Jagmeet Singh[1&2], Charanjit Singh[2], Davinder Singh[2], Khushdeep Goyal[2]

[1&2]Department of Mechanical Engineering, Chandigarh University, Mohali, Punjab, India, [2]Department of Mechanical engineering, Punjabi University Patiala, Punjab, India

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Corrosion challenges in high and low temperature systems: Mechanisms and thermal spray coating advances

ABSTRACT

Corrosion in boilers is now a major issue in thermal power generation industry, and it has a substantial effect on efficiency of equipments, maintenance expenses and life of the equipment. This study addresses the mechanisms of both high temperature and low temperature corrosion of boiler materials. The initiation of high-temperature oxidative attackis closely related to exposure to thetubes, deposition of slags and corrosive gases like H_2S and Cl_2 and causes severe degradation of water wall tubes and superheaters. The change in operating temperature would further promote the adventurous reactions between molten ash and sulphide species. Low-temperature corrosion generally arises from thecondensation of flue gases on colder surfaces like economizers and air preheaters, where sulphuric acid formation, alkali metal sulfates, deterioration of the oxide layer and thermal fatigue become more dominant below the dew point temperature. The situation is exacerbated by fly ash deposits that trap heat and tend to concentrate corrosive agents on the metal surface. Several of these have been investigated for corrosion protection using thermal spray technologies.Different types of thermal spray coatings have been investigated to overcome these problems. Coatings of CNT reinforced Cr_2O_3, Ni-based alloys and ZrO_2–Al_2O_3 composites have shown a very good resistance to corrosion and erosion under the harsh conditions of the boilers. These coatings are partly dependent on the deposition methods, including High-Velocity Oxy-Fuel (HVOF), Cold Spray processes and Atmospheric Plasma Spraying (APS). The developments of recent years with the use of nanoparticles and hydrophobic additives have further enhanced the durability of coatings and protection capabilities in harsh operating conditions. The application of advanced thermal spray coating material and optimized operation parameters to inhibit boiler corrosion, prolong the service life and increase the reliability of power generation equipment is highlighted in this study.

***Keywords**: Low Temperature Corrosion, High Temperature Corrosion, Thermal Spray Coatings, Material Protection*

1. INTRODUCTION

The heat or temperature rise in the majority of industries like electric power generation, gas turbines, aerospace, heat-treating, and mineral processing are more than 400°C. For such processes, an understanding of elevated temperature Effective corrosion control is imperative to ensure the reliability and efficiency of the material used [1]. It is damaging materials in the form of corrosion and significantly limits the operational lifetime of the majority of components.

*Corresponding author: Jagmeet Singh
E-mail: er.jagmeetdhaliwal@gmail.com
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It also has a tendency to limit the range of safe exposure conditions that can be utilized without compromising the integrity of the materials involved. Such limitations may lead to increased maintenance expenditure and decreased efficiency in power generation [2]. Sulfidation and hot corrosion types are the primary mechanisms by which high-temperature corrosion disrupts alloy performance in aggressive environments [3]. Temperature variations affect how steel corrodes. It identifies that temperature is an important factor and potentially influences the extent and speed of corrosion. The study intends to explore the correlation between the two factors under different conditions of temperature [4]. Over 400°C, elevated-temperature corrosion in hot gas settings is accompanied by a chemical reaction. Low-temperature corrosion is typically electrochemical in water environments. Corrosion attack includes thinning, degradation, erosion-corrosion, and embrittlement [5]. Corrosion occurs at elevated and low temperatures with significant rates in low oxygen potential environments, especially below 400°C due to aggressive oxidants like sulfur and chlorine.

