EXPERIMENTAL CHARACTERIZATION OF FOULING IN CONTEXT OF HEAT EXCHANGER DEVELOPMENT

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ABSTRACT

The development and experimental characterization of heat exchangers has been a key expertise at Fraunhofer ISE for many years. Besides the thermodynamic characterization and optimization of geometries, more recently we have begun to include the analysis of the fouling behavior of heat exchangers into their design and optimization.

This work presents the results of experimental investigations on four heat exchanger types for different applications: Crystallization fouling of CaCO3 is studied on a countercurrent double-pipe heat exchanger and fouling of oil-polluted water in a 20 kW plate heat exchanger. An innovative wire structure heat exchanger is compared to a state of the art wavy-fin, flat-tube heat exchanger in terms of airside particle fouling and thermodynamic performance. Airside crystallization fouling of CaCO3 is investigated on a laboratory scale indirect wet cooling tower and the evaluation method is then applied to a real system in the field.

Although the experiments were conducted on four different test facilities, the evaluation follows a similar approach and the results show that the performance drop of the heat exchangers due to fouling can be well characterized by integral methods.

INTRODUCTION

Fouling in general describes the accumulation and growth of particles on a heat transfer surface causing a decrease in performance due to the low thermal conductivity of the deposition material.

Financial losses in the order of 0.25% of the GDP for industrialized countries [1] reveal the importance of research on fouling and the need of optimized heat exchangers. At Fraunhofer ISE we have recently begun to include the analysis of the fouling behavior into the characterization and design process.

The heat exchangers presented in this work are divided into two categories according to their heat transfer media, water-water and air-water systems.

Depending on the heat exchanger and its field of application different types of fouling are investigated: (1) Waterside scaling of CaCO3 in a round tube has been studied before by many researchers [2–4]. In this work results from a Fraunhofer internal project are presented in which scaling on a coated and uncoated tube in parallel is investigated experimentally. The tube coating is provided by an industrial partner.

(2) While fouling of crude oil has been studied extensively [5,6], literature on fouling of vegetable oil in water dispersions with low oil content is scarce. In this work fouling of oil polluted water in a plate heat exchanger is studied, simulating an oil leakage into a process fluid.

(3) Fouling tests with three different types of dust have been conducted on air-to-water heat exchangers as used in HVAC systems, industrial processes, and automotive applications. A state of the art wavy-fin, flat-tube heat exchanger is compared with an innovative wire structure heat exchanger. The wire distances within these structures are typically in the range of a millimeter to 100 micrometers i.e. the increased heat exchanger surface acts like a filter to airborne particles. Therefore the characterization of particle fouling is essential for the development of innovative structures.

(4) Airside fouling of CaCO3 in wet cooling towers is a common problem [7,8]. In collaboration with Hartmann Chemietechnik, a project partner specialized on cleaning of cooling towers, a small cooling tower is run with spray water containing a high concentration of salts in order to provoke scaling on the tube bundle. The system was operated during several months and monitored constantly to evaluate the impact on performance.

THEORY AND METHODS

Although the type of the heat exchangers, their application and the examined fouling types differ a lot, all experiments follow a similar approach. Integrals methods are used to characterize the thermodynamic performance.

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Assuming steady state for the energy balance around a heat exchanger, the heat transfer rate $\dot{Q}$ can be described by

$$\dot{Q} = \rho \dot{V} c_p (T_{out} - T_{in}) \quad (1)$$

The logarithmic mean temperature difference of a heat exchanger operating in counter-flow is calculated by

$$\text{LMTD} = \frac{(T_{hot,in} - T_{cold,out}) - (T_{hot,out} - T_{cold,in})}{\ln\left(\frac{T_{hot,in} - T_{cold,out}}{T_{hot,out} - T_{cold,in}}\right)} \quad (2)$$

This allows evaluating the UA-value for the heat exchanger:

$$UA = \frac{\dot{Q}}{LMTD} \quad (3)$$

The overall thermal resistance R is defined as the inverse of the UA-value.

