Study on High Temperature Chlorination Corrosion of Metallic Materials on The Waste incineration boilers

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Abstract. There's a growing concern about the phenomenon of high temperature chlorination corrosion on the waste incineration boilers by researchers. This paper discusses the corrosion features of chlorination corrosion for metallic materials at high temperature, explore the mechanism of high temperature chlorination corrosion, analyze the main factors of effect chlorination corrosion, and preventive measures for the resistance to high temperature chlorination corrosion were proposed.

1. Introduction
With the continuous development of urbanization and the increasing population of the city, the problem of urban domestic garbage disposal is becoming more and more serious. According to statistics, the per capita annual output of garbage in China's cities is 400~500kg, the storage of urban domestic garbage has reached 6 billion tons, and the land area occupied is 500 million m2. More than 200 cities have been surrounded by garbage, with an annual growth rate of 8%~12%. The speed of % has increased rapidly, and garbage has become a hot and difficult issue in the society [1, 2].

At present, there are four methods for the treatment of municipal solid waste at home and abroad: incineration, landfill, composting, and harmless comprehensive treatment [3]. Among them, waste incineration power generation is an effective method to realize the harmless, reduced and resource treatment of urban garbage. Waste incineration is an effective means of treating industrial and municipal solid waste. It is valued at home and abroad because it can realize the harmlessness, volume reduction and resource utilization of solid waste [4, 5]. However, in the process of disposing of garbage, the corrosion problems of incineration equipment are becoming more and more prominent, and the actual life of many equipments cannot reach the design life. Among the various corrosions in waste incineration environments, high temperature chlorination corrosion has received the attention of researchers. Due to the large proportion of rubber and plastics in domestic garbage in developed cities or regions, acid gases such as HCl and SOX are produced during incineration, and the chlorine content in the garbage is high, which causes the early failure of many equipments to be related to high temperature chlorination corrosion. Through the study of corrosion characteristics and mechanism of high temperature chlorination corrosion, the high temperature corrosion of metal materials in waste incineration boilers is more clearly understood, and theoretical guidance for further prevention measures against high temperature chlorination corrosion is proposed.
2. High temperature chlorination corrosion characteristics

The results of high temperature corrosion of metals in chlorine-containing environments indicate [6-8]. Cl is very active and reacts with most metals in high temperature environments. The chloride formed by the reaction has a low melting point and a high vapor pressure. For example, FeCl$_2$ at 536°C, NiCl$_2$ at 607°C, CrCl$_3$ at 611°C can occur significant volatilization. The melting points of FeCl$_2$ and FeCl$_3$ are only 675°C and 305°C, respectively, and the chloride is more stable than other oxides and sulfides. Strong acceleration of corrosion of metallic materials when the metal is in a HCl, Cl$_2$ gas or chloride vapor atmosphere or when a chloride salt is deposited on the metal surface. The corrosion causes the oxide film to become very porous and porous, the surface is bubbled, and cracks and holes are generated, which no longer have good adhesion and protection. Metal chlorides can also be detected at the metal/oxide interface, ie so-called activated corrosion phenomena occur.

At present, rubber or plastics in domestic garbage in cities or regions account for a large proportion, and chlorine is contained in rubber, plastic or other industrial waste. Whether organic chloride or inorganic chloride produces HCl or Cl$_2$ after incineration. In the flue gas of the waste incinerator, the oxygen content is generally high (5%-10%), and the HCl content is 800-4000 mg/m$^3$[9]. At the metal/oxide interface, since O$_2$ is consumed a lot when participating in the corrosion reaction, the partial pressure of oxygen is small; at the same time, HCl and Cl$_2$ reach through the protective oxide film to make hydrogen chloride there. The partial pressure is higher. The HCl and Cl$_2$ at the metal interface will directly contact the metal material, and react with the elements such as Fe and Cr in the material to form a stable phase chloride. The reaction chemical formula is as follows:

$$M + n\text{HCl} \rightarrow MCln + (n/2) \text{H}_2 \quad (1)$$

(M is expressed as Fe, Cr, etc., the same below)

Cl$_2$(Cl-) passes through the oxide film to the oxide film/metal interface and reacts with the metal to form volatile chloride (MCl).

