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Control Techniques of Scaling and Corrosion in Geothermal Fluids

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ABSTRACT

A summary of the techniques of corrosion and scaling inhibitors in the geothermal fluids are presented in this report, especially those developed by our research group in recent years. Material selection of corrosion and fouling inhibition, coatings, fluid pretreatment, and chemical additive are emphasized. Future research areas required would mainly be helping to predict corrosion and scaling trends of; geothermal fluids, chemistry simulation, scaling mechanisms in geothermal fluids, strong combination forces between protection coatings and substrates, cathode protection and hybrid inhibition techniques.

1. INTRODUCTION

Scaling and corrosion often happen in production wells, pipelines, and surface equipment such as separator systems, heat exchangers, turbines, and valves in the power plants (Liu, 2015; Liu and Zhu, 2011). Scaling and corrosion phenomena in geothermal energy utilization are crucial challenges. Scaling on the heat transfer surface of heat exchanger will make both thermal resistance and pressure drop increase, leading to an increase of initial capital investment and operating cost. Corrosion on heat exchanger and pipeline surfaces, mainly including pitting and crevice corrosion of metal, will reduce their service lifecycles. In order to avoid scaling and corrosion, process mechanisms and controlling techniques have been investigated in the past several decades. This article briefly reviews the control techniques on scaling and corrosion in geothermal fluids.

In order to control the corrosion of metal materials for the installations of geothermal energy utilization it is considered to; select corrosion-resistant materials, modifying the metal substrates with anticorrosion coatings, add chemical inhibitors to prevent corrosion into the fluid flow systems, apply cathodic protection and pretreating geothermal fluids.

On the other hand, it is suggested that scaling of geothermal energy utilization systems are using; chemical scaling inhibitors, surface modification, coatings, pretreatment of geothermal fluids, applying various physical filed, enhancing the flow of the geothermal fluids.

A review of the detail descriptions on the control techniques of scaling and corrosion in geothermal fluids will follow.

2. CORROSION CONTROL TECHNIQUES

2.1 Utilizing corrosion resistant materials

In designing the pipelines of geothermal energy utilization, it is highly suggested to use corrosion resistant materials that will be used in the geothermal plant that will come into contact with the geothermal fluids.

Generally, non-metallic materials, such as polyvinyl chloride, do not corrode easily. However, there are some technical problems in the usage of the nonmetallic installations such as lower pressure resistance, lower heat resistance, quick aging of the equipment and the difficulty in the treatment.

Stainless steel, titanium, or alloys can also be used. However, under the condition of high chloride-ion content, the corrosion resistance of stainless steel is weaker than carbon steel, and the existence of dissolved oxygen will significantly accelerate the corrosion rate of stainless steel.

Titanium is not only relatively expensive, but also inefficient in heat transfer for heat exchanger. The use of corrosion-resistant metal materials in the whole geothermal system can make the geothermal system very reliable. However, the cost of such measures is too high. High alloy stainless steel, nickel-based alloy, titanium alloy and zirconium can also be used to increase the reliability of the geothermal system, but it is essential to consider the cost.

It can also be considered to increase the corrosion allowance of pipelines and other structural parts in the design, that is, to increase the thickness of the tube wall. It is difficult to fundamentally solve the corrosion problem as while as increase the investment of the plant.

Chen et al. (2010) studied the corrosion and scaling law of galvanized steel pipe in the simulated geothermal water environment at 50 °C, and found that in the flowing geothermal water environment, galvanized steel pipe is mainly corroded and its quality increases quickly. However, in the static geothermal water environment, the surface of galvanized steel pipe is mainly scaled, and the mass increase rate is slow. Next, Cai et al. (2009), Wu et al. (2009, 2010a, 2010b) and Zhu et al. (2010a, 2010b) respectively studied the effects of Ca^{2+}, Mg^{2+} and temperature on the corrosion and scaling behavior of galvanized steel pipe and 304 stainless steel in simulated geothermal water, and found that the concentration of Zn^{2+} and OH^- had an effect on the fouling nucleation on the surface of the pipe, and the spherical etchants on the surface were $Zn(OH)_2$ and ZnO. Acicular fouling is $CaCO_3$ and $MgCO_3$. Corrosion products and scaling products often interact with each other during the formation and growth of crystal nuclei. When fouling is formed, corrosion rate decreases and pitting area decreases. The crystal shapes of corrosion and scaling products in geothermal water at different temperatures are different. The change of geothermal water temperature strengthens the pitting sensitivity of 304 stainless steel material in simulated geothermal water, and the protection of passivation film on its surface also decreases with the increase of geothermal water temperature.

Furthermore, Pfennig et al. (2013) investigated the corrosion and fatigue characteristics of AISI 420C (X46Cr13) material in CO_2-saturated 60 °C simulated geothermal water, and found that pitting corrosion caused by carbonation occurred before cracks appeared in the material. In the same year, Klapper et al. (2013) studied the corrosion resistance characteristics of different steels at 100 °C ~ 150 °C simulated geothermal water in Molasse Basin. The results show that carbon steel API L80 and API Q125 have good resistance to uniform corrosion and pitting corrosion in simulated geothermal water, while duplex stainless steel alloy 2205 and austenitic stainless steel 316L also have good resistance to pitting corrosion and crevice corrosion in simulated geothermal water.

Last but not least, Mundhenk et al. (2013a) studied the corrosion rate characteristics of eight kinds of metal materials by using electrochemical method (potentiodynamic polarization curve method) in the laboratory and weightlessness method at the site of Soultz-sous-Forêts geothermal power station in France, and compared the consistency of the corrosion rate results obtained by the two test methods. The metal materials used include: non-alloy steel (P110, N80, P235GH), stainless steel (1.410 4, 1.440 4, 1.457 1, 1.453 9) and nickel-based alloy 2.485 6, etc. For non-alloy steel, the corrosion experiment conducted in in-situ geothermal water at 80 ° C for 5 months found that surface roughness and uniform corrosion existed on all surfaces, as well as pitting at a certain depth, and the average corrosion rate was less than 0.23 mm per year. For N80, the pitting penetration is 101 μm, and some dirt is formed on the surface. For stainless steel, local corrosion and obvious pitting corrosion occur. The one-month field corrosion test showed that 1.440 4 and 1.453 9 had no obvious corrosion and weight loss, while 1.410 4 had some pitting corrosion, which was related to the alloy content. The uniform corrosion rate of nickel base alloy 2.485 6 is small and negligible.