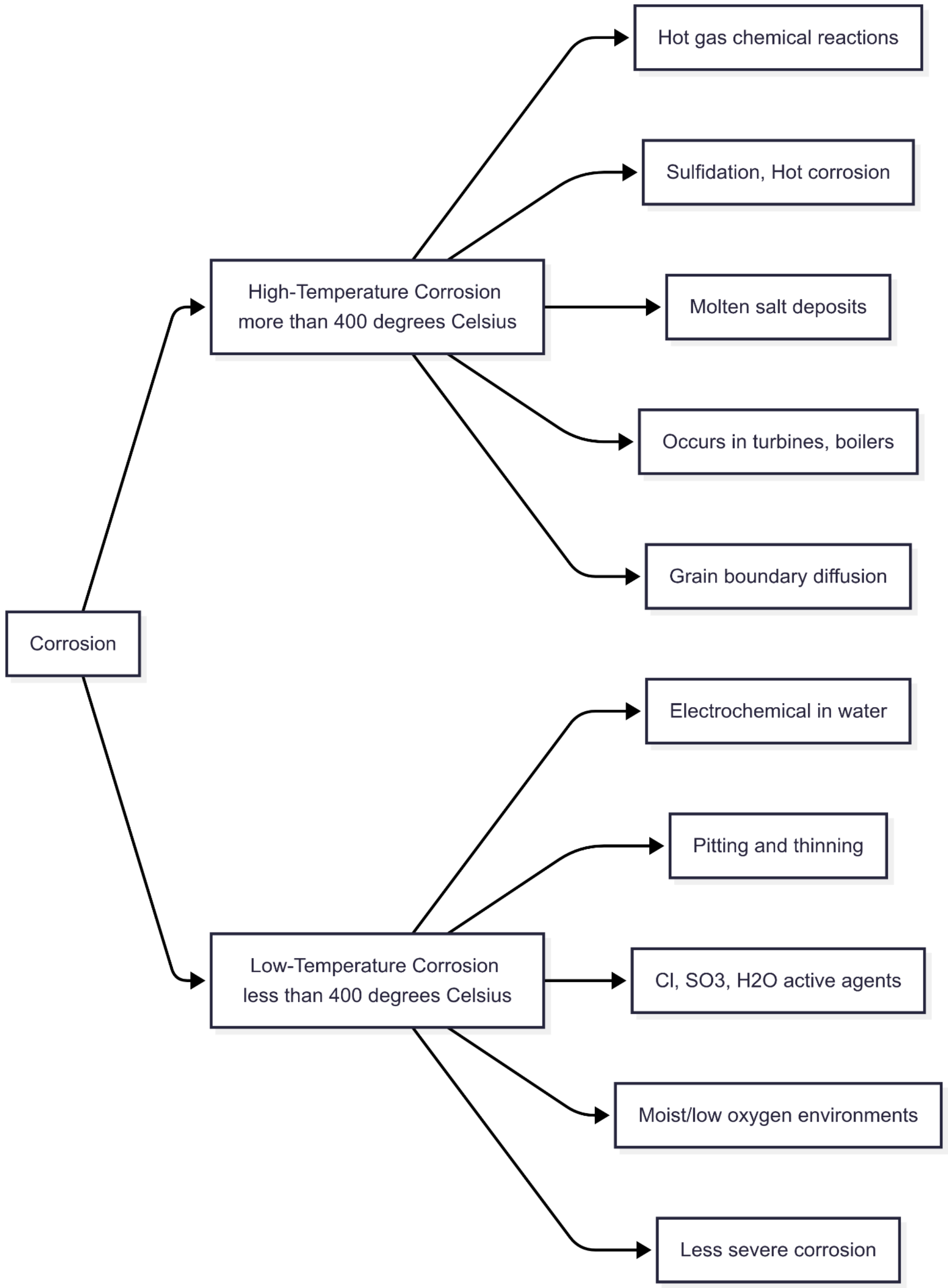

Figure 1. Corrosion at low and high temperature

High temperature hastens corrosion, particularly in coal burning and gasification processes [6]. High-temperature corrosion occurs rapidly in sulfur-bearing gases with high reaction rates, while low-temperature corrosion rates are low and of minor practical significance. Grain boundary diffusion is a significant process in both temperature ranges. High-temperature corrosion consists of complex interrelated processes [7]. Corrosion is one of the main causes of boiler failure, which can cost up to crores of rupees in lost production. Since it takes four days to identify and diagnose them, corrosion significantly disrupts plant operation. The reaction of corrosive species with metals and volatile oxides and the formation of material damage takes place [8]. When the temperature is high, the impurities in the salt will react and deposit a molten layer which will break the protective coating layer [9]. The phenomenon is primarily caused by the use of inferior fossil fuels because the high sulfur concentration in low-grade fuel combines with sodium to produce sodium sulfide, sodium carbonate and sodium acetate in the combustion process. When further reacts, this event causes depletion of Cr from the material at high temperatures (850°C to 950°C). A certain percentage of the fossil fuel oxidizes to SO_3. Sulphur trioxide (SO_3) combines with NaCl to form Na_2O_4, causing localized pitting attack. This type of corrosion is developed at short temperatures (650°C to 800°C) [10].

1.1. High temperature corrosion

The elevated temperature corrosioncontaining extreme heat, ash deposition, and corrosive flue gassessignificantly intensify material degradation [11]. It emphasizes that the corrosion process is predominantly dependent on two critical factors: the heat distribution along the furnace wall tubes and the concentration of hydrogen sulfide (H_2S). It is concluded that the rate of corrosionis exponentially comparative to the tube temperature, indicating a strong association between the tube temperature as well as the level of corrosion [12]. High-temperature corrosion, in conjunction with slag deposition, is a major problem as it reduces the thermal efficiency and reduces boiler life, resulting in high maintenance expenses and economic losses [13]. In addition, high temperature corrosion is the most challenging obstacle for improving the steam parameters in waste fired boiler because it adversely affects the efficiency and maintenance requirement in WTE plants [14]. In particular lead (Pb) is detected in the corrosion layers, where it is assumed to form lead sulfide (PbS) and is thus seen as an important corrosion promoter, indicating elevated temperature outlet gas condensation on the water wall tubes [15]. The paper also highlights problems in the components of the boilers due to the variation in temperature and pressure that are responsible for creep/ fatigue phenomenon. These mechanical stresses combined with corrosion, drastically reduce the durability of parts of the boiler [16]. High temperature corrosion is a phenomenon of corrosion that is caused by high temperature and chemically aggressive environments that results in degradation of the boiler material and reduction of boiler strength and performance [17].

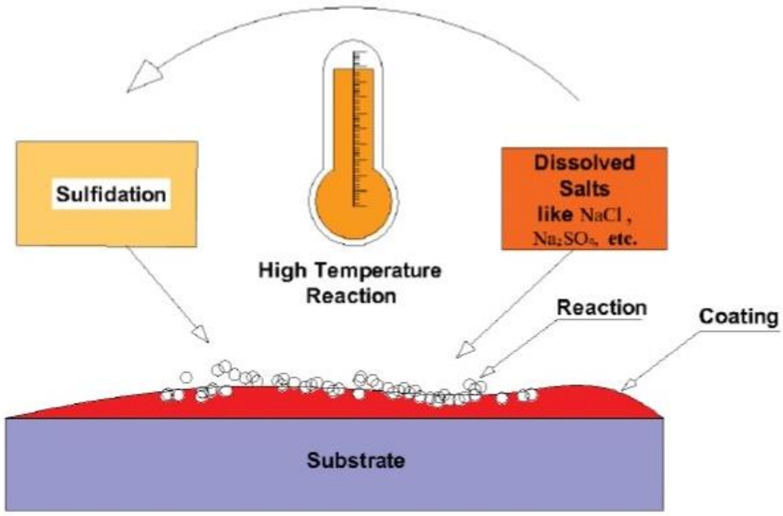

Figure 2. Hot Corrosion mechanism

This type of corrosion depends on the temperature and length of exposure and is a problem to the material's structural integrity. The authors reference models that exist to describe how surface layers are damaged and their growth over time [18]. Generally, corrosion in steam boilers mainly affects hot structural materials, which, under the condition of high sulfur and chlorine, erode severely due to the oxidation of the metal surface, thus requiring better protection of the surface and surface mechanical strength of the structural parts [19]. The study also mentions the problems arising from the aggressive chemical attacks on metals and alloys when they come into contact with molten salts and other reactive materials [20]. Hot corrosion is an important industrial problem that is associated with elevated temperatures and oxidizing media, frequently aggravated by the buildup of a molten salt or ash film on the metal's surface that leads to significant degradation of the metal's surface [21]. Additionally, high-temperature corrosion is exacerbated by the use of low-nitrogen burners and staged air systems, which elevate concentrations of CO and H_2S. Elevated wall temperatures, especially under cyclic boiler loading, intensify corrosion at the water wall tubes [22]. In the combustion of eucalyptus biomass, heat-induced deposits on heater surfaces, along with alkali and chlorine reactions, form complex layered structures that hinder heat transfer and overall efficiency [23].