$$M + 1/2\text{Cl}_2 \rightarrow M\text{Cl}(g) \quad (2)$$

MCl is oxidized again during continuous volatilization:

$$2M\text{Cl}(g) + O_2(g) \rightarrow 2M\text{O}(s) + \text{Cl}_2(g) \quad (3)$$

The chloride formed in the high temperature chlorination corrosion reaction has a high vapor pressure, and is volatilized under high temperature conditions, and these chlorides continuously diffuse into the surrounding environment through the oxide film. During the outward evaporation process, the partial pressure of oxygen is getting larger and larger, and the partial pressure of HCl is getting smaller and smaller. When the partial pressure of oxygen is large enough, a part of the metal chloride reacts with oxygen to form a solid metal oxide (such as a reaction formula). 3) At the same time, HCl and Cl$_2$ gases are released, and these gases are returned to the metal/oxide film interface through the oxide film, and the base metal reaction is continued to form an activated corrosion phenomenon. The reaction (3) produces oxides in the oxide film to destroy the integrity of the oxide film, forming a very loose oxide film, and generating cracks and pores; it is more loose than the oxide film in the absence of HCl or Cl$_2$ gas. Poor adhesion and loss of the original protection.

3. High temperature chloride rot mechanism

3.1. Tedmon equation

It can be seen from the results of previous scholars that in the high temperature oxidation process, if the ion diffusion process through the oxide film is the control step of the high temperature oxidation reaction, the oxidation kinetic curve is parabolic. In the case of controlling the reaction by the ion diffusion...
process, the rate of change of the thickness of the oxide film and the thickness of the oxide film itself are as follows:

\[ \frac{dx}{dt} = \frac{K_d}{x} \]  

(4)

The thickness of the x-oxide film in the equation, t-time, the constant controlled by the Kd-diffusion process. On the other hand, if the metal interface reaction process is a control step of oxidation, the oxidation rate does not change with time, and the relationship equation is as follows:

\[ \frac{dx}{dt} = K_s \]  

(5)

Ks is a constant that occurs in the control of the metal interface reaction process. The oxidation kinetics in accordance with equation (5) obey the straight line law.

If the diffusion of ions in the oxide film and the volatilization of the oxide film occur simultaneously at the time of oxidation, the oxidation law at this time is a superposition of equation (4) and equation (5), except that Ks in equation (5) is negative at this time. As a result of volatilization (or/and evaporation), the thickness of the oxide film is reduced. Equation (5) will become the following form:

\[ \frac{dx}{dt} = -K_s \]  

(6)

Therefore, the oxidation kinetics equation in which the ion diffusion in the oxide film and the volatilization of the oxide film occur simultaneously in oxidation are as follows:

\[ \frac{dx}{dt} = \frac{K_d}{x} - K_s \]  

(7)

This is the famous Tedmon equation.

The Tedmon equation was originally proposed for high temperature oxidation, but it has achieved important reuse in high temperature chlorination and even high temperature halogenation. Because most metal chlorides have a higher saturated vapor pressure than metal oxides, they are more volatile. The corrosion reaction of metals in a high-temperature chlorination atmosphere is more the case where metal ion diffusion and oxide film volatilization occur simultaneously. Especially when the metal is corroded in a high temperature oxidation/chlorination environment, the Tedmon equation is well applied.

Initially Tedmon equation (7), where x takes the change in oxide film thickness as a function of time, but under some complex corrosion conditions, the thickness of the oxide film is affected by the volatilization of certain corrosion products. Affects the application of the Tedmon equation. Here, it is more appropriate to replace the thickness of the oxide film with a change in the weight of the sample. At this point the Tedmon equation becomes:

\[ \frac{dW}{dt} = \frac{K_d}{x} - K_s \]  

(8)

Where w is the weight of the sample.