The same year Mundhenk et al. (2013b) used the same method to study 13 kinds of metal materials such as low carbon steel, CrNiMo alloy and non-iron foundation (APIN80, API P110, P235GH, P265GH low carbon steel, 430F, 316L and 316Ti stainless steel, The corrosion characteristics of 904L alloy, 318L biphase alloy and 31 super biphase alloy stainless steel, 59 and 625 Nickel-base alloy, secondary titanium, etc.) and the interaction between corrosion and scaling. The results show that when the fluid temperature ranges from 20 °C to 160 °C, the long-term uniform corrosion rate of the mild steel is lower than 0.2 mm per year with the formation of the dirt protective layer. However, there are also local corrosion, the pitting penetration depth is greater than 1 mm, which may cause short-term system failure. Ordinary 430F and 316L stainless steels have pitting corrosion; The uniform corrosion rate of high alloy material is 0.005 mm per year, which is suitable for geothermal utilization. However, pitting corrosion under scale also exists. Mundhenk et al. (2014) also investigated the corrosion resistance of different alloys in deoxidized 80 °C Soultz and Bruchsal hydrothermal water containing CO_2. The results showed that the spontaneous passivation of secondary titanium alloy and 625 alloy was a key step to slow the corrosion of alloys caused by pitting corrosion.

For the last few years, Yu et al. (2021) studied the corrosion scaling behavior of 304 stainless steel and 1050A aluminum alloy in simulated geothermal water, and conducted a kinetic analysis of the corrosion reaction. The results show that the corrosion degree of 304 stainless steel increases with the increase of time, and the current density at the later stage of corrosion increases by an order of magnitude. 1050A aluminum alloy is mainly point corrosion, surface passivation film is gradually dissolved and destroyed in the corrosion process, later due to the adhesion of corrosion products will form a dense oxide film to protect the matrix, and XRD shows that the main component of oxide film is Al_2O_3, so the overall corrosion trend is different from 304 stainless steel, first serious and then reduced. After soaking for 30 days, the arc radius of capacitive reactance is the largest, showing strong back passivation corrosion resistance. The corrosion kinetics results show that the corrosion thickness of the two kinds of pipes is a power function relationship with the time.

New anticorrosion materials need further inventing.

2.2 Anticorrosion coatings

Sugama et al. (2011) carried out systematic researches on anti-corrosion coatings between 1998 to 2006. They developed polyphenylene sulphide (PPS) composite coatings on carbon steel substrate, which is low cost, thermal stability, anti-corrosion, anti-scaling, anti-oxidation, wear-resistance and self-repairing functions. Based on PPS, polytetrafluoroethylene (PTFE) is an antioxidant, carbon fiber which is also a thermal conductive agent and reinforcing agent. Dicalcium aluminate powder is a self-repairing filler and boehmite is micro-scale crystalline powder. Boehmite crystal is used as a wear-resistant filler and crystalline zinc phosphate is used as a primer. Among them, zinc phosphate primer can enhance the adhesion between the coating and carbon steel, and inhibit the cathodic corrosion of the steel under the paint. The results show that the composite coating can be used for the anticorrosion of geothermal systems at 160 ~ 200 °C, and can also slow down the deposition of calcium silicate, while the stainless steel without coating produces strong bonded calcium silicate deposition.

Very recently, our research group also has developed several new types of anti-corrosion as well as anti-scaling material coatings for simulated hot-dry-rock and oil field related geothermal water (Xu et al., 2017; Song et al., 2018).

Various polysiloxane-ferroferric oxide composite coatings were fabricated on carbon steel substrates to control the corrosion in geothermal water. Potentiodynamic polarization curves and electrochemical impedance spectroscopy (EIS) in 3.5 wt.% NaCl solution tested the corrosion, simulating geothermal water of Huabei oilfield. The inhibition of corrosion for each carbon steel sample with composite coating improved because the corrosion current density decreases by one or two orders of magnitude. Corrosion mechanism for carbon steel with composite coating was analyzed with EIS measurement and equivalent circuit simulation. The composite polysiloxane coatings show good corrosion resistance and thermal stability (Xu and Liu, 2017).

The SiO_2, SiO_2-FPS and TiO_2 coatings on AISI304 stainless steel substrates were respectively prepared by sol-gel and liquid phase deposition methods to mitigate fouling and corrosion of heat transfer surfaces under forced convection in hot-dry-rock geothermal water with the temperature of 423.15K. It is shown that sol-gel SiO_2 and SiO_2-FPS coatings have better performance of antifouling and anticorrosion in moderately corrosive hot-dry-rock geothermal water with total dissolved solids (TDS) of about 7000mg/L (Song et al., 2018).

Although the use of anti-corrosive coatings in pipelines and equipment is a better scheme in geothermal, such as the use of various metal protective coatings, because of the different yield stress of carbon steel and anti-corrosive coatings, there are problems such as coatings not remaining adhesive.

Gao et al. (2001) applied A.T.O cermet coating to develop corrosion protection on the inner surface of geothermal water pipelines by using an automatic walking inner pipe spout. Protective coating thickness 220 μm, can spray pipe diameter to the inner surface of the more than 60 mm. No corrosion was found in the developed geothermal pipeline after two years of operation.

In order to make the equipment and pipe fittings of the geothermal power generation system with operating temperature up to 300 °C replace the commonly used expensive anticorrosive titanium alloy and stainless steel with cheap carbon steel and aluminum, solve the corrosion, scaling, oxidation and wear problems of the geothermal utilization system, and reduce equipment costs and operation and maintenance costs, Sugama (2006) take carbon steel as the base. Research has been carried out on coating materials with low cost, good thermal stability, corrosion resistance, scale resistance, oxidation resistance, abrasion resistance and self-healing. Sugama et al. (2006a, 2011) was coated with an intelligent and high performance Polyphenylenesulphide (PPS) composite coating system in carbon steel heat transfer equipment pipeline. The composite coating takes PPS as the base material, uses Polytetrafluoroethylene (PTFE) as the antioxidant of the coating, and uses micro-carbon fiber as the thermal conductivity and strengthening agent. dicalcium aluminate powder is the self-repairing filler, boehmite crystal is the wear-resistant filler, and crystalline zinc phosphate is the primer. The zinc phosphate primer can strengthen the adhesion between the coating and carbon steel, and inhibit the cathodic corrosion of the coated steel. Sugama (2006b) melted and dispersed nano-scale Montomorillonite (MMT) filler in PPS matrix and cooled to form PPS/MMT nanocomposites. When the nanocomposite is coated on carbon steel substrate, the coating with a thickness of 150 μm can protect carbon steel from the corrosion of hot geothermal water in the simulated geothermal environment at 300 °C. Sugama et al. (2006a, 2011) also developed and improved corresponding coating materials for the special requirements of anti-corrosion and anti-scale systems such as air-cooled condenser and soda separator. Aiming at the problem of corrosion scaling in geothermal well system during the drilling process, geopolymer (geopolymer) is developed, which is based on industrial by-products such as fly ash and slag, and is acid resistant and high temperature setting degree can be easily controlled based on inorganic polymer. Geopolymer (Geopolymer) is used as sealing material to enhance geothermal system and shows good application prospect.