1.2. Low temperature corrosion

Low-temperature corrosion (LTC) substantially impact the efficiencyand lifespan of industrial machinery, particularly in power generation, biomass burning, and desalination operations. Low-temperature corrosion in biomass-fired boilers results from acidic fumes condensation and hygroscopic salt deposition, such as $CaCl_2$ and K_2ZnCl_4, and this in turn causes repetitive failure of heat exchanger surfaces [24]. When biofuel boiler plants have low feed water temperatures (less than 100°C), aqueous phases stabilised by dissolved salts occur, which causes considerable corrosion on the low-temperature side. Salts such as $ZnCl_2$ and $CaCl_2$ were shown to be corrosion-critical, with critical relative humidity values ranging from 5 to 18% [25]. The enriched alkali and chlorine contentof biomass and oil shale raises concerns about low-temperature corrosion, despite the fact that circulating fluidised bed combustion (CFBC) effectively uses a variety of solid fuels. Fuel flexibility is increased by cofiring with retort gas, but the dangers of fouling, slagging and low-temperature corrosion are also increased [26]. SO_3 generated in flue gases is chiefly responsible for low-temperature boiler corrosion, which is produced when SO_2 oxidises or when fuel-bound sulphates break down. The existence of atomic oxygen and reaction conditions are two of the many variables that affect the oxidation process. Research indicates that SO_3 contributes significantly to low-temperature corrosion and deposit development by reacting with water vapour to create corrosive sulphuric acid [27].

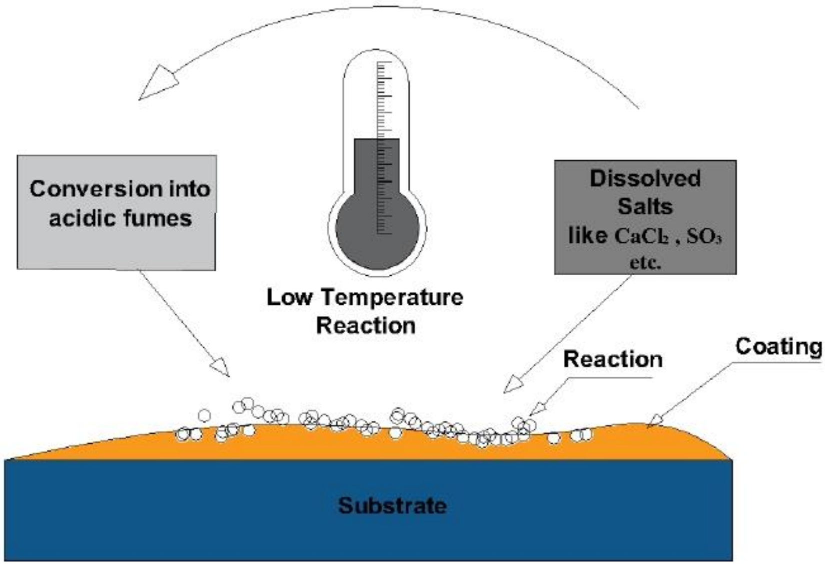

Figure 3. Low temperature corrosion

Flue gas desulfurization (FGD) systems must be optimized with respect to material selection and process design to counteract corrosion. pH and chloride concentration were determined to have significant effects on corrosion resistance and system cost-effectiveness overall [28]. In oil shale CFB boilers, LTC is caused by sub-dew point flue gas temperatures (55–80°C), generating acidic condensate on air preheater tubes. Protective coatings and dew point monitoring are advised to prevent damage [29]. Low-temperature desalination corrosion entails crevice and impingement corrosion at the initial stages in titanium and 904L alloys. Anodic protection and replacement of Cu-Ni tubing [30]. In seawater distillation facilities, lower operating temperatures were employed to minimize corrosion and scaling rates, which led to more effective and less complex plant design [31]. Studies on steel in reinforced concrete established that temperatures below decrease the resistivity and retard the rate of the cathodic reaction, relevant to civil structures exposed to thermal conditions [32]. High-calcium coal utility boilers were discovered to experience more critical ash-fouling problems under lower temperatures. Predictive modeling and sampling were advocated in the study to comprehend and avoid such problems [33]. Wet-process flue gas desulfurization system corrosion, particularly in coal-fired power plant reheaters, necessitates specially tailored material solutions because of the intricacy of secondary corrosion effects [34]. While concentrating mainly on nuclear reactor systems, studies on flow-accelerated and environmentally-assisted corrosion in carbon and low-alloy steel provide useful information on the mechanisms involved that are relevant to LTC conditions [35] . In combined heat and power plants fueled by biomass, iron chloride deposits were responsible for causing severe corrosion close to dew points, and air leaks in air preheaters exacerbated the situation [36].