3.2. High-temperature chlorination corrosion "activated oxidation" mechanism

From the single corrosive medium, the Tedmon equation is a good theoretical discussion of the corrosion mechanism of metals in oxygen-containing or chlorine-containing media. In reality, the corrosive atmosphere is often a mixture of two or more. For most chlorinated corrosive environments, other oxygen and other common corrosion are involved, and in the chlorination corrosion results, there is often a high concentration of chloride deposited at the oxide film/substrate interface. Researchers such as MacNallan have proposed the "activated oxidation" mechanism of high temperature chlorination corrosion[10,11].
The high temperature chlorination corrosion process is roughly as follows: First, the existing Cl\textsubscript{2} or HCl, chloride etc. in the atmosphere react to form Cl\textsubscript{2}.

\[ \text{2HCl+1/2O}_2=\text{Cl}_2+\text{H}_2\text{O} \]  \hspace{1cm} (9)

Or chloride reacts with oxide to give Cl\textsubscript{2}:

\[ \text{2NaCl+Fe}_2\text{O}_3+1/2\text{O}_2=\text{Na}_2\text{Fe}_2\text{O}_4+\text{Cl}_2 \]  \hspace{1cm} (10)

Cl\textsubscript{2}(Cl-) passes through the oxide film to the oxide film/metal interface and reacts with the metal to form volatile chloride (MCl).

\[ \text{M} + 1/2\text{Cl}_2\rightarrow\text{MCl(g)} \]  \hspace{1cm} (11)

MCl is oxidized again during continuous volatilization:

\[ 2\text{MCl(g)} + \text{O}_2(g)\rightarrow 2\text{MO(s)} + \text{Cl}_2(g) \]  \hspace{1cm} (12)

The mechanism of "activated oxidation" of high-temperature chlorination corrosion is mainly caused by the fact that O\textsubscript{2} is involved in corrosion in most chlorinated corrosion environments. The process is to form Cl\textsubscript{2}, HCl, Cl\textsubscript{2} (or Cl-) on the surface of the metal oxide film through the oxide film to reach the oxide film/metal interface, and directly react with the base metal (Fe, Cr element, etc.); the chloride formed by these reactions Diffuse to the surroundings, react with O\textsubscript{2} in the process of outward diffusion, produce products such as oxides, HCl and Cl\textsubscript{2}, while HCl and Cl\textsubscript{2} pass through cracking, loose defect oxide film, return to the oxide film/metal interface, and re-engage with Corrosion reaction of base metal. Cl\textsubscript{2} plays an autocatalytic role in this process. The above process is the so-called "active oxidation" as shown in Figure 1.

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Fig1. Schematic diagram of active oxidation process

However, the high temperature chlorination corrosion reaction is a complex reaction involving several processes. The key step in the chlorination corrosion reaction process is how the Cl diffuses rapidly from the surface of the oxide film to the oxide film/metal interface and how the volatile chlorides are outward from the interface. It was thought that Cl can diffuse through the oxide interface, or chloride ions instead of oxygen ions in the oxide film can reach the oxide film/metal interface in a lattice diffusion form. Since the activation of oxidation immediately after the introduction of HCl or the deposition of chloride on the oxide film, there is no incubation period, so the transport of Cl to the interface should not be mainly caused by slow solid diffusion and grain boundary diffusion. Even the direct penetration of defects such as cracks and microcracks on the oxide film in the form of gas molecules Cl\textsubscript{2} cannot explain the abrupt change in oxidation rate because macroscopic defects occurring in the oxide film can provide a fast diffusion path for this process, but It also allows O\textsubscript{2} to diffuse inward, resulting in the re-formation of the oxide film. To a certain extent, Cl\textsubscript{2} itself should have an effect on the formation of a
fast diffusing channel. However, this effect of chlorine cannot be clearly verified due to the looseness and scattering of the oxide film. Many mechanisms have been proposed for this researcher, but none of them can completely explain the oxidation process, how Cl diffuses, etc, and the mechanism has not yet formed a unified understanding. At present, the corrosion mechanism of chlorine tends to be high temperature chlorination corrosion "active oxidation" mechanism. Although the theory of activated oxidation has been proposed, it has been recognized and recognized by many researchers. However, the theory of activated oxidation also has limitations in explaining how chlorine diffuses rapidly from the surface of the oxide film to the oxide/metal interface and how volatile chlorides diffuse outward from the interface.

In the "activated oxidation" mechanism, the high temperature chlorination corrosion process inhibits the formation of a dense protective oxide layer. One process is that the metal chloride produced on the metal surface forms a high saturated vapor pressure which inhibits the growth of the continuous oxide film. In another process, the metal chloride diffuses outward through the pores, cracks, and voids of the oxide film, and reaches a region where the oxygen partial pressure is high to react with oxygen to form a metal oxide and chlorine gas, and further react to suppress the formation of the oxide film.

