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# Decoupling analysis on the variations of liquid velocity and heat flux in the test of fouling thermal resistance

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ABSTRACT

Fouling deposit is a common issue on the heat transfer surface caused by the impurity of working water. Many researchers conducted experimental test to study the relationship between the fouling thermal resistance and operating parameters, such as water quality, tube geometry, and liquid velocity, targeting at developing the accurate correlation of fouling thermal resistance on heat transfer tubes. The accurate test of fouling thermal resistance is critical for investigators. In fouling test, with the fouling deposit on the internal surface, both the liquid (water) velocity through the tube and the heat flux of the test tube deviated automatically. Although testers usually tried to adjust the water velocity and heat flux back to the original point, it is hard to be realized, thus the water velocity and heat flux deviated somehow inevitably. In fact, the variations of water velocity and heat flux would cause the change of overall thermal resistance of test tubes, which should be separated from the change caused by fouling deposit. This process could be named as "decoupling". This paper analyzed the effect of deviations of water velocity and heat flux on the test results of fouling resistance quantitatively based on experimental test, and a decoupling method and formulas were developed. One set of accelerated fouling test was conducted and result shows the fouling resistance with decoupling and non-decoupling had a maximum difference of 0.000002124 $m^2$ K/W for tube 1, and 0.000002363 $m^2$ K/W for Tube 2, 0.000001316 $m^2$ K/W for tube 3.


## 1. Introduction

Heat exchanger is an important part in HVAC&R system [1,2]. Enhanced tubes are usually used to make shell-and-tube condenser that is used in air conditioning system with a cooling tower due to their superior heat transfer performance. In an open-pattern cooling tower system, the water quality of cooling water is worse than that in the close-pattern one. After a period of running, fouling deposits on heat transfer surfaces in the waterside, which reduces the heat transfer efficiency of enhanced tubes seriously. A good understanding and accurate prediction of the negative impact of fouling on the heat transfer performance is significant in industry. In order to address the mechanism of fouling deposit and prediction model of fouling resistance on heat transfer surface, investigators conducted a series of research in this area. A total of six mechanisms were summarized which contribute to waterside fouling: precipitation, particulate, chemical reaction, corrosion, bio-fouling, and freezing fouling [3]. In cooling tower system, chemical reagents are added into the cooling water to minimize the biological fouling and corrosion fouling, thus the waterside fouling deposited on the internal surface of enhanced tubes is combined fouling of precipitation and particulate fouling mainly [4]. Therefore, fouling studies of enhanced tubes that used in cooling tower water system mainly focused on precipitation fouling and particulate fouling.

Because of the complexity of deposit process, combined fouling of enhanced tube was separated into particulate fouling and precipitation fouling and studied as an individual mechanism. Investigators conducted a series of particulate fouling researches of enhanced tubes. Kim and Webb [5,6] compared the fouling performance on enhanced tubes and plain tubes, and investigated the cleaning effectiveness of built-in brush in tubes. Somerscales and Ponteduro [7] found that the fouling resistance on enhance tubes in their test was higher than plain tube, but the heat transfer performance was still higher than plain tube. Webb and Chamra [8] reported that particle in cooling water with smaller diameter is favorable for the deposit of fouling. Chamra and Webb [9,10] conduced particulate fouling test on enhanced tubes with three-dimension ridge and compared their test data with the fouling results reported by Li and Webb [11], showing that the heat transfer performance was greater than helical ridged tubes, but a higher asymptotic fouling resistance was observed. Above studies

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## Nomenclature

| | |
|---|---|
| $A$ | heat transfer area, $m^2$ |
| $c_p$ | special heat capacity, J/kg K |
| $D_i$ | inner diameter of tube, m |
| $e$ | ridge height, mm |
| $h$ | convective heat transfer coefficient, $W/m^2$ K |
| $j$ | Colburn *j*-factor, dimensionless |
| $k$ | slopes, dimensionless |
| $K_m$ | mass transfer coefficient, m/s |
| $LMTD$ | logarithmic mean temperature difference, °C |
| $N_s$ | number of starts, dimensionless |
| $Nu$ | Nusselt number, dimensionless |
| $Pr$ | Prandtl-Taylor number, dimensionless |
| $q$ | heat flux, $W/m^2$ |
| $\Delta q$ | deviations of water velocity, % |
| $R_f$ | fouling resistance, $m^2$ K/W |
| $R^2$ | the goodness of fit, dimensionless |
| $Re$ | Reynolds number, dimensionless |
| $T_{w,i}$ | inlet water temperature, °C |
| $T_{w,o}$ | inlet water temperature, °C |
| $T_{r,sat}$ | saturation temperature of refrigerant, °C |
| $U$ | overall heat transfer coefficient, $W/m^2$ K |
| $\Delta U$ | deviation of overall heat transfer coefficient, % |
| $u$ | fluid velocity of the test water, m/s |
| $\Delta u$ | deviations of water velocity, % |
| $V$ | water flow rate, $m^3/s$ |
| $Y_q$ | correction factor of overall heat transfer coefficient caused by heat flux deviation, % |
| $Y_u$ | correction factor of overall heat transfer coefficient caused by velocity deviation, % |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | helix angle, degrees |
| $\rho$ | density of water, $kg/m^3$ |
| $v$ | kinematic viscosity, $m^2/s$ |
| $\beta$ | related to property of test water, $\beta = \rho c_p P_r^{-2/3} \upsilon^{0.181}$ |
| $\gamma$ | related to geometry of test tubes, $\gamma = N_s^{0.285} e^{0.323} D_i^{-0.504} \alpha^{0.505}$ |
| $\lambda$ | the thermal conductivity coefficient, W/m K |