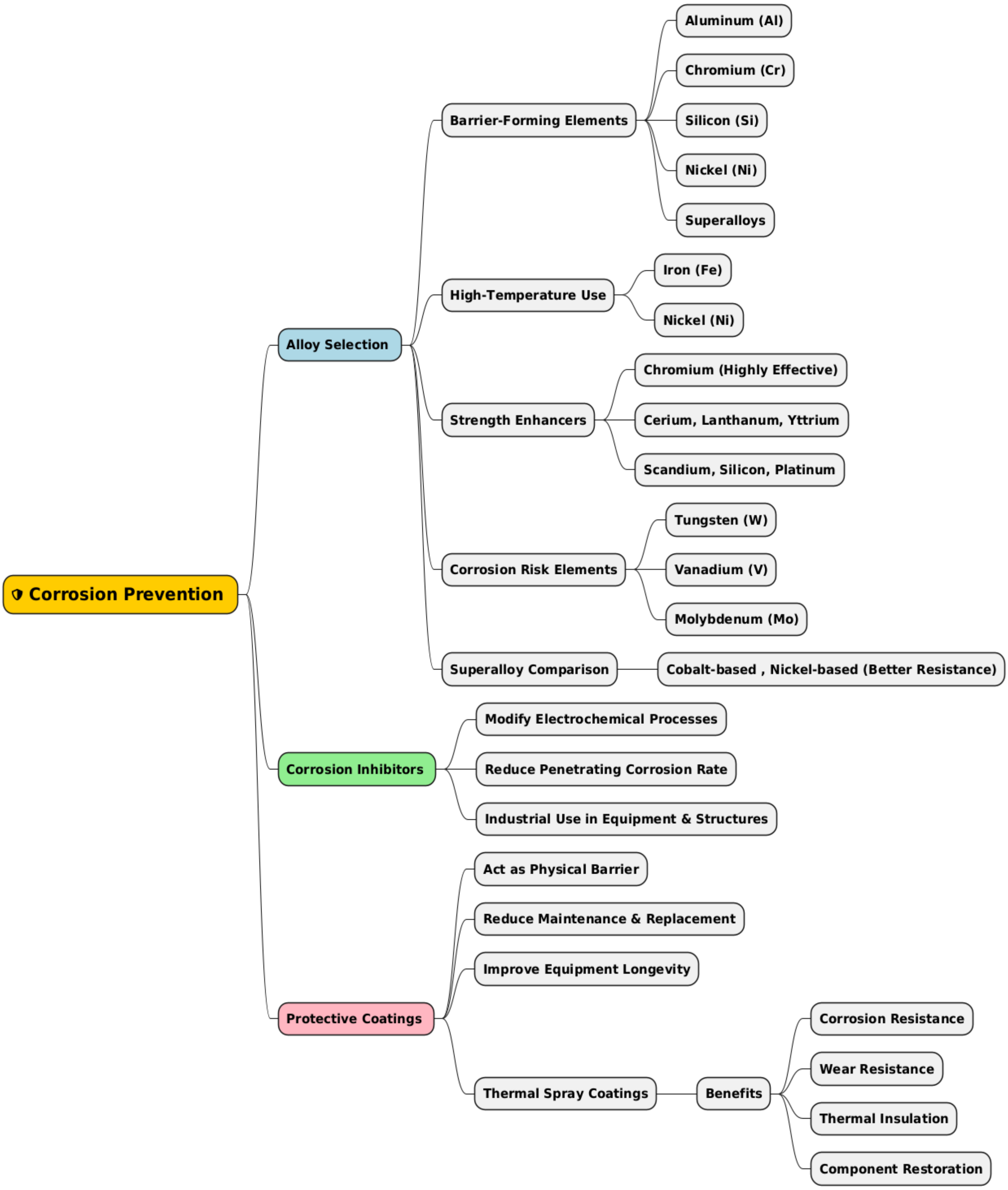

Figure 1. Corrosion prevention methods

Zirconium and Zircaloy-2 exhibited temperature, electrode potential, and pH-dependent corrosion behavior. Although not particularly pertinent to thermal power plants, they contribute to general knowledge regarding temperature-dependent corrosion [37]. Boiler preheaters are susceptible to condensation, corrosion, and ash clogging, particularly at the outer wall of the low-temperature section, reducing their service life and efficiency [38]. A detailed examination of low-temperature corrosion in solid waste and biomass furnacesdemonstrated that chlorine played a dominant role in the corrosion process[39]. Overall, prevention of low-temperature corrosion by material selection, protective coatings, and optimization of operating practices is essential to improve the lifespan and efficiency of the boiler systems in coal power plants1.3.Prevention measures

A number of active and passive measures are suggested to curb the material corrosion because of overly corrosive conditions. Al, Cr, Si and Ni as well as other superalloys tend to form a barrier against corrosion, with iron and nickel most commonly found in high-temperature applications. In addition, while superalloys improve mechanical properties, some like tungsten, vanadium, and molybdenum may further increase the rate of corrosion through hot corrosion [40]. On the other hand, chromium is highly effective, while cerium, lanthanum, yttrium, scandium, silicon, and platinum also enhance the overall strength of superalloys towards corrosion. Cobalt-based superalloys are especially known to have better resistance to corrosion when compared to nickel-based superalloys. For metals, corrosion inhibitors are crucial to achieve proportionality and regulate the degree of penetration of corrosion by altering electrochemical processes. These inhibitors are used to control the rate of penetration of corrosion of a metal. They have universal applications in various industries for the protection of equipment, structures, and other components.

By acting as a barrier between metals and the corrosive atmosphere, protective coatings tend to prevent or reduce corroding processes and easily control the rate of corrosion. Used widely across industries, these coatings further limit the needed maintenance and replace more traditional protection strategies, which greatly enhance the longevity of all equipment. Of those, thermal spray coatings include depositing of materials like metals, ceramics and polymers on surfaces of a substrate. The advantages of these coatings are numerous: They are corrosion resistant; They have better anti-wear properties; They provide a high level of thermal insulation; They are used to repair parts that are damaged or worn.

Latest Thermal Spray Coatings Cr_2O_3 coatings reinforced with CNTs have very high levels of protection against hot corrosion in high-temperature applications, which is very promising for thermal power plants [41]. As can be seen from the research, there is a definite trend: Increasing CNT content in the composite coating leads to corrosion rate is found to significantly decrease. This not only means an improved protection level, but also a longer life span of the boiler tube in extreme thermal conditions [42]. Epoxy and epoxy phenolic resin coatings also exhibited high corrosion resistance in steel and aluminum in various corrosive environments [43]. For low alloy steels, a number of corrosion-resistant coatings have been investigated and studied extensively, including their fabrication techniques, advantages and applications [44]. The advanced coating technologies such as hybrid coatings, thermal spray techniques and surface engineering technologies have proven to be highly effective, particularly in marine, biomedical and industrial applications, to overcome the wear-caused corrosion phenomenon (also known as “tribo-corrosion”) [45-46]. Some novel methods include the sulfur-selenium alloy coatings which have shown outstanding corrosion resistance with steel up to 99.9% protection level [47]. Combined first-principles and Multiphysics modelling have also been used to successfully explore the corrosion confrontation of Zirconium converted coatings for aluminum alloys [48]. TiSiN and ZrN coatings on CoCrMo alloys have also been shown to provide excellent resistance to fretting corrosion in biomedical applications, with no detrimental release of metal ions [49]. Likewise, sol-gel coatings on steel demonstrate that hydrolysis or condensation parameters are very critical to the anticorrosion properties of these coatings [50]. The incorporation of poly (arylene ether nitrile) in epoxy matrices significantly improved mechanical properties as well as corrosion protection, which indicates an interesting strategy for improving epoxy-based coatings for industrial applications [51]. Moreover, the hydrophilic to hydrophobic conversion of hybrid epoxy coatings results in the outstanding corrosion resistance of the coating structure by the introduction of long carbon chains and C–F bonds [52].