4. Factors affecting high temperature chlorination corrosion

The corrosion behavior in the chlorine environment is very complicated and is affected by many factors. Temperature, ambient gas composition, flow rate, HCl concentration, alloy composition and sedimentary salt are all factors influencing chlorination corrosion behavior. The study found that the influence of various factors on the corrosion behavior of chlorination is different, and the factors affecting corrosion are alloy composition and temperature.

4.1. Alloy composition

The effect of using different steels on chlorination corrosion is quite different. Bender and other studies have shown that in the 2% Cl2 mixed atmosphere, the nickel-based contract corrosion rate increases almost at a temperature of 800°C to 1000°C. Because the dense oxide film at high temperature inhibits the chlorine gas from further reacting with the metal matrix, the chlorination reaction occurs at NiO rather than at the metal substrate. The relatively low corrosion rate of nickel-chromium alloy in different chlorine-oxygen-rich atmospheres is due to the combination of the low partial pressure of the reaction product NiCl2 and the chromium oxide protective film. In an oxygen-containing environment, when the chromium content of the nickel alloy exceeds 8%, Cr2O3 or NiCr2O4 spinel is usually formed, which will cause the chlorine corrosion rate of the contract to be lower than that of pure nickel alloy. Bender et al. also found that molybdenum does not resist HCl corrosion in a reducing atmosphere at 900°C. This situation is completely contrary to the oxidizing atmosphere. Since the molybdenum element is rapidly disappeared to form a highly volatile product, especially the MoO2Cl2 product is found from the reaction temperature of 300°C. Even the MoO3 product having a melting point of 797°C has begun to volatilize at 700°C, and the volatile corrosion product has a high vapor pressure. A continuous dense oxide film is not formed on the surface of the metal substrate.

China's boilers use steel as Fe-based alloys, and alloying elements are mainly: Cr, Ni, C, Si, Mo, etc. Different elements have different chlorination corrosion conditions at high temperatures. Under certain circumstances, the degree of corrosion is determined by the high and low Gibbs free energy and high temperature stability of the product formed by the reaction of alloying elements and HCl. In general, the smaller the product Gibbs free energy, the better the high temperature stability, and the stronger the chlorination resistance of the alloy. But in most cases, the chlorination of carbon steel and alloy steel is very serious. Some researchers have changed the alloy's chlorination resistance by increasing the Cr content of alloy steel. The research results show that the increase of Cr content does not necessarily improve the chlorination corrosion resistance of the alloy, and even the corrosion resistance of some materials increases with the increase of Cr content[12]. In addition, studies have shown that Al-based nickel-based alloys have good corrosion resistance in chlorinated environments and are potential
materials with good chlorination resistance and the surface state and processing technology of the alloy also have a certain influence on its corrosion resistance[13].

4.2. Temperature

Ambient temperature is one of the main factors affecting chlorination corrosion. The effect of temperature on the corrosion process is to influence the order in which oxides and chlorides are formed and their stability. For example, when pure Fe is corroded in HCl, divalent ferric chloride is formed below 450°C, and the corrosion weight gain is parabolic with time; there is no initial weight gain at 600°C or higher, and the sample quality decreases linearly with time. The researchers explored the relationship between Fe-based alloys and temperature through a large number of experiments and found that corrosion increased significantly with increasing temperature.

At present, the relationship between temperature and chlorination corrosion has not yet been fully determined. It has been reported that high-temperature chlorination corrosion of metal materials such as carbon steel, alloy steel, stainless steel and nickel-based alloy in different temperature ranges, and it is found that the corrosion rate of carbon steel and alloy steel increases with the increase of temperature in the early stage; however, stainless steel and Nickel-based alloys tend to increase and then decrease with increasing temperature. Therefore, the relationship between temperature and corrosion is also related to the alloy composition.

