Review

Shrutika Sharma*, Mayank Sharma, Deepa Mudgal and Hiralal Bhowmick Adoption of strategies for clean combustion of biomass in boilers

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Abstract: Fossil fuels like coal, oil and natural gas are continuously being used for electricity generation. However, combustion of fossil fuels has raised environmental concerns which have forced the world to search for alternative sources of energy like geothermal, solar and biomass energy. Biomass is a carbon-based fuel, readily available in many parts of the world, highly volatile with less sulphur and nitrogen content, its ash possesses the property of absorbing carbon dioxide emissions, co-firing of biomass and coal increases thermal efficiency, it creates employment opportunities and provides a better way of utilization of agricultural waste. However, chlorine species from biomass combustion results in corrosion of boiler tubes at high temperature. In this review, challenges like fouling, agglomeration, gaseous emissions, emission of heavy metals, low heating value, storage and transportation problems and high temperature corrosion have been discussed, which can limit the flexibility, economy and reliability of biomass boilers. Each of these challenges has a relatively satisfactory solution except for hot corrosion, which has been addressed through several approaches with varying success and those approaches have been presented in this review. It is recommended that the implementation of the discussed remedies can surely provide efficient, economical and ecological biomass combustion.

Keywords: biomass-fuel; boilers; corrosion.

1 Introduction

With increase in population, there is a continuous need to secure energy, reduce wastage of non-renewable resources and utilize non-conventional sources of energy. Nonconventional sources of energy like solar energy, biomass and geothermal energy have the potential of energy generation in a sustainable and cleaner way, by which this source of energy can be utilized by our future generations, without depletion of these renewable sources of energy (Olah et al. 2018). For the conversion of energy into electricity, mostly fossil fuels like coal, oil and natural gas are being used (Barma et al. 2017). With an increase in demand, the consumption of fossil fuels is also increasing. However, it is expected that these sources of energy might deplete in the coming years. Also, the usage of fossil fuels is directly linked to carbon emissions that lead to environmental degradation. From 2009 to 2018, it was seen that 42% of carbon emissions were from coal, 38% emissions from oil, 19% emissions from natural gas, and 5% emissions from other sources (Peters et al. 2020). Due to the accumulation of carbon dioxide and other gases, the greenhouse effect takes place which further leads to global warming. Fossil fuel combustion leads to the formation of sulphur oxide and nitrous oxide resulting in acid rain and smog (Mahmoud et al. 2009). Due to all these environmental effects, the need to search for renewable sources of energy began to rise. Solar, geothermal and biomass energy have been selected as the alternative sources of energy with zero emission of carbon dioxide and other air pollutants.

Biomass refers to the organic materials derived from plant and animal wastes (Demirbas 2010). It consists of wood waste (sawdust, wooden pallets), woody crops (willow, silver maple), agricultural wastes (rice husk, corn waste), herbaceous crops (grass) and animal waste (cow dung) (Demirbaş and Demirbaş 2003). India is dominated by agricultural and forestry industries and so, biomass can be easily procured. Biomass mainly consists of cellulose, lignin and hemicellulose. The amount of these constituents are responsible for determining the heating value of biomass fuel (Zhang et al. 2010). Figure 1 shows carbon cycle of biomass which explains that if biomass is fully combustible, the content of carbon dioxide produced on being burnt is

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Figure 1: Carbon cycle of biomass explaining the carbon neutral behavior of biomass.

equal to that taken by biomass from atmosphere during its growing stage. So, net addition of carbon dioxide is zero (Saidur et al. 2011).On the other hand, burning the same amount of fossil fuels results in the release of large quantities of carbon dioxide in a short period. Moreover, when biomass is left in an open atmosphere, it releases its energy slowly resulting in wastage of energy. But, if biomass is burnt in the boiler, its energy can be utilized quickly for steam generation and rotation of the turbine (Saidur et al. 2011; Tock et al. 2010). Table 1 discusses about the particle sizes and bulk densities of various kinds of biomasses. The biomass fuel can be chosen depending on these properties.

Coal is used as a fuel in many power plants, however, on comparison of biomass with coal, biomass has a density of 500 kg/m³ whereas coal has a density of 1300 kg/m³. Biomass has carbon content of 42–54 wt% of dry fuel. It has an oxygen content of 35–45 wt% of dry fuel, which is comparatively higher than that of coal (2–15 wt% of dry fuel). The ignition temperature of biomass is between 418 and 426 K. It has a lower heating value of 14–21 MJ/kg, in comparison to that of coal (23–28 MJ/kg). Biomass when

used as a fuel is highly volatile, reactive, and contains very less carbon content (Demirbaş and Demirbaş 2003). It is an eco-friendly and renewable fuel with less nitrogen and sulphur content. Moreover, on the combustion of biomass. the amount of carbon dioxide in the atmosphere remains balanced. Also, if biomass is co-fired with coal, 93% reduction in carbon dioxide has been reported, in comparison to the combustion of hard coal as alkaline ash from biomass captures some of the sulphur dioxide and carbon dioxide emissions produced during combustion (Saidur et al. 2011). However, chlorine species from biomass result in corrosion of boiler tubes and biomass deposits are bulky and interfere in combustion so, proper cleaning is required to remove them. Due to the high amount of volatile matter, the ignition consistently takes place (Sami et al. 2001). The ash released from this fuel has the property of absorbing carbon dioxide and sulfur dioxide emissions (Saidur et al. 2011). The nitrogen present in biomass can be converted to ammonia during combustion, which can be used as burning fuel. It is cheaper than fossil fuels and since it uses low-quality soil so, the degraded land has the possibility of restoration. Agricultural waste can be utilized in a better way by converting it into biomass and our dependence on fossil fuels is also decreased. It has an added advantage of being used with fossil fuels to reduce harmful emissions of carbon dioxide and nitrous oxide. It was reported that co-firing of biomass with coal resulted in thermal efficiency of 92% (Xu et al. 2020). Also, employment opportunities will be enhanced as labour would be required to harvest and transport biomass. Every source of energy offers some disadvantages also which include low energy density and high content of moisture. Because of the low energy density, the transportation cost is also high in order to avoid road congestion. High content of moisture reduces the stability of the flame. High amount of particulate matter is released during its combustion due to which extra cost is required to employ methods that reduce particulates. Deforestation and biodiversity losses are also accompanied by the usage of biomass as wooden pellets are procured from forests which have resulted in deforestation in

Table 1: Particle size and bulk density of biomass fuels (Laboratory 2011).

Biomass fuel	Particle size (m)	Bulk density (kg/m³)
Sawdust	0.0003-0.002	300
Chopped straw	0.005-0.025	60
Greenwood chips	0.025-0.075	500
Wood pellets	0.006-0.008	600
Biomass briquettes	0.025-0.010	600
Cordwood	0.3–0.5	400

many parts of the world. Many energy companies cut mature trees for obtaining forest timber to be used as biofuel for biomass plants. This results in deforestation, soil erosion, habitat loss and destruction of natural beauty (Sage 2019). When incineration of waste takes place, toxic ash is released into the air, which settles on the ground, thus, polluting groundwater. Corrosion at high temperature takes place due to the presence of chlorine in biomass (De Best et al. 2008; Demirbaş 2003; Vassilev et al. 2010; Yusuf 2011). Figure 2 shows biomass fired boiler with various components and wood as fuel.

From the characteristics of biomass and its combustion, it has been found that it provides many social, economical and environmental benefits such as conservation of non-renewable fossil fuels, employment opportunities, financial saving due to low cost and reduction in emissions of carbon dioxide and sulphur oxide emissions. However, combustion of biomass can lead to issues like fouling, agglomeration, emission of heavy metals, low heating value, storage problems and hot corrosion due to chlorine species present in biomass. Hot corrosion has been responsible for causing shutdown of biomass boilers, reducing boiler efficiency and increasing productivity losses.

Currently, biomass is being used for the generation of electricity, household heating, cooking purposes, fueling of vehicles and providing heat for industrial processes. It can be used in boilers for combustion. Challenges related to biomass combustion can limit the reliability of biomass so, this review addresses solutions for challenges that are encountered in boilers due to the burning of biomass. The successful implementation of these solutions can make biomass boilers more efficient and cost-effective (Saidur et al. 2011).

2 Method

The literature for review was selected in two steps: (1) literature was identified based on keywords and relevant literature was selected based on some rules, and (2) final literature was extracted based on the topics and information discussed in the literature.

2.1 Literature identification

Literature was searched on Google Scholar and Science Direct with the help of keywords like "problems on combustion of biomass", "biomass as a fuel for boilers", "advantages and disadvantages of biomass", "recent trends on biomass usage" and "potential of biomass to be used as a source of energy". The literature that was obtained gave some introduction about the topic and all the problems of biomass were noted. After this, literature was searched for each problem with the help of keywords like "fouling", "agglomeration", "emission of heavy metals", "gaseous emissions", "low heating value of biomass", "storage and transportation problem of biomass" and "high-temperature corrosion on using biomass as a fuel for boilers". The literature obtained by each of these keywords gave an insight about the description of the problem. Then solutions were searched for each problem and the main focus was drawn on searching the latest solutions for each problem. The latest solutions were searched by entering the year of research and results were obtained for solutions of problems that were researched and published in the years 2018, 2019, and 2020.

Rules that were used as exclusion criteria for the purpose of literature review are as follows: 1) papers published before 2000 were excluded from the literature review; 2) papers in which biomass was burnt in coal-fired boilers were excluded.

2.2 Final literature

After the selection of initial literature, the content of all the research papers was carefully read. Depending on the objective of its research, methods used, type of biomass used, the material of boiler tubes and solutions are drawn to solve the problem, the papers were selected for the final literature review.



Figure 2: Biomass fired boiler (Hub 2018).

3 Combustion of biomass in boilers

Although, biomass is environment friendly but the usage of this fuel results in many problems that lead to a sudden interruption in the working of boilers and additional cost of repairing. These problems include fouling, agglomeration, emissions of heavy metals, gaseous emissions (CO, NO_x, N₂O, SO_x), low heating value, storage and transportation problems and high-temperature corrosion (Singh et al. 2018). The problems encountered in biomass combustion and their remedies are summarized in the table as follows (Table 2):

Table 2: Problems and solutions for combustion of biomass in boilers
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S.	Problems	Remedies	References
no.			
1.	Fouling	(a) Leaching or pre-treatment of biomass with water	Gudka et al. (2016) and Melissari (2017)
	0	(b) Optimization of airflow rate and deposition probe	Febrero et al. (2015)
		temperature	
		(c) Hybrid system design (neural networks and fuzzy	Romeo and Gareta (2009)
		logic system)	
		(d) Reduction of adhesion force by thermal spray	Naganuma et al. (2013)
		coatings	
		(e) Reducing the content of potassium with the help	Liao et al. (2015)
		of additives	
		(f) Reducing the content of chlorides with the help of	Kassman et al. (2013)
		ammonium sulfate	
2.	Agglomeration	(a) Optimization of bed temperature, fluidization ve-	Lin et al. (2003)
		locity and size of bed particles	
		(b) Proper selection of bed materials	Brus et al. (2004), De Geyter et al. (2007), Fernández Llorente
			et al. (2006), Grimm et al. (2012), and Silvennoinen (2019)
		(c) Change in reactor design	Bartels et al. (2008)
_		(d) Usage of additives in normal silica sand	Corcoran et al. (2014) and Davidsson et al. (2008)
3.	Emission of heavy	Absorption using silicates and aluminosilicates,	Knan et al. (2009)
	metals	adsorption using activated carbon and ion-exchange	
4	Cacoous omissions	(a) Design of longer freeboards, reaction with	(2012)
4.		(a) Design of longer freeboards, reaction with	Kildil et al. (2006), Laliberg et al. (2011)
	$(0, NO_x, N_2O, SO_x)$	(b) Air staging	Khan et al. (2009) livet al. (2013) and 7 abetta et al. (2005)
		(c) Selective non-catalyst reduction usage of ultra-	(a) et al. (2009), Electral. (2019), and Zabella et al. (2009) (a) et al. (2019), Electral. (2009) and Mladenović et al.
		fine limestone	(2003)
5.	Low heating value	(a) Usage of fuel with high extractive content	Demirbas and Demirbas (2009)
		(b) Torrefaction, densification techniques and hy-	Kambo and Dutta (2014), Keipi et al. (2014), and Wattananoi
		drothermal carbonization	et al. (2011)
		(c) Liquid hot water treatment	Runge et al. (2013)
		(d) Proximate analysis using artificial neural network	Uzun et al. (2017)
6.	Storage and trans-	(a) Setting up of intermediate storage facility	Rentizelas et al. (2009)
	portation problems	(b) Terminal site for continuous quality up-gradation	Gautam et al. (2017)
		(c) Model for fire risk reduction	Shabani and Sowlati (2013)
		(d) Usage of mixed transport, pipelines	Flodén and Williamsson (2016) and Malladi and Sowlati
			(2018)
		(e) Preprocessing of biomass at intermediate storage	Flisberg et al. (2015)
		location	
7.	High temperature	(a) Use of superalloys and high chromium steel as	Cho et al. (2012), Gao et al. (2012), Gupta et al. (2012),
	corrosion	materials for boiler tubes (Super 304H, Superni 718,	Kamal et al. (2010), Luo et al. (2012), Mishra et al. (2014),
		Superni 76, superfer 800H, Superni 75, Superni 600,	Mlonka-Mędrala et al. (2019), Mudgal et al. (2017), and
		Ni ₃ Al based alloy IC21, nickel based N0726)	Zhao et al. (2014)
		(b) Application of thermal coatings to boiler materials	Aguero et al. (2018), Bignal et al. (2008), Brus et al. (2005),
		and superalloys (75N125Cr, Cr_2O_3 , Cr_3C_2 -25N1Cr,	Demirbas (2005a), Demirbaş (2005b), Grimm et al. (2011),
		NICTALY, NI-SAL, NICTAL, PE-CT)	Heartey et al. (2016), Hussain et al. (2013, 2014), James et al. (2012). Khan et al. (2005). Makesh et al. (2008a h)
			ai. (2012), Midil et al. (2005), Manesh et al. (2008), D. Nawrot et al. (2006). Obman and Nordin (2000). Oksa et al.
			(2016) Prashanth et al. (2015) Viccor (2004) and Viccor et
			al (2008)

Further, each of these problems has been discussed, in detail, along with the ways of overcoming them.