In view of the corrosion problem of materials in geothermal power plant, Hu (2006) used low-temperature glaze spraying on metal surface and sintering to make inorganic glaze film for anti-corrosion, and studied the optimal sintering process of glaze film and its properties of acid, alkali, brine and adhesion resistance.

In order to improve the temperature resistance and water resistance of the geothermal water anticorrosive coating, Wang et al. (2009) prepared a normal temperature curing anticorrosive coating by adding a certain amount of mica iron oxide ash and mica into epoxy modified silicone resin with high silicon content. The optimized proportions of epoxy modified organosilicone resin, mica iron oxide ash, sericite, curing agent, dispersant and defoaming agent were determined. The structure and performance are stable in the simulated geothermal water corrosion liquid at 120 °C.

Soon afterwards, Chen et al. (2012) prepared micro-nano SiO_2 material coating on copper substrate by liquid deposition method. The chemical composition, surface morphology, film thickness, roughness, contact angle, surface free energy and electrochemical impedance spectra of these coatings were measured and characterized, and the corrosion and scaling characteristics of different coatings were evaluated. Saturated $CaCO_3$ water solution was used for scaling experiment, and simulated geothermal water was used for corrosion experiment. According to the water composition and configuration of No.2 geothermal well in Tianjin University, the hot water there is not easy to scale and corrosivity water system. The temperature of the solution during the experiment is less than or equal to 90 °C. The results show that, compared with the polished substrate without coating treatment, the scale formation rate of $CaCO_3$ on the surface of the liquid deposition SiO_2 coating is significantly reduced, and the corrosion of the coating is also inhibited to a certain extent. However, the corrosion resistance of the coating decreases after prolonged soaking.

The use of coating anticorrosion has not solved the problem of coating and substrate bonding due to the difference in yield stress between carbon steel and other metal substrates (especially organic coatings), which is the focus of attention in the future.

2.3 Chemical additives

Adding chemicals is still an effective anti-corrosion method for geothermal energy utilization. Green chemicals could be developed. However, from the point of view of environmental protection, this approach should be limited.

In some cases, adding chemical agents is an effective method of geothermal protection. Buyuksagis et al. (2013) investigated the anticorrosive properties of additives such as sodium tripolyphosphate and maleic anhydride for the Afyonkarahisar geothermal heating system in Turkey. However, from the perspective of environmental protection, its application should be limited.

2.4 Cathodic protection

Cathodic protection can keep the protected metal structure in a thermodynamic stable state and achieve effective corrosion control. Bandy and Van Rooyen (1984) reported the results of cathodic protection of carbon steel and AISI 316 stainless steel with zinc as sacrificial anode in simulated geothermal water at 90~150 °C. It was found that under cathodic protection, the weight loss of carbon steel was significantly reduced, and pitting corrosion of stainless steel was inhibited.

Li et al. (2004) studied the electrochemical performance of aluminum base sacrificial anode alloy (A1-Zn-In-Ga-Si) in geothermal water. The electrochemical sample adopts common pipe (API) J55 carbon steel. Three electrode system is used for electrochemical measurement. The experimental fluid is Dagang geothermal well water. The results show that AI-Zn-In-Ga-Si alloy has no obvious polarization tendency in the temperature range of 20 °C ~ 90 °C, and the self-corrosion potential is stable, which is suitable for J55 steel cathodic protection material in geothermal water wells.

Han (2010), aiming at the geothermal water temperature and low conductivity system, used electrolytic chloride method to prepare the non-liquid connected exposed Ag/AgCl reference electrode, which was used to study the applicability of geothermal water cathodic protection and corrosion protection. The response time and stability of the reference electrode in geothermal water (Tianjin University No. 2 geothermal well, outlet temperature 50 °C, pH 7.61) were tested. The results show that the Ag/AgCl reference electrode has stable self-corrosion potential, good reproducibility and short response time, which meets the requirements of being used as reference electrode in geothermal water.

Nie (2010) conducted corrosion electrochemical tests in geothermal water at 25 °C ~ 95 °C for Q235 steel and GB3091 steel, commonly used pipeline materials in the process of geothermal utilization. The results show that the corrosion resistance of pipeline steel is better than that of Q235 steel at different temperatures. The gap between the corrosion resistance of the two steel materials shrinks gradually with the increase of temperature. The corrosion is very serious at 85 °C and 95 °C, and there is a tendency of local corrosion. The total immersion aging experiment showed that within one week of the experiment, visible scale layer was formed on the surface of the material after 40 h, and the scale layer reached a relatively stable state in the middle stage of soaking, and the protection effect of the material was better at this temperature. At the later stage of immersion, the scale layer is destroyed and becomes unstable, and the corrosion of the material is intensified. The scale layer formed by pipeline steel at different temperatures is denser and more uniform than that of Q235 steel at the same temperature, so the corrosion resistance of pipeline steel is better than that of Q235 steel. The corrosion properties of Q235 steel in geothermal water at various temperatures with cathodic protection were studied and the electrochemical properties of different sacrificial anode materials were evaluated comprehensively. The results show that Al-Zn-In aluminum alloy is a good sacrificial anode material with the lowest self-corrosion potential, less polarization resistance and lower breaking potential.

However, the research on cathodic protection and anticorrosion of a geothermal system is still in its early phase of development. For geothermal utilization systems with specific high temperatures, there will be greater challenges in the selection of electrode materials.

2.5 Geothermal fluids pretreatment

The 450°C superheated steam contained acid gas and was highly corrosive when it condensed making it unsuitable for utilization without scrubbing. Hauksson et al. (2014) carried out material tests and scrubbing experiments at the IDDP-1well in the Krafla geothermal field in Iceland. The acid gas could effectively be scrubbed from the steam with water. The steam contained both silica dust and dissolved silica, which was effectively washed from the steam with wet scrubbing. This is a pretreatment approach.