4.3. O₂

The oxygen content has a certain influence on the chlorination corrosion. In the O₂ and Cl₂ atmospheres, the difference in O₂ content affects the high temperature chlorination corrosion reaction. Latreche et al.[14] studied high temperature chlorination corrosion in four different O₂ partial pressure environments (Fig. 2). The steps involved in chlorination corrosion under different O₂ partial pressures are different: 1. When pO₂ is lower than pO₂eq atmosphere, Within this range, only the Cl₂ reacts directly with the metal to form a metal chloride, but no metal oxide is formed. 2. When pO₂eq < pO₂ < pO₂ox atmosphere, it belongs to the range of low oxygen partial pressure, chloride ion selectively reacts with metal, and there is no oxide film formation. When pO₂eq < pO₂ < pO₂sh atmosphere, It belongs to the range of oxygen partial pressure. The chlorination corrosion process is mainly “activated oxidation”, and the reaction forms an oxide film with cracks and porosity. 4. When pO₂ < pO₂sh atmosphere, It belongs to the high oxygen partial pressure range, and there is enough oxygen to make the reaction form a dense oxide film. The corrosion process is characterized by the fact that Cl₂ reacts directly with metal oxides to produce volatile metal chlorides, and the corrosion reaction becomes complicated.

Ihara et al found that the chlorination of Fe in the HCl atmosphere at 300–800°C depends mainly on the formation and volatility of FeCl₂. When filled with 20%-50% O₂, the corrosion of Fe is significantly accelerated. When the content of O₂ exceeds 50%, since a protective oxide film is formed on the surface of the alloy, the degree of corrosion is reduced. Figure 2 shows the effect of O₂ content on the corrosion of iron in HCl [15]. Chlorination of the alloy under O₂ conditions, the role of oxygen is to produce oxides or oxygen-chlorides. It is effective if the oxide forms an oxide film against corrosion, but if the oxygen-chloride is more volatile in the HCl, O₂ environment than the oxide formed in the pure oxidizing environment, oxidation is harmful, otherwise it is beneficial.
Fig. 2 High temperature chlorination corrosion in four different reaction types in different O\textsubscript{2} atmospheres

5. Protective measures against chlorination

5.1. Reduce HCl concentration
With the economic development, the proportion of rubber and plastic in urban domestic waste has increased. First, after the waste is classified and pretreated, the concentration of HCl generated during the waste incineration process is reduced. Secondly, the use of garbage and other fuel mixed combustion technology, because the content of Cl in the garbage is relatively high, mixed with coal can reduce the content of Cl in the flue gas, thereby reducing the high temperature chlorination corrosion of the alloy. In addition, a certain amount of additives can be added to the waste incinerator, such as adding lime, limestone and the like, and reacting with HCl and C1\textsubscript{2} gas to reduce the concentration of corrosive HCl gas in the high temperature region, and to achieve high temperature chlorination corrosion.

5.2. Use high-temperature alloy steel with good corrosion resistance
The high temperature corrosion in the waste incinerator is mainly Cl. When selecting materials for waste incinerators, it is necessary to consider the corrosion characteristics of S and Cl and the corrosive atmosphere. Nickel-based alloy steel with good corrosion resistance is selected to resist high temperature chlorination corrosion. The melting point of nickel chloride formed by the reaction of chlorine with Ni element is as high as 1000\degree C, which is higher than the melting point of FeCl\textsubscript{2} and FeCl\textsubscript{3} formed by the reaction of iron-based alloy with Cl. Nickel chloride is more stable than ferric chloride, and Ni-based alloy has better resistance to high temperature chlorination than Fe-based alloy. However, considering the high price of Ni-based alloys, the selection of boiler steel must measure material consumption, service life and economy. Limited by the relevant factors, the types of steel used in China's boilers are: 625, Q245, C276, etc. In addition, some researchers have added rare earth elements such as Y and Ce to the alloy to improve the distribution of elements in the alloy, prevent the aggregation of carbides, increase the bonding strength of the oxides, and enhance the adhesion of the oxide film to the alloy, thereby improving the alloy. Corrosion resistance in chlorine-containing environments [16].

5.3. Coating protection
A protective coating on the surface of the alloy is effective against chlorination. At present, protective coatings are mainly divided into two categories: thermal spray corrosion resistant metal coatings and high temperature corrosion resistant coatings. Thermal Spray Corrosion Resistant Metal Coating is a metal coating that forms a barrier between the alloy surface and the corrosive medium. Thermal spraying technology mainly includes supersonic flame spraying, plasma spraying and arc spraying. Among them, arc spraying has the advantages of good coating performance, high spraying efficiency, low cost and
good economy. It is widely used in the preparation of corrosion-resistant metal coatings. The metal coating has good corrosion resistance against Cl and S.

