ARTICLE IN PRESS
CJCHE-00973; No of Pages 8
Chinese Journal of Chemical Engineering xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Chinese Journal of Chemical Engineering
journal homepage: www.elsevier.com/locate/CJChE

Energy, Resources and Environmental Technology

Effect of heat flux and inlet temperature on the fouling characteristics of nanoparticles☆

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ARTICLE INFO

Article history:
Received 12 May 2017
Received in revised form 27 September 2017
Accepted 15 October 2017
Available online xxxx

Keywords:
Inlet temperature
Heat flux
Particulate fouling characteristics
Single-phase flow
Subcooled-flow boiling

ABSTRACT

In order to study the effect of heat flux and inlet temperature on the fouling characteristics of nanoparticles, and to further reveal the fouling mechanism for insights into proper operating conditions, γ-Al_2O_3/water suspensions were chosen as the subject of this research. The particulate fouling characteristics of γ-Al_2O_3/water suspensions on the surface of stainless steel have been experimentally studied by varying the heat flux and the inlet temperature under single-phase flow and subcooled-flow boiling conditions. The results show that in the condition of single-phase flow, the asymptotic value of fouling resistance decreases with increasing of heat flux and inlet temperature. The asymptotic value of fouling resistance under single-phase flow is much higher than for the subcooled-flow boiling condition. The effect of heat flux on the fouling resistance under the two flow states has an inverse relationship, and there exists a minimum value of fouling resistance between these two states. For subcooled-flow boiling, the asymptotic value of fouling resistance increases with increasing heat flux, whereas the effect on fouling resistance by the inlet temperature is negligible.

1. Introduction

Fouling is the deposition of undesirable material on a heat transfer surface, which may diminish heat transfer performance and increase the pressure drop in heat exchangers. Due to fouling, the costs of operation and maintenance increase significantly. Particulate fouling is defined as the deposition of fine particles on a heat transfer surface and is considered one of the most common fouling occurrences when cooling water, and the formation process and mechanism of particulate fouling have been well studied by many researchers. Previous experimental studies in particulate fouling have focused on the effect of chemical composition on the fouling rate during isothermal laminar [1] and turbulent flows [2]. Karabelas *et al.* [3] experimentally studied particles with a mean size of 5 μm in plate heat exchangers. The experimental results suggested that the flow velocity and the flow passage geometry significantly affect fouling resistance. Turner *et al.* [4] experimentally studied the fouling characteristics of colloidal magnetite particles at an alkaline pH under single-phase flow and flow boiling. Basset *et al.* [5] used chemical and radiotracing techniques to investigate the deposition of magnetite particles from suspension in water at 90 °C, and the results showed that mechanisms based on diffusion and thermophoresis controlled deposition, while removal was found to negligible with non-boiling conditions. Henry *et al.* [6] found that particulate fouling generally arises from the continuous deposition of colloidal particles on initially clean surfaces, and this process can even lead to a complete blockage of a fluid cross-section. They also proposed numerical models to describe later stages in the fouling process, and they developed a new Lagrangian stochastic approach to understand clogging in industrial case. Grandgeorge *et al.* [7] investigated the liquid-phase particulate fouling in stainless steel corrugated-plate heat exchangers, with deionized water containing TiO_2 particles being chosen as the foulant fluid. The results showed that there is an obvious asymptotic value of fouling resistance, and the influence of physic-chemical conditions on fouling behavior. Zhang *et al.* [8] investigated water-side fouling inside four corrugated-plate heat exchangers by experimental and theoretical methods. The experiments were primarily focused on the effects of concentration and average velocity, and observing the microscopic fouling structures by scanning electron microscope (SEM). Yiantsions *et al.* [9] experimentally studied micron-sized particle deposition on a flat surface, aimed at delineating the effects of hydrodynamic and physicochemical interactions on particle transport and attachment mechanisms. Particle stickiness significantly affected the process of fouling. Lipp *et al.* [10] conducted a membrane test with both artificial and natural water, the results showed that, the membrane permeability decreased over time during the filtration experiments, indicating that the nanoparticles blocked the membrane pores. Under these the experimental conditions, the concentration of nanoparticles seemed to have no obvious influence on membrane fouling.

There are many factors that affect fouling formation on heat exchangers, with temperature being one of the most influential factors. When the temperature of the heat transfer surface exceeds the saturation temperature, the flow state transits to the subcooled-flow boiling regime. Fouling on the heat transfer surfaces during single-phase flow and subcooled-flow boiling is an important challenge in thermal

☆ Supported by the National Natural Science Foundation of China (51476025).
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https://doi.org/10.1016/j.cjche.2017.10.022
1004-9541/

Please cite this article as: J. Wang, *et al.*, Effect of heat flux and inlet temperature on the fouling characteristics of nanoparticles, *Chin. J. Chem. Eng.* (2017), https://doi.org/10.1016/j.cjche.2017.10.022