The Reynolds number is defined as

$$Re = \frac{v \cdot d_h}{\nu} \quad (4)$$

where v is the flow velocity, d_h the hydraulic diameter and ν the kinematic viscosity. The Nusselt number is calculated by

$$Nu = \frac{h \cdot d}{\lambda} \quad (5)$$

where h is the convection heat transfer coefficient and λ the thermal conductivity.

EXPERIMENTAL EVALUATION AND DISCUSSION

Waterside fouling

Scaling in a double pipe heat exchanger

A test rig as shown in Figure 1 was designed to perform scaling tests on sample tubes provided by an industrial partner. Two seamless stainless steel tubes of 1 meter length (20 x 2 x 1000 mm) are characterized at the same time in parallel flow.

The aim of this work was to investigate whether a hydrophobic coating can be used to prevent or reduce crystallization fouling of calcium carbonate ($CaCO_3$) on the inner tube surface.

A supersaturated salt solution is prepared according to [9] by mixing 150 g of calcium chloride dehydrate ($CaCl_2 \cdot 2H_2O$) and 150 g of sodium bicarbonate ($NaHCO_3$) salts into 500 liter preheated deionized water. The salt solution is circulated and heated in the two parallel double-pipe heat exchangers. Downstream the solution is cooled down again in a plate heat exchanger. The heat is supplied by two process heaters. The heating fluid is pumped through the shell (2.5 mm gap) of the two double-pipe heat exchangers at high velocities (Re=28000). The temperature of the heating circuit is set to 85°C while the temperature of the salt solution entering the test section is approximately 40°C.

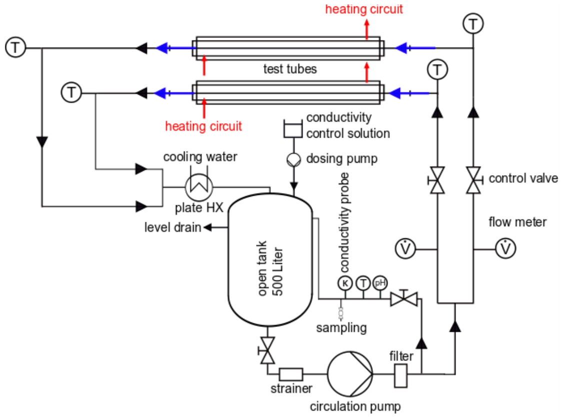

Figure 1: Experimental setup for parallel testing of two double-pipe heat exchangers

Inlet and outlet temperatures of both circuits are measured by calibrated Pt100 resistance temperature sensors in a 4-wire configuration (±0.02 K) and the volume flow rates by electromagnetic flowmeters with an accuracy of ±0.2%.

A reference measurement is conducted at preheated steady state before the salts are added into deionized water. During preparation of the salt solution the heater and the cooling water are turned off while the salt solution continues to circulate. When the conductivity has stabilized it is assumed that the salts are fully mixed. Then, the heater and the cooling water are turned on again and the evaluation period of the measurement begins. A conductivity control solution is added continuously to the tank by a dosing pump to replace ions that are removed from the solution by the fouling process. The experiments were conducted at flow velocities of 0.5 and 1 m/s, which the industrial partner indicated is a typical range of velocities in his real application (Re=13000-26000). After each test run the tubes are removed and replaced by new clean tubes. The entire setup is flushed with DI-Water.

Based on the inverse of the UA-value (equation (3)) and referring to the heated inner tube surface the integral fouling resistance in [m^2K/W] is calculated by

$$R_f = R(t) - R_0 \quad (6)$$

where R_0 is the mean value of the thermal resistance during the reference period. Figure 2 shows its trend for coated and uncoated tubes at both flow velocities.

