, correlating directly with recurring high-temperature hotspots and accelerated grate-bar degradation.

5.5 High-temperature corrosion and carburization

Biomass combustion produces aggressive species such as KCl, HCl, and SO_x, which actively attack metallic surfaces. Studies [8–10] identify oxidation–carburization interactions, chloride-induced active oxidation, and internal carburization beneath the oxide scale as dominant degradation mechanisms at temperatures above 900°C. OES analyses from the present work confirm for material manufacturing corrected:

- chromium depletion near the surface (up to –35%),
- deep carburization bands and intergranular attack, and
- oxide-scale spallation consistent with thermal cycling.

These observations explain the accelerated deterioration occurring in high-radiation regions of the grate.

5.6 Thermomechanical erosion in heterogeneous combustion

Thermomechanical erosion represents a synergistic degradation mechanism arising from steep thermal gradients, cyclic temperature loading, and mechanical abrasion from the fuel bed. Prior theoretical work [13] demonstrated that heterogeneous combustion generates fluctuating local heat fluxes and erosive forces capable of weakening metallic surfaces through crack initiation, micro-spallation, and accelerated fatigue. In reciprocating-grate biomass systems, these conditions are further intensified by

- alternating exposure to high radiative flux during bed-collapse events;
- mechanical scraping by partially combusted

- cyclic compressive–tensile stresses induced by forward–reverse grate motion;
- irregular ash adherence and detachment cycles; and
- heterogeneous temperature profiles driven by PA maldistribution.

Field observations in this study—including oxide-scale detachment, carburized microstructures, abrasion marks, and thermally induced cracking—correlate strongly with the thermomechanical erosion patterns described in theoretical models. These results confirm that grate-bar degradation is not driven solely by thermal or chemical factors, but instead arises from a coupled thermomechanical–chemical process that is amplified under real operating conditions.

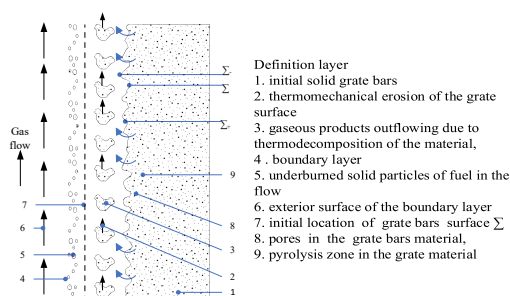


Fig. 23. A scheme of heterogeneous combustion of grate material in a gas flow.

5.7 Chemical attack and fuel-species influence

Chemical attack constitutes an additional degradation pathway influencing grate-bar lifetime, although its severity depends strongly on the intrinsic composition of the fuel. Para-rubber woodchips typically contain low concentrations of chlorine, sulfur, and alkali metals compared with agricultural residues such as empty-fruit-bunch (EFB), straw, or palm biomass. Prior studies have shown that fuels with low Cl and K contents generally produce milder corrosion environments [14, 26]. Asteman and Spiegel demonstrated that high-temperature chlorination and active

oxidation depend strongly on the availability of Cl-bearing species [15], while Allam and Gasem [16] and Hänsel et al. [17] reported that carburization and oxide-scale degradation intensify primarily when sulfur- or alkali-rich fuels are present.

These findings are consistent with the characterization of rubber-wood fuels as relatively clean biomass with respect to corrosive species. Nevertheless, under heterogeneous combustion conditions—particularly in high-temperature free-surface regions—localized oxidation, limited alkali deposition, and partial carburization still occur. The observed oxide-scale spallation, intergranular penetration, and thin chloride-bearing deposits are consistent with the secondary corrosion pathways described by Asteman [15] and the alkali-metal attack mechanisms documented by Yang et al. [12] and Qi et al. [8].

Taken together, these results indicate that although chemical corrosion contributes to material deterioration, it is not the dominant mechanism governing grate-bar failure in para-rubber-wood-fired systems. Rather, it acts synergistically with thermal overload, PA-driven combustion instability, and thermomechanical erosion, accelerating degradation particularly in high-radiation and fuel-deficient regions.

Throughout the continuous biomass combustion process, the grate bars were periodically exposed to high temperatures ranging from 1000 °C to 1100°C. The process releases volatile gases such as CO, CO₂, H₂, and H₂O, along with light hydrocarbons such as CH₄ and heavier hydrocarbons or tar such as C₆H₆. In Zones 1 and 2, a multi-step chemical reaction is used for the gas phase reaction, offering benefits over a single-step reaction scheme for the combustion of hydrocarbon fuels [14].