In the IDDP-1 well of Krafla geothermal field in Iceland, 450 °C superheated water vapor contains a small amount of HCl, HF, H_2S, CO_2 and other acidic gases (Hauksson et al. 2014). If the steam is directly used for power generation, the water vapor condensate (pH=2.62) will seriously corrode equipment, pipelines and other systems. The flow of silicon particles in the gas and liquid phases also wears down the system. Therefore, the superheated water vapor in the geothermal field should be pretreated before geothermal utilization. Hauksson et al. (2014) used pure water, steam condensate, NaOH aqueous solution and cold groundwater to conduct wet washing experiments on geothermal water steam, and tested the corrosion and wear resistance of metal and ceramic coating materials. Pitting resistance nickel alloy Inconel 625 and Ni-Cr-Mo high nickel alloy are used as metal materials. Due to the plugging of silicon particles, the corrosion and wear resistance of the alloy need further study. However, attention should be paid not to excessive geothermal energy loss in the process of antiseptic pretreatment of geothermal fluid.

3. SCALING CONTROL TECHNIQUES

Because of the interaction relationship between corrosion and scaling, it is sometimes impossible to peel off each layer for research. At the same time, some anticorrosion methods can also be used to prevent fouling, such as anti-scaling coatings, chemical additives and geothermal fluid pretreatment. In this report, those methods will be described briefly, and other approaches will be illuminated in more detail.

3.1 Coatings

As mentioned above (subsection 2.2), Sugama et al. (2011) also carried out systematic researches on anti-scaling behavior of prepared coatings. PPS and PTFE-doped PPS coatings were coated on the heat transfer surface of carbon steel-based heat exchanger for scale prevention in geothermal environment. It was found that the anti-fouling property of the mixed PTFE was attributed to the isolation of oxide by the coating and the hydrophilicity of the doped PTFE surface.

Crude oil fouling on heat transfer surface (HTS) is very troublesome for the utilization of oilfield geothermal water in which slight crude oil exists. Surface hydrophilization via anodization, flow velocity enhancement and chemical addition three measures were adopted to solve the problem of crude oil soiling via weakening the adhesion force between crude oil and HTS as well as intensifying the interaction between water and crude oil. Obvious oil-fouling inhibition effects were presented. The effect was reflected by the decrease of fouling thermal resistance (Xu et al., 2017).

Sugama et al. (2002) soaked carbon steel plate, PPS coated steel plate and PTFE mixed PPS coated steel plate respectively in geothermal water containing silica at 200 °C for 7 days to investigate the deposition characteristics of silicon scale on the surface of carbon steel with Fe_2O_3 iron oxide layer (which has strong hydrophilicity to silica). The results show that the whole surface of the steel plate is deposited with a layer of silicon scale which is hard to be removed. PPS hydrophilic coating surface has silicon scale layer, but very thin (about 5 nm). This is due to the oxidation induced by geothermal water and the formation of sulfur oxide derivative layer on the surface of PPS, which is easy to induce the formation of silicon scale layer. The surface of PPS hydrophobic coating mixed with PTFE is not easy to oxidize due to the presence of antioxidant PTFE, which shows good hydrophobic and scale inhibition characteristics, suitable for geothermal environment containing silica. The micro-nano SiO_2 material coating prepared by Chen et al. (2012) also has certain geothermal scale resistance effect.

Wang et al. (2011a) prepared composite anti-scale coating by mixing zinc and graphite (Zn-C) alloy powder with epoxy-organosilicone resin, and placed the coating in aqueous solution formed by $CaCl_2$ and $NaHCO_3$. It is found that Zn-C alloy powder can release Zn^{2+} ions on the surface of composite coating, and inhibit the nucleation and growth of $CaCO_3$ crystals on the surface of composite coating. Therefore, $CaCO_3$ fouling is easy to be deposited in solution rather than on the surface of composite coating, and the crystal changes from calcite to aragonite. Wang et al. (2012) prepared an epoxy-organosilicon composite anti-scale coating containing Ni-Cu-Al alloy powder based on the principle of galvanic corrosion, and studied the scaling characteristics of the composite coating in simulated geothermal water, and compared the fouling characteristics of 304 stainless steel and epoxy-organosilicon composite coating. It is found that the Ni^{2+}, Cu^{2+} and Al^{3+} ions dissolved into the simulated geothermal water due to electrochemical corrosion can prevent the crystallization nucleation and growth of $CaCO_3$, and it is not easy to firmly adhere to the epoxy-silicone composite coating doped with Ni-Cu-Al alloy powder, more precipitates in solution, and has better scaling resistance.

Wu et al. (2010c, 2010d) prepared and investigated the corrosion resistance of PTFE-PPS coating at 80 °C static simulated geothermal water and the effect of preventing $CaCO_3$ fouling. They found that the surface had good corrosion resistance, and the scaling speed was significantly lower than that of 304 stainless steel and PPS coating. It is suggested to replace 304 stainless steel pipe in geothermal water environment. Zhu et al. (2010c) studied the corrosion and scaling characteristics of coatings based on PPS materials in the simulated geothermal water environment at 50 °C, and found that the scale inhibition effect of PPS-polyfluoroethylene propylene (FEP) coating is better than that of simple PPS coating and PPS-PTFE coating, and it also has a good anti-corrosion effect on the substrate.

In addition, Liu et al. (2010) invented a method to induce the repair of the inner surface coating of metal pipe fittings in geothermal water by using the nucleation and growth mechanism of scaling substances in geothermal water simulation. The scaling substance is applied to the crack of the coating in the pipeline, and the pipeline is immersed in simulated geothermal water for a certain time, so that the scaling substance filled is fully grown and thickened to fill in the crack, and the micro-crack is repaired. It is suitable for metal pipes with coating cracks caused by curing process and mechanical damage. It is also suitable for the repair of geothermal water pipes after a period of use. Inspired by the spontaneous mineralization process of dirt in geothermal water, Wang et al. (2011b) prepared cactus $CaCO_3$ coating by biomimetic self-assembly with stainless steel as the base in simulated geothermal water. The superhydrophobic properties of the coating were obtained by modifying the coating with a single molecular layer of sodium stearate low surface energy material.

