International Journal of Heat and Mass Transfer xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A novel fouling measurement system: Part I. design evaluation and description

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

ARTICLE INFO

Article history:
Received 9 January 2017
Received in revised form 28 February 2017
Accepted 8 March 2017
Available online xxxx

Keywords:
Enhanced tubes
Cooling tower
Fouling
Thermal resistance
Uncertainty

ABSTRACT

The enhanced tube is being used more often in water-chiller condensers because of their superior performance in heat transfer. Both the predicted and real-world performance of these heat exchangers is affected by the fouling build-up on the heat transfer surfaces. Thus, accurate quantification of fouling thermal resistance is required to address the correlation between the fouling resistance of heat transfer tubes and operation conditions. A newly developed Fouling Measurement System (FMS) supports research on the relationships between fouling development and operation condition by measuring fouling thermal resistance on the heat transfer surface. Part I of this two-part series describes the design and evaluation of FMS. An uncertainty analysis of fouling thermal resistance was conducted to identify measurement component contributions to the uncertainty of final results and guide component selection. In Part II, FMS commissioning was performed, and a primary fouling test and analysis on cooling water quality were conducted. The FMS consists of three subsystems: heat pump subsystem, cooling/chilled water subsystem and control and data acquisition (DAQ) subsystem. The FMS has three heat pumps individually installed with a shell-and-tube condenser and separately equipped with a cooling/chilled water supply loop. In the cooling/chilled water subsystem, these three heat pumps share the same cooling water pool and chilled water pool, which ensures that the cooling/chilled water supplied to each heat pump is uniform. A cooling water tower was installed outside the Air Quality Lab in University of Illinois at Urbana-Champaign to cool down the cooling water of the FMS, and to evaporate water and keep the cooling water at the required range. In the control and DAQ subsystem, the control of water temperature, water quality, water velocity, and refrigerant saturation temperature are described.

1. Introduction

Internally enhanced tubes are becoming popular in the application of commercial heat exchangers due to the improved heat transfer performance. The use of enhanced tubes in cooling tower applications is a very common application in HVAC systems. According to industry statistics, the annual North American market for water cooled chillers over 100 tons, where this type of configuration (shell-and-tube condenser) is common, is approximately $580 million. The annual energy costs associated with operating this new equipment and the installed base of similar equipment worldwide are staggering. There is a very significant investment in this equipment on the part of both building owners/end users and manufacturers of HVAC equipment. A particular area of concern is the application of a shell-and-tube condenser in cooling tower systems, where the flow loop is "open" and the water quality and chemical characteristics are varied. The open nature of these systems increases the potential of fouling on the internal surface of enhanced tubes and creates a significant impact on heat transfer compared to a closed flow loop. As reported by Webb and Kim [1] and Webb and Chamra [2], the fouling rate of enhanced tubes is higher than that of plain tubes. Because fouling ultimately affects the efficiency of heat exchangers, understanding and accurately predicting the negative impacts of fouling on enhanced tube heat transfer is something that should not be ignored. Specifically, the common use of constant fouling factors in the industry may not be adequately representing the performance of enhanced tubes over the lifetime of installed equipment.

Deposit of fouling is slow, thus most fouling studies have been done based on an accelerated fouling test using a very high foulant concentration. This allows significant fouling to occur within several hours or several days. Several investigators have performed accelerated particulate fouling in enhanced tubes, including Kim

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

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.026
0017-9310/

Nomenclature

A	heat transfer area, m^2
c	specific heat of water, J/kg K
d_o	the external diameter of tube, m
e_i	rib height on internal surface, m
L	tube length, m
$LMTD$	logarithmic mean temperature difference, °C
n	Number of starts, dimensionless
Q	the heat exchange rate, W
R_f	fouling resistance, m^2 K/W
$T_{w,i}$	inlet water temperature,°C
$T_{w,o}$	outlet water temperature,°C
$T_{r,sat}$	saturation temperature of refrigerant,°C
U	the overall heat transfer coefficient, W/m^2 K
U_f	the overall heat transfer coefficient at fouled condition, W/m^2 K
U_c	the overall heat transfer coefficient at clean condition, W/m^2 K
V	water flow rate, m^3/s
Δ	absolute error
$\sum_{x_i}$	Sum the calculated data based on all $x_1, x_2, \ldots x_n$