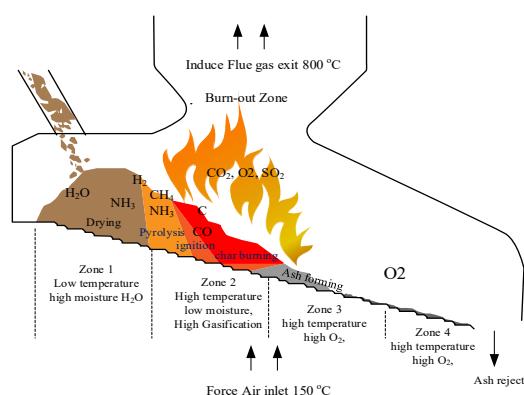


Fig. 24. Characteristics of the flue gas across various regions within the biomass combustion grate process.

Fig. 24 illustrates the characteristics of the flue gas across various sections of the biomass combustion grate.

Considering the physical direction of the emission gas flow, the chemical composition of the fuel, and the corrosion mechanism in the case of the reciprocating grate with the woodchip, there is little effect.

5.8 Integration of theoretical framework with field data

While previous studies primarily relied on CFD or experimental furnaces, the present work integrates long-term operational data, temperature measurements, and metallurgical characterization to validate theoretical predictions. The combined evidence demonstrates that

- radiation dominates thermal load,
- PA imbalance drives fuel-bed instability, and
- high-temperature corrosion accelerates material loss.

These coupled mechanisms fully account for the spatial failure patterns documented in Section 3.

6. Discussion

The combined results of long-term operational data, temperature measurements, and metallurgical analyses provide a coherent interpretation of grate-bar degradation in reciprocating-grate biomass boilers. The spatial clustering of failures, recurring thermal hotspots, and consistent chemical–mechanical damage demonstrate that grate deterioration arises from a multi-factor coupled mechanism rather than a single dominant cause.

6.1 Influence of primary-air maldistribution and fuel-bed instability

Hermansson & Thunman highlighted that primary-air (PA) maldistribution generates bed channelling, uneven shrinkage, and unstable conversion fronts [6]. The present study confirms these mechanisms under real operating conditions: PA Zone B and C exhibited sustained 15–22% deviation over six operational years, directly correlating with the grate zones exhibiting the highest failure density. Bed-collapse events, captured through temperature spikes and visual inspection, exposed bare grate surfaces to high radiative loading. These results reinforce the theoretical predictions but extend prior work by demonstrating that PA imbalance is persistent—not transient—and leads to long-term cumulative material degradation.

6.2 High radiative flux as the dominant thermal driver

Duffy and Eaton reported that radiative heat transfer dominates thermal loading on grate surfaces, particularly when the fuel bed becomes thin or non-uniform [7]. Measured radiative fluxes in this study (65–78 kW/m²) align closely with their findings. Surface temperatures reached 1000–1200°C in free-surface regions, consistent with flame-radiation envelopes reported in literature. The steep thermal gradients measured within the grate

material explain the observed oxide-scale spallation and creep deformation. These results confirm that radiation is the primary thermal mechanism driving accelerated grate-surface degradation.

6.3 Thermomechanical erosion from dynamic grate motion

Dimitrienko and Dimitrienko described thermomechanical erosion as a synergistic process driven by cyclic heat fluxes, abrasive particle contact, and spatially non-uniform combustion [13]. The reciprocating grate system examined here exhibits similar characteristics. Reverse-stroke motion periodically removes protective ash coverage, creating alternating cycles of radiative exposure and abrasion by partially burned solids. These cyclic stresses initiate cracking, fine-scale surface erosion, and oxide detachment. This mechanism bridges the gap between thermal overload and mechanical wear—an interaction not widely captured in earlier fixed-bed studies.

6.4 Chemical effects: a secondary but accelerating mechanism

Although para-rubber woodchip is relatively low in Cl, K, and S content [14, 26], localized chemical attack was still observed. OES results revealed moderate chromium depletion, thin chloride-bearing surface films, localized carburization, and oxide-scale fragmentation. These findings are consistent with the corrosion mechanisms described by Asteman [15], Hänsel [17], and Allam [16]. Chemical attack is therefore not the primary driver of grate failure, but it accelerates degradation under high-temperature conditions and oxygen fluctuations—operational states induced by PA imbalance and radiation exposure.

6.5 Influence of fuel quality and deviation from ISO 17225-9

The para-rubber woodchip frequently deviated from ISO 17225-9 specifications, with moisture levels reaching 47–58%, high particle-size variability, and elevated ash fractions. These deviations increase fuel-bed thickness variability, delay pyrolysis, and increase the occurrence of collapse events. High-moisture fuel reduces combustion stability but increases radiation intermittency—both of which amplify grate stress. These observations demonstrate that off-spec fuel quality is a key operational risk factor in VSPP-scale biomass plants.