3.1 Fouling

3.1.1 Description

Fouling, also known as deposits, refers to the deposition of ash on heat transfer tubes. Sulfur, chlorine and silicon are responsible for increasing the volatility of sodium and potassium (alkali compounds). These alkali compounds combine with chlorine to form alkali chlorides, which escape in the form of gas. Flue gases on cooling, deposit on heat exchanger tubes. In the presence of silicon, alkali silicates are formed; having low melting temperature, leave a sticky surface for increased deposition. The nonvolatile compounds present in the fuel form ash, which consists of elements like magnesium, calcium, silicon with small amounts of sodium, potassium and aluminium (Altobelli et al. 2013). Coarse particles are found as deposits on surfaces of the heat exchanger. Potassium reacts with calcium and silicate present in ash to form a glassy structure, which is responsible for heavy deposits. Thus, fouling or deposits lead to decreased boiler efficiency and heat transfer. They also result in increased operating cost, carbon monoxide and nitrogen oxide emissions (Demirbas 2005a; Jiménez and Ballester 2007; Khan et al. 2009).

3.1.2 Solutions

Through leaching or pre-treatment of biomass with water, the ash content can be reduced (Table 2). With an increase in temperature of the water used for pre-treatment, the melting point of ash increases, which eventually improves the efficiency of the combustion process. The content of chlorine, potassium, sodium and sulfur can be reduced by 30-100%, 50-90%, 10-90% and 0-95% respectively. The concentration of silicon, titanium and aluminium can be reduced by 15% with the help of cold washing. Reduction in concentrations of the above-mentioned elements can reduce fouling (Gudka et al. 2016; Melissari 2017).

The second way of reducing fouling in wooden biomass is through the optimization of airflow rate and deposition probe temperature (Table 2). When the airflow rate and probe temperature are increased from 11 to 25 m³/h and 25–65 °C respectively, the amount of unburnt carbon can be reduced. Many non-volatile compounds like calcium, magnesium, silicon, aluminium, and titanium remain in the ash but the content of sulfur can be reduced to a great extent. The content of chlorine should be reduced in the biomass to reduce its deposition on boiler tubes (Febrero et al. 2015). Another way for reduced fouling is the design of a hybrid system using neural networks and the Fuzzy Logic Expert System (Table 2), which is responsible for simulation, prediction, and control of soot blowing cycles. It performed thermal monitoring, fouling or deposit prediction, analysis of boiler behavior, and finding the number and timing of soot blowing cycles. The system will suggest a certain number of soot blowing cycles and the rest of them will be done automatically. This method not only reduces fouling but also helps in energy saving. On the implementation of this system, 3.5% of energy can be saved (Romeo and Gareta 2009).

The mechanism of fouling was studied and it was found that alkali sulfates play an important role in increasing the adhesion force. The reduction of adhesion force can be a solution to fouling. So, nickel alloy thermal spray coating can be done on boiler tubes, which helps in reducing adhesion force (Table 2) (Naganuma et al. 2013).

Reducing the content of potassium can also be a solution to fouling, as mentioned in Table 2. Composite additive with 20–50% blowing air, 25–65% kaolin, 20–60% MgO, and 15–30% activated alumina reduced the content of potassium and so, fouling was also reduced. With an increase in combustion temperature, the additives worked in a better way and CaO can be added to reduce the emission of HCl (Liao et al. 2015).

Chlorides are very harmful to biomass boilers and so, strategies can be adopted to reduce the content of chlorides (Table 2). Ammonium sulfate can be used as an additive for the conversion of KCl to its sulfate through which, the chloride content can be highly reduced. Combustion of biomass with peat can also be a strategy for the reduction of chlorides. Components like aluminium, sodium, and calcium present in peat ash are responsible for capturing potassium and converting its chloride into sulfate (Kassman et al. 2013).

3.2 Agglomeration

3.2.1 Description

Agglomeration results when particles of ash form layers around particles of bed material (mostly quartz sand). It takes place due to chemical reactions, liquid phase presence, and solid-state sintering. If the melt or ash is highly viscous, it gives a glassy structure, which on cooling, does not crystallize. If the melt is less viscous, the alkali compounds melt increasing the stickiness of the particles. The alkali compounds act like bonding agents, thus, enhancing agglomeration (Llorente et al. 2006). The chemical reaction includes the reaction of potassium phosphate with either silicon or calcium, which results in silicates of potassium and calcium with a low melting point.

In fluidized biomass boilers, the main cause of agglomeration is the partial melting of inorganic compounds. In an agglomerated bed particle, the inner layers have a composition similar to that of the bed material and the outer layers have a composition similar to that of the fuel. Two phenomena have been studied: melt-induced agglomeration and coating induced agglomeration. In melt-induced agglomeration, the bed particles adhere to each other due to high local temperature and on the other hand, a uniform coating is present on particles of bed material. In this coating, the formation of neck starts and as this neck formation continues, a high-temperature zone forms which help in melt formation, thus, promoting agglomeration (Melissari 2017; Visser 2004; Visser et al. 2008).

According to Ohman et al. (2000), the deposition of ash on bed material is a combination of processes that include: attachment of small particles on grains of bed material followed by condensation of alkali compounds (potassium, potassium chloride, and potassium sulfate) followed by reaction of alkali compounds with the bed material surface. On deposition, each inner layer undergoes sintering and gets strengthened. Agglomeration takes place due to any of the three mechanisms. First, due to the reaction between bed material and alkali compounds, potassium silicate is formed which promotes the formation of bed layers. Second, the reaction takes place directly between gaseous potassium and bed material particles, which results in the formation of potassium silicate that initiates agglomeration. Third, adhesion of bed particles by partially melted potassium silicate and potassiumcalcium/magnesium phosphates from fuel (Brus et al. 2005; Grimm et al. 2011).

It has been reported that biomass with herbaceous materials results in increased agglomeration due to the high concentration of alkali compounds. Alkali compounds like potassium, calcium, magnesium, silicon, and aluminium are highly responsible for agglomeration problems. The bottom ash captures vaporized potassium, which combines with silica present in bed material leading to agglomeration (Lin et al. 2003; Llorente et al. 2006). Biomass has a bright future and so, it is important to control the problem of agglomeration since eliminating it is not possible.

3.2.2 Solutions

The selection of bed materials can help in reducing agglomeration (Table 2). Quartz sand contains silica, potassium, and calcium and is responsible for the formation

of silicate compounds with low melting points whereas olivine contains silica, calcium, and magnesium (responsible for increasing the melting temperature of potassium silicate). Results have shown that agglomeration was lesser in the case of olivine bed material in comparison to quartz sand (Brus et al. 2004; De Gevter et al. 2007; Grimm et al. 2012). Limestone of particle size 0.25-2 mm with fluidization velocity of 1.2 m/s has shown lesser agglomeration deposits than silica sand when used as bed material. In the case of limestone, calcium carbonate, calcium oxide, and calcium hydroxide escape bed material to reduce ash deposits on boiler tubes (Fernández Llorente et al. 2006). Other bed materials like alumina, ferrite oxide, and dolomite have problems related to chemical stability. Agglostop can be used as bed material because it can handle alkali related agglomeration problems (Silvennoinen 2019).

Change in reactor design can also be a solution to this problem by implementing a stirrer to break up agglomerates (which can break easily) or by passing a high-velocity gas stream or by using the concept of the hydro-beam floor in which coarse bed particles are removed repeatedly (Table 2) (Bartels et al. 2008).

Another alternative to reduce agglomeration is the usage of additives in normal silica sand (Table 2). Kaolin can reduce the concentration of potassium chloride and so, agglomeration can be reduced. But, kaolin is so expensive so, it can be replaced by ammonium sulfate, which gives the highest efficiency and is most effective in the elimination of agglomeration, after kaolin (Davidsson et al. 2008). Other additives like dolomite and alumina can also be used which do not allow reaction between potassium and silica. Ilmenite has the advantage of absorbing potassium particles from ash, thus, reducing agglomeration when used with sand bed material (Corcoran et al. 2014).

Operating parameters can be altered to control the problem of agglomeration, as mentioned in Table 2. Lower bed temperature, higher fluidization velocity, and finer bed particles are ideal for reduced agglomeration. Lower bed temperature reduces the ash-melting rate. When the velocity of the gas is high, defluidization time is more and so, breaking of agglomerates can take place easily. With finer bed particles, the defluidization time is more (Lin et al. 2003).

3.3 Emissions of heavy metals

3.3.1 Description

Heavy metals like arsenic, cadmium, arsenic and lead are highly toxic for the environment that are released during burning of biomass. Low quantities of copper, zinc, cobalt, selenium, nickel and manganese are required by human body for molecular and biological functions but large quantities of these heavy metals given out in the form of ash during biomass combustion pose a threat to the environment (Prashanth et al. 2015). The concentration of these heavy metals depends on the source of biomass and how far is it from the source of pollution. Heavy metals are usually found in fuel ash with particles smaller than 1 μ m. Moreover, their concentration increases with the decreasing temperature of precipitation and the size of the particle (Demirbas 2008; Demirbaş 2005b). Cadmium as heavy metal is harmful to humans as it accumulates in the kidneys and causes cancer. Lead is also a toxic metal that is harmful to the brain even at low concentrations (Nawrot et al. 2006).

In the boiler, metals like cadmium, argon, zinc, and lead volatilize in the form of oxides and chlorides and deposit in the form of ash. During combustion, cadmium, and lead vapourize in the form of cadmium chloride and lead chloride respectively. Although zinc is present in fuel ash in its stable form, but the small amount of zinc gets converted to zinc chloride. Thus, sublime metal is passed on to fly-ash with the help of chlorine. Non-volatile metals such as aluminium, copper, and iron are found in coarse fly-ash because they are converted to oxide form which is very stable (Khan et al. 2009). Some heavy metals like selenium and mercury escape the biomass boiler in the form of gases from flue gas outlet. Workers may be exposed to gaseous pollutants and particulate matter generated from biomass handling, transportation, storage and ash generated from post combustion processes like cleaning of flue gases and removal of carbon dioxide. Trucker is involved in transportation of ash, fuel handling operative is involved in storage of biomass leading to exposure to off-gases from storage chamber, cleaner is involved in removal of deposits from plant, maintenance engineer is involved in maintenance of boiler leading to exposure to combustion gases and ash handling operative is involved in ash removal and its transportation to ash storage chamber (Rohr et al. 2015).

3.3.2 Solutions

The presence of heavy metals in fly-ash is a serious problem for which the following measures can be taken.

For control of heavy metals, absorption of lead and cadmium with absorbents like silicates and aluminosilicates has proved to be very effective (Table 2). The chemical reaction of heavy metals with adsorbents like alumina, silica, and bauxite can also be one of the solutions. Methods like adsorption using activated carbon, ion-exchange process, and post precipitation can also be employed to reduce heavy metal emissions to a great extent (Table 2). For the metal concentrated ash to not cause any harm to the boiler tubes, it can be disposed to a landfill (Table 2) (Khan et al. 2009). To reduce the amount of ash that is deposited to the landfill, sieve fractionation method should be preferred to reduce the amount of unburnt carbon present in the ash and followed by gasification process for removal of highly important elements that should not go to the landfill and get leached with surrounding environment (James et al. 2012). These processes basically separate out the solid unburnt and harmful soluble compounds from fly-ash.