An initiation period or a roughness delay time as described in [10], in which first nucleation sites are formed on the surface and heat transfer increases due to increasing surface roughness, could not be

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observed in these experiments. Nucleation sites might already have been formed by remaining particles in the piping system during the preparation period. The time required to heat up the 500 Liter tank and reach steady-state conditions for the inlet temperatures was up to 15 hours.

The plateauing of the fouling resistance is typical for crystallization fouling under forced convection and is observed when the difference between deposition rate and removal rate decreases with time and the removal rate becomes equal to the deposition rate [3].

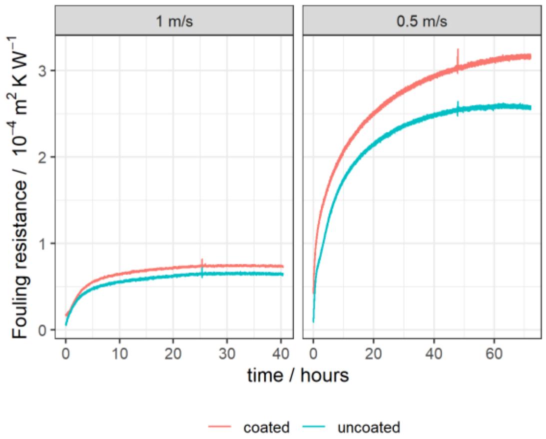

Figure 2: Fouling resistance over time for coated and uncoated tubes at flow velocities of 0.5 m/s and 1 m/s

As expected, higher fouling resistances are reached at lower flow velocities due to reduced shear forces (lower removal rate): The fouling resistances at 0.5 m/s are approximately 4 to 5 times higher compared to the 1 m/s tests.

The results indicate that the provided coating does not achieve a reduction in fouling resistance. In both tests, the uncoated tube had lower fouling resistances. An initially higher thermal resistance can be explained by the additional thermal resistance of the coating. Even after 40 hours of testing, the hydrophobic coating provided no positive effect on preventing scaling.

Fouling of oil-polluted water in a plate heat exchanger

Another test facility as shown in Figure 3 was designed at Fraunhofer ISE to characterize plate heat exchangers under different contaminants. First experiments were conducted with oil-polluted water simulating an oil leakage into a process fluid.

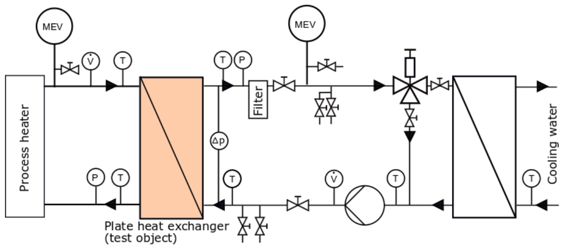

Figure 3: Experimental setup for testing of plate heat exchangers

Reference measurements are conducted with deionized water for three different volume flow rates (350, 500, 750 Liter/hour), heating temperatures between 62°C and 80°C and inlet temperatures on the process fluid side of 30-50°C. Each set of operating parameters is run for 2 hours. Within these intervals a 20 min steady-state interval is identified and arithmetic mean values are calculated. The measurements are repeated with oil-polluted water under identical operating conditions. Rapeseed oil is used as contaminant and tests are conducted with two different concentrations, 1.75 wt% and 3.5 wt%. For the calculation of the thermal power (see equation (1)), temperature dependent values of density and specific heat capacity are used. For the oil-polluted measurements a mixture of oil and water is assumed. Figure 4 shows the thermal power calculated by Equation (1) versus the logarithmic mean temperature difference for the three different volume flow rates.