The high temperature resistant anticorrosive coating is a coating that is coated with a corrosion resistant coating on the surface of the alloy. The heat-resistant coating is applied to the super heater pipe wall and the cold water wall pipe of the garbage incineration system to achieve the purpose of preventing high-temperature chlorination corrosion. At present, heat-resistant and corrosion-resistant coatings are widely used in various high-temperature corrosive environments.

6. Conclusion
Common waste incineration boilers at home and abroad cause high-temperature chlorination corrosion of metal materials, causing boiler failure problems. Through high-temperature chlorination corrosion of metal materials in waste incineration boilers, researchers have obtained high-value results: a. Many factors affecting high-temperature chlorination corrosion: temperature, flow rate, \( \text{O}_2 \), water vapor, \( \text{HCl} \) concentration, Alloy composition, deposited salts, and other gas components. Preventive measures against high temperature chlorination include: reducing HCl concentration, using high temperature alloy steel with better corrosion resistance, coating protection and reducing system operating temperature.

At present, although the high-temperature chlorination corrosion of metal materials in waste incineration boilers has been studied in depth. However, there is still no complete theory for the high temperature chlorination corrosion process and corrosion mechanism, which requires further research and improvement by the researchers to provide technical support for the safe movement and reliability life assessment of waste incineration boilers.

Acknowledgments
This work was financially supported by Guangzhou Science and Technology Project(201804010273) of “Development and Application of New Chromium-free Passivation Technology Based on Graphene”.

References
[1] Zhang Qian, Xu Haiyun. Current status and development proposals of domestic waste incineration technology [J]. Environmental Engineering, 2012, 30(2): 79-81.
[2] Zhu Jianzhong, Chen Lieqiang, Gan Gan. Corrosion mechanism of alkali metal chloride in waste incineration atmosphere [J]. Journal of South China University of Technology (Natural Science Edition).
[3] Pan Lunying, High Temperature Corrosion of HCl in Superheater Zone of Waste Incinerator [D]. Master thesis, Zhejiang University, 2003.
[4] Wu Feng. Characteristics of high temperature chlorine corrosion [J]. Power System Engineering, 2003, 19(1): 13-15.
[5] Wei Qi, Wang Rui, Li Hui, et al. High-temperature chlorination corrosion status and protection research [C]. The 13th International Thermal Spraying Symposium (ITSS, 2010) and the 14th National Thermal Spraying Annual Conference (CNTSC, 2010), Suzhou: China Surface Engineering Association Spraying Professional Committee, 2010.
[6] James P J, Pinder L W. CORROSION/97, NACE International, Houston, TX 1997, 133.
[7] Nakagawa K, Isozaki T. CORROSION/94, NACE International, Houston, TX 1994, 177.
[8] Spiegel M, Schroer C, Grabke H J. Materials science forum, 1997, 251/ 254 :527.
[9] Armin Zahs, Michael Spiegel, Hans Jurgen Grabke. Chloridation and oxidation of iron, chromium, nickel and their alloys in chloridizing and oxidizing atmospheres at 400±700 °C[J]. Corrosion Science, 2000, (42): 1039–1122.
[10] Y.Y.Lee, M.J.McNallan, Metall.Trans.A.1987(18A):1099.
[11] E.Reese, H.J.Grabke. Mater. Corros, 1993(43):547.
[12] Li Yuanshi, Niu Zhong, Wu Wei. Journal of Chinese Society for Corrosion and Protection [J], 2002, (22): 27.
[13] Saunders S R J, Gohil D D. Materials science forum, 1997, 251/ 254:583.
[14] Latreche H, Doublet S, Schütze M. Development of corrosion assessment diagrams for high temperature chlorine corrosion Part II: Development of “Dynamic” Quasi-stability Diagrams[J]. Oxidation of metals, 2009, 72(1-2): 31-65.

[15] Y. Ihara, H. Ohgame, K. Sakiyama, K. Hashimoto. Corrosion Sei.1981(21):805. Pang Qi cai. Anti-corrosion coating coating and quality control [M]. Beijing: Chemical Industry Press, 2004.

[16] A Shi zhen. Corrosion causes and countermeasures of common waste incineration boilers, boiler pressure vessel safety technology [J], 2001 (6): 4-6.