3.4 Gaseous emissions (CO, NO_x, N₂O, SO_x)

3.4.1 Description

Emissions from biomass generally include CO, NO_x , N_2O and SO_x emissions.

CO emissions are usually a result of incomplete burning, excess air, shorter residence time, low temperature, and high concentration of carbon content in the fuel. A sudden decrease in the temperature of the flame and poor mixing of fuel with air often leads to increased CO emissions. The main reason for CO emissions is the usage of the boiler that was once used for coal combustion and has undergone no modification for the combustion of biomass. A large amount of volatile matter is present in biomass which requires longer freeboards for longer residence time, which is sometimes not provided by small-scale industries, resulting in high CO emissions. Also, heat exchangers decrease the temperature of the boiler due to which carbon monoxide cannot be fully converted to carbon dioxide. It has been reported that high moisture content, low boiler demand, the large size of fuel particle and high ash content are responsible for high CO emissions (Bignal et al. 2008; Demirbas 2005a; Khan et al. 2005, 2009).

 NO_x emissions include nitrogen oxide and nitrogen dioxide, which are responsible for the formation of smog, particulate matter, and acid rain. Volatile matter consists of nitrogen-containing species (NH₃ and HCN) which oxidize to form NO_x . These emissions do not depend much on the operating conditions of the boiler but mostly depend on the nitrogen content present in the fuel, amount of available oxygen for combustion, and fuel reactivity. High moisture content and improper dosage of fuel result in high NO_x emissions. Proper regulation of oxygen also plays an important role in NO_x emissions (Khan et al. 2009; Vitázek et al. 2016).

N₂O oxidizes into NO in the presence of sunlight which further causes depletion of the ozone layer. Biomass fuel composition plays an important role. On the combustion of biomass, the more is the production of cyano species, the more are N_2O emissions and on the other hand, the production of NH_3 results in lower N_2O emissions. These emissions greatly depend on boiler temperature and excess air supply. At high temperature, N_2O converts into N_2 , and thus, high temperature is suitable for N_2O reduction, and on the supply of excess air, there is a decrease in temperature which increases the formation of NO and N_2O . From the literature, it has been observed that biomass combustion results in lower N_2O emissions than coal and natural gas (Bai et al. 2013; Khan et al. 2009).

 SO_x emissions include SO_2 , SO_3 , and other alkali sulfates, which react with chlorine resulting in corrosion of boiler tubes. In the boiler, at the time of flue gas cooling, the sulfates get deposited on the surfaces. It has been reported that on using biomass with coal, SO_2 emissions can be reduced because of the presence of calcium oxide and magnesium oxide that can absorb SO_2 emissions (Khan et al. 2009; Williams et al. 2012).

3.4.2 Solutions

Gaseous emissions play a major role in polluting the environment, so, the issue of release of gaseous emissions needs to be resolved. One of the solutions to reduce carbon monoxide emissions can be the design of longer freeboards which can increase the residence time of biomass in the boiler for its proper combustion (Table 2). The heat exchanger present in the freeboard should also be removed as a heat exchanger decreases the temperature which is not suitable for CO emission reduction. Air staging and boiler load should be optimized according to the carbon content in the fuel. Selective catalyst reduction is a successful method of reducing CO and NO_x emissions (Table 2). Reagent like ammonia is used which reacts with NO_x and CO in the presence of a catalyst which oxidizes CO to carbon dioxide and reduces NO_x to nitrogen. By this process, CO emissions are reduced by 70–85%, and NO_x emissions are reduced by 70-95% (Khan et al. 2008; Lamberg et al. 2011). Air staging is also an effective solution for the reduction of NO_x emissions, which prevents the insufficient supply of fuel and oxygen for proper combustion (Table 2). This inhibits the chemical reaction of nitrogen being converted to NO_x. The secondary air inlet, when placed above the fuel bed, has proved to reduce NO_{y} emissions significantly. Proper mixing between primary and secondary combustion zone products can reduce gaseous emissions to a great extent. The type of biomass fuel can also be changed with wood being used as biomass fuel because of its low sulfur and nitrogen content, resulting in reduced gaseous emissions (Khan et al. 2009; Liu et al. 2013; Zabetta et al. 2005).

The selective non-catalyst reduction can play a major role in the reduction of N_2O emissions with feeding urea in

the post-combustion chamber and ammonia can continue as a reducing agent in selective catalyst reduction (Table 2). This hybrid technique has been reported as the most successful one for N₂O reduction. Recently, the usage of ultrafine limestone with a particle size of 20 μ m has emerged as an innovative solution for the reduction of N₂O and SO_x emissions (Table 2). The content of ultra-fine limestone needs to be optimized for nitrogenous emissions (Cai et al. 2019; Grosso et al. 2009; Mladenović et al. 2003). With the increase in particle size of limestone, the efficiency of desulphurization decreases, which results in increased SO_x emissions.

3.5 Low heating value

3.5.1 Description

The heating value of biomass can be defined based on high heating value (HHV) which is the overall heat content of the fuel. Low heating value can be obtained by subtracting the amount of energy required to remove the moisture content of biomass. This low heating value of biomass can be attributed to low density, high moisture, and oxygen content. Due to this, biomass experiences problems in flame stability. Coal has a higher heating value (23-28 MJ/kg) in comparison to biomass (14–21 MJ/kg). It has been reported that compounds containing carbon and hydrogen tend to increase the heating value of biomass while oxygen tends to decrease it. When compared to lignin, it has been observed that hemicellulose and cellulose present in biomass have lower heating value due to their oxidation. Ash content is also a major factor responsible for low heating value, thus, making its combustion inefficient (Demirbas 2005b; Khan et al. 2009; Saidur et al. 2011).

3.5.2 Solutions

One of the solutions to increase the heating value can the usage of fuel with high extractive content. Wood has a high concentration of extractives which directly affects the heating value of the fuel. It has been reported that extractives play an important role in increasing the heating value, thus, making the fuel desirable for combustion (Table 2) (Demirbas and Demirbas 2009).

Torrefaction and densification techniques have proved to be advantageous in improving the heating value of the fuel (Table 2). Torrefaction is a process in which biomass, in the form of chips or crushed, is fed for pyrolysis in an inert atmosphere at 200–300 °C which results in fuel with bettergrinding properties and high carbon content. The solid fuels with a heating value of 21 MJ/kg had a significant increase in their heating value (23.2 MJ/kg) after a torrefaction time of 60 min. The torrefaction time needs to be optimized as after some time, it does not affect the heating value. Moreover, this process can reduce the chlorine content of fuel up to 90% with results in reduced ash content. With an increase in torrefaction temperature, the carbon and hydrogen contents increase in a significant amount, and oxygen content is reduced. After torrefaction, often densification is done in pellet mills to increase the density of the biomass fuel, which eventually increases the heating value of the same, thus, improving the combustion properties. Hydrothermal carbonization is also a pre-treatment method that has a better effect on fuel properties than torrefaction (Table 2). The durability and density of fuels undergoing hydrothermal carbonization decrease with increasing temperature. When miscanthus was used as a fuel, this process was highly effective in reducing the concentration of alkali metals, ash content, and increasing the carbon content, resulting in the increased heating value of the fuel (Kambo and Dutta 2014; Keipi et al. 2014; Wattananoi et al. 2011).

Liquid hot water treatment has also proved to be an effective solution for increasing the heating value of the fuel (Table 2). Hot water treatment results in increased heating value with a density increase of 16–25%. An increase in density increases the forces between molecules so that more heat is required to break those forces (Runge et al. 2013).

Proximate analysis using the artificial neural network can also be used to predict the heating values of different fuels depending on their compositions and accordingly, the fuel can be changed for increased heating value (Table 2) (Uzun et al. 2017).

3.6 Storage and transportation problems

3.6.1 Description

The storage problem is directly linked to the moisture content present in the biomass. Biomass fuels with low moisture content (around 15–20%) can be stored without drying but biomass fuels with high moisture content (around 40-50%) must be dried before storage otherwise it leads to deterioration of biomass, fire risks and loss of useful energy. Often, biomass is left open on fields for drying which does not reduce its moisture content to an acceptable level and also leads to loss of material. The farmers working nearby may experience serious health issues due to the formation of fungus and spores. Farmers are required to prepare the land for the next crop and so, they hardly allow storage of biomass on open fields. Storage at intermediate places also results in increased transportation cost due to transportation of biomass from source to intermediate place and then from that storage place to the power plant. Moreover, due to the low density of biomass, a huge amount of material is required for a considerable amount of energy. Storage can be done at supply, intermediate, and conversion sites but supply and conversion sites are usually time-constrained for agricultural and wood residues, therefore, intermediate storage is often preferred for them. Forest residues and remain in forests for several months during which open-air drying takes place. On storage, it was noticed that internal heat generation and decay of biomass can lead to fire so, it is necessary to take measures for solving storage and transportation problems (He et al. 2014; Malladi and Sowlati 2018, 2017; Rentizelas et al. 2009).

3.6.2 Solutions

Setting up of intermediate storage facility close to the power plant can be one of the solutions to handling storage problems (Table 2). The moisture content can be reduced to an acceptable level with no formation of fungus and spores. The energy of biomass can be converted efficiently with reduced transportation costs. Usually, biomass that is collected from fields contains high amount of moisture and needs to be dried in storage facilities before using as a fuel for biomass boilers. Drying of biomass usually takes place by external drving process which involves the use of hot air as an input. So, biomass containing low moisture can be dried using external drying process and will cause no degradation of biomass during the drying process. But, biomass containing high amounts of moisture can be degraded with time so, this process is not favorable for biomass containing high moisture content due to the risk of biomass degradation (Rentizelas et al. 2009). Other solutions can be adopted for biomass with high moisture content

A terminal site can be made in between the supply and conversion sites where continuous quality up-gradation can take place which would prevent deterioration of the biomass and this terminal site can provide biomass in varied seasons (Table 2). 4–11% of moisture content can be removed from biomass at this terminal site. The model has been designed which performs calculations on the amount of biomass which is to be supplied from open-air storage to closed shed storage and the amount of biomass that is to be stored in each storage (Gautam et al. 2017).

A model has been made to reduce the risk of fire when the amount of biomass exceeds the limit (Table 2). When storage is more than the prescribed limit, the model applies extra handling and personnel charges so that proper care is given to biomass, resulting in reduced risk of fire (Shabani and Sowlati 2013).

To reduce transportation costs, mixed transport can be used which may include transportation from the supply site to the intermediate site through trains, and then final transportation from the intermediate site to the conversions site can be through trucks (Table 2). Pipelines can also be used for long-distance transportation of biomass mixed with carrying fluid like oil or water but it results in

liamsson 2016; Malladi and Sowlati 2018). Pre-processing of biomass is another solution for efficient storage and transportation because pre-processing of agricultural and forest residues results in increased density which reduces storage and transportation costs (Table 2). Preprocessing includes the conversion of agricultural residues into bales, forest residues undergo chipping and grinding. The pre-processing of biomass at intermediate storage locations has proved to be highly efficient (Flisberg et al. 2015).

the reduced heating value of biomass (Flodén and Wil-

3.7 High-temperature corrosion

3.7.1 Description

Corrosion is a serious problem due to which rupture and thinning of boiler tubes takes place resulting in an unwanted shutdown of boilers. Superheater, reheater, economizer, and air preheater are often at the risk of corrosion (Kawahara 2016b). In comparison to fossil fuels, biomass contains higher amounts of alkali metals, ash content and moisture. On the combustion of biomass, alkali metals are often vaporized in the form of salts containing sulfur, silicon, potassium, and chlorine, which are highly corrosive (Jiamin and Zhansong 2009). With boilers operating at a temperature of 750 °C, these salts get deposited on boiler tubes. The tubes used in boilers are such that they form a protective oxide layer on them at high temperatures. On the deposition of these salts, the oxide layer dissolves, thus, leaving the boiler tubes unprotected. When moisture present in biomass reacts with unprotected surfaces, it leads to hightemperature corrosion which degrades the surfaces, resulting in combustion inefficiency and ineffectiveness (Coleman et al. 2008; Demirbas 2005a; Fauchais and Vardelle 2012; Mahajan and Chhibber 2019; Oksa et al. 2014a; Yuan and Wang 2010).

3.7.2 Solutions

From the literature, mainly two solutions have come up to control corrosion. First is the use of superalloys as a material for boiler tubes (Table 2). The second solution is the application of thermal coatings, by different thermal spray techniques, on the existing material of boiler tubes (Kalivodova et al. 2005; Sidhu et al. 2006; Zhang et al. 2020) (Table 2). Another solution for corrosion reduction can be the implementation of techniques, for reducing chlorine content present in biomass, which includes pre-treatment, adsorption, and absorption using various chemicals as discussed above. Table 3 shows the chemical composition of alloys used in this literature.