In recent years, Yu et al. (2023) used aminopropyltriethoxy silane (KH-550) to modify graphene oxide (GO) and nano-silicon dioxide (nano-SiO_2), and used infrared spectroscopy (FT-IR), X-ray diffraction spectroscopy (XRD) and scanning electron microscopy (SEM) to characterize the structural changes before and after modification. The modified GO/SiO_2 composite coating was prepared. The hardness, contact Angle, foaming and shedding of the coating under acid-base conditions were analyzed. The corrosion behavior of the coating in simulated geothermal water environment was analyzed by means of rotating hanging film, scanning electron microscope (SEM) and polarization curve (Tafel), and its corrosion resistance was tested. The results show that the hardness, adhesion and acid and alkali resistance of the composite coating are excellent at the optimal ratio, and the corrosion resistance of the composite coating in the simulated geothermal water environment is significantly improved.

In summary, the development of geothermal fluid anti-scale material coating is one of the research hotspots at present. However, it is necessary to pay attention to the study of the anti-scale mechanism, as well as practical problems such as the binding force between coating and substrate.

3.2 Chemical additives

At present, the chemical inhibitor is still an option to inhibit fouling in geothermal utilization systems. However, it is better to use a non-toxic and environmentally friendly method.

The scaling inhibition by geothermal water acidification pH method can also be classified as this approach. With the decrease of pH value in geothermal water solution, the silicic acid polymerization process in geothermal water will be inhibited, thus slowing down the formation of amorphous or metal-based silicate scale. Adding acid to the geothermal water system is an effective way to reduce the pH value. However, adding acid will increase the corrosiveness of geothermal water. The research and practice show that by controlling the pH value less than 4.5, it can achieve a compromise between scale prevention and corrosion prevention.

The method of acidifying pH value of geothermal water to inhibit fouling can also be summarized into this category (Gallup, 2011; Amjad and Zuhl, 2010; Chalaev and Omarov, 1999). With the decrease of pH value in the geothermal water solution, the silicic acid polymerization process in the geothermal water will be inhibited, thus slowing down the formation of amorphous or metal-based silicate scale. Adding acid to a geothermal water system is an effective way to reduce pH. However, the addition of acid will make the geothermal water more corrosive. Gallup (2011) 's research and practice show that by controlling pH value less than 4.5, a compromise can be achieved to prevent scale and prevent corrosion aggravation.

Lu et al. (2020) developed a compound scale inhibitor ZGJ-6 using maleic anhydride, acrylic acid, hydroxyethyl methacrylate (MAH), EDTMPS, PASP and HDTMPA as raw materials, which can simultaneously and efficiently prevent the scale of calcium carbonate, calcium sulfate and barium strontium sulfate. When the dosage is 60 mg/L, the scale inhibition rate of calcium salt (calcium carbonate, calcium sulfate) scale reaches 94.52%, and that of barium strontium sulfate scale reaches 95.32%. The scale inhibition effect is better than that of conventional scale inhibitors. The field application experiment shows that after adding ZGJ-6 60 mg/L to the pipeline, the test piece is bright and no scaling, and the monthly average water injection under the same pressure decreases and the monthly average pressure increases by 2%~3%, which changes gently, fundamentally solving the scaling problem of the pipeline.

Besides, Li (2022) recently developed a new scale inhibitor that can inhibit calcium carbonate scaling of high-temperature geothermal fluids and its scale inhibition ratio can reach more than 96% at 150 °C to 200 °C.

During the same year, Ma et al. (2022) developed a scale inhibitor to inhibit the production of calcium carbonate scale in geothermal fluid inside geothermal wellbore, including a solution composed of polymaleic anhydride and polyaspartic acid heat exchange polyacrylic acid. The solution polymaleic anhydride, polyaspartic acid, polyacrylic acid volume ratio is (0.5-1.5): (0.5-1.5): (3.0-5.0). The fouling inhibitor is used to solve the problem of calcium carbonate scale forming on the inner wall of geothermal shaft blocking the shaft, and the environmental pollution is small.

Subsequently, Ma et al. (2023) selected four common green scale inhibitors (hydrolyzed polymaleic anhydride (HPMA), polyaspartic acid (PASP), polyepoxide acid (PESA), polyacrylic acid (PAA)) for compound experiment, and studied the scale inhibition performance of the compound inhibitor. Calcium ion complexometric titration was used to determine the scale inhibition rate. Under the condition of 80 °C, HPMA, PASP, PAA at the optimal volume ratio (HPMA: PASP: PAA=1:1:4), the scale inhibition rate can reach 97%, which is higher than that of single component. When the temperature is higher than 100 °C, the scale inhibition rate decreases, but at 210 °C, the scale inhibition rate can still reach 93%. Calcium carbonate can be used to inhibit the scale formation of high temperature geothermal fluid, which has the prospect of industrial application.

3.3 Geothermal fluid pretreatment

Pre-crystallization precipitation and filtration of geothermal water before entering the utilization systems can slow down the formation of scaling. Some plants are using this pre-filtration system.

Meanwhile, for geothermal water rejection process, it can be improved by pre-scale removal through membrane process and then inject it. Desalination pretreatments by membrane filtration include composite ultrafiltration and reverse osmosis membrane filtration, trace elements such as total soluble particles, boron, iron, fluorine and arsenic can be removed and discharged into surface water or used as drinking water. Phosphating scaling inhibitor is challenging to prevent scaling of the formation in membrane process, while hydrochloric acid acidification can prevent scale formation. Other methods, such as ion exchange and adsorption, can also be classified as such.

Bai et al. (2022) disclosed a geothermal fluid descaling and anti-scaling device, which is mainly used for the pre-treatment of geothermal water, which can effectively reduce the calcium and magnesium ions in geothermal water, reduce the concentration of calcium and magnesium ions in geothermal water, and effectively prevent scaling in the subsequent use of geothermal resources. Gao et al.(2022) disclosed a general geothermal fluid carrier induced descaling integrated device, which can fully remove calcium, magnesium and silicate ions in geothermal fluids by carrier descaling method, effectively reduce the drop of ions in geothermal fluids due to temperature and pressure, and calcium carbonate scale, silica scale, calcium sulfate scale and other substances caused by changes in the PH value of geothermal fluid.

Similarly, the pretreatment of geothermal fluids will inevitably result in the loss of geothermal energy.

