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Research Paper

Antifouling and anticorrosion behaviors of modified heat transfer surfaces with coatings in simulated hot-dry-rock geothermal water

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HIGHLIGHTS

- SiO_2, SiO_2-FPS and TiO_2 coatings on SS304 substrates were prepared.
- Roughness and microscopic roughness heat transfer surfaces were suggested.
- A roughness coefficient was suggested to evaluate the microscopic roughness degree.
- Fouling on coatings in simulated hot-dry-rock geothermal water at 423 K was studied.
- Antifouling and anticorrosion mechanisms of these coatings were revealed.

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ABSTRACT

Fouling and corrosion of heat exchanger and pipeline caused by geothermal water is one of the bottlenecks that restrict the efficient utilization of geothermal energy. To mitigate fouling and corrosion of heat transfer surfaces in hot-dry-rock geothermal water with the temperature of 423.15 K, 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. The effects of surface morphology, roughness and surface free energy on fouling deposition rate were studied. Based on the characteristics of two-dimension roughness profiles of surfaces, surfaces were classified into rough surface and microscopic rough surface. For microscopic rough surface, roughness coefficient was defined, which could preferably describe the characteristic of the microscopic roughness degree. The fouling and corrosion behaviors of different coatings and AISI304 stainless steel substrate in simulated hot-dry-rock geothermal water at about 423.15 K were investigated systematically under forced convection heat transfer. The results showed that the liquid phase deposition TiO_2 and sol-gel TiO_2 coatings had favorable antifouling property in the calcium bicarbonate type simulated geothermal water. The sol-gel SiO_2 and SiO_2-FPS coatings had better performances of antifouling and anticorrosion in moderately corrosive hot-dry-rock geothermal water with total dissolved solids (TDS) of about 7000 mg/L.

1. Introduction

As useful amounts of energy from the large, ubiquitous resource under the earth, the geothermal energy from hot-dry-rock (HDR) has been developed for more than forty years [1]. The extraction of geothermal energy from HDR requires the circulation of fluids through fractured rock masses between two boreholes [2]. So far, the researches of HDR were mainly focused on the geochemical evolution of hydrothermal systems [3,4] and on the water-rock interactions by means of laboratory or in-situ experiments [5–7]. As well known, fouling and corrosion problems of heat exchanger are the crucial challenges in the process of geothermal energy utilization [8–10]. Fouling on the heat transfer surface of heat exchanger will make both thermal resistance and pressure drop increase, then increasing the initial capital investment and operating cost [11]. Besides, corrosion of heat exchanger mainly includes pitting and crevice corrosion of metal [10], which reduces the service life of heat exchanger. Fouling and corrosion also exist in the utiliza-

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Notation

R_a	arithmetical mean deviation of evaluated profile, μm
R_z	mean roughness depth, μm
R_t	profile total height, μm
R_{pm}	mean value of the maximum heights of profile peaks in "n" sampling lengths, μm
R_s	mean value of the widths of profile peaks in a sampling length, μm
R_{sm}	mean value of the widths of profile elements, μm
R_z	ten point height of microcosmic irregularities, μm
y_{pi}	five highest peak heights of the profiles in a sampling length, μm
y_{vi}	five lowest valley depths of the profiles in a sampling length, μm
I	roughness coefficient, dimensionless
K	surface texture parameter, dimensionless
U	total heat transfer coefficient, W·m^{-2}·K^{-1}
R_f	fouling resistance, m^2·K·W^{-1}
ΔP	differential pressure at the two ends of double-pipe heat exchanger, kPa
K_f	total heat transfer coefficient of the heat transfer surface having fouling, W·m^{-2}·K^{-1}
K_0	total heat transfer coefficient of clean surface, W·m^{-2}·K^{-1}
E	corrosion potential, V
I_c	corrosion current density, A·m^{-2}
R_p	corrosion resistance, Ω·cm^2
CR	annual corrosion rate, mm/a
R_s	solution resistance, Ω·cm^2
Q_c	capacitance of coating, μF·cm^{-2}
R_{po}	electrical resistance of coating, Ω·cm^2
Q_{dl}	double layer capacitance, μF·cm^{-2}
R_t	charge transfer resistance, Ω·cm^2
n_1	power of constant phase element of coating, dimensionless
n_2	power of constant phase element of double electric layer, dimensionless