Failure usually takes place due to residual stresses and intergranular corrosion so, Gao et al. (Gao et al. 2012) developed a novel stainless steel Super 304H with hightemperature strength and excellent corrosion resistance. Boiler tubes made with this material have proved to be corrosion resistant. Superalloy C22 when tested as superheater material, in 80 wt% KCl + 20 wt% K₂SO₄ for 218 h, has shown best corrosion resistance due to stable nickel, iron and chromium oxides present on it, which were responsible for corrosion-resistant behavior (Luo et al. 2012). On comparing the corrosion resistance of Superni 718 and Superni 76, it was observed that Superni 76 showed better corrosion resistance due to the presence of chromium oxide, ferrous oxide and NiO. This superalloy, when tested at 900 °C in $Na_2SO_4 + 60\% V_2O_5$, gave the best corrosion resistance out of Superni 718 and Superfer 800H due to the presence of protective oxides. Thus, Superni 76 can be used as boiler tube material (Gupta et al. 2012; Kamal et al. 2010). Ni₃Al based alloys have also shown good corrosion resistant properties with IC21 having the best corrosion resistance out of IC32 and IC6. Ni₃Al based IC21 is favorable for its usage in the salt environment of the boiler, with the addition of yttrium and chromium which are responsible for improving the corrosion resistance of IC21 alloy. Nickel-based N07263 has shown good corrosion resistance in the presence of salts due to its dense, adherent and continuous layer on surfaces (Cho et al. 2012; Zhao et al. 2014). When superallovs like Superni 75, Superni 600, Superni 718 and superfer 800 were placed in a boiler environment at 540 °C for 1000 h, maximum weight loss was observed for Superni 600 and minimum weight loss was observed for Superni 718. Fly-ash particles often deposit on superalloy surfaces, forming oxides which further prevent penetration of other particles, thus, forming a protective layer against corrosive species (Mishra et al. 2014).

Coatings on superalloys and other substrates have come up as an economical solution for controlling hightemperature corrosion (Kaur et al. 2008). Usually, the cost is very high on changing the material of boiler tubes and so, coatings are mostly preferred. On detonation spray of 75Ni25Cr on 347HSS, the coating remained intact to the substrate with less metal loss in comparison to that of the bare sample. Cr₂O₃, K₂CrO₄ and NiCr₂O₄ oxides were responsible for corrosion resistance while iron oxides

Table 3: Composition of substrates

lame of substrate								Ele	:ments (wt%)										
	Fe	N	Mn	Ċ	CĽ	٥W	Si	⊨	U	Ta	AI	z	S	۵	B	S	≥	>	Re
uper 304H	Bal.	8.58	0.8	17.74	2.7	0.4	0.2	0.2	0.08			0.1	<0.01	0.15	<0.001				l
Superni 718	18.5	Bal.	0.2	19	0.2	3.1	0.2	0.9	0.04	5.1	0.5								
Superni 75	m	Bal.		19.5				0.3	0.1										
Superni 76	19.69	Bal.	0.3	21.5		9.1	0.4		0.09				0.002	0.01		1.6	1		
superni 600	10	Bal.	0.5	15.5					0.1										
superfer 800	Bal.	32	1.5	21			1	0.3	0.1		0.3								
Superalloy C22	6	Bal.	0.5	22.5		15	0.1		0.02				0.02	0.02		2.5	4	0.4	
C21		Bal.		2.5		13				4	8.3								7
107263	0.5	51.35	0.1	20		5.8	0.1	2.4	0.05		0.5					19.2			
147HSS	Bal.	13	0.5-2.0	17-20			0.8		0.04-0.08	1			0.3	0.03					
22 alloy			0.3-0.6	1.9-2.6		0.87-1.13			0.05 - 0.15				0.025	0.03					
VSTM-SA210 grade A1 steel			0.9				0.1		0.27				0.035	0.04					
																			L

failed to serve the purpose because of their porous nature (Gada et al. 2019). The application of chromium oxide coating (plasma-sprayed) on SA213-T22 alloy has helped in preventing cracks, spalling, scales and weight gain during corrosion at 850 °C. Apart from chromium oxide, Cr₃C₂-25NiCr (HVOF spraved) has also reduced corrosion of base material by the formation of protective oxides with a 25% decrease in corrosion after application of the coating. The addition of molybdenum and aluminium to nickel-based HVOF coatings enhanced the high-temperature corrosion resistance of the substrate. The coating of NiCr on ASTM-SA210 Grade A1 alloy gives the best corrosion resistance while WC-Co coating gives the worst corrosion resistance. Chromium rich oxide scale due to Cr₃C₂-NiCr coating has contributed to corrosion reduction on SAE-347H steel at 700 °C (Kaur et al. 2009, 2012; Oksa et al. 2014a; Singh et al. 2006, 2017).

Coatings can also be applied to superalloys to enhance their corrosion-resistant behavior. Superni 76 has already proved to increase the corrosion resistance of boiler steel but the application of NiCrAlY coating can further improve the corrosion resistance of superalloy by forming a continuous layer of aluminium oxide (Rana et al. 2014). The corrosion resistance of Superfer 800 can be increased by the application of either Ni-5Al or NiCrAl coatings through HVOF spraying technique, which leads to the formation of aluminium and chromium oxides, preventing further penetration of corrosive species (Mahesh et al. 2008a,b). For improving corrosion resistance of Cr₃C₂-25NiCr coated Superni 600, ceria oxide can be added to Cr₃C₂-25NiCr in an optimum weight percentage, leading to the formation of CeO₂ and CeS, which are responsible for reducing porous scale and weight loss in bare Superni 600 (Kamal et al. 2008; Mudgal et al. 2014a). On addition of ceria oxide, along with CeO₂ and CeS, the formation of Cr₂O₃, NiCr₂O₄, NiS and Ni was also observed which provided high temperature corrosion resistance to Superni 600. Table 4 summarizes the performance of various alloys, in which the "Performance" column shows comparison of alloys in decreasing order of their corrosion resistance.

Application of coatings enhances the corrosion resistance of alloys which can be observed from Table 5. HVOF thermal spraying technique of a coating with high chromium content has been preferred for substrates because of the good adherence and high-density properties achieved by HVOF process. Also, chromium coating on reaction with salts forms chromium oxide which plays a key role in improving the corrosion resistance of the substrate. However, it has been observed that the type of biomass being burnt and thermal cycles taking place inside the biomass boiler also play a

Corrosion performance Application of alloys Alloy name with coating **Testing atmosphere** Testing atmo-(if used) sphere temperature 20#Steel, TP347H, Super-80 wt% KCl + 20 wt% 650 °C for cycle Superalloy C22 > TP347H > 20#Steel Superheaters of alloy C22 (Luo et al. 2012) K_2SO_4 of 218 h boilers Superni 75, Superni 718, Na₂SO₄-60%V₂O₅ 900 °C Superni 75 > Superni 718 > Superfer 800H Superheater tubes, Superfer 800H (Kamal turbine engines et al. 2010) Superni 76, Superni 718 Silicon carbide tube 900 °C for 100 Superni 76 > Superni 718 Boiler tubes, gas (Gupta et al. 2012) furnace turbines cvcles N06230, N07263, N06625 LiCl-Li₂0 650 °C N07263 > N06230 > N06625 **Electrolytic reduction** (Cho et al. 2012) environment Ni₃Al based IC21, IC6 75 wt% Na2SO4-25 wt 900 °C IC21 > IC6 Superheater tubes, (Zhao et al. 2014) % NaCl turbine engines Superni 75, Superni 600, Thermal power plant 540 °C for 10 Superni 718 > Superni 75 > Superfer Superheater tubes of Superfer 800, Superni 718 (superheater zone) 800 > Superni 600 thermal power plants cycles (Mishra et al. 2014) 347HSS (bare) and Actual husk fired boiler 750 °C Coated 347 HSS > uncoated 347 HSS Economizers, 75Ni25Cr coated 347HSS reheater, superheater, (Gada et al. 2019) air preheater Y₂O₃ added Superni 75 > Y₂O₃ added Superfer 800H, Superco Na₂SO₄-60%V₂O₅ 900 °C Steam boiler tubes, Superfer 800H > Y2O3 added Superco 605 gas turbines 605, Superni 75 with addition of Y2O3 (Singh et al. 2009) 700 °C for 50 Coated 347 HSS > uncoated 347 HSS 347H Steel, Cr₃C₂-NiCr Na2SO4-82Fe2(SO4)3 Superheater tubes, coated 347H steel (Kaur cycles steam turbines et al. 2009) T22 Steel, 75Cr₃C₂-25NiCr Na₂SO₄-82Fe₂(SO₄)₃, 700 °C Coated T22 > uncoated T22 boiler steel in all Boiler tubes, steam coated T22 Steel (Kaur air, actual boiler there environments turbines et al. 2012) environment Biomass fired boiler 360-400 °C Tubes at hot and cold Carbon steel tube St 35.8, Highest melting state in NiCr10Al and unmolten particles were observed in economizers of boilers Ni-24Cr-16.5Mo, Ni-22Cr < 5Fe-9Mo-4Nb, Ni-22Cr-NiCr16Mo and NiCr9Mo 10Al-1Y (Oksa et al. 2014a) 850 °C for 25 Coated T22 > uncoated T22 T22 steel, Cr₂O₃ plasma 60%Na₂SO₄-40%V₂O₅ Superheater tubes sprayed T22 steel (Singh in silicon carbide tube cvcles et al. 2017) furnace 900 °C Superni 76, NiCrAlY coated $Na_2SO_4 + 60\%V_2O_5$ Coated Superni 76 > uncoated Superni 76 Superheater tubes, Superni 76 (Rana et al. in silicon carbide tube gas turbines 2014) furnace Ni-5Al coated Superni 76, $Na_2SO_4 + 60\%V_2O_5$ 900 °C Coated Superfer 800 > coated Superni Boiler tubes Superni 750, Superfer 800 76 > coated Superni 750 (Mahesh et al. 2008b) 900 °C for 100 Hot corrosion boiler NiCrAl coated Superni 76, $Na_2SO_4 + 60\%V_2O_5$ Coated Superni 750 > coated Superfer 800 > coated Superni 76 tubes and turbines Superni 750, Superfer 800 cycles (Mahesh et al. 2008a) components

 Table 4:
 Corrosion resistance performance of various alloys based on literature.

primary role in the determination of the coating required. Therefore, for the wood-fired plant with less number of thermal cycles, Ni and Ni₂Al₃ coatings are preferred, which on the other hand, show poor behavior in fire straw plants

with high thermal cycles (Oksa et al. 2013; Wu et al. 2018). Thus, the coating to be used depends on the material of the boiler tube, number of thermal cycles, coating technique and type of biomass being burnt.

4 Corrosion-specific discussion

From the literature, it can be observed that the maximum shutdown of biomass-fired boilers was due to the problem of corrosion at high temperatures. The introduction of biomass boilers with high-temperature steam has resulted in the rise of high-temperature corrosion of superheater tubes. The concentrations of chlorine and potassium present in the biomass fuel being burnt can significantly increase the oxidation and corrosion of boiler tubes. The presence of chlorine results in accelerated metal loss, corrosion, the formation of voids and loosening of scales (Mudgal et al. 2014b). The HCl gas that is often derived in the form of flue gas does not possess high partial pressure to cause severe high-temperature corrosion but the combination of HCl gas with sulfides can enhance corrosion, resulting in impingement of flame with poor combustion (Parthiban 2006). The presence of alkali chloride salts in deposits can accelerate corrosion by metal surfaces by combining with Sulphur dioxide gas, which results in sulfation of deposits, liberating HCl gas close to the superheater tubes (Berlanga and Ruiz 2013; Frandsen 2005; Nielsen et al. 2000). Therefore, research has been done and is still continuing to search for solutions that can combat the high-temperature corrosion problem in biomass-fired boilers. With an increase in hightemperature corrosion, the production losses have also increased, resulting in ineffective biomass combustion (Sharpconsultant 2011). Other biomass combustion problems like fouling, agglomeration, emissions of heavy metals, low heating value and storage problems can be easily solved with the help of low-cost solutions but hightemperature corrosion requires the use of coatings and superalloys, the usage of which is not so economical. So, researchers are continuously searching for cost-friendly solutions that can prevent the sudden shutdown of biomass boilers.

