International Journal of Heat and Mass Transfer 85 (2015) 336–342

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A method for developing a prediction model of water-side fouling on enhanced tubes

Chao Shen [a,b], Chris Cirone [b], Xinlei Wang [b,*]

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

ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form 24 January 2015
Accepted 26 January 2015

Keywords:
HVAC&R system
Enhanced tube
Precipitation and particulate fouling
Prediction model
Cooling water tower

ABSTRACT

Enhanced tubes have been used widely in the condenser of air conditioning systems with a cooling tower due to their superior heat transfer performance. Both the predicted and real-world performance of these heat exchangers is affected by the build-up of fouling on the heat transfer surfaces. An accurate model to predict the negative impact of fouling on heat transfer of enhanced tubes is important to the HVAC&R industry. In this paper, a method to develop a prediction model of fouling on enhanced tubes is presented. Based on this method, a generalized calculation approach can be developed to determine an appropriate fouling resistance for the application of enhanced tubes in a cooling-tower water heat exchanger application. The combined fouling (precipitation and particle fouling) is considered in this method to make a more accurate prediction. A correlation of the total dry matter concentration with respect to Langelier's Saturation Index (LSI) is proposed to refer to the water quality in the fouling model. The application of this model will allow equipment manufacturers and designers in the HVAC&R industry at large to estimate typical fouling allowances.

1. Introduction

Internally enhanced tubes for liquid flow are very important in commercial heat exchanger applications. The HVAC&R industry routinely uses roughness on the water-side of large refrigeration evaporators and condensers. 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, therefore, the water quality and chemical characteristics are inconsistent during operation. The open nature of these systems increases the potential for fouling which creates a notable impact on heat transfer compared to a closed loop chilled water design. Webb and Kim [1] and Webb and Chamra [2] reported that the fouling rate is higher for enhanced tubes than for plain tubes.

There is a long history of studying the impacts of fouling in scientific literature. In the 1930s, to satisfy the need of heat exchanger designers, Sieder [3] developed the concept of using a fouling factor instead of the cleaning factor in the process of heat exchanger design. In 1941, the values of the fouling factor were recommended by the Tubular Exchanger Manufacturers' Association (TEMA) as a standard [4]. Later, in the 1950s, Kern and Seaton [5] created a particulate fouling model which was named Kern–Seaton model by later researchers. In 1962, Hasson [6] developed a model about precipitation fouling. Yet, before the U.S. oil crisis in the early 1970s, fouling was still considered as an unsolved problem in the heat transfer field of study [7].

Taborek [8] summarized fouling processes and affecting factors, and described the basic behavior of the fouling process through the use of a deposition and removal rate function. In addition, Taborek et al. identified that the accepted way for designers to account for fouling was to add a fouling resistance in the designing process which is very vague in relation to the actual operating conditions. In the middle of the 1980s, Heat Transfer Research, Inc. (HTRI) and Tubular Exchanger Manufacturers Association, Inc. (TEMA) jointly checked, modified and supplemented the fouling factors recommended by TEMA, and published the new values of fouling factors [9]. Until now, shell-and-tube heat exchanger designers and rating standards still make use of this simple fouling model, which is a constant fouling resistance that does not address differences in flow conditions, water quality, or the tube enhancement characteristics and geometry. Today's designers and users of this type of equipment typically apply the fouling factors that are recommended in *the AHRI Guideline E – Fouling Factors: A Survey of Their Application in Today's Air Conditioning and Refrigeration Industry* and in equipment rating standards such as *AHRI 550/590 – Performance*

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

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.128
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Nomenclature