Abbreviations

HDR	hot-dry-rock
PTFE	Polytetrafluoroethylene
LPD	liquid phase deposition
SS	stainless steel
FPS	heptadecafluorodecyltri-isopropoxysilane, $C_{19}H_{25}F_{17}O_3Si$
V	vessel or storage tank
F	Y-type filter
P	pump
CWM	water-cooling machine
SV	sampling valve
HE	heat exchanger
CA	contact angle
EIS	electrochemical impedance spectroscopy
EEC	equivalent electrical circuit
CPE	constant phase element

Greek symbols

γ_s	surface free energy, mJ·m^{-2}
γ_s^{LW}	dispersion (Lifshiz-van der Waals) component of surface free energy, mJ·m^{-2}
γ_s^{AB}	nondispersion (Lewis acid-base) component of surface free energy, mJ·m^{-2}
γ^-	electron donor component of acid-base interaction energy, mJ·m^{-2}
γ^+	electron acceptor component, mJ·m^{-2}
θ	contact angle, °
θ_W	contact angle of doubly distilled water against surface, °
θ_F	contact angle of formamide against surface, °
θ_D	contact angle of diiodomethane against surface, °
β_a	Tafel slope of anode, V·dec.$^{-1}$
β_c	Tafel slope of cathode, V·dec.$^{-1}$

tion system of HDR geothermal energy, and may be even more serious under certain conditions due to higher temperature and peculiar fluid composition of HDR hydrothermal reservoir [12].

Several measures have been adopted to avoid fouling and corrosion in heat exchanger referring to the types and severities of fouling and corrosion [13–16]. In order to avoid fouling, the techniques including scale inhibitor [17], surface modification [18], mechanical cleaning [13], and electromagnetic treatment [19,20] had been employed. Besides, methods including chemical additives [14,17,21], alloy materials [22], surface treatment and coatings [15,16] had been put to use for anticorrosion. Among them, the modification of heat transfer surface and coatings are identified as the most promising techniques [18], which perhaps possess both of antifouling and anticorrosion properties. There are many factors that affect the fouling generation, adhesion, and growth on heat transfer surface such as surface property, temperature difference, supersaturation degree and fluid flow characteristics [18]. However, other parameters are not comfortable to change except for the heat transfer surface property in some special heat transfer processes such as the utilization system of HDR geothermal energy.

To improve the antifouling property of heat transfer surface, the focus of modern antifouling strategies is mainly put on the physicochemical properties of the heat transfer surface contacting with fluids [18,23]. It is generally believed that the adhesion of fouling is significantly influenced by the surface free energy of surface material. Reduction of surface free energy can mitigate the fouling formation on heat transfer surface [18,24]. Hence, several kinds of surface modification techniques were employed to reduce the surface free energy [18,23], then to extend the induction period. However, owing to the effects of surface roughness, contact angle, as well as surface geometry at microscopic and macroscopic scales, the fouling deposit rate is not only determined by the surface free energy. For instance, Zettler et al. [25] investigated the influence of surface properties on the CaSO$_4$ crystallization fouling in corrugated plate heat exchanger made of AISI 316 stainless steel. The plate heat exchanger consisted of four plates forming two channels for hot water and one central channel for heated CaSO$_4$ solution, and the effective plate length and width were 0.3960 m and 0.1000 m, respectively. The tests were conducted with the solution temperature of 51.5 °C in a solution tank and the solution flow velocity of 0.35 m/s. It was found that although the total surface energy of TaC-treated plate is the lowest of all the investigated plates, the fouling resistance of TaC-sputtered plates increased rapidly, resulting in a high value of the pressure drop, because of the higher measured surface roughness of TaC-treated plates than that of the other plates. Zhao et al. [26] studied the effects of surface free energies of Ni-Cu-P-PTFE coatings on the adhesion of microbial and mineral deposits. The crystalline fouling test was carried out in a pool boiling test rig containing 1.2 g/L CaSO$_4$ solution at atmospheric pressure. It was concluded that when the surface free energy of the coated surfaces was in the range of