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Novel methods of oil fouling inhibition on surface of plate heat exchanger in simulated oilfield geothermal water

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ABSTRACT

Crude oil fouling on heat transfer surface (HTS) is a very troublesome problem for the utilization of oilfield geothermal water in which slight crude oil exists. The deposition of crude oil on HTS will decrease heat transfer efficiency, increase the pressure drop of fluid flow, and even block flow channel. In this study, 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. Contact angle measurement and microscopic morphology study were conducted on the highly-hydrophilic surface fabricated via anodization. Oil-soiling experiments accompanied with three mentioned techniques were carried out in plate heat exchanger (PHE) apparatus, and obvious oil-fouling inhibition effects were presented. The effect was reflected by the decrease of fouling thermal resistance. For 110 °C simulated oilfield geothermal water, which contained approximate 1 vol.% crude oil soiling, with 0.24 m/s flow velocity, the fouling induction period extended to 500 min from 0 min when surface hydrophilization was applied through anodization. In anodized PHE with titanium plates, the value of fouling thermal resistance decreased by about 77.8% when the flow velocity of 110 °C hot fluid without chemical additive increased from 0.24 m/s to 0.72 m/s, and the value could be reduced by around 62.5% after the addition of 0.29 g/L chemical additive LIUXU-10 mainly composed of sodium dodecyl sulfonate (SDS), when the flow velocity of 110 °C hot fluid was 0.12 m/s. Compared with PHE with titanium plates (Ti-PHE) at 0.24 m/s hot fluid flow velocity, the fouling thermal resistance decreased by approximate 93.3% when the Ti-PHE was anodized to be highly hydrophilic, the hot fluid flow velocity increased to 0.6 m/s and 0.87 g/L chemical additive was added.

1. Introduction

Due to the excessive exploitation of fossil energy such as petroleum and natural gas, people start to seek newer substituted energy source. With the advantages of wide distribution, abundant reserves, low cost and low contamination, geothermal energy gradually becomes a kind of potential new energy [1]. While scaling or fouling in heat exchanger is a ubiquitous problem existing in the utilization of geothermal source. Fouling problems, which cause severe decrease of heat transfer coefficient in heat exchanger, exist in about 90% heat exchangers [2] and bring economic loss which takes up to 0.25% of GNP (Gross National Product) at developed country [3]. Therefore, it is very necessary to understand the process of fouling deposition and exploit new methods to solve the heat exchanger fouling problems.

Plenty of researches have been focused on the fouling behaviors through experiments or modelling [4–8]. Besides, many antifouling methods have also been attempted to mitigate the fouling attachment on HTS. These methods include electromagnetism antifouling technology [9–11], ultrasonic antifouling technology [12,13], optimizing operation parameters or HTS textures [5,14,15], physical or chemical addition [16–19], and surface coating [20–34]. For electromagnetism antifouling technology, the scaling will become fragmented and loose under electric field, which contributes to the fouling mitigation on HTS [11]. For ultrasonic antifouling

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Nomenclature

A_0	effective heat transfer area (m^2)
A'	projected heat transfer area (m^2)
C_p	fluid specific heat capacity at constant pressure (J/(kg·K))
$C_{p,h}$	hot fluid specific heat capacity at constant pressure (J/(kg·K))
$C_{p,c}$	cold fluid specific heat capacity at constant pressure (J/(kg·K))
C, K_p, z	constants
D_p	port diameter (mm)
d_e	equivalent diameter of fluid channel in PHE (m)
f_p	mean cross-sectional flow area per channel (m^2)
f	friction coefficient
H	corrugation amplitude or mean channel spacing (mm)
h	mean flow channel spacing (m)
L_v	vertical distance between centers of ports (mm)
L_h	horizontal distance between centers of ports (mm)
L_w	plate width inside gasket (mm)
L_{eff}	effective flow length in PHE (m)
l	length of fluid flow (m)
M	number of passes in PHE
P	corrugation pitch (mm)
Pr_f	fluid Prandtl number
Pr_h	hot fluid Prandtl number
Pr_c	cold fluid Prandtl number
Q_c	heat transfer load of cold fluid (W)
R_f	fouling thermal resistance ((m^2·K)/W)
Re_f	fluid Reynolds number
Re_h	hot fluid Reynolds number
Re_c	cold fluid Reynolds number
R_a	arithmetical mean deviations of profile (μm)
$T_{h,i}$	hot fluid inlet temperature (°C)
$T_{h,o}$	hot fluid outlet temperature (°C)
$T_{c,i}$	cold fluid inlet temperature (°C)
$T_{c,o}$	cold fluid outlet temperature (°C)
U	overall heat transfer coefficient (W/(m^2·K))
U_0	initial overall heat transfer coefficient (W/(m^2·K))
V	volumetric flow rate of fluid (m^3/s)
V_h	volumetric flow rate of hot fluid (m^3/s)
v_h	flow velocity of hot fluid (m/s)
V_c	volumetric flow rate of cold fluid (m^3/s)