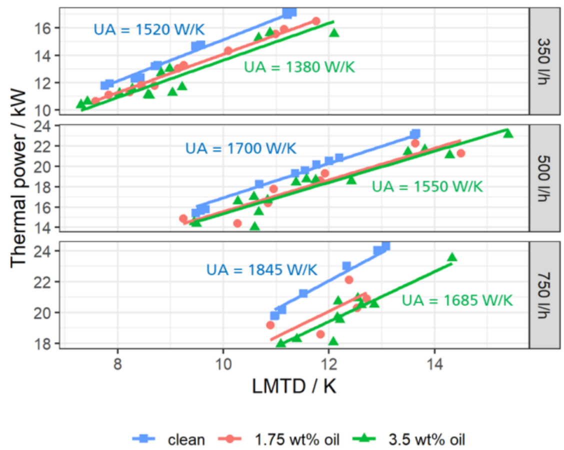

Figure 4: Thermal power versus logarithmic mean temperature difference for three different volume flow rates. Comparison of clean reference and measurements with oil-polluted water

The slope of the regression lines through the origin corresponds to the global UA-values. The resulting UA-values for oil-polluted water are about 7-12% lower compared to the clean reference. The decrease in heat transfer can be caused by two different effects: The deposition of a thin oil layer on the heat transfer surface and the change of

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thermal properties of the heat transfer fluid due to the oil dispersed in water. To determine the influence of the two effects the knowledge of the thermal properties is essential, as Reynolds and Nusselt numbers are functions of the dynamic viscosity and thermal conductivity. The viscosity is calculated by a simple approach from Taylor [11]. For the tested oil fractions the differences in viscosity are in the range of 4-8% compared to clean water. Differences in thermal conductivity are assumed to be small and are neglected in this first approach. In order to separate the fouling effect from the effect caused by changing thermal properties of the heat transfer fluid, effective Nusselt and Reynolds numbers are calculated according to equation (4) and (5). The heat transfer coefficient on the oil-polluted side is calculated from the global UA-value and the heat transfer coefficient on the heating side. The latter is obtained from a given Nusselt correlation. The calculated effective Nusselt number implies besides the convective heat transfer a potential thermal resistance caused by fouling. The results are shown in Figure 5.

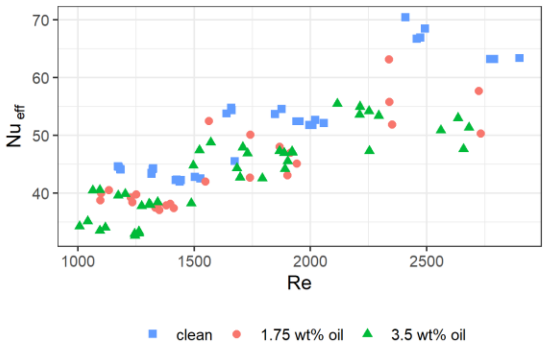

Figure 5: Effective Nusselt versus Reynolds number on the polluted side for clean and oil-polluted measurements

The Nusselt numbers in clean state are 10-25% higher than under polluted conditions. This indicates that the decrease in overall heat transfer is caused by a contamination of the heat exchanger surface rather than by changing thermal properties. The influence of uncertainties resulting from viscosity and thermal conductivity calculations is assumed to be 8-10%.

Airside Fouling

Particle fouling and geometry optimization

A test facility [12] for thermal-hydraulic performance measurements of air-to-water heat exchangers has been extended to allow particle fouling measurements. Standard heat exchangers and new developments of heat exchanger designs can be evaluated for their thermal-hydraulic performance in clean operation and their sensitivity for fouling can be evaluated. Figure 6 shows a section of the test facility with the main components. In the standard test, cold air is entering the air channel, fed with dust and flows thereafter through the heat exchanger. Meanwhile hot water flows in cross-flow direction through the heat exchanger. The inlet/outlet temperatures and pressure drops of both fluids are measured during this testing.

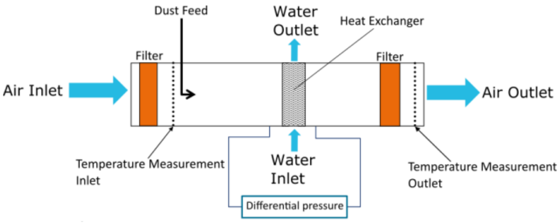

Figure 6: Schematic view on the dust feeding in the channel before the heat exchanger and main sensor and filter positions.