In order to know more about the research that has been done and is still continuing on high-temperature corrosion, 73 research papers were considered to know about the techniques that are being used to mitigate the problem of high-temperature corrosion at 400–900 °C in biomass boilers. Figure 3 discusses the techniques of coatings and the usage of superalloys for reducing hightemperature corrosion of superheater tubes. The application of thermal spray coatings has proved to be more effective in the deposition of highly dense and durable coatings over metal surfaces (Bradshaw et al. 2013; Ruusuvuori et al. 2011; Singh et al. 2012; Uusitalo et al. 2002). This led to the development of high velocity oxy fuel (HVOF) process because the deposition of fine powder at high velocity results in high bonding and mechanical strength of the coated metal surface (Kawahara 2016a; Zhou et al. 2016). Around 47.95% of the literature accounted for the use of HVOF technique for the application of coatings. This is because HVOF results in highly dense and well-adhered coatings that can significantly reduce high-temperature corrosion (Paul and Harvey 2013). HVOF employs the use of high coating particle velocity with low particle temperature which results in dense coatings (Oksa et al. 2013). 23.29% of the literature preferred the use of superalloys as superheater materials due to their advanced corrosion-resistant properties. Superni 718, Superni 75 and Superfer 800H have been mostly used as material for superheater tubes. During biomass combustion. Superni 75 results in the formation of scales containing NiO, Cr₂O₃ and NiCr₂O₄ that provide resistance against high-temperature corrosion. Superni 718 and Superfer 800H also provided corrosion resistance due to the formation of iron oxides and sulphides of Ni and Fe (Kamal et al. 2010). 8.22% literature accounted for detonation gun (D-gun) sprayed coating because this process of thermal coating results in the deposition of coating with fine grains with very low porosity (Kamal et al. 2008). Plasma spray was also used by 5.48% literature for coating the superalloys with Ni-Al coating. This coating was preferred for applications requiring Ni-Al coating because of its ability to provide a coating with the porosity of 2.0-5.0% (Prakash et al. 2005; Sidhu et al. 2006; Sidhu and Prakash 2003; Singh et al. 2007). Cold spray technique was used for the coating of Ni-Cr coatings on boiler steel, which accounted for 1.37% of the literature. The formation of chromium oxide with NiCr₂O₄ provided high oxidation resistance from chloride and potassium salts (Bala et al. 2009). 13.7% literature used chemical vapour deposition (CVD), electroless deposition, cementation, electroplating, aluminizing, weld overlay, laser cladding, and high velocity air fuel (HVAF) coating



Figure 3: Techniques used to control high temperature corrosion resistance of biomass fired boiler tubes based on 73 publications.



Figure 4: Various coating materials being used in anti-corrosive coatings based on 54 publications.

techniques which also provided corrosion resistance to boiler tubes at high temperature (Liu et al. 2014; Sadeghimeresht et al. 2017, 2018). Weld overlay is not a mature technology for biomass boilers as research needs to be done in this field for improvement of cost and adequate selection of material, which will help in improving durability in future (Kawahara 2016a).

The various proportions of coating materials that are being used for making coatings with high-temperature corrosion resistance were also investigated based on 54 works of literature. Figure 4 depicts the various coating materials being used for the formation of anti-corrosive coatings. It was observed that 27.78% of the literature used Ni-Cr coating for improving the high-temperature corrosion resistance of the boiler tube material. Ni and Cr combine to form NiO and Cr_2O_3 in the oxide scale that acts as a barrier, providing protection against high-temperature corrosion (Kaushal et al. 2011, 2014; Meißner et al. 2020; Montero and Galetz 2019). 12.96% of literature preferred the addition of aluminium and yttrium to Ni-Cr coating. On the usage of NiCrAl as coating, apart from NiO and Cr₂O₃, Al₂O₃ was also formed which enhanced the corrosion resistance of the substrate at high temperature. On addition of vttrium to NiCrAl coating, Al₃Y was also formed along with NiO, Cr₂O₃ and Al₂O₃. With an increase in the number of cycles, the sublayers of Cr₂O₃ and Al₂O₃ in the oxide scale depleted and the dense layer of Al₃Y was responsible for providing hightemperature corrosion resistance (Mahesh et al. 2008a; Rana et al. 2014). Cr₃C₂–NiCr was accounted by 25.93% literature for improvement in corrosion resistance of the superheater tubes. During biomass combustion, Cr₃C₂-NiCr coating led to the formation of protective oxides like NiCr₂O₄ and Cr₂O₃, which were responsible for improving the corrosion resistance of the superheater material at high temperature (Kaur et al. 2012; Mudgal et al. 2014c,d). Ni-Al coating was used in 16.67% literature because due to the formation of chromium band close to the coating substrate, the high-temperature corrosion resistance was enhanced for Superfer 800 superalloy. Ni-Al acts as a protective coating for boiler tubes due to the formation of protective NiAl₂O₄ spinels that provide

 Table 5: Hot corrosion resistance of coated alloys.

Base alloy	Coating used	Performance of base and coated alloys	XRD analysis
Superni 76 (200 cycles) (Rana et al. 2014)	NiCrAlY coating by HVOF technique	Coated Superni 76 performed better than uncoated superalloy. Weight change became constant after 100 cycles due to corrosion resistance offered by coating.	After 100 cycles, peaks of Cr_2O_3 , Al_2O_3 and Al_3Y were obtained. After 200 cycles, peaks of Al_2O_3 and Al_3Y intensified for corrosion resistance.
347HSS (Gada et al. 2019)	75Ni25Cr coating by HVOF technique	Coated 347HSS performed better as average thickness loss for bare steel = 2.516 mm and for coated steel = 0.044 mm.	For coated steel, peaks of NiCr ₂ O ₄ , K ₂ CrO ₄ , Mg ₂ SiO ₄ , Fe ₂ O ₃ and Ni ₂ SO ₄ were obtained. Ni and Cr oxides were protective against corrosion.
SAE 347H Steel (50 cycles) (Kaur et al. 2009)	Cr ₃ C ₂ -NiCr coating by HVOF technique	Coated steel performed better as cumulative weight loss/area for coated steel = 2.925 mg/cm^2 and for uncoated steel = 6.174 mg/cm^2 .	Peaks were obtained for Cr_2O_3 and Cr_7C_3 . Rich chromium oxide protected the metal against corrosion.
Superni 600 (Kumar et al. 2013)	Cr ₃ C ₂ –NiCr coating by detonation gun technique	Coated Superni 600 performed better as weight change/area changed from 1.4 to 0.3 mg/cm ² on application of coating.	Cr_2O_3 , Cr_7C_3 and $NiCr_2O_4$ peaks were obtained that provided corrosion resistance to Superni 600.
T22 Steel (50 cy- cles) (Singh et al. 2017)	Cr ₂ O ₃ coating by plasma spray technique	Coated steel performed better as weight gain/area for coated steel = 50.936 mg/cm^2 and for uncoated steel = 65.164 mg/cm^2 .	For uncoated steel, peak was obtained for Fe_2O_3 and for coated steel, peak was obtained for Cr_2O_3 that provided corrosion resistance.
ASTM SA213 T22 boiler steel (Kaur et al. 2012)	Cr ₃ C ₂ –NiCr coating by HVOF technique	Coated steel performed better as thickness of metal loss for coated steel was 0.03 mm and that for un- coated steel was 0.046 mm.	Fe_2O_3 and Cr_2O_3 peaks were obtained for uncoated steel. CrNi, Cr_3Ni_2 , $NiCr_2O_4$, Cr_2O_3 and Cr_7C_3 peaks were obtained for coated steel.

Alloy with coating name and method	Boiler environment	Oxides formed	Comments
T22 steel, Ni–20Cr coating by HVOF and D-gun technique (Kau- shal et al. 2011)	Na ₂ SO ₄ -60%V ₂ O ₅ (900 °C) and superheater of thermal power plant (700 °C)	NiO, Cr ₂ O ₃ , NiCr ₂ O ₄ , Fe ₂ O ₃	 HVOF showed no spallation of oxides. Fe₂O₃ with Al₂O₃ and SiO₂ were responsible for corrosion. Layer of NiO and Cr₂O₃ in oxide scale provided corrosion resistance.
T22 steel, Ni20Cr coating by HVOF, D-gun and Cold spray techniques (Kaushal et al. 2014)	Paste of Na ₂ SO ₄ -60%V ₂ O ₅ was applied and then placed in sili- con carbide tube furnace (900 °C)	Cr ₂ O ₃ , NiCr ₂ O ₄ , Fe ₂ O ₃ , NiO, NaVO ₃	 D-gun spray technique was best. NaVO₃ and Fe₂O₃ acted as oxygen carriers, leading to corrosion of base metals. Cr₂O₃, NiCr₂O₄ oxide layer provided provided provided and the second second
Superni 76, Superni 750, Superfer 800, NiCrAl coating by HVOF technique (Mahesh et al. 2008a)	Na ₂ SO ₄ -60%V ₂ O ₅ (900 °C)	Cr ₂ O ₃ , Fe ₂ O ₃ , Al ₂ O ₃ , NaVO ₃ , NiO, SiO ₂ , MnO, V ₂ O ₅	 Superni 750 performed the best. NaVO₃ and Fe₂O₃ acted as corrosive species for superalloys. Oxide scale layer rich in Cr₂O₃ and Al₂O₃ and subscale regions containing nickel
Superni 76, NiCrAlY coating by HVOF technique (Rana et al. 2014)	Na ₂ SO ₄ -60%V ₂ O ₅ (900 °C)	Al ₃ Y, Al ₂ O ₃ , Cr ₂ O ₃ , NiV ₂ O ₈ , YVO ₄	 rich splats provided corrosion resistance. 1) YVO₄ and Cr depleted layer acted as corrosive species. 2) Under Cr depleted layer, Al oxidized to form sublayer of Al₂O₃ along with Al₃Y, which provided corrosion resistance.
T22 steel, 75Cr ₃ C ₂ –25NiCr coating by HVOF technique (Kaur et al. 2012)	Na ₂ SO ₄ -82Fe ₂ (SO ₄) ₃ in silicon carbide tube (700 °C)	Fe ₂ O ₃ , Al ₂ O ₃ , SiO ₂ , CrNi, Cr ₃ C ₂ , Cr ₂ O ₃ , FeS, NiCr ₂ O ₄	 Fe₂O₃, Al₂O₃ and SiO₂ acted as corrosive species. Oxide scales consisting of NiCr₂O₄ and Cr₂O₄ provided corrosion resistance.
Superfer 800, Superni 76, Superni 750, Ni–Al coating by HVOF tech- nique (Mahesh et al. 2008b)	Na ₂ SO ₄ –60%V ₂ O ₅ in silicon carbide tube furnace (900 °C)	NiO, NiAl ₂ O ₄ , NiCr ₂ O ₄ , MnO, Cr ₂ O ₃ , Fe ₂ O ₃	 Cr₂O₃ provided corrosion resistance. For uncoated superlloys, Fe₂O₃ and V₂O₅ resulted in corrosion. Al₂O₃, NiO and Cr₂O₃ provided corrosion resistance to coated superalloys. Superfer 800 performed the best due to the formation of NiAl₂O₄ spinels under sublayer of Al and Cr.
Stainless steel, Inconel 625 coating by cold spray, HVAF, HVOF and arc spray techniques (Fan- tozzi et al. 2016)	KCl salt deposits (550 °C)	K ₂ CrO ₄ , Cr ₂ O ₃ , NiO	 Inconel 625 coating could not perform well and chlorine was able to penetrate coated specimens. K₂CrO₄ was also responsible for sample damage. HVOF and arc spray methods resulted in reduced porosity.
T92 Steel, FeCrAl coating by HVOF technique (Hussain et al. 2015)	Coal biomass co-fired boiler (700–800 °C)	Fe ₂ O ₃ , chromium and aluminium rich oxides	 Sulphur was responsible for corrosion of samples. Mixed outer oxide of Al and mixed inner oxide of Cr provided corrosion resistance. Cr oxides containing Al rich phases were present in inter splat oxides that also provided corrosion resistance.
SS304, FeCrB coating by HVOF and laser cladding techniques (Bai et al. 2018)	Fireside corrosion test, with and without KCl deposits (700 °C)	MnWO ₄ , Fe ₂ O ₃ , Fe ₃ O ₄ , Cr ₂ O ₃ in the absence of deposits. MnCl ₂ , Fe ₃ O ₄ , Fe ₂ O ₃ in the presence of deposits.	 Sample loss was observed in laser cladding without deposits and Cr₂O₃ provided protection against corrosion. In the presence of deposits, corrosion resistance could not be provided and chlorine was found underneath the oxides that resulted in severe corrosion of metal.

Table 6: Corrosion resistance mechanism of alloys based on literature.

