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Research Paper

Experimental research of descaling characteristics using circumfluence dilution and uniform-temperature perturbation in a vacuum furnace

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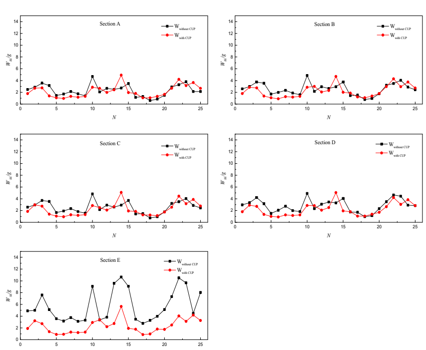
HIGHLIGHTS

- CUP can reduce pipe scaling quality and achieve scaling distribution uniformity along the pipeline.
- CUP can make the optimum and average descaling cycle deferred rate increase by 102.2% and 73.4%, respectively.
- The optimum parameters are obtained.

GRAPHICAL ABSTRACT

Fig. 1. Contrast of the scaling amount of each section after 8 h. Five canals were sequentially named as A, B, C, D, and E starting from the inlet section. A total of 25 comparative experiments with and without circumfluence dilution and uniform-temperature perturbation (CUP) were conducted to obtain the each section of pipe scaling mass. Because of circulation of the water with high temperature and low ion concentration from heat exchange tubes outlet, the water temperature of the inlet of the heat exchange tubes increases, the scaling reaction in the front section of the tube increases. This method mitigates the scaling degree of the rear section of the heat exchange tubes, and the scaling layer tends to be uniformly distributed along the tube. Even the deferred rate is unchanged, the descaling cycle extends, as shown in Fig. 1.



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ABSTRACT

Vacuum furnace corrosion and scaling problem have seriously constrained the normal operation of the oil mixing transmission system in China. This study explores the effects of descaling in vacuum furnace tubes at the oil mixing transportation system with circumfluence dilution and uniform-temperature perturbation (CUP) to reduce scaling ion density and improve water velocity in heat exchange tubes and scaling distribution uniformity along the tubes. Applying circumfluence by-path tube (CBT) enables a part of the outlet water from the heat exchange tubes to flow back to the inlet and achieve improved water velocity in heat exchange tubes. The improved water velocity in heat exchange tubes enhanced the scouring of the wall layer, thereby reducing the scaling quality and scaling ion density in hot water because of recirculation. This method improved the average temperature of water in the heating process under the same outlet temperature of the vacuum furnace. Scaling sediments were transferred to the tube entrance section, thereby reducing the intensity of the scaling sediments congregated in the outlet segment of the tube. These three measures slowed down the scaling and improved the uniformity of scaling along the pipeline of the vacuum furnace. Moreover, scaling was distributed on the surface of the vacuum furnace

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pipeline, which extended the boiler cycle. Scaling weighing was used to investigate the effects of ion concentration, unboiled water velocity, heat exchange temperature difference, and circulation rate on descaling. Experimental results show that CUP has improved the optimum descaling cycle deferred rate and average descaling cycle deferred rate by 102.2% and 73.4%, respectively. CUP can effectively extend the scaling time of the boiler tube and maintenance cycle, thereby improving the operating efficiency of the boiler and reduce operating costs.

Nomenclature

C	ion concentration (°)	$\bar{n}$	average deferred rate (%)
CR	circulation rate (%)	r_i	distribution rate of each section (%)
l	descaling cycle deferred (%)	$\bar{r}$	average distribution rate (%)
m	uniform distribution rate (%)	u	unboiled water velocity (m·s^{-1})
N	number of the experimental group	W'	scaling mass with circumfluence by-path tube (g)
n	deferred rate (%)	W	scaling mass without circumfluence by-path tube (g)
n_{opt}	the best deferred rate (%)	ΔT_m	heat exchange temperature difference (°C)