3.4 Physical fields

Ultrasonic technology mainly uses the four principles of cavitation effect, activation effect, shear effect and inhibition effect to achieve the effect of anti-scaling and descaling, the main advantages are high descaling efficiency, simple equipment and small size, short reaction time, etc. (Wang, 2016).Yasuda et al.(2014) used the cavitation of ultrasound to change the concentration of silicic acid in geothermal water, and found that ultrasonic radiation under the conditions of 500 kHz and maximum pH = 8.5 increased the rate of silicic acid polymerization, resulting in the formation of large-diameter polymer particles, and the concentration of silicic acid in geothermal water decreased, thereby reducing the possibility of silica scale formation. Song et al.(2023) invented a geothermal fluid transport pipeline structure that can be cleaned independently, involving the field of geothermal fluid transportation technology. The structure includes ultrasonic generator, geothermal fluid delivery pipeline, microcomputer controller and shell, which can be independently descaled at a fixed frequency, without downtime, and the overall cost is relatively low.

High-frequency electromagnetic field technology mainly uses electromagnetic field to quickly dissolve calcium scale before formation, and at the same time enhances the molecular content of active water in the return water and affects the precipitation, crystallization and polymerization of scaling salts, so as to achieve the purpose of scale prevention (Gan and Shi, 1990).Chou and Lin (1989) studied the changes of water molecular structure and the solubility and polymerization of silicon under magnetic field in the laboratory, and investigated the silica scale suppression characteristics of strong magnetic field on geothermal water flowing in titanium tubes, and a week's experiment showed that the magnetic field significantly reduced the formation of dirt.

High-pressure water jet technology uses a high-pressure generator such as a high-pressure pump High-pressure water is generated, and the impulse force is used to attach dirt or well/pipe wall to the wall removal (Song, et al, 2014). Its advantages are thorough descaling and high efficiency, and the disadvantage is installation Large capacity, large water consumption, water treatment and other problems, closed pipelines System not applicable. This method can only remove relatively soft dirt, in Kenya geothermal power plants are the first to primarily adopt this method for turbines The dirt accumulated on the stage nozzle is removed (Cai et al, 2018).

Physical field anti-scaling is a non-contact method, which has a certain application prospect. However, attention should focus on the difficulties brought by physical fields such as amplification and noise effects.

3.5 Increasing pressure of flow system

An electric submersible pump can keep geothermal water in single liquid phase, keep CO_2 acid gas in liquid phase, prevent geothermal water flash, lower pH value, and keep carbonate in unsaturated state all the time, thus inhibiting the formation of calcium carbonate fouling. However, this method requires additional energy consumption.

3.6 Direct contact heat exchange

For geothermal fluid heat transfer systems, other methods can also be considered. For example, in order to avoid scaling of geothermal water heat exchanger with indirect heat transfer, direct contact heat exchanger, without heat transfer temperature difference and without reducing the initial temperature of geothermal utilization, can be considered (Bott and Gudmundsson, 1979).

3.7 Fluidized bed heat exchange

A fluidized bed heat exchanger can also be considered in the geothermal utilization systems because it is a kind of zero heat exchanger (Allen et al., 1976).

Luo et al. (2021) provide a self-cleaning tube heat exchange structure, add solid particles anti-scaling method, the technical scheme of the decentralized self-cleaning fluidized bed heat exchanger can better solve the existing heat exchanger equipment in the pipe process easy to appear adhesion scaling, after long-term use of the thermal resistance rises, heat exchange efficiency is significantly reduced and other problems. An attempt can be made to apply such heat exchangers to geothermal fluid systems.

3.8 Other methods

Other methods such as ion deposition can also be considered (Gallup et al., 2003).

Calcium, magnesium, sulfur, silicon and other ionic elements dissolved in water change in the environment, such as water is heated, pressurized or flows through valves, bends to produce turbulence, will first occur on the pipe wall crystallization reaction, forming insoluble in water hard scale. German Merus Company uses lasers and quantum technology to store molecular oscillations at the subatomic level of quantum rings, and when the ring-shaped processor is installed on the pipeline, the particles in the water are transformed into crystal nuclei that can make ions attach to form small molecules, and promote ions to crystallize on these crystal nuclei (Xie et al, 2023). The reacted crystals are no longer attached to the tube wall in solid form, but suspended in water in the form of flowing particles. At the same time, the scale that has formed on the pipe wall gradually separates from the pipe wall to achieve the purpose of anti-scaling, descaling and anti-corrosion.

4. CONCLUDING REMARKS AND FURTHER DIRECTIONS

The main approaches have briefly been summarized and advantages and disadvantages are reviewed.

Further research is required; helping with predicting corrosion and scaling trends of geothermal fluids and chemistry simulation, scaling mechanisms in geothermal fluids, strong combination forces between protection coatings and substrates, cathode protection and hybrid inhibition techniques and many more.

REFERENCES

Allen, C. A., Grimmett, E. S., Wagner, K. L.: Fluidized Bed Heat Exchangers for Geothermal Applications, *Proceedings,* 11th Intersociety Energy Conversion Engineering Conference, AIChE, New York, (1976).

Amjad, Z., Zuhl, R. W.: The role of water chemistry on preventing silica fouling in industrial water systems, International Corrosion Conference Series, NACE International-Corrosion 2010 Conference and Exposition, (2010).

Bandy, R., Van Rooyen, D.: Cathodic protection in simulated geothermal environments. *NACE(National Association of Corrosion Engineers)*, 1984, 20-31.

Bott, T. R., Gudmundsson, J. S.: The Problem of Fouling in the Utilisation of Geothermal Energy, International Conference on Future Energy Concepts, Institution of Electrical Engineers, London, (1979).

Buyuksagis, A., Erol, S.: The examination of Afyonkarahisar's geothermal system corrosion, *Journal of Materials Engineering and Performance*, **22**, (2013), 563-573.

Bai Jingmei, Xie Bo, Wang Zhanyong, et al. A geothermal fluid scale removal and anti scaling device: CN216837345U [P], 2022.

Cai, P. P., Li, W. P., Chen, Y. C., Zhu, L. Q., Hu, W.: Corrosion and Scaling on Carbon Steel and Galvanized Steel Pipe in Simulated Geothermal Water, *Corrosion and Protection*, **30**, (2009), 454-458.

Cai Zhengmin, Li Gang, Li Yuan, et al. Daily maintenance of scaling problem in Kenya geothermal power station [J]. Technology Perspective, 2018 (25): 41-43.

Chalaev, D. R., Omarov, M. A.: Methods of struggle with calcium carbonate overgrowth of geothermal heat equipment, *Transactions-Geothermal Resources Council*, 23, (1999), 397-398.

Chen, W., Li, W. P., Liu, H. C., Zhu, L. Q.: Corrosion and Scaling of the Galvanized Steel Pipe in Flowing Geothermal Water, *Corrosion and Protection*, **31**, (2010), 600-603+614.