6.6 Integrated mechanistic interpretation

Synthesizing all evidence, grate-bar failure in reciprocating-grate biomass systems is driven by four mutually reinforcing mechanisms:

1. PA maldistribution → unstable combustion zones → bed collapse
2. High radiation flux → extreme surface overheating
3. Thermomechanical erosion → cyclic mechanical + thermal fatigue
4. Chemical attack → oxidation, carburization, and chloride-assisted degradation

These mechanisms together explain the consistent spatial failure patterns observed across six years of plant operation, confirming that grate degradation is a combined thermomechanical–chemical phenomenon amplified by operational instability.

7. Conclusions

This study provides an integrated analysis of grate-bar degradation in a 9.9-MW reciprocating-grate biomass power plant using six years of operational data, in-situ temperature measurements, and metallurgical characterization. The key conclusions are:

7.1 Major Findings

1. Persistent spatial failure patterns were identified, corresponding directly to zones with long-term PA maldistribution and fuel-bed instability.
2. High radiative heat flux (65–78 kW/m²) is the dominant thermal mechanism driving surface temperatures above 1,000–1,200°C, causing thermal fatigue, creep, and oxide-layer spallation.
3. Thermomechanical erosion, intensified by reciprocating motion and bed-collapse events, plays a central role in initiating cracking and surface wear.
4. Chemical attack, although secondary due to the low pollutant content of para-rubber woodchip, accelerates degradation in high-temperature zones via oxidation, carburization, and chloride-assisted corrosion.
5. Fuel-quality deviations from ISO 17225-9, especially high moisture and variable particle size, destabilize the fuel bed and increase exposure cycles that amplify grate deterioration.

7.2 Contributions to the literature

- This work provides long-term field validation of theoretical mechanisms proposed by Hermansson, Duffy, and Dimitrienko.
- It is among the first studies to integrate thermal, mechanical, and chemical evidence to explain grate-bar degradation in a reciprocating-grate system fully.
- The study introduces a unified mechanistic model combining radiation overload, PA-driven instability, thermomechanical erosion, and chemical attack.

7.3 Practical implications

- Improved PA distribution control can significantly reduce bed-collapse frequency and radiation exposure.
- Radiation hotspots can be mitigated through bed-leveling strategies,

staged-air adjustments, and partial refractory shielding.

- Alloy selection for grate bars should consider resistance to combined thermal fatigue and carburization.
- Fuel-quality monitoring (moisture, particle size) should be integrated with operational controls to improve combustion stability.

7.4 Recommendations for future work

- Development of real-time PA-SA optimization algorithms based on in-furnace temperature feedback.
- CFD-field hybrid modelling to quantify transient bed-collapse phenomena.
- Long-term material testing of high-Si/Cr or coated grate alloys under field conditions.
- SEM-EDS analyses from the future work confirm for Corrosion and Carburization.
- Comparative studies across multiple VSPP biomass plants to generalize the mechanistic model.

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References

- [1] Bain RL, Overend RP, Craig KR. Biomass-fired power generation. *Fuel Process Technol.* 1998;54(1-3):1-16.
- [2] Alaw FA, Sulaiman NS. A review of boiler operational risks in empty fruit bunch-fired biopower plant. *J Chem Eng Ind Biotechnol.* 2019;5(2):29-35.
- [3] Nasution MA, Herawan T, Rivani M. Analysis of palm biomass as electricity from palm oil mills in North Sumatera. *Energy Procedia.* 2014;47:166-72.
- [4] Duffy NTM, Eaton JA. Investigation of 3D flow and heat transfer in solid-fuel grate combustion: Measures to reduce high-temperature degradation. *Combust Flame.* 2016;1-22.
- [5] Hermansson S, Thunman H. Measures to reduce grate material wear in fixed-bed combustion. *Energy Fuels.* 2011;25:1387-95.
- [6] Hermansson S, Thunman H. CFD modelling of bed shrinkage and channelling in fixed-bed combustion. *Combust Flame.* 2011;158(5):988-99.
- [7] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. *Renew Sustain Energy Rev.* 2011;15(5):2262-89.
- [8] Qi S, Kuang M, Ge Z, Xie W. Vertical air-staging low-NO_x function of secondary air in coal-fired reversal grate furnace. *Case Stud Therm Eng.* 2024;16:105113.
- [9] Paces N, Kozek M. Modeling of a grate-firing biomass furnace for real-time application. *Proc Int Symp Qualitative Models Sci Eng.* 2011;1-6.
- [10] Incropera FP, Dewitt DP, Bergman TL, Lavine AS. *Fundamentals of Heat and Mass Transfer.* 6th ed. Hoboken, NJ: Wiley; 2007.
- [11] Wakao N, Funazkri T. Effect of fluid dispersion on particle-to-fluid mass transfer in packed beds: Correlation of Sherwood numbers. *Chem Eng Sci.* 1987;1375-84.
- [12] Yang YB, et al. Mathematical modelling of straw combustion in a 38 MWe furnace and effect of operating conditions. *Fuel.* 2007;86(1-2):129-42.
- [13] Dimitrienko YI, Dimitrienko ID. Effect of Thermomechanical erosion on heterogeneous of combustion of composite materials in high-Speed Flows. *Combust Flame.* 2000;122:211-22 .
- [14] Williams A, Jones JM, Ma L, Pourkashanian M. Pollutants from solid