A noticeable improvement in the corrosion resistance of Q235 carbon steel has been achieved by adding CeO_2 and benzotriazole (BTA) to the epoxy resin matrix. Various experimental methods confirmed that composite epoxy formulation showed excellent protection performance [53]. It was found that Inconel 625 coating on steel performed better in erosion–corrosion resistance than Inconel 718-coated steel under actual boiler environments [54]. Likewise, NiCrTiCRe coatings that were cold sprayed were found to be useful against erosion–corrosion of T22 boiler steel as compared to HVOF coatings, proving their usefulness in the thermal power plant infrastructure [55].

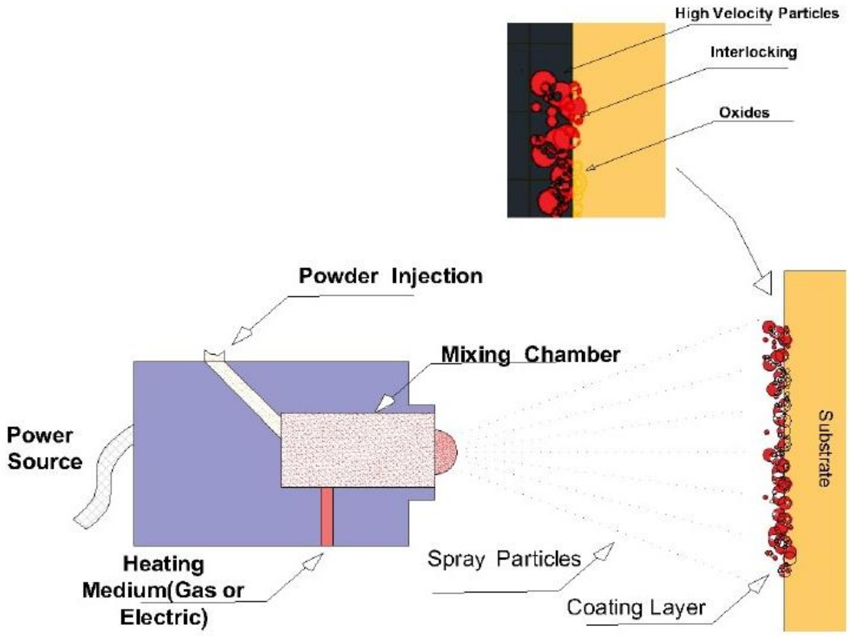

Figure 5. Illustrated View of Thermal Spray Coating

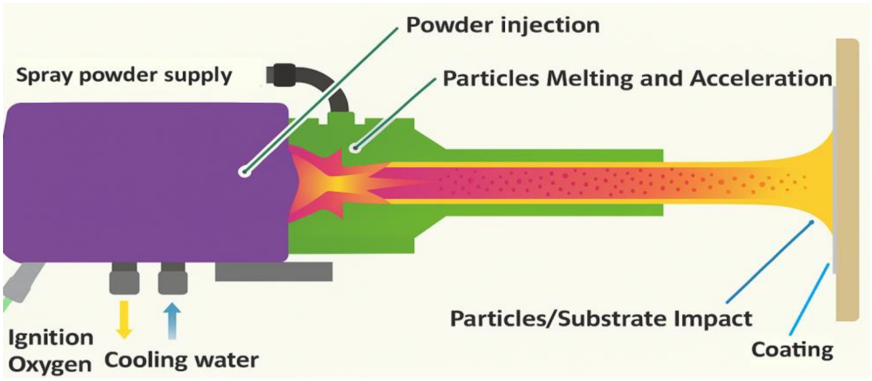

Figure 6. Schematic view of HVOF

Comparative tests have been carried out between dissimilar thermal spray approaches, like Cold Spray, High-Velocity Oxygen Fuel (HVOF), Atmospheric Plasma Spray (APS), and Detonation-Gun (D-gun) methods and it has been found that the selection of the method is a crucial parameter controlling the corrosion and oxidation confrontation of Ni and Fe based alloy coatings [56]. More importantly, CNT reinforced coatings are known to augment the strength of components in unkind environments and are effective to mitigate hot corrosion damage [57]. Also, better corrosion protection has been reported for Al_2O_3 coatings enriched with ZrO_2, and the more ZrO_2 the better the protection [58]. The investigations of detonation-sprayed coatings and HVOF show that protective oxide scales (mostly consisting of nickel and chromium) are formed under high temperatures. These oxide scales are effective corrosion barriers and support the configuration of stable corrosion protective layers. The analysis concludes that thermal spray Coatings are indispensable for enhancing the durability of industrial equipment subjected to high temperature and chemically aggressive environments, which results in increased operational life and efficiencies of such equipment, as in the case of gas turbines and superalloy parts [59].