Chen, N., Liu, M., Zhou, W. D.: Fouling and corrosion properties of SiO_2 coatings on copper in geothermal water, *Industrial Engineering Chemistry Research*, **51**, (2012), 6001-6017.

Chou S F, Lin S C. Magnetic effects on silica fouling[J]. ASME, Heat Transfer Division, 1989, 108: 239-244.

Gallup, D. L.: Brine pH modification scale control technology. 2. A review, *Transactions-Geothermal Resources Council*, **35**, (2011), 609-614.

Gallup, D. L., Sugiaman, F., Capuno, V., Manceau, A.: Laboratory Investigation of Silica Removal from Geothermal Brines to Control Silica Scaling and Produce Usable Silicates, *Applied Geochemistry*, **18**, (2003), 1597-1612.

Gan Ansheng, Shi Peng. The effect of alkalinity on the anti scaling effect of magnetized water [J] Industrial Water Treatment, 1990, 10 (6): 11-12.

Gao Jun, Feng Biao, Yue Zhiwei, et al A universal geothermal fluid carrier induced descaling integrated device: CN202210584706.1 [P]. 2022.

Gao, X. D., Cheng, G. P., Wang, Z. Y.: The application of A.T.O metal-ceramics coating in corrosion protection of the geothermic water pipeline, *Corrosion &Protection*, **22**, (2001), 64-65+86.

Han, J.: Study on corrosion resistance of Q235 and GB3091 steel in Tianjin geothermal water, Tianjin University, (2010), 1-70.

Hauksson, T., Markusson, S., Einarsson, K., Karlsdóttir, S. N., Einarsson, A., Möller, A., Sigmarsson, Þ.: Pilot Testing of Handling the Fluids from the IDDP-1 Exploratory Geothermal Well Krafla N.E. Iceland. *Geothermics*, **49**, (2014), 76-82.

Hu, C.: The optimizing of geothermal electric factory equipments' material & The research of the sinter manufacture and capability of anti-corrosion ceramic glaze film, Chengdu, Sichuan University, (2006), 1-81.

Klapper, H. S., Bäßler, R., Sobetzki, J., Weidauer, K., Stürzbecher, D.: Corrosion resistance of different steel grades in the geothermal fluid of Molasse Basin, *Materials and Corrosion*, **64**, (2013), 764-771.

Li, C. F., Wang, B., Dai, J. L., Liu, D. H., Luo, J. M.: Study of the Electrochemical Performance of a New Type of Al-Zn-In-Ga-Si Anode in Terrestrial Heat Water of Different Temperature, *Journal of Southwest Petroleum Institute*, **26**, (2004), 56-58.

Li, S.: A simple model for the location of geothermal wellbore flow scaling and scale inhibitor exploration, Tianjin University, (2022), 1-83.

Liu, H. C., Li, W. P., Wang, G. G., Zhai, J. Y., Guan, Q., Zhu, L. Q.: The utility model relates to a method of induced repair of inner surface coating of metal pipe fittings in geothermal water by using scale forming substances in geothermal water, China: CN101929589A. 2010-12-29.

Liu, M.Y., and Zhu, J.L. Progress of Corrosion and Fouling Prevention in Utilization of Geothermal Energy, *Chemical Industry and Engineering Progress*, **30**, (2011), 1120-1123.

Liu, M.Y.: A Review on Controls of Corrosion and Scaling in Geothermal Fluids, *Advances in New and Renewable Energy*, **3**, (2015), 38-46.

Lu, J. P., Shen, Y. B., Wang, J., Li, J. H., Xie, Y., Zhou, Y.: Scaling analysis of oilfield water injection well pipeline and development and application of scale inhibitor, *Applied Chemical Industry*, **49**, (2020), 2555-2559+2580.

Luo Chengjing Yan, Gu Junmin, Pei Yixia, et al. Self cleaning tube heat exchange structure, fluidized bed heat exchanger, and anti scaling method: CN112710175A [P], 2021.

Ma, Y. L., Yan, J. J., Liu, M. Y., Liu, M. Y., Sun, S. Y., Zhang, J. P., Li, S.: The utility model relates to a scale inhibitor that inhibits calcium carbonate scale generation in geothermal fluid inside geothermal wellbore, CN202210878834.7, (2022).

Ma, Y. L., Yan, J. J., Liu, M. Y., Sun, S. Y., Zhang, J. P., Li, S., Liu, M. Y.: Compound Scale Inhibitors for Calcium Carbonate in High Temperature Geothermal Fluids, *Advances in New and Renewable Energy*, **11**, (2023), 8-13.

Mundhenk, N., Huttenloch, P., Bäßler R, Kohl, T., Steger, H., Zorn, R.: Electrochemical study of the corrosion of different alloys exposed to deaerated 80°C geothermal brines containing CO_2, *Corrosion Science*, **84**, (2014), 180-188.

Mundhenk, N., Huttenloch, P., Kohl, T., Steger, H., Zorn, R.: Metal corrosion in geothermal brine environments of the Upper Rhine graben-Laboratory and on-site studies, *Geothermics*, **46**, (2013a), 14-21.

Mundhenk, N., Huttenloch, P., Sanjuan, B., Kohl, T., Steger, H., Zorn, R.: Corrosion and scaling as interrelated phenomena in an operating geothermal power plant, *Corrosion Science*, **70**, (2013b), 17-28.

Nie, X. H.: The performance of reference electrode and the sacrificial anodes in low conductivity water at room temperature, Tianjin University, (2010), 1-64.

Oner S G, Kabay N, Güler E, et al. A comparative study for the removal of boron and silica from geothermal water by cross-flow flat sheet reverse osmosis method[J]. Desalination, 2011, 283: 10-15.

Pfennig, A., Wiegand, R., Wolf, M., Bork, C. P.: Corrosion and corrosion fatigue of AISI 420C (X46Cr13) at 60°C in CO_2-saturated artificial geothermal brine, *Corrosion Science*, **68**, (2013), 134-143.

Song, J.C., Liu, M.Y., Sun, X.X., Wang, J.S., Zhu, J.L.: Antifouling and Anticorrosion Behaviors of Modified Heat Transfer Surfaces with Coatings in Simulated Hot-dry-rock Geothermal Water, *Applied Thermal Engineering*, **132**, (2018), 740–759.

Song Jiahui, Liu Changlin, Xu Shengtao, et al. High pressure water jet cleaning technology and its application in pipeline descaling [J] Chemical Equipment and Pipeline, 2014, 51 (5): 79-82.

