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A novel fouling measurement system: Part II. Commissioning

Chao Shen [a], Lin Wang [b], Steven E. Ford [b], Cancan Zhang [b], Xinlei Wang [b,*]

[a] Department of Building Thermal Energy Engineering, Harbin Institute of Technology, Harbin 150090, China
[b] Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

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ABSTRACT

The Fouling Measurement System (FMS) supports research on the relationships between fouling deposit and operation condition involving water velocity, water quality and tube geometry by measuring variation of fouling resistance on a heat transfer tube during long-term running. Part I of this series provides the description and design evaluation of the newly developed FMS. Part II of this series describes FMS commissioning and documents the entire system performance and primary fouling test with nine same type enhanced tubes. Results of system commissioning demonstrated that the FMS would take 128 min to reach steady-state. Water velocity could be controlled at three velocities of ∼0.9 m/s, ∼1.6 m/s and ∼2.4 m/s respectively to satisfy the experiment requirement. Saturation temperature can be adjusted in the range of ∼34.0–35.5 °C at water velocity of 0.99 m/s, as a result, the heat flux varied from ∼20.1 kW/m^2 to 26.5 kW/m^2 correspondingly. The rising rate of electrical conductivity (EC) was 130 μs/cm per day. All the parameters of the cooling water were controlled at the required range, except calcium hardness, which is 480–860 ppm and much higher than the upper limit of 391 ppm. The fouling resistances increased to 0.3865–0.5078 m^2 K/kW after 60 days at an amplitude of 12.48% around the averaged value of 0.4864 m^2 K/kW. The water-side pressure drop decreased from 4.34–4.62 kPa at clean condition to 2.90–3.10 kPa at fouled condition after 60-day continuous running at ∼0.99 m/s.

1. Introduction

Part I of this series [1] introduced the design evaluation and description of the Fouling Measurement System (FMS) which consists of a refrigerant unit loop, chilled water loop, cooling water loop integrated with cooling tower, and control and data acquisition system. The objective of FMS is to support research on the relationships between fouling development and operation condition through measuring fouling thermal resistance on the heat transfer surface. The evaluation performed in Part I documented a systematic design case of FMS, in which the operation parameters were adjustable and controllable, thus can be used to conduct fouling tests at different operating conditions. The design of FMS provides a useful reference and significant knowledge for fouling researchers. An analytical approach to the design analysis was critical to assess the contributions of individual parameter uncertainties and their effects on the uncertainty of experimental results. An initial running in Part I was also performed to evaluate integrity of the physical system, and test results show the FMS had a normal performance as well as reliable control function.

In addition to the systematic design of the FMS in Part I, commissioning of the system after construction is required to (1) verify performance of the FMS at different operating conditions; (2) investigate the water quality variation during long-term running; (3) identify the fouling resistance of nine same type enhanced tubes in a primary long-term running; thus, giving a basic systematic error based on these data. Commissioning is the final step before full implementation and includes information associated with FMS operation, identification of systematic errors and variability of operating parameters.

The literature is severely lacking in long-term fouling data of enhanced tubes using foulant concentrations typical of that in actual operating systems. Rabas [2] made in-plant fouling tests of electric utility steam condenser tubes using river water as the foulant. This work compared corrugated and plain tubes. Haider and Webb [3] performed long-term tests of water used in the evaporator tubes of flooded water chillers. This study showed negligible fouling, principally because the water was very clean and particulate fouling was the only possible fouling mechanism. Webb and Li [4] addresses long-term fouling of cooling tower water in a refrigerant shell-and-tube condenser consisting of enhanced tubes. The fouling tests were performed in a separate fouling condenser, using the cooling tower water supplied to the main refrigerant condenser. But in that test, the water quality was not monitored

* Corresponding author.
E-mail address: xwang2@illinois.edu (X. Wang).

