Effect of Condensation Temperature and Water Quality on Fouling of Brazed-Plate Heat Exchangers

Lorenzo Cremaschi, PhD  Atharva Barve  Xiaoxiao Wu
Member ASHRAE  Student Member ASHRAE  Student Member ASHRAE

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ABSTRACT
Brazed-plate heat exchangers (BPHEs) have been recently introduced in the air-conditioning industry because they could provide higher heat-transfer rate per unit volume and are more compact than conventional tube-and-shell exchangers. This paper presents experimental data of waterside fouling performance of BPHEs used in direct refrigerant-to-water condensers for cooling tower applications. The effects of refrigerant condensation temperature and water quality were experimentally investigated and asymptotic values of the fouling resistance were determined. Two saturation temperatures of 105.5°F and 120°F (~41°C and ~49°C) and two water qualities for high- and medium-fouling potentials were applied in controlled laboratory fouling experiments and BPHEs with soft chevron corrugation angles were significantly affected by these operating parameters. For hard chevron corrugation angles, the fouling resistance was still dependent on the refrigerant saturation temperature, but the degradation of the heat flux in fouled condition was only of few percents. The fouling of the plates affected the waterside pressure drop significantly, which was from 10% higher up to 11 times higher than the corresponding waterside pressure drop across the BPHE in clean conditions. The effect of the cooling tower water quality was also quantified in the present work and asymptotic values of the fouling resistance were derived for water with moderate to severe mineral scaling conditions.

INTRODUCTION
Brazed-plate heat exchangers (BPHEs) have been recently introduced in the air-conditioning industry as refrigerant condensers because they provide higher heat transfer coefficients and are more compact than conventional tube-and-shell exchangers. They are able to handle high refrigerant pressure and provide significant cooling capacity, thus increasing the overall system energy efficiency. The performance of BPHEs relies on the internal geometry of their corrugated plates, which often incorporate a herringbone pattern. This type of pattern is designed to maximize effective surface area of the plates, promote turbulence, and distribute the fluid flow. Depending on the internal geometry of the plates, the flow pattern could either be in the form of “zigzag” or “double-cross” flow (Luan, et al. 2008). In both flow patterns, the fluid streams intersect each other at the intersection, which induces turbulent flow and at the same time increases pressure drop inside the BPHE (Focke et al. 1985). The stacked plates are assembled with thin copper sheets between the plates before the unit enters a furnace. The melted copper acts as a brazing agent to seal the edges of the BPHE plates and also bonds the meeting points of the corrugation ridges to provide pressure retention strength.

In condensers for small chillers, heat is rejected from the refrigerant side to the water side, and the water often circulates in cooling tower loops. Circulating cooling tower water typically contains an excess amount of mineral ions, such as calcium and magnesium, due to evaporation of water, thus making the water hard (Cho, et al. 2003). When hard water is heated inside compact BPHEs, the calcium and bicarbonate ions precipitate because a drop in local solubility occurs. This phenomenon is referred to as precipitation fouling and this deposition of unwanted material on the heat transfer surface reduces the overall heat transfer coefficients and increases the resistance to the fluid flow (Zubair and Qureshi 2006).

Lorenzo Cremaschi is an assistant professor and Atharva Barve and Xiaoxiao Wu are graduate research assistants at the School of Mechanical and Aerospace Engineering at Oklahoma State University, Stillwater, OK.
In cooling tower applications, four major mechanisms of fouling are expected: (a) precipitation fouling (scaling), (b) biological fouling (slime), (c) corrosion fouling, and (d) particulate fouling (sedimentation) (Haider, et al. 1991, 1992). The extent of the fouling problem depends upon the water quality, operating conditions, monitoring system, and maintenance practices. Users of this type of equipment have typically applied the same fouling factors that are recommended for tube-type heat exchangers, which are summarized in the AHRI (Air-Conditioning, Heating, and Refrigeration Institute) Guideline E (AHRI 1997). Guidance to the industry has also been provided by AHRI Standard 450 (AHRI 2007) and from recommendations by the Tubular Exchanger Manufacturers’ Association (TEMA 2007). A recent study on the waterside fouling performance was presented by Cremaschi et al. (2011). The authors measured the fouling resistance in BPHEs having different aspect ratios and chevron angles and with Langelier Saturation Index (LSI) (Langelier 1936) from 2 up to 3.5. This range of LSI is representative of severe scaling conditions and a reduction of 28% in heat flux was observed. The authors pointed out the local phenomenon of flow blockage due to both precipitation and particulate fouling and the pressure losses augmented more than 250% with respect to the pressure drop of the water side across the BPHE in clean conditions. In addition, the chevron angle was found to be a main factor affecting the fouling resistance. For BPHEs with similar geometries, the measured fouling resistance for soft chevron angle of 30° (measured from the direction of the flow) was ten times larger than that with hard chevron angle of 63°.

In spite of these findings, understanding the fouling mechanism in BPHEs and the key factors controlling the fouling process are still open questions. This paper presents experimental data of fouling behavior of BPHEs when these heat exchangers are used as direct refrigerant-to-water condensers in small chiller applications. This paper addresses the need to isolate and quantify the effect due to the plate wall temperatures, which are controlled by the refrigerant saturation temperature during condensation, and of the water quality. Through a series of intensive laboratory experiments, the impact of refrigerant saturation temperature and water quality on the fouling resistance was determined.