A_c	cross-sectional area, m^2
A_w	inside wetted surface area, m^2
a_{1-6}	undetermined coefficient, dimensionless
b_{1-2}	undetermined coefficient, dimensionless
A_{nom}	nominal internal surface area, m^2
Ca	calcium concentration, ppm as $CaCO_3$
C_b	bulk particle concentration, kg/m^3
C'_b	dry matter concentration, kg/m^3
c_p	special heat capacity, J/kg K
D_i	inner diameter of tube, m
e	rib height, m
f	friction factor of tube, dimensionless
h	convective heat transfer coefficient, W/m^2 K
j	Colburn *j*-factor, dimensionless
k_f	thermal conductivity of deposition, W/m K
K_D	particle deposit coefficient, m/s
K_m	mass transfer coefficient, m/s
LSI	Langelier's Saturation Index, dimensionless
M_{alk}	"M" alkalinity, ppm as $CaCO_3$
m_{1-5}	undetermined index number, dimensionless
n_{1-3}	undetermined index number, dimensionless
N_s	number of starts, dimensionless
P	sticking probability, dimensionless
pH_{ac}	actual PH value of cooling water, dimensionless
pH_s	saturation pH value at given water temperature, dimensionless
Pr	Prandtl–Taylor number, dimensionless
ΔP	tube-side pressure drop, Pa
R_f	fouling resistance based on A_{nom}, m^2 K/W
R_f^*	asymptotic fouling thermal resistance, m^2 K/W
Re	Reynolds number, dimensionless
St	Stanton number, dimensionless
Sc	Schmidt number, dimensionless
TDS	total dissolved solid, ppm
T_w	water temperature, °C
t	time, s
u	fluid velocity (water), m/s
x_f	thickness of the deposit, m

Greek symbols

α	helix angle, degrees
ϕ_d	deposition rate, kg/m^2 s
ϕ_r	removal rate, kg/m^2 s
τ_s	wall shear stress, N/m^2
ξ	deposit bond strength, Ns/m^2
ρ_w	density of water, kg/m^3
ρ_f	density of fouling, kg/m^3
μ	dynamic viscosity, Ns/m^2
v	kinematic viscosity, m^2/s
β	area index, $\beta = (A_w/A_{wp})/(A_c/A_{cp})$
σ	fouling process index, $\sigma = (P\xi)/(P_p\xi_p)$
η	efficiency index, $\eta = (j/j_p)/(f/f_p)$
ψ	working condition index, $\psi = (C'_b/C'_{b,p})/(u/u_p)$

Subscripts

f	fouling
p	plain surface
w	water
pt	particle

Rating Of Water-Chilling and Heat Pump Water-Heating Packages Using the Vapor Compression Cycle. Some general guidelines to the industry may also be found in the TEMA Standards. However, the fouling allowances in the literature are based upon cases, histories, and design practices that have unknown applicability to current tube enhancements and cooling tower applications.

There are six mechanisms contributing to waterside fouling: scaling (otherwise referred to as precipitation fouling), particulate, chemical reaction, corrosion, bio-fouling, and freezing fouling [10,11]. Because of the widespread use of inhibitor chemicals to reduce the potential for biological fouling and corrosion, fouling in a condenser cooled by water circulating through a cooling tower at typical cooling tower operational temperatures is dominated by the precipitation and particulate fouling mechanisms [12]. Therefore, most studies regarding fouling in enhanced tubes used in water cooling towers have appropriately focused on the two kinds of fouling: precipitation and particulate fouling.

In order to address the fouling issue in the water cooling tower, a number of investigators carried out research in this field. Because of the complexity of fouling mechanisms, they have been primarily studied as individual mechanisms. Experimental studies are more relevant to particulate fouling in cooling tower applications [2,13–17]. These studies presented 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 in conditions more severe than that expected in the field and, therefore, are questionable indicators of how an enhanced tube might perform. Results of accelerated particle fouling tests 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 [15]. Whilst some models based on particulate fouling were reported, Kim and Webb [14] developed a model to predict the fouling behavior of repeated rib tubes. As further research, studies conducted by Webb's research group [18,19], were dedicated to improving the fouling models. These studies did not consider precipitation fouling and is based on an accelerated fouling test, and the enhanced tube geometries considered do not encompass the types of geometries commonly used today.

Webb and Li [12] 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 (not accelerated test) of 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 also, the water quality is not controlled and analyzed, but which is an important impact factor for fouling resistance. Therefore, the experimental data in that test is very limited to develop a fouling prediction model of combined fouling. A companion paper [20] tried to demonstrate a relationship between long-term fouling data (precipitation and particle fouling) and accelerated particle fouling data, but it is not applicable in practice.

Based on the long-term test data reported by Webb and Li [12], a series of follow-up publications on modeling fouling of cooling water were presented. Li and Webb [21] tried to develop a long term fouling model for cooling tower water flow inside enhanced tubes using the Chilton–Colburn analogy. Li [22] updated a previous fouling model to address the area basis of the fouling factor applied by equipment manufacturers. Li [23] tried to develop a