1. Introduction

The 2014 "BP Statistical Review of World Energy" cited oil as the dominant fuel, accounting for 32.6% of the global primary energy consumption. Many countries regard petroleum as a global strategic property [1]. In petroleum and gas exploration in China, most crude oil displays a high wax content, freezing point, viscosity [2]. Hot water mixed with crude petroleum is commonly adopted between the wellhead of petroleum wells and metering or relay stations to avoid petroleum, gas, and water congealment during crude petroleum gathering and transportation and thus achieve low viscosity and safe transportation [3]. A vacuum furnace is widely applied to produce hot water for the oil mixing transportation system. However, vacuum furnace corrosion occurs along with scaling problems, which have seriously constrained the normal operation of the mixing transmission system. Inside scaling of vacuum furnace tubes increases flow resistance, reduces the heat exchanger coefficient, and accelerates the corrosion of metal pipe wall, resulting in energy waste and material losses. Fig. 1 shows the scaling problems in the mixing transportation system after ongoing operation for only 4 months. The thickness and velocity of the scaling were 0.8 cm and 21.3 mm/a, respectively, to anatomize the outlet pipeline (Fig. 1). The outlet water temperature decreased from 65 °C in the preliminary stage to 54 °C in the later stage. In 2007, Japan, Germany, the United Kingdom, the United States, and other developed countries suffered economic losses caused by scaling, affecting up to 0.25% of the gross domestic product on that year. Around the world (excluding the East), the economic losses caused by scaling in the oil refinery industry reached 4.4 billion U.S. dollars [4]. In recent years, anti-scale techniques have been actively explored, and new methods to slow down vacuum furnace scaling have been developed. Scaling is a major issue with universal significance in the oil industry.

The comprehensive formation of scaling involves quality, heat, and momentum exchange, and is the result of multiple complex dynamic processes. The three main influential factors in the scaling of vacuum furnace tubes are the following [5]:

(1) Scaling ion density [6]. The scaling quality increases with increasing scaling ion density [7,8].
(2) Water velocity [9–13]. Different flow states (laminar or turbulent) have different effects on scaling. The scaling quality decreases when the water velocity increases within a certain range [8,14–24].
(3) Heating temperature [25]. Scaling consequences become serious as the temperatures in the heat exchange tube wall and water increase.

The scaling rate changes when crystal particles are added into the solution, and the effect is influenced by the flow rate. In addition, many scholars have studied chemical and physical methods of slowing down or removing scaling [26–30].

In addition, the water temperature distribution along the heating tube path exerts a certain extensive effect on $CaCO_3$ precipitation [31]. Larger difference in the inlet and outlet water temperatures indicates more nonuniform scaling along the tube and higher possibility for premature rapid scaling [32], thereby inducing pipe blockage. The life cycle of the equipment is shortened as well. The temperature of the hot water boiler in the oil mixing transportation system is near 50 °C. The trend of rapid scaling because of the chemical reaction between Ca^{2+} and HCO^{3-} in water is strengthened. The water quality changes into a strong scaling character, and the tube outlet exhibits severe congestion. Masses of $CaCO_3$ scale sediments are deposited in the outlet section of the heat exchange tube, resulting in severe congestion in the pipe outlet. Aiming at the urgent requirement to solve the corrosion and scaling problems in China's oil production and considering that there are a lot of referential works on scaling and corrosion mechanism, this study mainly focused on the investigation of effective methods of extending the scaling time of the boiler tube and maintenance cycle. This study proposed a new method in scaling mitigation, namely, circumfluence dilution and uniform-temperature perturbation technique (CUP). The application of a circumfluence by-path tube (CBT) enables a part of the outlet water from the heat exchange tubes to flow back to the inlet of the tube to realize:

(1) Reduction in scaling ion density. The ion density of inlet water of the tube is diluted with the outlet water of the tube. And reduced scaling ion density reduces the scaling quality.
(2) Improvement in water velocity. The inlet water and the part of outlet water mix and flow through the tube. Water velocity improves and enhances the scouring on the tube wall, thereby reducing the scaling quality.
(3) Improvement in inlet water temperature. The method also improves the average temperature of water along the tube under the same outlet water temperature of the vacuum furnace. Because the temperature increasing in the tube