So far, three different types of dust have been used: Gypsum, Arizona test dust, and ASHRAE test dust. The Arizona test dust has a large share of round and granular particles, whereas the ASHRAE test dust has additionally cotton linters and carbon black powder. Gypsum is used for first tests of operation. In this paper, the performance evaluation of two types of heat transfer surface area enhancement is presented. The first surface enhancement is a standard meandering fin, the second is a wire structure [13]. The latter enhancement allows strong mass reduction compared to the meandering fins. Both enhancements are installed on the air side of a flat tube heat exchanger with air side cross section of 200 mm x 217 mm (see Figure 7).

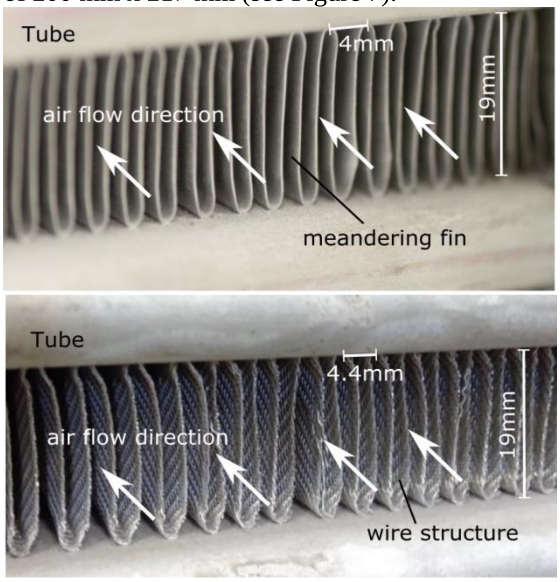

Figure 7: Details of surface enhancements used in particle fouling measurements.

The measurement procedure is as follows. (i) The water side volume flow rate and temperature are fixed for the whole procedure at 0.3 m/h and 60°C, respectively. Air side temperature is fixed at 25°C and relative humidity is set to 20%. (ii) The determination of thermal-hydraulic performance

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(Pressure drop and heat transfer coefficient) of the clean heat exchanger for different air velocities takes place. (iii) Dust feeding with specific amount of dust per time (from 5 g/h to 15 g/h) at a constant air velocity (similar to design specification: 2.25 m/s) is performed for 5 to 7 hours. (iv) The determination of thermal-hydraulic performance of the fouled heat exchanger for different air velocities takes place.

In Figure 8 the pressure drop and the product of air-side heat transfer coefficient and surface area is shown as a function of air velocity for the two enhancements in clean and fouled conditions. For the clean condition, the wire structure shows slightly higher heat transfer with a strong increase in pressure drop compared to the meandering fin. This strong increase in pressure drop is due to a repeating interruption of the fluid flow boundary layer and inhomogeneous arrangement of the wires. The advantages of a higher heat transfer and a lightweight structure can compensate the disadvantage of a high pressure drop only in specific applications. For these applications, the additional decrease in heat transfer of around 20% (compare Figure 8 b) in the fouled condition could be another argument for the standard heat exchanger with meandering (or similarly plain) fins.