Greek symbols

δ	plate sheet thickness (mm)
Φ	enlargement factor
ρ	fluid density (kg/m^3)
ρ_h	density of hot fluid (kg/m^3)
ρ_c	density of cold fluid (kg/m^3)
η	experimental relative error of overall heat transfer coefficient (%)
α	convective heat-transfer coefficient (W/(m^2·K))
α_h	convective heat-transfer coefficient of hot fluid (W/(m^2·K))
α_c	convective heat-transfer coefficient of cold fluid (W/(m^2·K))
v	fluid flow velocity in PHE channel (m/s)
v_h	hot fluid flow velocity in PHE channel (m/s)
μ_f	fluid viscosity in flow channel of PHE (Pa·s)
μ_w	fluid viscosity at wall temperature in PHE (Pa·s)
μ_h	hot fluid viscosity in flow channel of PHE (Pa·s)
μ_c	cold fluid viscosity in flow channel of PHE (Pa·s)
λ_f	fluid thermal conductivity (W/(m·K))
λ_h	hot fluid thermal conductivity (W/(m·K))
λ_c	cold fluid thermal conductivity (W/(m·K))
λ	thermal conductivity of titanium (W/(m·K))
ΔP	pressure drop between hot fluid outlet and hot fluid inlet (kPa)
ΔP_f	friction pressure drop of hot fluid (Pa)
ΔP_h	flow channel pressure drop of hot fluid in PHE without fouling deposition (Pa)
$\Delta P'_h$	flow channel pressure drop of hot fluid in PHE with fouling deposition (Pa)
τ_f	friction shear stress (N)
ΔG_{SWO}^{T}	interfacial free energy between solid surface and oil surface in aqueous medium (mJ/m^2)
ΔG_{SO}^{T}	interfacial free energy between solid surface and oil surface (mJ/m^2)
ΔG_{OO}^{T}	interfacial free energy between oil surface and oil surface (mJ/m^2)
θ_1	water contact angle on substrate (°)
θ_2	glycerol contact angle on substrate (°)
θ_3	diiodomethane contact angle on substrate (°)
θ_{OW}	intersection angle between solid-oil interfacial tension and oil-water interfacial tension (°)
θ_{PTFE}	contact of water with the addition of LIUXU-10 on PTFE (°)
θ_{PMMA}	contact of water with the addition of LIUXU-10 on PMMA (°)
γ_{S}^{LW}	Lifshitz-van der Waals component of surface energy for substrate (mJ/m^2)
γ_{W}^{LW}	Lifshitz-van der Waals component of surface tension for water (mJ/m^2)
γ_{O}^{LW}	Lifshitz-van der Waals component of surface tension for oil soiling (mJ/m^2)
γ_{S}^{+}	electron-acceptor component of surface energy for substrate (mJ/m^2)
γ_{W}^{+}	electron-acceptor component of surface tension for water (mJ/m^2)
γ_{O}^{+}	electron-acceptor component of surface tension for oil soiling (mJ/m^2)
γ_{S}^{-}	electron-donor component of surface energy for substrate (mJ/m^2)
γ_{W}^{-}	electron-donor component of surface tension for water (mJ/m^2)
γ_{O}^{-}	electron-donor component of surface tension for oil soiling (mJ/m^2)
γ_{SW}	solid-water interfacial tension (mN/m)
γ_{SO}	solid-oil interfacial tension (mN/m)
γ_{OW}	oil-water interfacial tension (mN/m)
γ_{water}^{LW}	Lifshitz-van der Waals component of surface tension for water with the addition of LIUXU-10 (mJ/m^2)
γ_{water}^{+}	electron-acceptor component of surface tension for water with the addition of LIUXU-10 (mJ/m^2)
γ_{water}^{-}	electron-donor component of surface tension for water with the addition of LIUXU-10 (mJ/m^2)
γ_{water}	surface tension for water with the addition of LIUXU-10 (mN/m)
γ_{PTFE}^{LW}	Lifshitz-van der Waals component of surface energy for PTFE (mJ/m^2)
γ_{PMMA}^{LW}	Lifshitz-van der Waals component of surface energy for PMMA (mJ/m^2)
γ_{PMMA}^{-}	electron-donor component of surface energy for PMMA (mJ/m^2)

Subscripts

c	cold fluid
p	constant pressure
e	equivalent
v	vertical
h	horizontal/hot fluid