Table 6:	(continued)
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Alloy with coating name and method	Boiler environment	Oxides formed	Comments
Inconel 625, Cr ₃ C ₂ -WC-NiC- oCrMo and Cr ₃ C ₂ -25(NiCr) coat- ings by HVOF technique (Zhou et al. 2017)	NaCl-KCl-Na ₂ SO ₄ (500 °C)	Fe ₂ O ₃ , NiCr ₂ O ₄ , NiO, Cr ₂ O ₃ for Cr ₃ C ₂ –NiCr coating. Cr ₂ O ₃ , NiO,MoO ₃ , Co ₂ O ₃ , WO ₃ , NiCr ₂ O ₄ for Cr ₃ C ₂ – WC–NiCoCrMo coating	 Chloride salts and Fe₂O₃ were responsible for degradation of substrate. Cr₃C₂-WC-NiCoCrMo performed better and corrosion resistance was increased due to the formation of W, Co, Mo and Cr oxides.

resistance against high-temperature corrosion (Mahesh et al. 2008b; Wu et al. 2017, 2019). 3.7% literature used Ni based Inconel 625 coating for protection of metal surfaces against high-temperature corrosion. However, this coating failed to provide corrosion resistance above 750 °C and chlorine were found to penetrate boiler tubes inspite of the application of Inconel 625 coating (Fantozzi et al. 2016; Kaushal et al. 2014). Fe-Cr coatings have been used in 9.26% literature and it has been found that Ni-Cr coatings show better hightemperature corrosion resistance than Fe-Cr coatings. Ni has proved to be more corrosion resistant than Fe (Oksa et al. 2015b). Other elements like boron, tungsten and aluminium are often added to Fe-Cr coating to enhance the corrosion resistance properties of Fe-Cr (Oksa et al. 2014b). The addition of aluminium resulted in the formation of aluminium rich mixed oxide on the outer layer and chromium-rich mixed oxide on the inner layer of the substrate-coating interface. Boron addition to Fe-Cr resulted in the formation of protective CrB₂ which provided resistance against corrosion at high temperature (Hussain et al. 2015; Reddy et al. 2017). 3.7% of other coatings include silicon aluminide and Cr₃C₂-WC-NiCoCrMo coatings which have also helped in improving high-temperature corrosion resistance of substrate materials. Cr₃C₂-WC-NiCoCrMo is said to perform better than Cr₃C₂-NiCr coating because of the presence of elements like tungsten, cobalt, molybdenum and chromium have certainly proved to reduce the corrosion rate of boiler tubes (Zhou et al. 2017). The corrosion resistance mechanisms for various alloys discussed in the literature have been summarized in Table 6.

5 Summary and conclusions

Biomass exhibits carbon-neutral behavior in the environment. It absorbs solar energy and carbon dioxide in its growing stage. When it is burnt in oxygen, it gives out carbon dioxide and when fully burnt, it is believed to give out the same amount of carbon dioxide that it had absorbed during its growing stage. On the other hand, burning the same amount of fossil fuels results in the release of large quantities of carbon dioxide in a short period. Thus, biomass is a potential resource that can be used in boilers to completely replace fossil fuels, saving the environment from harmful fossil emissions. From the literatures, it has been found that biomass is highly volatile and reactive fuel with very low carbon content. It is an eco-friendly and renewable fuel with reduced nitrogen and Sulphur content. Also, if biomass is co-fired with coal, 93% reduction in carbon dioxide has been reported, in comparison to the combustion of hard coal. Agricultural waste can be properly utilized as biomass which reduces our dependence on fossil fuels. For storage and transportation of biomass, labor will be required, thus, generating employment opportunities.

Burning of biomass in boilers often results in ashrelated problems like fouling, agglomeration, emission of trace metals, gaseous emissions (CO, NO_x, N₂O and SO_x), low heating value, storage and transportation problems and corrosion at high temperature.

These problems can be easily tackled by using the following countermeasures:

Fouling can be reduced by the addition of a composite additive to lower the content of potassium in the biofuel. The reduction of chloride by the addition of ammonium sulfate is also an effective countermeasure. Leaching and optimization of process parameters like airflow rate and deposition probe temperature have also been effective in reducing fouling.

Olivine bed material has resulted in reduced agglomeration. Change in reactor design and the use of additives like kaolin and ammonium sulfate have reduced agglomeration. Lower bed temperature, higher fluidization velocity and finer bed particles have proved to be ideal operating parameters for the reduction in agglomeration.

Heavy metals like lead and cadmium can be adsorbed by silicates and aluminosilicates. Activated carbon, postprecipitation method and ion-exchange method have been very effective in the reduction of heavy metal emissions. Gaseous emissions produced by the burning of biomass can be controlled by selective catalyst reduction with ammonia as a reagent. The design of the boiler can also be improvised for reducing CO emissions. Proper supply of fuel and oxygen helps in reducing NO_x emissions. Selective non-catalyst reduction and use of ultra-fine limestone have been able to successfully achieve reduced N_2O and SO_x emissions.

The low heating value of biomass fuel results in ignition problems. The heating value can be increased by usage of a high extractive content fuel like wood. Torrefaction has also been successful in increasing the heating value of the fuel with optimized torrefaction time and temperature. Hydrothermal carbonization with optimized carbonization temperature was very effective in the increasing density of biomass fuel which eventually led to an increase in heating value. Liquid hot water treatment has been effective in increasing heating value with a density increase of 16-25%.

Storage and transportation problems can be resolved by setting up an intermediate station close to the conversion station. A terminal site can also be set up for continuous upgradation of biomass fuel which would prevent its deterioration with time. An automatic system can be used which charges a penalty of over-storage of biomass leading to fire risk. For effective and economical transportation, mixed modes of transportation and transportation through pipelines can be used.

High-temperature corrosion is also one of the serious problems which can be significantly controlled by either replacing boiler tube material with superalloys or spraying of thermal coatings over boiler material. The type of coating with substrate material and operating conditions also govern the rate of high-temperature corrosion.

Biomass combustion has a promising future, considering these remedies are followed, as they have tremendous potential and also are beneficial, both economically and ecologically.

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References

Agüero, A., Baráibar, I., Gutiérrez, M., Hernández, M., Muelas, R., and Rodríguez, S. (2018). Biomass corrosion behavior of steels and coatings in contact with KCl/K₂SO₄ at 550° C under an oxy-fuel combustion atmosphere: a screening laboratory test. Surf. Coating. Technol. 350: 188–200.

- Altobelli, R., Cristina, M., and De Oliveira, L. (2013). Corrosion in biomass combustion: a materials selection analysis and its interaction with corrosion mechanisms and mitigation strategies. Corrosion Sci. 76: 6–26.
- Bai, J., Yu, C., Li, L., Wu, P., Luo, Z., and Ni, M. (2013). Experimental study on the NO and N₂O formation characteristics during biomass combustion. Energy Fuel. 27: 515–522.
- Bai, M., Reddy, L., and Hussain, T. (2018). Experimental and thermodynamic investigations on the chlorine-induced corrosion of HVOF thermal sprayed NiAl coatings and 304 stainless steels at 700° C. Corrosion Sci. 135: 147–157.
- Bala, N., Singh, H., and Prakash, S. (2009). High-temperature oxidation studies of cold-sprayed Ni–20Cr and Ni–50Cr coatings on SAE 213-T22 boiler steel. Appl. Surf. Sci. 255: 6862–6869.
- Barma, M.C., Saidur, R., Rahman, S.M.A., Allouhi, A., Akash, B.A., and Sait, S.M. (2017). A review on boilers energy use, energy savings, and emissions reductions. Renew. Sustain. Energy Rev. 79: 970–983.
- Bartels, M., Lin, W., Nijenhuis, J., Kapteijn, F., and van Ommen, J.R. (2008). Agglomeration in fluidized beds at high temperatures: mechanisms, detection and prevention. Prog. Energy Combust. Sci. 34: 633–666.
- Berlanga, C. and Ruiz, J.A. (2013). Study of corrosion in a biomass boiler. J. Chem. 2013: 272090.
- Bignal, K.L., Langridge, S., and Zhou, J.L. (2008). Release of polycyclic aromatic hydrocarbons, carbon monoxide and particulate matter from biomass combustion in a wood-fired boiler under varying boiler conditions. Atmos. Environ. 42: 8863–8871.
- Bradshaw, A., Simms, N.J., and Nicholls, J.R. (2013). Development of hot corrosion resistant coatings for gas turbines burning biomass and waste derived fuel gases. Surf. Coating. Technol. 216: 8–22.
- Brus, E., Öhman, M., Nordin, A., Boström, D., Hedman, H., and Eklund, A. (2004). Bed agglomeration characteristics of biomass fuels using blast-furnace slag as bed material. Energy Fuel. 18: 1187–1193.
- Brus, E., Öhman, M., and Nordin, A. (2005). Mechanisms of bed agglomeration during fluidized-bed combustion of biomass fuels. Energy Fuel. 19: 825–832.
- Cai, R., Ke, X., Huang, Y., Zhu, S., Li, Y., Cai, J., Yang, H., Lyu, J., and Zhang, M. (2019). Applications of ultrafine limestone sorbents for the desulfurization process in CFB boilers. Environ. Sci. Technol. 53: 13514–13523.
- Cho, S.H., Park, S.B., Lee, J.H., Hur, J.M., and Lee, H.S. (2012). Cyclic corrosion behavior of Ni-based superalloys in hot lithium molten salt. Oxid. Metals 78: 153–165.
- Coleman, K.E., Simms, N.J., Kilgallon, P.J., and Oakey, J.E. (2008). Corrosion in biomass combustion systems. Mater. Sci. Forum 595: 377–386.
- Corcoran, A., Marinkovic, J., Lind, F., Thunman, H., Knutsson, P., and Seemann, M. (2014). Ash properties of ilmenite used as bed material for combustion of biomass in a circulating fluidized bed boiler. Energy Fuel. 28: 7672–7679.
- Davidsson, K.O., Åmand, L.E., Steenari, B.M., Elled, A.L., Eskilsson, D., and Leckner, B. (2008). Countermeasures against alkali-related problems during combustion of biomass in a circulating fluidized bed boiler. Chem. Eng. Sci. 63: 5314–5329.

De Best, C.J.J.M., Van Kemenade, H.P., Brunner, T., and Obernbergert, I. (2008). Particulate emission reduction in small-scale biomass combustion plants by a condensing heat exchanger. Energy Fuel. 22: 587–597.

De Geyter, S., Öhman, M., Boström, D., Eriksson, M., and Nordin, A. (2007). Effects of non-quartz minerals in natural bed sand on agglomeration characteristics during fluidized bed combustion of biomass fuels. Energy Fuel. 21: 2663–2668.

Demirbaş, A. (2003). Sustainable cofiring of biomass with coal. Energy Convers. Manag. 44: 1465–1479.

Demirbaş, A. and Demirbaş, M.F. (2003). Biomass and wastes: upgrading alternative fuels. Energy Sources 25: 317–329.

Demirbas, A. (2005a). Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Prog. Energy Combust. Sci. 31: 171–192.

Demirbaş, A. (2005b). Heavy metal contents of fly ashes from selected biomass samples. Energy Sources 27: 1269–1276.

Demirbas, A. (2008). Hazardous emissions from combustion of biomass. Energy Sources, Part A Recovery, Util. Environ. Eff. 30: 170–178.

Demirbas, A. (2010). Fuels from biomass. Green Energy Technol. 26: 33–73.

Demirbas, T. and Demirbas, C. (2009). Fuel properties of wood species. Energy Sources, Part A Recovery, Util. Environ. Eff. 31: 1464–1472.

Fantozzi, D., Matikainen, V., Uusitalo, M., Koivuluoto, H., and Vuoristo, P. (2016). Chlorine-induced high temperature corrosion of Inconel 625 sprayed coatings deposited with different thermal spray techniques. Surf. Coating. Technol. 318: 233–243.

Fauchais, A. and Vardelle, P. (2012). Thermal sprayed coatings used against corrosion and corrosive wear. Adv. Plasma Spray Appl. 10: 34448.

Febrero, L., Granada, E., Regueiro, A., and Míguez, J.L. (2015). Influence of combustion parameters on fouling composition after wood pellet burning in a lab-scale low-power boiler. Energies 8: 9794–9816.

Fernández Llorente, M.J., Escalada Cuadrado, R., Murillo Laplaza, J.M., and Carrasco García, J.E. (2006). Combustion in bubbling fluidised bed with bed material of limestone to reduce the biomass ash agglomeration and sintering. Fuel 85: 2081–2092.

Flisberg, P., Frisk, M., Rönnqvist, M., and Guajardo, M. (2015). Potential savings and cost allocations for forest fuel transportation in Sweden: a country-wide study. Energy 85: 353–365.

Flodén, J. and Williamsson, J. (2016). Business models for sustainable biofuel transport: the potential for intermodal transport. J. Clean. Prod. 113: 426–437.

Frandsen, F.J. (2005). Utilizing biomass and waste for power production — a decade of contributing to the understanding, interpretation and analysis of deposits and corrosion products. Fuel 84: 1277–1294.

Gada, H., Mudgal, D., Parvez, S., and Ahmad, B. (2019). Investigation of high temperature corrosion resistance of Ni25Cr Coated and Bare 347H SS in actual husk fired boiler atmosphere. Eng. Fail. Anal. 108: 104256.

Gao, Y., Zhang, C., Xiong, X., Zheng, Z., and Zhu, M. (2012). Intergranular corrosion susceptibility of a novel Super304H stainless steel. Eng. Fail. Anal. 24: 26–32. Gautam, S., LeBel, L., and Carle, M.A. (2017). Supply chain model to assess the feasibility of incorporating a terminal between forests and biorefineries. Appl. Energy 198: 377–384.