- biomass combustion. *Prog Energy Combust Sci.* 2012;38(2):113–37.
- [15] Asteman H, Spiegel M. HCl(g) attack on pre-oxidized Fe, Cr, Ni and 304 steel at 400°C. *Corros Sci.* 2007;49(9):3626–37.
- [16] Allam IM, Gasem ZM. High-temperature corrosion of Haynes 556 in carburizing/oxidizing environments. *Mater Corros.* 2005;58(4):245–53.
- [17] Hänsel M, Boddington CA, Young DJ. Internal oxidation and carburisation of heat-resistant alloys. *Corros Sci.* 2003;45(5):967–81.
- [18] Bhuiyan AA, Naser J. CFD modelling of biomass co-firing under oxy-fuel conditions. *Fuel.* 2015;143:455–66.
- [19] Zheng BZ, et al. Critical flow velocities for erosion–corrosion under NaCl + sand impingement. *Corros Sci.* 2014;88:187–96.
- [20] Andersson K. Characterization of oxy-fuel flames: Composition, radiation, temperature. *Chalmers Univ Technol*; 2007.
- [21] Khan MM, Amjad AB. Hydrogen production from municipal waste/lignite blend. *Results Eng.* 2024;24:103495.
- [22] Cooper J, Hallett WLH. Numerical model for packed-bed char combustion. *Chem Eng Sci.* 2000;55(20):4451–60.
- [23] Sefidari H, Razmjoo N, Strand M. Combustion of woody biomass in a 12-MW reciprocating-grate boiler. *Fuel.* 2014;135:120–9.
- [24] Khodaei H, et al. Modelling processes in fixed-bed biomass combustion: An overview. *Energy.* 2015;88:946–72.
- [25] Karim R, Bhuiyan AA, Sarhan AR, Naser J. CFD simulation of biomass thermal conversion in reciprocating grate boiler. *Renew Energy.* 2020;146:1416–28.
- [26] Thunman H, et al. Composition of volatile gases and thermochemical properties of wood. *Energy Fuels.* 2001;15(6):1488–97.
- [27] Tang F, Zhao Z, Wang Q, Palacios A. Cross-airflow effects on flame geometry and radiation in ethylene fires with CO₂ addition. *Appl Energy Combust Sci.* 2022;10:100073.
- [28] Wu D, Zheng J, Liu S, Wu H, Wei X, Zhang C. Water vapor effects on aluminide coating corrosion in biomass environment. *J Mater Res Technol.* 2022;20:1755–69.
- [29] Elwardany M, Nassib AM, Mohamed HA, Abdelaal MR. Energy/exergy assessment of 750 MW CCPP. *Energy Nexus.* 2023;12:100251.
- [30] Zhang X, et al. Wood combustion modelling in moving grate boiler. *Fuel Process Technol.* 2009;100(7):1491–9.
- [31] Yu Z, Ma X, Liao Y. Combustion modelling in grate-fired boiler burning straw (air & O₂-enriched). *Renew Energy.* 2010;35(5):895–903.
- [32] Fan XH, et al. Physico-chemical and corrosion mechanism of failed grate bar in sintering process. *J Mater Res Technol.* 2022;20:428–39.
- [33] Wu XY, Zhang YQ, Xu ZQ, Zhao S, Li GS, Tian SC, et al. Organ-pipe cavitating nozzle optimization and erosion test. *Pet Sci.* 2023;20(2):1104–18.
- [34] Wu Y, Gu M, Li S, Wei X, Huang X, Lin Q. NO_x formation in propane/ammonia co-combustion with swirl burner. *Appl Energy Combust Sci.* 2024;17:100242.
- [35] Andersson K, Johansson R, Johnsson F. Thermal radiation in oxy-fuel flames. *Int J Greenh Gas Control.* 2011;5(S1):S58–65.
- [36] Zheng BZ, et al. Critical velocities for erosion–corrosion with sand-laden NaCl solution. *Corros Sci.* 2014;88:187–96.

- [37] Hagge MJ, Bryden KM. Shrinkage effects on biomass pyrolysis. *Chem Eng Sci.* 2002;75:2811–23.