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Experimental study on fouling in the heat exchangers of surface water heat pumps

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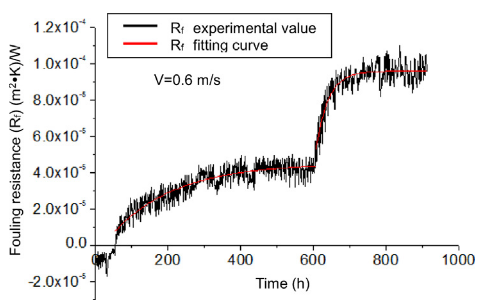
HIGHLIGHTS

- Field and laboratory experiments are taken to measure the fouling variation.
- Fouling growth process can be divided into four stages.
- We recommend fouling resistance allowances for certain conditions.
- A fouling prdiction model is developed and validated.

GRAPHICAL ABSTRACT



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ABSTRACT

Fouling in the heat exchangers plays a key role on the performance of surface water heat pumps. It is also the basement for the system design criteria and operation energy efficiency. In this paper, experimental measurements are performed both in the field and the laboratory with different water qualities, temperatures and velocities. The research will focus on the dynamic growth characteristics of fouling and its main components. By studying the variation rules of fouling resistance, the fouling resistance allowance for certain water condition is recommended. Furthermore, a fouling prediction model in surface water heat pump will be developed and validated based on elaborating with fouling principle under specified water conditions.

1. Introduction

Surface water heat pumps (SWHPs), especially the open-loop systems, have been widely used in engineering applications for the reduction of excavation costs and energy consumption [1]. Fouling resistance (R_f) is one of the major factors to determine the heat pump performance and actual energy efficiency [2]. The earlier research focused on the formation and classification of fouling [3]. A few recent studies were directed towards the prediction model and monitoring technology of fouling both theoretically and experimentally [4–6]. The fouling growth characteristics have quite diversities between different water qualities and operating temperatures while the existing studies are not applicable to SWHP systems. In this paper, experimental methods including field and laboratory measurements are employed to study on the fouling formation mechanism and its dynamic characteristics in SWHP heat exchanger. The objectives of this research are: (1) to obtain the fouling growth characteristics by field and laboratory measurements using river water and configured water respectively; (2) to

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Nomenclature

R_f	fouling resistance, m^2 K/W
U_c	overall heat transfer coefficient in clean condition, W/(m^2 K)
U_f	overall heat transfer coefficient in fouling condition, W/(m^2 K)
q	total heat rejection rate, W
A	total heat transfer surface, m^2
LMTD	logarithmic mean temperature difference, °C
c_p	specific heat at constant pressure of water (kJ/kg K)
m	mass flow rate, kg/s
t_{wl}	leaving water temperature, °C
t_{we}	entering water temperature, °C
t_s	saturated condensing temperature, °C
v	flow velocity, m/s
d_{50}	median diameter, μm
θ	operating time, h

recommend the fouling resistance for SWHP in Chongqing or similar conditions; (3) to build and demonstrate the fouling prediction model for river water.

2. Methodology

2.1. Fouling resistance monitoring method

Fouling resistance monitoring method is the most traditional and classic fouling monitoring model in thermodynamics. The fouling resistance can be defined as [7]

$$R_f = \frac{1}{U_f} - \frac{1}{U_c}. \tag{1}$$

In order to calculate the fouling resistance on the cooling waterside, the overall heat transfer coefficient in both clean and fouling conditions should be measured successively. If the real-time changes of U_f can be monitored, the relation curves that fouling resistance varies with time are obtained. According to the basic heat transfer theory, U_c can be expressed as [8]

$$U_c = \frac{q}{A \times (\mathrm{LMTD})_c}, \tag{2}$$

where:

$$q = c_p m \cdot (t_{wl} - t_{we}), \tag{3}$$

$$\mathrm{LMTD} = \frac{t_{wl} - t_{we}}{\ln \frac{t_s - t_{we}}{t_s - t_{wl}}}. \tag{4}$$

The same procedure can be adapted to calculate U_f. Above all, the physical parameters need to be monitored are: t_{wl}, t_{we}, t_s and m.

2.2. Experiment process

While the R_f hinges on the water qualities, it is necessary to understand the water conditions of the experimental areas before research. Previous research has shown that higher water temperature triggers greater fouling resistance [9]. Our preliminary study has found that sediment concentration and turbidity are the key factors in utilizing water of Yangtze River and Jialing River as source water. Therefore, cooling season which is the most unfavorable conditions in water temperature and water qualities is selected as the experimental period. An experiment system is established on a boat on Jialing River in Ciqikou area, Chongqing to study the fouling growth characteristics (Fig. 1). In the experiment, river water of different velocities flows through three heat exchanger tubes (Table 1). T1 is cleaned by fresh water with double velocity and T3 is cleaned by nylon brush before the dynamic experiment (numbered T1* and T3*) in the regrowth process. When R_f becomes steady in T2, fouling samples are taken to analysis the components by weight-loss, EDS (Energy Dispersive Spectrometer) and SEM (Scanning Electron Microscope) methods. For a further study, another similar experiment system is developed in laboratory. Source water of different median diameters is configured and flows through three heat exchanger tubes at a speed of 0.62 m/s.

3. Results and analysis

3.1. Fouling growth characteristics

Fouling growth process (Figs. 2–4) can be divided into four stages in both field and laboratory experiments: (a) the induction period when R_f is negative and increases by power function; (b) the slow-growth period when R_f turns positive and rises slowly by exponential function to achieve a temporary balance; (c) the fast-growth period when R_f increase rapidly by exponential function; and (d) the stable period when R_f reaches the maximum value and remains steady. Table 1 shows the main characters performed in all cases, with the relative error of 8 ~ 15%. The results are discussed below:

(1) In the induction period, the convective coefficient plays more of a role than R_f because the sediment enhances convective heat transfer. The induction periods in laboratory measurement are all shorter than that in the field measurement, because the configured water has a larger sediment concentration and lower flow velocity than the river water. The consequence shows that a greater flow velocity or median diameter results in longer induction period and more hysteretic negative effect of fouling.

(2) R_f of T4 and T5 are close and much larger than that of T6 in both slow-growth and stable periods. It can be inferred that the influence of sediment on heat transfer is inconspicuous when the d_{50} is small (such as less than 10.98 μm). In parallel, when the d_{50} is large (such as more than 22.90 μm), R_f stabilizes at a low value and remains large fluctuation, because the large particles may flush the fouling and perform a significant impact on heat transfer.

(3) In T1* and T3* where systems are monitored after cleaning, the fouling growth only takes place in the last two stages. It is found that the fouling layer consists of two parts: the adhesive layer which is easy to remove by decontamination measures, and the base layer which is hard to clean. For a cleaned tube, the main process is the growth of adhesive layer, without an induction or slow-growth period which reflects the formation of the base layer.

3.2. Fouling components

One fouling sample is burned at 520 °C and another is dried at 120 °C, resulting in 4.86% and 31.38% weight-losses respectively. It is found that the fouling is dominant in particles, where water and organic matter represent 36.24% of the total weight. The EDS analysis finds that silicon and oxygen account for 75.8% of the total mass, which indicates that the principal ingredient of the fouling is mud particles (silica). Meanwhile, salts are also proved to exist in