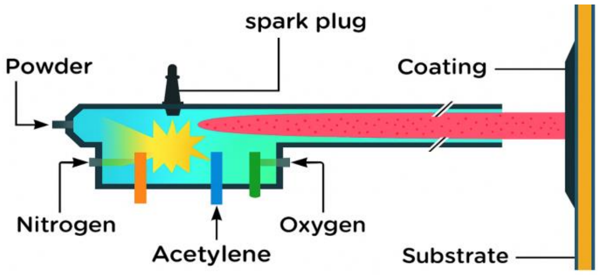

Figure 7. Illustration of the detonation spray system

2. EXISTING EXPERIMENTAL PARADIGM

From the above discussion, it can be concluded that the addition of Y_2O_3 as reinforcement suppresses hot corrosion deteriorationby using Cr_2O_3-based composite coatings at high temperatures, as recommended by Singh et al. [60]. The coating was obtained in the salt bath Na_2SO_4 – $60V_2O_5$ wt.%, which is characterized by the lowest corrosion amount and highest corrosion resistance. On comparison, the coated specimen was found to show a corrosion reduction of 85.58% as associated to the uncoated sample. The alumina-titanium composite coatings with CNTs showed higher corrosion confrontation than alumina coatings exposed to industrial boiler atmospheres, which was confirmed by Goyal et al. [61]. The developed CNT-reinforced Al_2O_3–TiO_2 coating showed only 7.33% abrasive wear, which was attributed to the dense structure of the CNT to reduce the porosity and raise the surface hardness. Additionally, Goyal et al. [62] applied the use of CNTs in composite coatings to improve its low porosity and high hardness because of its uniform distribution in the Cr_2O_3 matrix. With the addition of CNTs, lower porosity and higher hardness were observed, as CNTs acted as a chemical reinforcement in the spraying process.

The HVOF sprayed Cr_3C_2–NiCrMoNbAl coatings were found to be highly resistant to heat corrosion by Zhou et al. [63]. These coatings exhibited the improved deposition efficiency and lesser porosity, and smoothest coating layer (1.2%) than Cr_3C_2. Bolelli et al. [64] examined the wear performance of Tribaloy-700 (Mo–15%, Ni–32%, Cr–3%Si) and HVOF applied Tribaloy-800 (Co–28%, Mo–17%, Cr with 3%Si) on 100Cr6 steel and sintered Al_2O_3. It was observed that these coatings had enhanced solidity and adjustablility after 1-hour heat treatment at 600 °C. Sidhu et al. [65] conducted study on 93(WC–Cr_3C_2)–7Ni and 83WC–17Co HVOF coatings on T-22 and T91 boiler steels, respectively, and exposed the coatings for 10 cycles in the actual boiler environment. The hot corrosion resistance of T91 was better with 93(WC–Cr_3C_2)–7Ni coating than other specimens. Sundaresan et al. [66] treated T91 steel with Ni–Co–Cr–AlY coatings produced using APS and D-Gun sprays and determined that the coatings formed by the D-Gun spray were more corrosion resistant because they had a lower porosity and were dense and rough. Sidhu et al. [67] applied $75Cr_3C_2$–25NiCr, 93(WC–Cr_3C_2)–7Ni, 86WC–10Co–4Cr, and 83WC–17Co coatings to ASME SA213 T91 steel using HVOF. The 93(WC–Cr_3C_2)–7Ni coating had the highest corrosion resistance, followed by $75Cr_3C_2$–25NiCr, which was more corrosion resistant than uncoated samples at 900 °Cover 10 cycles. Qi et al. [68] evaluated abrasive wear resistance of Ni-based matrix coatings with TiC reinforcement.

Nanostructured TiC phases provided superior wear resistance compared to microstructured ones. Singh et al. [69] applied aluminum oxide coatings via plasma spraying on ASME SA213 T-22 boiler steel at 850 °C. Using a SiC tube furnace and a 40% V_2O_5–60% Na_2SO_4 salt mix, Cr_2O_3 plasma-coated specimens showed higher corrosion resistance than untreated ones. Chatha et al. [70] evaluated coatings of $75Cr_3C_2$–25NiCr and Ni–20Cr alloys at 900 °C, determining that Ni–20Cr coatings on steel resisted Cr_2O_3 corrosion better. In coal-fired boiler atmospheres, Ni–Cr coatings enhanced corrosion protection, high-temperature oxidation, and degradation resistance. Sidhu et al. [71] applied Ni- and Co-based coatings on boiler tube steel at 755 °C. Ni–20Cr coatings increased resistance, with Stellite-6 on Gr-Al substrate achieving the highest corrosion resistance (92.2%), reducing porosity and improving microstructure. Raza et al. [72] explored coating parameters and found that optimizing spray distance, oxygen flow rate, and material type improved coating density and heat resistance under harsh conditions. Bolelli et al. [73] compared two TiC–Fe–Cr–Al coatings on stainless steel using HVOF. Samples with oxygen flow rates of 214 SLPM and 188 SLPM had thicknesses of 307 µm and 520 µm, respectively. The coatings exhibited significant hardness and strong substrate adhesion, making them suitable for wear resistance. Vignesh et al. [74] optimized HVOF parameters for iron-based amorphous metallic coatings. The resulting coatings had reduced porosity, higher hardness, and enhanced protection against wear and corrosive attack. Picas et al. [75] investigated the in-flight particles generated during HVOF spraying and their influence on WC–Co–Cr coating, as a function of O/F ratio. Particle velocity and temperature were also greatly affected, influencing final coating characteristics.

Overall, 93(WC–Cr_3C_2)–7Ni and CNT–Al_2O_3–TiO_2 provide a good performance across a number of parameters, with Y_2O_3–Cr_2O_3 having a moderate performance, with good hardness and corrosion protection.

2.1. Current thermal spray techniques for corrosion protection

Thermal spray coating technology has appeared as a reliable solution to protect industrial parts subjected to severe environments like high temperature, corrosion, erosion, and oxidation. The coatings are extensively applied in the aerospace sector, the marine and offshore industry, steel sector, hydrogen fuel cells and boilers to improve the durability of surfaces and prolong their service life. The following thermal spray processes are commonly used due to their ability to form coatings with high bonding strength, low porosity and corrosion and wear resistance: Flame spraying, electric arc spraying, plasma spraying, Atmospheric Plasma Spraying, Vacuum Plasma Spraying, Cold Spraying, Detonation Gun Spraying, HVOF, and HVAF processes. [76-77]. HVOF and HVAF coatings are highly preferred as they provide high oxide content, low thermal damage on coating and are more dense in microstructure, whereas cold spray coatings are preferred as they have low temperature process for coating which does not result in high oxidation or thermal damage during coating [78-79].Thermal spray coatings are also increasingly used in hydrogen fuel cells and water electrolysis systems, where APS, VPS, and HVOF coatings help improve corrosion resistance and electrical conductivity of bipolar plates [80]. In high-temperature environments, coatings such as WC–Co, WC–CoCr, and Cr_3C_2–NiCr provide excellent resistance against hot corrosion, oxidation, and erosion in boilers and aero-engine components [81-82].