*Subscripts*

| | |
|---|---|
| $c$ | cleaning condition |
| $f$ | fouled condition |
| $i$ | test $i$ |
| $ref$ | the reference point |

reported the data associated with "accelerated" particulate fouling of enhanced surfaces using test water with much higher concentration of particulate than that in practical system. Webb and Li [4] conducted a long-term test of combined fouling (precipitation fouling and particulate fouling) in seven different enhanced tube geometries plus one plain tube, in which test the circulating water was from practical cooling tower on campus. This is the first set of long-term fouling data of enhanced tubes that can be found in literatures. The seven test tubes had different helical ridged geometries. The water velocity was set at 1.07 m/s which is lower than that in most practical projects. Shen [12] conducted a primary test of combined fouling on enhanced tubes using the cooling water created in terms of the method proposed by Cremaschi [13].

A fouling test is very meticulous research due to the requirement of accuracy. Generally, uncertainty of fouling results comes from two aspects: test system and data reduction. As for the test system, the capacity of units should be large enough [14] and the precision of measuring instruments should be high enough to satisfy the requirements of accuracy [15]. As for data reduction, could we just simply use Eq. (1) to calculate the fouling thermal resistance based on test data? The analysis is given as following.

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

$$U = \frac{c\rho V(T_{w,o} - T_{w,i})}{A \cdot LMTD} \tag{2}$$

$$LMTD = \frac{(T_{r,sat} - T_{w,i}) - (T_{r,sat} - T_{w,o})}{\ln\left(\frac{T_{r,sat} - T_{w,i}}{T_{r,sat} - T_{w,o}}\right)} \tag{3}$$

where $U$ is the overall heat transfer coefficient of the test tube involving the convective heat transfer on the internal/external surfaces of the test tube and the conductive heat transfer of the fouling and tube wall. In a clean condition, the overall heat transfer coefficient of the test tube is written as $U_c$. In a fouled condition, the overall heat transfer coefficient is written as $U_f$ and the fouling resistance is given as $R_f$.

In a fouling test, the water velocity and heat flux are usually required to keep constant through adjusting manually. But it can be imagined that with the deposit of fouling on the internal surface of test tube, both the water velocity and heat flux would change inevitably. Without manual intervene, the water velocity would increase and heat flux decreases automatically due to the deposit of fouling on the internal surface of tubes. In addition, the water velocity through the test tube usually varies due to the fluctuation of electricity voltage provided to water pump. The water velocity is very hard to be adjusted to initial value absolutely. In a long-term fouling test, the water velocity even is not adjusted thoroughly. As for the heat flux, in most test set-ups, several different tubes are installed in one condenser, because they share one saturation temperature, and the growth rate of fouling resistance in each test tube is different to each other, it is impossible to keep the heat flux of each tube constant absolutely. In addition to fouling resistance on enhanced tubes, the change of water velocity and heat flux will also affect the overall heat transfer coefficient $U$, which could not be considered wrongly as the effect of fouling thermal resistance. In literature [16], Kim also realized that deviation of water velocity would affect the accuracy of fouling resistance. He suggested correcting the overall heat transfer coefficient of clean tube, $U_c$, as a function of water velocity during the calculation of fouling resistance. But he did not consider the effect caused by variation of heat flux, and no value of correction factor was given in that paper. The accurate test of fouling thermal resistance is critical for fouling researchers when the mechanism of fouling deposit was investigated. Especially, when the tested fouling resistance was used to develop a fouling model which would be considered to publish as the ASHRAE Standard, the test fouling resistance should be decoupled carefully due to the precision requirement. How to remove the effect of deviation of water velocity and heat flux? How much is the effect? A decoupling analysis should be addressed. To our best knowledge, no report could be found in current literatures. In this paper, the effects of deviation of both water