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Nomenclature

A_c	cross-sectional area, m^2
A_w	inside wetted surface area, m^2
Ca	Calcium concentration, ppm as $CaCO_3$
D_i	inner diameter of tube, m
e	Rib height, m
f	friction factor of enhanced tube
EC	electrical conductivity, ppm
LSI	Langelier's Saturation Index
M_{alk}	"M" alkalinity, ppm as $CaCO_3$
N_s	number of starts
pH_{actual}	actual PH value of cooling water
pH_s	saturation pH value at given water temperature
ΔP	tube-side pressure drop, Pa
Re	Reynolds number
TDS	total dissolved solid, ppm
T_w	water temperature, °C
$T_{w,i}$	entering water temperature, °C
$T_{w,o}$	leaving water temperature, °C
$T_{r,sat}$	saturation temperature of refrigerant, °C
$T_{r,o}$	refrigerant temperature at the out of condenser, °C
u_w	water velocity, m/s
U	the overall heat transfer coefficient, W/m^2 K

Greek symbols

α	Helix angle, degrees
ρ_w	density of water, kg/m^3
δ	thickness of fouling, m

Subscripts

p	plain surface

and was extremely hard. In addition, only one low water velocity of 1.07 m/s was set during the fouling test. Therefore, fouling experienced is not typical of that expected in commercial installations.

The main goal of this work was to introduce and describe the performance of the FMS (full description of the system is available in Part I). In the commissioning phase, the function of adjusting the operating condition of the FMS was assessed, followed by a water quality variation test and long-term fouling resistance test. To achieve these goals, the following objectives were completed:

1. Validation on the adjustability and controllability of the FMS's operating parameters, subdivided into four sections:
   (a) Entering water temperature of test tubes.
   (b) Saturation temperature of refrigerant.
   (c) Three sets of water velocities.
   (d) System dynamics, in order to determine the time to reach steady-state operation condition.
2. Investigation of the water quality variation and control strategy, including:
   (e) Variation of EC and pH monitored continuously by on-line water meter.
   (f) Chemistry components analysis based on water sample day-by-day conducted in the chemical LAB.
   (g) Calculation and analysis of LSI of the cooling water in the test system.
3. Investigation of fouling resistance variation based on nine same type enhanced tubes, including:
   (h) Long-term fouling resistance measurement and analysis.
   (i) Systematical error analyzed based on nine same type enhanced tubes.
   (j) Water-side pressure drop analysis with the deposit of fouling.

This commissioning analysis fulfills the need to establish and document a procedure successfully conducting a series of fouling tests with the FMS. This procedure also applies to other fouling test systems in operation, or to future designs.

2. Materials and methods

2.1. Materials

2.1.1. Water

The cooling water in the fouling experiment was created in terms of a previous procedure reported in ASHRAE Project RP-1345 [5]. The high fouling potential of simulated water was created by cycling low fouling potential water through a cooling tower. The low potential water was made in our LAB. The reagent grade chemicals used to create the low fouling water were $CaCl_2$, $MgSO_4$, and $Ca(OH)_2$. The amount of each reagent is as follows:

a. Magnesium Sulfate: 38.8 g
b. Calcium chloride: 67.4 g
c. Calcium hydroxide: 12.5 g

The reagents were dissolved in 0.432 m^3 of DI water, which was stored in a 150-gallon batch tank. This made-up water was used to charge into the system at the beginning of the experiment as well as to supplement the water lost due to evaporation. Since the made-up water contains some minerals, it is expected that the concentration of minerals in the system gradually increases over time. As a result, the water in the system was going to be concentrated into low, medium and high fouling potential water. During the long-term running of the fouling test, the mineral concentration of the cooling water will increase over the upper limit of the required range listed in Table 1 in Part I [1]. At this time, some of the concentrated water in the system would be discharged and the made-up water stored in the batch tank would be charged into the system until the concentration was down to the lower limit of the required range. This process is known as a blow-down process and controlled by the water meter automatically. In this commissioning phase, the cooling water used in the system was controlled at the high fouling potential.

This project mainly focuses on precipitation and particulate fouling. Therefore, during the preparation of the low fouling potential water, sodium Tolytriazole (TTA) and chlorine were added to the water to prevent corrosion and microbial deposits.

2.1.2. Test tubes

All of the nine enhanced tubes used in the commissioning test have the same geometry which is not presented in this paper due to business confidentiality. Both the internal and external surface have augmented geometry.

2.2. Method

First of all, different saturation pressures and water velocities tests were conducted based on the FMS; at the same time the control of the entering water temperature of the test tubes was verified. Secondly, a continuous long-term running with an occasional