In addition, the iron and steel industry uses thermal spray coatings to reduce surface degradation and replace environmentally harmful hard chrome plating methods with safer and more efficient alternatives [83]. Recent advancements such as nanostructured coatings, duplex coatings, AI-based process optimization, and Industry 4.0 monitoring systems have further improved coating performance, quality control, and long-term reliability [84-85]. Overall, thermal spray coatings offer a promising and sustainable approach for protecting industrial components against severe corrosive attack and thermal deterioration in modern engineering applications.

Table 1. A summary of corrosion studies on different methods and temperature range

S.no	Material	Methods	Brief Summary
1	AISI 4140	Twin Wire arc sprayed	Ni-Al/Ni-20Cr coating improved oxidation & erosion resistance; AISI 4140 showed better performance.[86]
2	SS 316L	HVOF vs. APS sprayed NiCrBSiFe	HVOF coatings showed superior steam oxidation resistance due to thickness/density; APS failed under aging.[87]
3	T22 BS	Cr-Ni alloy coating	Nickel coatings resist abrasion, erosion, and high-temp corrosion; widely used in power gen.[88]
4	Boiler Steel	Thermal Spray Technique	Analyses nickel-based coatings' resistance to oxidation/erosion at high temperature.[89]
5	2.25Cr-1Mo steel	CeO_2 coating	CeO_2 improves corrosion resistance in oxidation-sulphidation environments due to scale plasticity and adhesion.[90]
6	Low alloy & mild steel	NiCr coating (0.2–0.25 mm) in molten salt (750°C), SEM/EDX analysis	NiCr coating enhanced resistance against high-temp corrosion at 750°C. [91]
7	Mild steel	NiCr coating of varying thickness, hot corrosion testing	NiCr coating improved hardness and reduced oxidation; thicker coatings performed better.[92]
8	AISI 422 steel	NiCr coatings (varied thickness), tested in $Na_2SO_4$and 60%V_2O_5 at 600–900°C	NiCr coatings improved corrosion resistance; thinner coatings performed better.[93]
9	T22 and 347H boiler steels	Cr_3C_2–NiCr coating via detonation gun, tested under exposure to molten salt (Na_2SO_4–$Fe_2(SO_4)_3$)	Cr_3C_2–NiCr coating formed protective oxides, enhancing corrosion resistance.[94]
10	ASTM A213 TP347H boiler steel	HVOF-coated Ni-20Cr and Ni-50Cr alloys tested at 700°C	Ni-50Cr is better corrosion confrontation compare to Ni-20Cr under high-temp conditions.[95]

11	Boiler tube steel	Cr_3C_2–NiCr coatings, tested in molten salt at 900°C	Some Cr_3C_2–NiCr coatings formed protective layers, improving hot corrosion resistance.[96]
12	T22 & 347H boiler steels	HVOF-sprayed Ni-20Cr, lab tests under thermal conditions	NiCr coatings enhanced oxidation resistance; 347H showed max protection.[97]
13	Boiler tube steels	LPG-assisted HVOF NiCr wire spray, molten salt exposure	NiCr coatings prevented spalling, reduced corrosion via oxide scale formation.[98]
14	Boiler tube steels	HVOF-sprayed CrC-Ni,WC	WC-CrC-Ni coatings formed diffusion barriers; tungsten/chromium carbides sustained strength.[99]
15	347H SS	Ni25Cr coating tested in husk-fired boiler	75Ni25Cr coating provided strong protection at ~750°Cover 150 hrs vs. uncoated steel.[100]
16	Low alloy & mild steel	NiCr and WC coatings via various thermal spray techniques	NiCr coatings resist hot corrosion in aggressive environments; high hardness and corrosion resistance.[101]
17	Mild steel	Nickel aluminide via pack cementation with rare earths	Ni aluminide coatings improved oxidation resistance; rare earths further enhanced performance.[102]
18	Low alloy & mild steel	HVAF-sprayed NiCr, NiAl, NiCrAlY coatings	NiAl and NiCrAlY showed strong corrosion resistance in biomass/waste-fired boiler use.[103]
19	Boiler steel (T22, SA516)	Wire arc sprayed Ni-20Cr, Ni-5Al	Ni-Cr and Ni-Al coatings significantly reduced erosion-corrosion in real boiler conditions.[104]
20	Mild & low alloy steel (T22, SA516)	Wire arc coated Ni-20Cr and Ni-5Al alloys	Ni-20Cr with Ni-5Al coatings improved oxidation resistance via protective phases and reduced porosity.[105]
21	Boiler steels	HVAF sprayedNi-Cr	Bi-layer NiCr by using HVAF coatings offer better hot corrosion resistance under different conditions .[106]
22	Low alloy 2.25Cr–1Mo steel	Y_2O_3 (yttria) coating	Y_2O_3 enhanced oxidation resistance via microstructure refinement and improved scale adhesion.[107]
23	347H SS	75Ni25Cr coating (air & husk-fired boiler)	75Ni25Cr coating significantly reduced corrosion compared to bare steel under high-temp conditions.[108]
24	T91 boiler tube steel	$75Cr_3C_2$-25NiCr via HVOF	$75Cr_3C_2$-25NiCr coating improves corrosion resistance, good adhesion, no internal oxidation.[109]
25	Various industrial components	Cr_3C_2-NiCr thermal spray	Cr_3C_2-NiCr coatings provide excellent corrosion and oxidation resistance up to 900°C.[110]
26	T11 and Gr A1 BST	Ni-20Cr, Ni-5Al based Wire arc sprayed	Ni-20Cr better than Ni-5Al; better oxide layer and lower porosity enhanced resistance.[111]
27	ASTM-SA213-T22 steel	Plasma sprayed FeCrNiC/Cenospheres	Coating improves corrosion resistance due to stable oxide layer formation.[112]

3. DISCUSSIONS

Corrosion from both high temperature and low temperature are major factors against the efficiency and the life of thermal and waste to energy (WtE) power plants. 12Cr1MoVG and T91 are particularly vulnerable to corrosion in the high temperature range, as high temperatures, combined with flue gases with high levels of H_2S and CO, can cause significant corrosion of the tube walls. Research has shown that the surface temperature is the single most important influencing parameter, with the corrosion rate increasing in an exponential manner. Besides, ash, molten salts and condensation of volatile constituents of flue gases increase the concentration of aggressive compounds like PbS and alkali metal sulfates leading to decreased mechanical strength of components. This along with mechanical stresses such as creep and fatigue causes boiler tubes to thin out rapidly and fail prematurely.