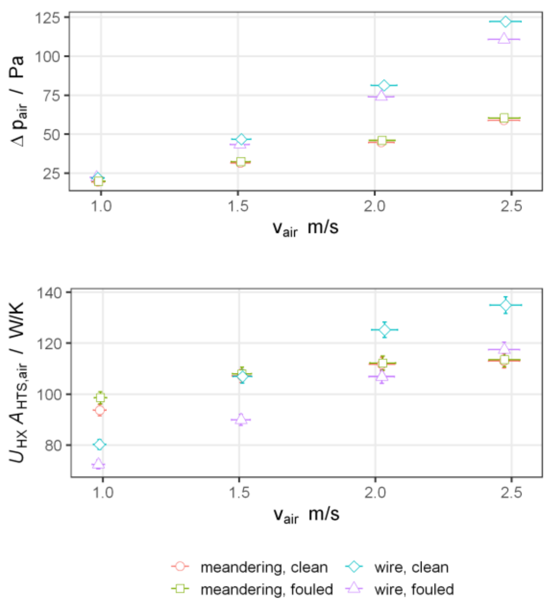

Figure 8: (a) pressure drop and (b) heat transfer for clean and fouled surface enhancements

Scaling in cooling towers

Evaporative cooling systems, which are often used in refrigeration systems to dissipate condenser heat to the environment, are very susceptible to fouling as they usually operate with untreated ambient air and spray water containing suspended solids and dissolved salts.

An exemplary scaling process of a small capacity closed circuit wet cooling tower (Gohl VK 8-5 with 18 tube rows) was monitored in detail during one year of operation. The test setup and the measuring concept is described in [14,15]. During the entire operation period, scaling thickness on the tube bundle was recorded twice a week with an inductive measuring device. The photos in Figure 9 show the scaling of the top tubes of the bundle over the course of time, the graph provides the corresponding thickness measurements. The variations are a consequence of the uneven surface and lime occasionally chipping off.

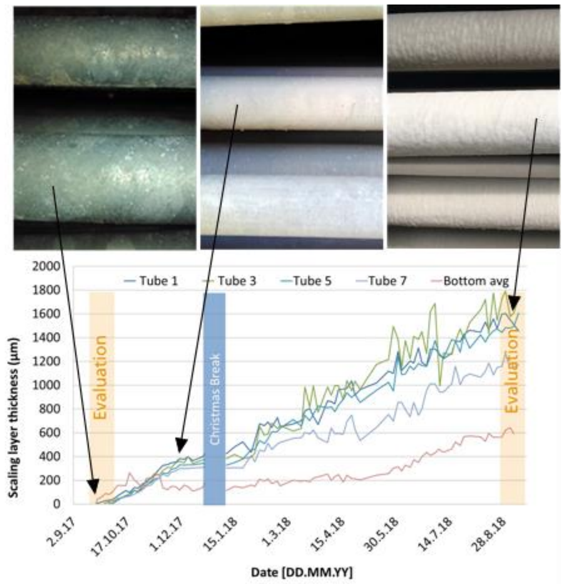

Figure 9: Evolvement of the scaling layer thickness

The impact of the fouling on the performance of the cooling tower is evaluated by a simple 1-node model according to [16]. The model was calibrated with operation data of the clean (new) cooling tower first. The predicted performance by the model is then compared to the actual performance under scaled conditions. Figure 10 shows the corresponding results for the measurements at the beginning and the end of the one-year test period: a performance decrease of ~15% at a scaling thickness of ~1.1 mm (averaged over the entire tube bundle).

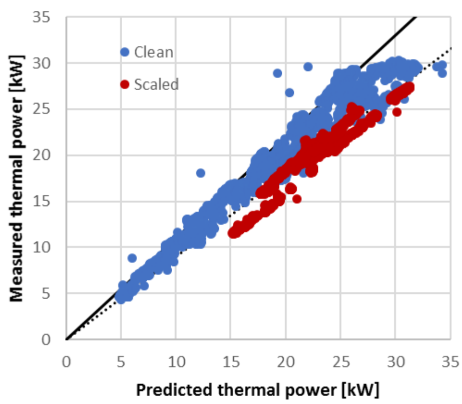

Figure 10: Comparison of predicted and measured thermal power under clean and scaled conditions

The same approach can be applied for evaluating the condition of cooling towers in the field. If the relevant operational data are not recorded by the central building/system control system, a non-intrusive measurement system can be installed. Figure 11 presents the results for a cooling tower of the chiller which supplies the cold water network at Fraunhofer ISE. The presented data correspond to one week before (red/scaled) and after (blue/clean) the annual maintenance, respectively. As the difference in the slope of the linear trends indicate, the performance had been 5% lower before the cleaning than after. Additionally, the maintenance of the chiller itself, which included an adaption of the control, lead to a more stable operation of the entire system with less cycling and thus less scattering of the data.