engineering and process industries. Hasan *et al.* [11] experimentally studied crystallization fouling in a channel for a cross flow of hot saturated sodium sulfate (Na_2SO_4) solution over a pipe of cold water. The results showed that the temperature of the salt solution significantly affected the fouling rate. The fouling rate of crystallization fouling decreases with the increase of the pipe surface temperature. Pääkkönen *et al.* [12] investigated the surface crystallization of $CaCO_3$ and its effect on the fouling rate for a heated surface. The results showed that the crystallization fouling rate can be controlled by the wall temperature, and it was noted that the flow velocity affects the fouling rate especially at high wall temperature. Al-Otaibi *et al.* [13] investigated the fouling characteristics of coated carbon steel and titanium tubes. The experiments were carried out in various brackish waters under different velocities and different tube surface temperatures. The results showed that the asymptotic value of fouling resistance increases with the increase of tube wall temperature, and increasing the flow velocity could mitigate the formation of fouling. Abd-Elhady *et al.* [14] investigated the influence of gas-side temperature on particulate fouling layers in a gas cooler. Their findings showed that sintering significantly affects the particulate fouling rate in the gas cooler, explaining why the growth rate of particulate fouling decreases with gas-side temperature. Mwaba *et al.* [15] conducted experiments to investigate the rate of deposition at different positions. The results indicated that the growth of fouling layers increases increasing surface temperature and decreases with the increase of flow velocity. The rate of fouling growth as a function of position increases with the initial wall temperature distribution. Peyghambarzadeh *et al.* [16,17] experimentally studied the effect of operating conditions such as fluid velocity and bubble generation on fouling formation. The results revealed that achieving the boiling condition has an opposite influence on crystallization and particulate fouling. Furthermore, a model for predicting fouling resistance is applied for mixed salts and particulate fouling. Zhao *et al.* [18] experimentally studied the effect of temperature on structure and morphology of the crystallization fouling. The results revealed that the changes of temperature not only affect the type of crystallization fouling, but also the lattice parameter and particle size of the precipitated phase.

Our previous works [19–22] suggested that the operating conditions could affect fouling characteristics more or less, such as the temperature, the inlet velocity and the concentration. Temperature significantly affects crystallization fouling and microbial fouling. According to the literatures, most of the previous studies have focused on the effect of temperature on crystallization fouling and microbial fouling, with little attention to the effect of heat flux and inlet temperature on the particulate fouling. In this work, the γ-Al_2O_3/water suspension was chosen as the research object. The fouling characteristics of the γ-Al_2O_3/water suspension on a surface of stainless steel have been experimentally studied by changing the heat flux and the inlet temperature under single-phase flow and subcooled-flow boiling conditions, with mechanism analysis by a visible spectrophotometer.

2. Experiment

2.1. Experimental apparatus

A schematic of the experimental setup is shown in Fig. 1, consisting of working fluid circulation, temperature control, and data acquisition systems. (1) The working fluid circulation system stores the working fluid in a constant temperature water tank with a volume of 27 L (THD-0530-L), and the working fluid flows into the loop through isolated pipes and where it is continuously circulated by a circulating water pump. A mass flowmeter is installed at the inlet of the loop (manufactured by Beijing Sincerity Automatic Equipment Co.). The working fluid is heated in the annular loop, which employs heating rods operating with a voltage rating of 110 V. This heating is supplied by a DC power supply (manufactured by Shanghai GOODENG Electric Co.) with a voltage range from 0 to 120 V, a current range from 0 to 30 A, and a maximum power of 3600 W. (2) The temperature control system draws heat away from the circulating working fluid ensure it remains at a set temperature. The heated working fluid flow is primarily cooled before entering the experimental section, where it then flows into the constant temperature water tank. The control system of the constant temperature water tank can be operated over the temperature range from −5 °C to 95 °C. Its precision is ±0.05 °C for good control to achieve a constant inlet temperature. (3) The data acquisition system measures the wall temperatures through four Pt100 resistance thermometers with diameter of 2 mm, which have been installed close to the heat transfer surface. The thermocouple position is in the middle of the heating rod. The inlet and the outlet temperatures are also measured by Pt100 resistance thermometers with a diameter of 3 mm. All of the measurement signals are acquired by the data acquisition system (manufactured by ICP DAS Co.) and are stored and processed by an industrial-grade personal computer. The system has a high level of autonomy and can monitor the system for 24-h with online connectivity.

Mechanical drawings of experimental apparatus are depicted in Fig. 2. The heat transfer cylinder is made of stainless steel type 316 L. The cylinder is heated by a DC bolt heater inserted into the middle of the cylinder, and the bolt heater (manufactured by HZLD Automation Equipment Co.) has a diameter of 14 mm, a length of 250 mm, and a

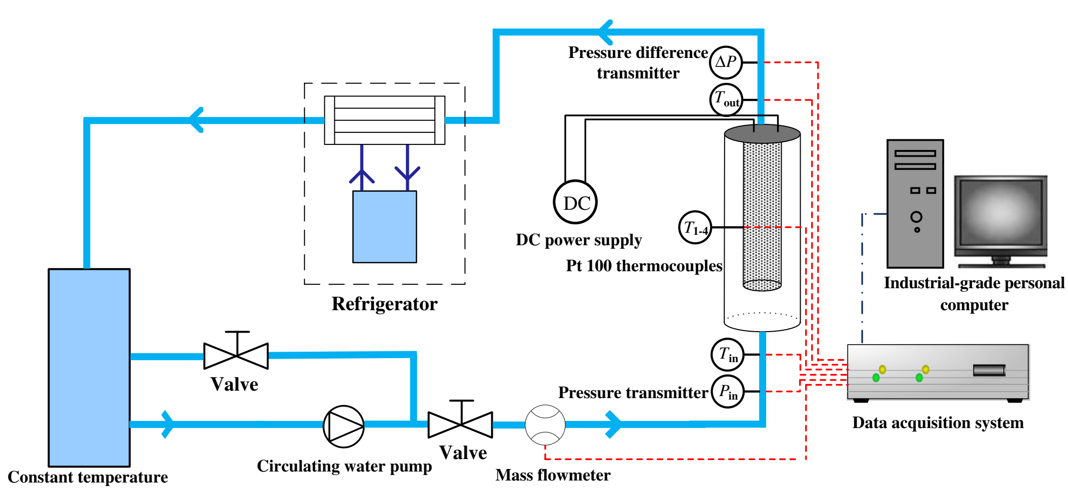

Fig. 1. A schematic of the experimental setup.

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