Low temperature corrosionis mostly arising from alkali metal sulfate formation and sulfuric acid from condensation below dew point, especially in economizers and air preheaters. Under these conditions, protective oxide scales are apt to spalling off with each temperature cycle, leaving fresh metal surface to corrosive attack. The problem is increased with the introduction of Cland Ca-rich deposits caused by biomass combustion which promotes local pitting and accelerates loss of material.

Thermal spray coatings have gained significant attention as a solution tothese problems. The coatings that have been evaluated have shown to be very effective for oxidation and hot corrosion resistant in aggressive boiler gas conditions, including CNT-reinforced Cr_2O_3, cold-sprayed NiCrTiCRe, Inconel 625 and HVOF-sprayed 93(WC–Cr_2O_3)–7Ni. For example, the corrosion resistance of the Cr_2O_3 matrix reinforced with Y_2O_3 was enhanced by more than 85% and the wear resistance (7.33% abrasive wear) of the Al_2O_3–TiO_2 matrix reinforced with CNTs was excellent because it was found that the porosity was lessened and the hardness was increased. Likewise, Ni–20Cr and Stellite-6 coatings have demonstrated excellent corrosion protection within coal combustion environments, with Ni–20Cr providing 91.8% and Stellite-6 providing 92.2% reductions in corrosion.

The technique (HVOF, APS, D-Gun or cold spray) used for applying the coating can greatly affect the micro-structural density, porosity, adhesion strength, and corrosion confrontation of the coating. To ensure maximum protection, key deposition constraints such as stand-off distance and oxygen-to-fuel ratio and particle temperature have to be optimized. Overall, the use of advanced thermal spray coatings in combination with proper operational techniques is a very effective means of preventing boiler corrosion, extending component life and enhancing overall plant reliability under challenging high- and low-temperature service conditions.

4. CONCLUSIONS

i. Corrosion is paramount at high and low temperature for efficiency, safety and equipment life.
ii. The aggressive oxidation, sulfidation and slag deposition at high tube wall temperatures are the main causes of high-temperature corrosion.
iii. Corrosion caused by low temperature is caused by acid condensation, thermal fatigue below the acid dew point and alkali salt deposition.
iv. The influence of flue gas components like H_2S, CO, chlorine and alkali metals on these processes is aggravating.
v. In many cases, protective oxide layers are formed on boiler equipment that can break down under extreme conditions, causing rapid degradation.
vi. Thermal spray coatings have proven very successful for corrosion protection in corrosive applications.
vii. The coatings of Ni-based, ceramic and hybrid epoxy can enhance resistance through the formation of shielding layers on the material, while the CNT-reinforced epoxy provides superior resistance through the reinforcement of carbon nanotubes.
viii. The coating performance and life are greatly influenced by the coating process used, such as HVOF, APS or Cold Spray.
ix. The selection of coating material and processes can have a profound effect on boiler component longevity.
x. Incorporating protective coatings along with the optimization of operating practices is an effective way to minimize corrosion.

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IZVOD

IZAZOVI KOROZIJE U SISTEMIMA VISOKE I NISKE TEMPERATURE: MEHANIZMI I NAPREDAK U TERMIČKOM PRASKIVANJU

Korozija u kotlovima je sada glavni problem u industriji proizvodnje termoenergije i ima značajan uticaj na efikasnost opreme, troškove održavanja i vek trajanja opreme. Ova studija se bavi mehanizmima korozije materijala kotlova na visokim i niskim temperaturama. Pokretanje oksidativnog napada na visokim temperaturama usko je povezano sa izlaganjem cevima, taloženjem zgure i korozivnih gasova poput H_2S i Cl_2 i uzrokuje ozbiljnu degradaciju cevi sa vodenim zidovima i pregrevača. Promena radne temperature dodatno bi podstakla burne reakcije između rastopljenog pepela i sulfidnih vrsta. Korozija na niskim temperaturama generalno nastaje kondenzacijom dimnih gasova na hladnijim površinama poput ekonomajzera i pregrevača vazduha, gde formiranje sumporne kiseline, sulfati alkalnih metala, propadanje oksidnog sloja i termički zamor postaju dominantniji ispod temperature tačke rose. Situaciju pogoršavaju naslage letećeg pepela koje zadržavaju toplotu i imaju tendenciju da koncentrišu korozivne agense na površini metala. Nekoliko njih je ispitano radi zaštite od korozije korišćenjem tehnologija termičkog prskanja. Različite vrste termičkih premaza su ispitivane kako bi se prevazišli ovi problemi. Premazi od Cr_2O_3, legura na bazi Ni i ZrO_2–Al_2O_3 ojačanih CNT-om pokazali su veoma dobru otpornost na koroziju i eroziju u teškim uslovima kotlova. Ovi premazi delimično zavise od metoda nanošenja, uključujući visokobrzinski kiseonik-gorivo (HVOF), procese hladnog prskanja i atmosfersko plazma prskanje (APS). Razvoj poslednjih godina sa upotrebom nanočestica i hidrofobnih aditiva dodatno je poboljšao trajnost premaza i zaštitne mogućnosti u teškim uslovima rada. U ovoj studiji je istaknuta primena naprednog materijala za termičko prskanje i optimizovanih parametara rada za inhibiciju korozije kotlova, produženje veka trajanja i povećanje pouzdanosti opreme za proizvodnju električne energije.

Ključne reči: *Korozija na niskim temperaturama, korozija na visokim temperaturama, termički premazi, zaštita materijala*

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Jagmeet Singh: https://orcid.org/0009-0008-3889-7622
Charanjit Singh: https://orcid.org/0000-0002-2856-0152
Davinder Singh: https://orcid.org/0000-0001-6001-6475
KhushdeepGoyal: https://orcid.org/0000-0001-5269-8744