Grimm, A., Skoglund, N., Boström, D., and Öhman, M. (2011). Bed agglomeration characteristics in fluidized quartz bed combustion of phosphorus-rich biomass fuels. Energy Fuel. 25: 937–947.

Grimm, A., Öhman, M., Lindberg, T., Fredriksson, A., and Boström, D. (2012). Bed agglomeration characteristics in fluidized-bed combustion of biomass fuels using olivine as bed material.
Energy Fuel. 26: 4550–4559.

Grosso, M., Diiar, M., and Rigamonti, L. (2009). *Experimental* assessment of N₂O emissions from waste incineration: the role of NO_x control technology. Turn. waste into ideas. ISWA/APESB World Congr. B, Milano, p. 311.

Gudka, B., Jones, J.M., Lea-Langton, A.R., Williams, A., and Saddawi, A. (2016). A review of the mitigation of deposition and emission problems during biomass combustion through washing pretreatment. J. Energy Inst. 89: 159–171.

Gupta, O.P., Mudgal, D., Puri, D., and Prakash, S. (2012). High temperature cyclic oxidation of Ni based superalloys at 900° C in air. Int. J. Adv. Sci. Res. Technol. 2: 486–492.

He, X., Lau, A.K., Sokhansanj, S., Lim, C.J., Bi, X.T., and Melin, S. (2014). Investigating gas emissions and dry matter loss from stored biomass residues. Fuel 134: 159–165.

Hearley, J.A., Liu, C., Little, J.A., and Sturgeon, A.J. (2016). Corrosion of Ni–Al high velocity oxyfuel (HVOF) thermal spray coating by fly ash and synthetic biomass ash deposits. Br. Corrosion J. 36: 111–120.

Hub, T.R.E. (2018). Biomass bioler types. The different types of biomass boilers, Available at: https://www.renewableenergyhub.co.uk/main/biomass-boiler-information/ biomass-boiler-types-the-different-types-of-biomass-boilers/> (Accessed 13 March 2021).

Hussain, T., Dudziak, T., Simms, N.J., and Nicholls, J.R. (2013). Fireside corrosion behavior of HVOF and plasma-sprayed coatings in advanced coal/biomass Co-fired power plants. J. Therm. Spray Technol. 22: 797–807.

Hussain, T., Simms, N.J., and Nicholls, J.R. (2014). Modelling fireside corrosion of thermal sprayed coatings in co-firing of coal/ biomass. Mater. Corros. 65: 197–205.

Hussain, T., Simms, N.J., Nicholls, J.R., and Oakey, J.E. (2015). Fireside corrosion degradation of HVOF thermal sprayed FeCrAl coating at 700–800° C. Surf. Coating. Technol. 268: 165–172.

James, A.K., Thring, R.W., Helle, S., and Ghuman, H.S. (2012). Ash management review: applications of biomass bottom ash. Energies 5: 3856–3873.

Jiamin, Y.I.N. and Zhansong, W.U. (2009). Corrosion behavior of TP316L of superheater in biomass boiler with simulated atmosphere and deposit. Chin. J. Chem. Eng. 17: 849–853.

Jiménez, S. and Ballester, J. (2007). Formation of alkali sulphate aerosols in biomass combustion. Fuel 86: 486–493.

Kalivodova, J., Baxter, D., and Schu, M. (2005). Gaseous corrosion of alloys and novel coatings in simulated environments for coal, waste and biomass boilers. Mater. Corros. 56: 882–889.

Kamal, S., Jayaganthan, R., Prakash, S., and Kumar, S. (2008). Hot corrosion behavior of detonation gun sprayed Cr₃C₂-NiCr coatings on Ni and Fe-based superalloys in Na₂SO₄-60% V₂O₅ environment at 900° C. J. Alloys Compd. 463: 358-372.

Kamal, S., Jayaganthan, R., and Prakash, S. (2010). High temperature cyclic oxidation and hot corrosion behaviours of superalloys at 900° C. Bull. Mater. Sci. 33: 299–306.

Kambo, H.S. and Dutta, A. (2014). Strength, storage, and combustion characteristics of densified lignocellulosic biomass produced via torrefaction and hydrothermal carbonization. Appl. Energy 135: 182–191.

Kassman, H., Pettersson, J., Steenari, B.M., and Åmand, L.E. (2013). Two strategies to reduce gaseous KCl and chlorine in deposits during biomass combustion – injection of ammonium sulphate and co-combustion with peat. Fuel Process. Technol. 105: 170–180.

Kaur, M., Singh, H., and Prakash, S. (2008). A survey of the literature on the use of high velocity oxy-fuel spray technology for high temperature corrosion and erosion-corrosion resistant coatings. Anti-Corrosion Methods Mater. 55: 86–96.

Kaur, M., Singh, H., and Prakash, S. (2009). High-temperature corrosion studies of HVOF-sprayed Cr₃C₂–NiCr coating on SAE-347h boiler steel. J. Therm. Spray Technol. 18: 619–632.

Kaur, M., Singh, H., and Prakash, S. (2012). High-temperature behavior of a high-velocity oxy-fuel sprayed Cr₃C₂-NiCr coating. Metall. Mater. Trans. A 43: 2979–2993.

Kaushal, G., Singh, H., and Prakash, S. (2011). Comparative high temperature analysis of HVOF-sprayed and detonation gun sprayed Ni–20Cr coating in laboratory and actual boiler environments. Oxid. Metals 76: 169–191.

Kaushal, G., Bala, N., Kaur, N., Singh, H., and Prakash, S. (2014). Comparative high-temperature corrosion behavior of Ni–20Cr coatings on T22 boiler steel produced by HVOF, D-gun, and cold spraying. Metall. Mater. Trans. A Phys. 45: 395–410.

Kawahara, Y. (2016a). An overview on corrosion-resistant coating technologies in biomass/waste-to-energy plants. Coatings 6: 34.

Kawahara, Y. (2016b). Controlling factors of localized corrosion in boiler. Oxid. Metals 85: 127–149.

Keipi, T., Tolvanen, H., Kokko, L., and Raiko, R. (2014). The effect of torrefaction on the chlorine content and heating value of eight woody biomass samples. Biomass Bioenergy 66: 232–239.

Khan, A.A., de Jong, W., and Spliethoff, H. (2005). Biomass combustion in fluidized bed boiler. In: *Bioenergy in wood industry*. FINBIO – The Bioenergy Association of Finland, Finland, pp. 365–370.

Khan, A.A., Aho, M., de Jong, W., Vainikka, P., Jansens, P.J., and Spliethoff, H. (2008). Scale-up study on combustibility and emission formation with two biomass fuels (B quality wood and pepper plant residue) under BFB conditions. Biomass Bioenergy 32: 1311–1321.

 Khan, A.A., de Jong, W., Jansens, P.J., and Spliethoff, H. (2009).
 Biomass combustion in fluidized bed boilers: potential problems and remedies. Fuel Process. Technol. 90: 21–50.

Kumar, S., Mudgal, D., Singh, S., and Prakash, S. (2013). Cyclic oxidation behavior of bare and Cr₃C₂–25 (NiCr) coated super alloy at elevated temperature. Adv. Mater. Lett. 4: 754–761.

Laboratory, B.E. (2011). Biomass properties and handling, Available at: <https://www.engineering.iastate.edu/brl/ files/2011/10/brl_biomassppop_instructor.pdf> (Accessed 13 March 2021). Lamberg, H., Sippula, O., Tissari, J., and Jokiniemi, J. (2011). Effects of air staging and load on fine-particle and gaseous emissions from a small-scale pellet boiler. Energy Fuel. 25: 4952–4960.

Liao, Y., Wu, S., Chen, T., Cao, Y., and Ma, X. (2015). The alkali metal characteristic during biomass combustion with additives. Energy Procedia 75: 124–129.

Lin, W., Dam-Johansen, K., and Frandsen, F. (2003). Agglomeration in bio-fuel fired fluidized bed combustors. Chem. Eng. J. 96: 171–185.

Liu, H., Chaney, J., Li, J., and Sun, C. (2013). Control of NO_x emissions of a domestic/small-scale biomass pellet boiler by air staging. Fuel 103: 792–798.

Liu, S., Liu, Z., Wang, Y., and Tang, J. (2014). A comparative study on the high temperature corrosion of TP347H stainless steel, C22 alloy and laser-cladding C22 coating in molten chloride salts. Corrosion Sci. 83: 396–408.

Llorente, M.J.F., Laplaza, J.M.M., Cuadrado, R.E., and García, J.E.C. (2006). Ash behaviour of lignocellulosic biomass in bubbling fluidised bed combustion. Fuel 85: 1157–1165.

Luo, W.W., De Liu, Z., Wang, Y.T., and Yang, R.J. (2012). High temperature corrosion behaviors of the superheater materials. Procedia Eng. 36: 212–216.

Mahajan, S. and Chhibber, R. (2019). Hot corrosion studies of boiler steels exposed to different molten salt mixtures at 950° C. Eng. Fail. Anal. 99: 210–224.

Mahesh, R.A., Jayaganthan, R., and Prakash, S. (2008a). Evaluation of hot corrosion behaviour of HVOF sprayed NiCrAl coating on superalloys at 900° C. Mater. Chem. Phys. 111: 524–533.

Mahesh, R.A., Jayaganthan, R., and Prakash, S. (2008b). A study on hot corrosion behaviour of Ni–5Al coatings on Ni- and Fe-based superalloys in an aggressive environment at 900° C. J. Alloys Compd. 460: 220–231.

Mahmoud, A., Shuhaimi, M., and Abdel Samed, M. (2009). A combined process integration and fuel switching strategy for emissions reduction in chemical process plants. Energy 34: 190–195.

Malladi, K.T. and Sowlati, T. (2017). Optimization of operational level transportation planning in forestry: a review. Int. J. For. Eng. 28: 198–210.

Malladi, K.T. and Sowlati, T. (2018). Biomass logistics: a review of important features, optimization modeling and the new trends. Renew. Sustain. Energy Rev. 94: 587–599.

Meißner, T.M., Grégoire, B., Montero, X., Miller, E., Maier, J., and Galetz, M. (2020). Long-term corrosion behavior of Cr diffusion coatings on ferritic-martensitic superheater tube material X20CrMoV12-1 under conditions mimicking biomass (co-) firing. Energy Fuel. 34: 10989–11002.

Melissari, B. (2017). Ash related problems with high alkali biomass and its mitigation- experimental evaluation. Mem. Invest. Ing. 12: 31–44.

Mishra, S.B., Chandra, K., and Prakash, S. (2014). Erosion–corrosion behaviour of nickel and iron based superalloys in boiler environment. Oxid. Metals 83: 101–117.

Mladenović, M., Paprika, M., and Marinković, A. (2003). Denitrification techniques for biomass combustion. Renew. Sustain. Energy Rev. 82: 3350–3364. Mlonka-Mędrala, A., Magdziarz, A., Kalemba-Rec, I., and Nowak, W. (2019). The influence of potassium-rich biomass ashes on steel corrosion above 550° C. Energy Convers. Manag. 187: 15–28.

Montero, X. and Galetz, M.C. (2019). Cr diffusion coatings on a ferriticmartensitic steel for corrosion protection in KCl-rich biomass cofiring environments. Corrosion Sci. 164: 108343.

Mudgal, D., Kumar, S., Singh, S., and Prakash, S. (2014a). Corrosion behavior of bare, Cr₃C₂-25%(NiCr), under molten salt at 900° C.
 J. Mater. Eng. Perform. 23: 3805-3818.

Mudgal, D., Singh, S., and Prakash, S. (2014b). Corrosion problems in incinerators and biomass-fuel-fired boilers. Int. J. Corrosion 2014: 505306.

Mudgal, D., Singh, S., and Prakash, S. (2014c). Hot corrosion behavior of bare, Cr₃C₂-(NiCr) and Cr₃C₂-(NiCr) + 0.2wt.% Zr coated SuperNi 718 at 900° C. J. Mater. Eng. Perform. 24: 1–15.

Mudgal, D., Singh, S., and Prakash, S. (2014d). Evaluation of ceria-added Cr₃C₂-25(NiCr) coating on three superalloys under simulated incinerator environment. J. Therm. Spray Technol. 24: 496–514.

Mudgal, D., Ahuja, L., Singh, S., and Prakash, S. (2017). Evaluation of corrosion performance of Superni 600 hung in secondary chamber of medical waste incinerator operating at 1050° C. Mater. A. T. High. Temp. 34: 45–52.

Naganuma, H., Ikeda, N., Ito, T., Matsuura, M., Nunome, Y., Ueki, Y., Yoshiie, R., and Naruse, I. (2013). Reduction mechanisms of ash deposition in coal and/or biomass combustion boilers. Fuel 106: 303–309.