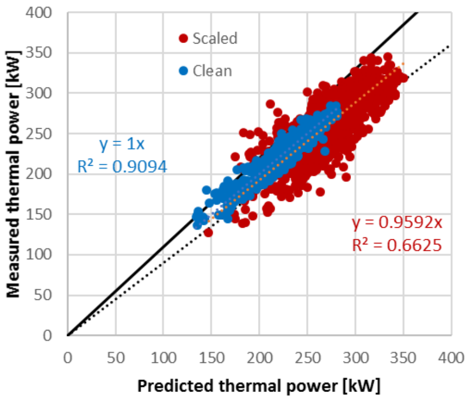

Figure 11: Comparison of predicted and measured thermal power of a field installation

CONCLUSION

In this work four heat exchanger types for different applications were characterized experimentally:

(1) Calcium carbonate scaling was investigated on a tube-in-tube counter-flow heat exchanger under forced convection. Tests were run with coated and uncoated tubes. Scaling was induced successfully using a supersaturated salt solution. The fouling resistance over time showed a typical asymptotic behavior. The results indicate that the coating does not provide a benefit in terms of reducing the fouling resistance. In all experiments, the measured resistance of the coated tube exceeded that of the uncoated tube.

(2) An oil leakage into a process fluid and its impact on the heat transfer performance of a plate heat exchanger was simulated by adding defined volume fractions of rapeseed oil into deionized water. The measured decrease in overall heat transfer was about 7-12%. Nusselt and Reynolds numbers were calculated to determine whether the decrease was due to fouling, i.e. an oil layer on the heat transfer surface or due to changing thermal properties. The Nusselt numbers in clean state were 10-25% higher compared to the oil-polluted measurements, indicating that the decrease in overall heat transfer performance is caused by formation of oil deposits on the heat exchanger surface.

(3) Airside particle fouling has been investigated experimentally on two types of air-to-water heat exchangers: A state of the arte wavy fin and an innovative wire structure heat exchanger. Three different kinds of dusts were used to create fouling on the heat transfer structure. The measured changes in pressure drop due to fouling are small for both heat exchangers. While the decrease in heat transfer performance is around 20% for the innovative wire structure, the performance of the state of the art heat exchangers remains almost unchanged.

(4) Airside scaling on the tube bundle of an evaporative cooling tower was successfully characterized by comparing the actual performance to the predicted performance of a 1-node model. A performance decrease of approximately 15% was measured at an average scaling layer thickness of 1.1 mm. The same method was furthermore applied to a cooling tower in the field where a performance increase of 5% was detected after the annual cleaning.

NOMENCLATURE

A	Surface area, m^2
c_p	Specific heat capacity, J kg/K
d	Diameter, m
h	Convection heat transfer coefficient, W/(m^2 K)
$LMTD$	Logarithmic mean temperature difference
Nu	Nusselt number, dimensionless
$\dot{Q}$	Heat transfer rate, W
R	Thermal resistance, K/W
Re	Reynolds number, dimensionless
T	Temperature, °C
U	Overall heat transfer coefficient, W/(m^2 K)
v	Flow velocity, m/s
$\dot{V}$	Volume flow rate, m^3/s
Δp	Pressure drop, Pa
ρ	Density, kg/m^3
ν	Kinematic viscosity, m^2/s
λ	Thermal conductivity, W/(m K)

Subscript

0	Reference (clean)
f	fouling
h	hydraulic
HTS	Heat transfer surface
HX	Heat exchanger
in	inlet
out	outlet

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