Greek symbols

α	helix angle, °
ρ	density of water, kg/m^3

and Webb [3,4], Somerscales [5], Webb and Chamra [2], Chamra and Webb [6] and most recently in reports by Webb [7]. Watkinson [8] performed accelerated precipitation fouling tests on internally enhanced tubes. Morse and Knudsen [9] performed a series of fouling tests with simulated cooling water on an exterior of a smooth tube in an annulus. Shen [10] summarized much of the prior relevant work on fouling of enhanced tubes in the cooling water system applications. These studies present data associated with "accelerated" fouling of enhanced surfaces using controlled amounts of foulant added to water circulating through the tubes. All of the studies were performed at conditions more severe than that expected in the field and, therefore, are not good indicators of how an enhanced tube might perform. Results of accelerated particle fouling test also indicated that in most cases, the enhanced tubes had higher fouling rates compared to plain tubes, yet still had a much higher heat transfer rate than the plain tubes after fouling [5]. While some models based on particulate fouling were reported, Kim and Webb [4] developed the first model to predict fouling behavior of repeated rib tubes. As further research indicates, studies conducted by Chamra and Webb [11] and Webb and Narayanamurthy [12] were dedicated to improving the fouling models. Shen [10] summarized much of the relevant fouling model of enhanced tubes as well. These studies are based on an accelerated and single-fouling test, and the enhanced tube geometries considered do not encompass the types of geometries commonly used today.

The literature is severely lacking in long-term fouling data of enhanced tubes tested using foulant concentrations typical of that in practical operating systems. Rabas et al. [13] 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 [14] performed long-term tests of water used in the evaporator tubes of flooded water chillers. This study showed negligible fouling, mainly because the water was very clean and particulate fouling was the only possible fouling mechanism. Webb and Li [15] studied a combined fouling mechanism of both precipitation and particulate fouling in seven different enhanced tube geometries. This is the first study to report long-term fouling tests of actual cooling tower water. The tube geometries examined in this study were various helical ridged geometries in addition to a plain surface. However, the water velocity is constant and much lower than a real project, and the cooling water quality in that test was not controlled because the test was conducted based on the campus facility.

In this study, an actual (non-accelerated) fouling measurement system (FMS) was built in our laboratory and was based on a series of fouling tests conducted at different controlled conditions. A fouling test is challenging work which has high requirements on test devices. It is possible that this paper could provide useful information to future designers of fouling test systems. This study precedes Part II of this series, in which the system commissioning and the two month "trial" fouling test was conducted on nine of the same type of tubes before the "real" test. Separation of the design evaluation and commissioning phases emphasizes the need to first use the uncertainty analysis to guide such a demanding system design and then focus the capacity design of system and accuracy selection of measurement devices, and finally to identify the performance and uncertainty of the fouling test system based on empirical test information before the start of "real" test.

2. Design of the FMS

2.1. Mission of the FMS

The FMS will be used to conduct tests on precipitation and particulate fouling on internally enhanced copper tubes of shell-and-tube condensers. Refrigerant flows outside of the test tube and

Table 1
Chemistry component for low-, medium- and high-fouling potential water.

Fouling potential	Total hardness	Calcium (as $CaCO_3$)	Magnesium (as $CaCO_3$)	M-alkalinity (as $CaCO_3$)	P-alkalinity (as $CaCO_3$)	Chloride (ppm)	Sulfate (ppm)
Low	180–358	13–92	16–53	54–91	4–15	102–258	64–133
Medium	345–533	18–265	28–109	106–289	6–77	208–884	139–603
High	557–1765	129–391	76–183	204–1813	58–417	491–1947	319–1947
	Sodium (ppm)	Iron (ppm)	Copper* (ppm)	pH	Total dissolved solid (ppm)	EC (μS/cm)	LSI
Low	43–93	<0.1	NA	8.2–8.4	428–897	649–1359	<1.0
Medium	87–373	<0.1	NA	8.4–8.8	826–2896	1251–4360	1.0–2.0
High	192–741	<0.1	NA	9.0–9.6	2000–7971	3030–11,690	2.0–3.8