Song Jinyu, Zhang Xiaotong, Song Liang, et al. A geothermal fluid delivery pipeline structure that can independently remove scale: CN202310063454.2 [P]. 2023.

Sugama, T.: High-performance coating materials: final report, Brookhaven National Laboratory, Washington, D.C, (2006a).

Sugama, T.: Polyphenylenesulfied/montomorillonite clay nanocomposite coatings: Their efficacy in protecting steel against corrosion, *Materials Letters*, 60, (2006b), 2700-2706.

Sugama, T., Butcher, T., Ecker, L.: Experience with the Development of Advanced Materials for Geothermal Systems. *Ceramic Transactions*, **224**, (2011), 389-401.

Sugama, T., Gawlik, K.: Anti-silica fouling coatings in geothermal environments, *Materials Letters*, **57**, (2002), 666-673.

Tian Tao, Chen Yulin, Yao Jie. Prediction of water scaling in geothermal reinjection systems [J] Groundwater, 2011, 33 (6): 27-29.

Tomaszewska B, Bodzek M. Desalination of geothermal waters using a hybrid UF-RO process. Part I: Boron removal in pilot-scale tests[J]. Desalination, 2013, 319: 99-106.

Tomaszewska B, Bodzek M. Desalination of geothermal waters using a hybrid UF-RO process. Part II: Membrane scaling after pilot-scale tests[J]. Desalination, 2013, 319: 107-114.

Wang, G. G., Zhu, L. Q., Liu, H. C., Li, W. P.: Galvanic corrosion of Ni–Cu–Al composite coating and its anti-fouling property for metal pipeline in simulated geothermal water, *Surface & Coatings Technology*, **206**, (2012), 3728-3732.

Wang, G. G., Zhu, L. Q., Liu, H. C., Li, W. P.: Self-assembled biomimetic superhydrophobic $CaCO_3$ coating inspired from fouling mineralization in geothermal water, *Langmuir*, **27**, (2011b), 12275-12279.

Wang, G. G., Zhu, L. Q., Liu, H. C., Li, W. P.: Zinc-graphite composite coating for anti-fouling application, *Materials Letters*, **65**, (2011a), 3095-3097.

Wang, H. L., Qiao, N., Wei, G.: Study of an anti-corrosive coating for pipelines in geothermal water, *Journal of Beijing University of Chemical Technology (Natural Science)*, **36**, (2009), 61-64.

Wang Zhihua. Research on the mechanism of ultrasonic technology for descaling and its application in heat exchangers [D] East China University of Science and Technology, 2016.

Wu, K. H., Li, W. P., Liu, H. C., Zhu, L. Q.: Effect of temperature on corrosion and scaling of galvanized steel pipe in simulated geothermal water, *Journal of Beijing University of Aeronautics and Astronautics*, **36**, (2010a), 1239-1243.

Wu, K. H., Li, W. P., Liu, H. C., Zhu, L. Q.: Scaling and electrochemical corrosion behavior of 304 stainless steel pipes in a simulated geothermal water environment, *Journal of University of Science and Technology Beijing*, **31**, (2009), 1263-1269.

Wu, K. H., Zhu, L. Q., Li, W. P., Liu, H. C.: Effect of Ca^{2+} and Mg^{2+} on corrosion and scaling of Galvanized steel pipe in simulated geothermal water, Corrosion Science, **52**, (2010b), 2244-2249.

Wu, K. H., Zhu, L. Q., Li, W. P., Liu, H. C.: Anti-scaling characterization of PTFE/PPS composite coating in the geothermal water environment, *Acta materiae Compositae Sinica*, **27**, (2010c), 47-54.

Wu, K. H., Li, W. P., Liu, H. C., Zhu, L. Q.: Nucleation behavior of CaCO3 scale on the surface of PTFE/PPS composite coatings in geothermal water environments, *Journal of University of Science and Technology Beijing*, **32**, (2010d), 1321-1326.

Xie Yingchun, Li Yiman, Wang Zongman, et al. Research progress on anti scaling and descaling technologies in the development and utilization of geothermal fluids [J]. New Energy Progress, 2023, 11 (1): 21-28.

Xu, Y., Liu, M.Y., Zhu, J.L., Li, H.T., Zhou, W.D.: Novel Methods of Oil Fouling Inhibition on Surface of Plate Heat Exchanger in Simulated Oilfield Geothermal Water, **113,** (2017), 961-974.

Xu, Y., Liu, M.Y.: Corrosion Behavior of Polysiloxane-ferroferric Oxide Coating Coated on Carbon Steel in NaCl Solution and Geothermal Water, *Geothermics*, **70**, (2017), 339-350.

Yasuda K, Takahashi Y, Asakura Y. Effect of ultrasonication on polymerization of silicic acid in geothermal water[J]. Japanese Journal of Applied Physics, 2014, 53: 07KE08-1-3.

Yu, R., Lei, H., Zhou, X. D., Zhang, C.: Study of Corrosion Resistance of Modified GO/SiO_2 Epoxy Coatings in Simulated Geothermal Water, *Contemporary Chemical Industry*, **52**, (2023), 87-91+96.

Yu, R., Lu, S. W., Yan, D., Chen, X.: Study on Corrosion Scaling Behavior and Kinetics of Metal Pipes in Simulated Geothermal Water, *Contemporary Chemical Industry*, **50**, (2021), 535-540+544.

Yun Zhihan, Ma Zhiyuan, Zhou Xin, et al. The Effect of Carbonate scaling on the recharge of medium and low temperature geothermal fluids: A case study of Xianyang geothermal field [J]. Groundwater, 2014, 36 (2): 31-33.

Zhu, L. Q., Chen, W., Li, W. P., Liu, H. C.: Experiment of stainless steel corrosion and scaling in geothermal water supply pipeline, *Journal of Jiangsu University (Natural Science Edition)*, **31**, (2010a), 292-295.

Zhu, L. Q., Wu, K. H., Li, W. P., Liu, H. C.: Scaling and Corrosion of 304 Stainless Steel and Galvanized Steel Pipes in a Simulated Geothermal Water Environment, *Acta Physico-Chimica Ainica*, **26**, (2010b), 39-46.

Zhu, L. Q., Wu, K. H., Li, W. P., Liu, H. C.: Anti-scaling performance of PPS composite coatings in a circulated and simulated geothermal water environment, *Journal of Functional Matrials*, **41**, (2010c), 1046-1049.