Nawrot, T., Plusquin, M., Hogervorst, J., Roels, H.A., Celis, H., Thijs, L., Vangronsveld, J., Van Hecke, E., and Staessen, J.A. (2006). Environmental exposure to cadmium and risk of cancer: a prospective population-based study. Lancet Oncol. 7: 119–126.

Nielsen, H.P., Frandsen, F.J., Dam-johansen, K., and Baxter, L.L. (2000). The implications of chlorine-associated corrosion on the operation of biomass-fired boilers. Prog. Energy Combust. Sci. 26: 283–298.

Ohman, Anders and Nordin, M. (2000). Bed agglomeration characteristics during fluidized bed combustion of biomass fuels. Energy Fuel. 14: 169–178.

Oksa, M., Tuurna, S., and Varis, T. (2013). Increased lifetime for biomass and waste to energy power plant boilers with HVOF coatings: high temperature corrosion testing under chlorinecontaining molten salt. J. Therm. Spray Technol. 22: 783–796.

Oksa, M., Auerkari, P., Salonen, J., and Varis, T. (2014a). Nickel-based HVOF coatings promoting high temperature corrosion resistance of biomass-fired power plant boilers. Fuel Process. Technol. 125: 236–245.

Oksa, M., Varis, T., and Ruusuvuori, K. (2014b). Performance testing of iron based thermally sprayed HVOF coatings in a biomass- fired fluidised bed boiler. Surf. Coating. Technol. 251: 191–200.

Oksa, M., Metsajoki, J., and Karki, J. (2015). Thermal spray coatings for high-temperature corrosion protection in biomass co-fired boilers. J. Therm. Spray Technol. 24: 194–205.

Oksa, M., Metsajoki, J., and Karki, J. (2016). Corrosion testing of thermal spray coatings in a biomass co-firing power plant. Coatings 6: 65.

Olah, G., Goeppert, A., and Prakash, S.G.K. (2018). *Beyond oil and gas: the methanol economy*, 3rd ed. John Wiley & Sons, Germany, pp. 2636–2639. Parthiban, K.K. (2006). Chorline induced high temperature superheater corrosion in biomass power plants. Venus Energy Audit System, India.

Paul, S. and Harvey, M.D.F. (2013). Corrosion testing of Ni alloy HVOF coatings in high temperature environments for biomass applications. J. Therm. Spray Technol. 22: 316–327.

Peters, G.P., Andrew, R.M., Canadell, J.G., Friedlingstein, P., Jackson, R.B., Korsbakken, J.I., Le Quéré, C., and Peregon, A. (2020). Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. Nat. Clim. Change 10: 3–6.

Prakash, S., Puri, D., and Singh, H. (2005). Hot corrosion behaviour of plasma sprayed coatings on a Ni-based superalloy in Na₂SO₄-60% V₂O₅ environment. ISIJ Int. 45: 886–895.

Prashanth, L., Kattapagari, K.K., Chitturi, R.T., Ramana, V., Baddam, R., and Prasad, L.K. (2015). A review on role of essential trace elements in health and disease. J. Dr. NTR Univ. Health Sci. 4: 75–85.

Rana, N., Jayaganthan, R., and Prakash, S. (2014). Stepwise depletion of coating elements as a result of hot corrosion of NiCrAlY coatings. J. Mater. Eng. Perform. 23: 643–650.

Reddy, L., Shipway, P., Davis, C., and Hussain, T. (2017). HVOF and laser-cladded Fe–Cr–B coating in simulated biomass combustion: microstructure and fireside corrosion. Oxid. Metals 87: 825–835.

Rentizelas, A.A., Tolis, A.J., and Tatsiopoulos, I.P. (2009). Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew. Sustain. Energy Rev. 13: 887–894.

Rohr, A.C., Campleman, S.L., Long, C.M., and Peterson, M.K. (2015). Potential occupational exposures and health risks associated with biomass-based power generation. Int. J. Environ. Res. Publ. Health 12: 8542–8605.

Romeo, L.M. and Gareta, R. (2009). Fouling control in biomass boilers. Biomass Bioenergy 33: 854–861.

Runge, T., Wipperfurth, P., and Zhang, C. (2013). Improving biomass combustion quality using a liquid hot water treatment. Biofuels 4: 73–83.

Ruusuvuori, K., Holmstro, S., Tuurna, S., Varis, T., and Penttila, K. (2011). Optimised selection of new protective coatings for biofuel boiler applications. Mater. Corros. 62: 642–649.

Sadeghimeresht, E., Reddy, L., Hussain, T., Markocsan, N., and Joshi, S. (2017). Chlorine-induced high temperature corrosion of HVAF-sprayed Ni-based alumina and chromia forming coatings. Corrosion Sci. 132: 1–15.

Sadeghimeresht, E., Reddy, L., Hussain, T., Huhtakangas, M., Markocsan, N., and Joshi, S. (2018). Influence of KCl and HCl on high temperature corrosion of HVAF-sprayed NiCrAlY and NiCrMo coatings. Mater. Des. 148: 17–29.

Sage, E. (2019). Environmental impacts of biomass, Available at: <https://www.energysage.com/about-clean-energy/biomass/ environmental-impacts-biomass/> (Accessed 13 March 2021).

Saidur, R., Abdelaziz, E.A., Demirbas, A., Hossain, M.S., and Mekhilef, S. (2011). A review on biomass as a fuel for boilers. Renew. Sustain. Energy Rev. 15: 2262–2289.

Sami, M., Annamalai, K., and Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. Prog. Energy Combust. Sci. 27: 171–214.

Shabani, N. and Sowlati, T. (2013). A mixed integer non-linear programming model for tactical value chain optimization of a wood biomass power plant. Appl. Energy 104: 353–361. Sharpconsultant, S. (2011). Superheater corrosion in biomass boilers: today's science and technology, Available at: <https://info.ornl. gov/sites/publications/files/Pub32757.pdf> (Accessed 13 March 2021).

Sidhu, B.S. and Prakash, S. (2003). Evaluation of the corrosion behaviour of plasma-sprayed Ni₃Al coatings on steel in oxidation and molten salt environments at 900° C. Surf. Coating. Technol. 166: 89–100.

Sidhu, T.S., Prakash, S., and Agrawal, R.D. (2006). Hot corrosion performance of a NiCr coated Ni-based alloy. Scripta Mater. 55: 179–182.

Silvennoinen, J. (2019). A new method to inhibit bed agglomeration problems in fluidized bed boilers. Int. Conf. Fluidized Bed Combust. 36800: 377–385.

Singh, A., Sharma, V., Mittal, S., Pandey, G., Mudgal, D., and Gupta,
P. (2018). An overview of problems and solutions for components subjected to fireside of boilers. Int. J. Ind. Chem. 9: 1–15.

Singh, G., Goyal, K., and Bhatia, R. (2017). Hot corrosion studies of plasma-sprayed chromium oxide coatings on boiler tube steel at 850° C in simulated boiler environment. Iran. J. Sci. Technol. Trans. Mech. Eng. 42: 149–159.

Singh, H., Singh, B., and Prakash, S. (2006). The role of HVOF coatings in improving hot corrosion resistance of ASTM-SA210 GrA1 steel in the presence of Na₂SO₄-V₂O₅ salt deposits. Surf. Coating. Technol. 200: 5386–5394.

Singh, H., Puri, D., Prakash, S., and Ghosh, T.K. (2007). Hot corrosion of a plasma sprayed Ni₃Al coating on a Ni-base superalloy. Mater. Corros. 58: 857–866.

Singh, H., Singh, S., and Prakash, S. (2009). Applied surface science high temperature corrosion behaviour of some Fe-, Co- and Nibase superalloys in the presence of Y₂O₃ as inhibitor. Appl. Surf. Sci. 255: 7062–7069.

Singh, S., Sidhu, H.S., and Sidhu, B.S. (2012). Characterisation and corrosion-erosion behaviour of carbide based thermal spray coatings. J. Miner. Mater. Char. Eng. 11: 569–586.

Tock, J.Y., Lai, C.L., Lee, K.T., Tan, K.T., and Bhatia, S. (2010). Banana biomass as potential renewable energy resource: a Malaysian case study. Renew. Sustain. Energy Rev. 14: 798–805.

Uusitalo, M.A., Vuoristo, P.M.J., and Mäntylä, T.A. (2002). Elevated temperature erosion – corrosion of thermal sprayed coatings in chlorine containing environments. Wear 252: 586–594.

Uzun, H., Yıldız, Z., Goldfarb, J.L., and Ceylan, S. (2017). Improved prediction of higher heating value of biomass using an artificial neural network model based on proximate analysis. Bioresour. Technol. 234: 122–130.

Vassilev, S.V., Baxter, D., Andersen, L.K., and Vassileva, C.G. (2010). An overview of the chemical composition of biomass. Fuel 89: 913–933.

Visser, H.J.M. (2004). The influence of fuel composition on agglomeration behaviour in fluidised-bed combustion. Energy Res. Centre Netherlands ECN Biomass 44: 1–44.

Visser, H.J.M., Van Lith, S.C., and Kiel, J.H.A. (2008). Biomass ash-bed material interactions leading to agglomeration in FBC. J. Energy Resour. Technol. 130: 0118011–0118016. Vitázek, I., Klúčik, J., Mikulová, Z., and Vereš, P. (2016). Effects on concentration of selected gaseous emissions at biomass combustion. AIP Conf. Proc. 1768: 020022.

Wattananoi, W., Khumsak, O., and Worasuwannarak, N. (2011). Upgrading of biomass by torrefaction and densification process. Clean Energy Technol. 2011: 209–212.

Williams, A., Jones, J.M., Ma, L., and Pourkashanian, M. (2012). Pollutants from the combustion of solid biomass fuels. Prog. Energy Combust. Sci. 38: 113–137.

Wu, D., Dahl, K.V., Madsen, J.L., Christiansen, T.L., Montgomery, M., and Hald, J. (2018). Effects of different fuel specifications and operation conditions on the performance of coated and uncoated superheater tubes in two different biomass-fired boilers. ACS Appl. Energy Mater. 1: 1463–1475.

Wu, D.L., Dahl, K.V., Christiansen, T.L., Montgomery, M., and Hald, J. (2017). Microstructural investigations of Ni and Ni₂Al₃ coatings exposed in biomass power plants. Mater. A. T. High. Temp. 35: 255–266.

Wu, D.L., Dahl, K.V., Christiansen, T.L., Montgomery, M., and Hald, J. (2019). Corrosion behaviour of Ni and nickel aluminide coatings exposed in a biomass fired power plant for two years. Surf. Coating. Technol. 362: 355–365.

Xu, Y., Yang, K., Zhou, J., and Zhao, G. (2020). Coal-biomass co-firing power generation technology: current status, challenges and policy implications. Sustainability 12: 3692.

Yuan, L. and Wang, H.M. (2010). Hot corrosion behaviors of a $Cr_{13}Ni_5Si_2$ -based metal silicide alloy in $Na_2SO_4 + 25$ wt.% K_2SO_4 and $Na_2SO_4 + 25$ wt.% NaCl molten salts. Intermetallics 18: 324–329.

Yusuf, S. (2011). Environmental impacts of biofuels. ENERGY Educ. Sci. Technol. PART A-ENERGY Sci. Res. 26, Available at: https://avesis.ktu.edu.tr/yayin/2f27613f-006e-4639-9c9c-78a72d76aee2/environmental-impacts-of-biofuels (Accessed 13 March 2021).

Zabetta, E.C., Hupa, M., and Saviharju, K. (2005). Reducing NO_x emissions using fuel staging, air staging, and selective noncatalytic reduction in synergy. Ind. Eng. Chem. Res. 44: 4552–4561.

Zhang, L., Xu, C. (Charles), and Champagne, P. (2010). Overview of recent advances in thermo-chemical conversion of biomass. Energy Convers. Manag. 51: 969–982.

Zhang, X., Liu, H., Chen, T., Wang, G., Li, H., Hu, H., Yu, Y., and Yao, H. (2020). Application of coatings to alleviate fireside corrosion on heat transfer tubes during the combustion of low-grade solid fuels: a review. Energy Fuel. 34: 11752–11770.

Zhao, W., Liu, Y., Li, S., and Gong, S. (2014). Hot corrosion behavior of a Ni₃Al-based IC21 alloy in a molten salt environment. Oxid. Metals 81: 631–644.

Zhou, W., Zhou, K., Deng, C., Zeng, K., and Li, Y. (2016). Hot corrosion behaviour of HVOF-sprayed Cr₃C₂–NiCrMoNbAl coating. Surf. Coating. Technol. 309: 849–859.

Zhou, W., Zhou, K., Deng, C., Zeng, K., and Yuxi, L. (2017). Hot corrosion behavior of HVOF-sprayed Cr₃C₂–WC–NiCoCrMo coating. Ceram. Int. 43: 9390–9400.

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