LITERATURE REVIEW

One of the main driving potentials for the fouling deposition is the concentration of the minerals within the water stream. Although there are several inversely-soluble minerals found in typical cooling tower water, calcium carbonate (CaCO₃) seemed to be the predominant mineral found in fouling deposits. Hence, fouling of heat exchangers by precipitation of CaCO₃ has been the main focus of many researchers for the past two decades. The first study performed regarding precipitation fouling was done by Langelier (1936). He proposed the Langelier Index, now commonly known as Langelier Saturation Index or LSI. This parameter is used to predict the solubility of CaCO₃ in water. The parameters used to determine the LSI are the amount of total dissolved solids, calcium hardness, total alkalinity, fluid temperature, and actual pH of the water. LSI is defined as the difference between actual pH of the water sample and its computed saturation pH, \( pH_f \), which is the pH at which the calcium concentration in a given water sample is in equilibrium with the total alkalinity. In the current work, the saturation pH values were approximated using the following equations (Pearson 2003):

\[
LSI = pH_{\text{actual}} - pH_s \quad (1)
\]

\[
pH_s = 12.18 + 0.1 \log_{10} (\text{TDS}) - 0.0084 (T_{\text{water}}) - \log_{10} (\text{Ca}) - \log_{10} (M_{\text{alkalinity}}) \quad (2)
\]

Where:
- \( \text{TDS} \) = total dissolved solid (ppm)
- \( T_{\text{water}} \) = water temperature (°F)
- \( \text{Ca} \) = calcium concentration (ppm as CaCO₃)
- \( M_{\text{alkalinity}} \) = “M” alkalinity (ppm as CaCO₃)

Other models to compute the saturation \( pH_f \) are available in the literature and they generally provide similar values of the LSI (Lim 2010). If the LSI is higher than 2, the condition is referred to as high-fouling potential water; in particular, if LSI is greater than 3, then the water is considered to be in severe mineral scaling conditions and very strong scale formation is expected. Moderate to strong scaling conditions are expected for LSI between 1.1 and 2 and small to no scale formation is usually observed for LSI less than 0.5.

Fouling studies are extensive in the literature and several researchers investigated variables that could affect the fouling process in cooling tower. For example, Xu and Knudsen (1986) analyzed experimental data of fouling resistance and change in overall heat transfer coefficients for cooling tower applications. The authors suggested the idea that at constant fluid velocity, the shear stress responsible for interference in the fouling process would also be constant. Their study indicated that deposit strength, in terms of adherence and toughness, increased with an augment of the surface temperature of the heat exchanger. Other researchers developed strong experimental work by developing laboratory facilities constructed ad-hoc to study fouling performance of heat exchangers in a parametric fashion. An experimental facility was developed by Grandgeorge et al. (1998) to measure the particulate fouling of heat exchangers. The work by Chamra and Webb (1993) also focused on particulate fouling inside enhanced tubes. Webb and Li (2000) studied fouling in enhanced tubes using actual cooling tower water. In their work, the fouling mechanism was a combination of particulate and precipitation fouling, which was similar to the fouling mechanism of the present investigation. The fouling tests
in the Webb and Li study were conducted with water velocity of 3.5 ft/s (1.1 m/s) and Reynolds number of about 16,000. The total hardness of cooling tower water was approximately 800 ppm CaCO₃, electrical conductivity of 1600 to 1800 μW, and pH = 8.5. Webb and Li observed that there were more mineral deposits found in enhanced tubes than those found in the plain tubes and concluded that there was a strong relationship between asymptotic fouling resistance and the internal geometry of the enhanced tubes. In another work, Chamra focused on fouling inside smooth and enhanced shell-and-tube refrigerant condensers by using copper alloy tubes (Chamra 2007). In his work, a water loop and a refrigerant loop were connected through the test section, which consisted of a shell-and-tube heat exchanger with refrigerant flowing through the shell and water flowing through the inner tube. The author investigated the waterside fouling performance using only water with a very low concentration of minerals, resulting in an LSI less than 0.3. In these conditions, measurements suggested that low-fouling potential water did not produce any measurable fouling effects.

In general, the effect of surface temperature on fouling rate is not well defined. Increasing the surface temperature may increase, decrease, or have no effect on the fouling rate. Awad et al. (2009) studied the effect of surface temperature on particulate fouling in a 5.92 cm (2.3 in.) diameter tube heat exchanger. In their experiments, the fouling was investigated at different surface temperatures of the tube heat exchanger and asymptotic values of fouling resistance were estimated. Their results suggested that the surface temperature had a significant effect on the particulate fouling resistance but a small effect on the crystalization fouling. The authors concluded that particulate fouling is of the asymptotic type while crystallization fouling is of the linear type. As the surface temperature increased, the particulate fouling resistance decreased, while the crystalline fouling resistance increased. Thus, depending on the local water quality, the authors recommended operation of the heat transfer equipment at the highest possible temperature if particulate fouling needed to be minimized, and vice versa if hindering crystallization fouling was the critical factor to improve the performance of the heat exchanger. Zan et al. (2009) studied the fouling characteristics in plate heat exchangers at various temperatures and flow velocities. Their work examined the fouling resistance and flow pressure drop for heat pump working conditions. The results indicate that the fouling occurs in a plate heat exchanger in three different periods. The initial period consists of 3.58 days followed by a growth period and an asymptotic layer thickness period. The rate of fouling formation increases with an increase in the temperature. As a result of this phenomenon, the fouling occurs faster in the spring and summer. A recent work on fouling was conducted by Cremaschi et al. (2011), who focused on developing a test methodology and laboratory procedures to measure the fouling resistance in BPHEs for different geometries and operating conditions. The authors proposed an approach to create a simulated cooling tower water stream with very strong scaling conditions based on a small-scale water concentrator, which was integrated in line with the brazed-plate condenser. The water concentrator was built ad-hoc to evaporate the water in the loop at low ambient temperature. This method allowed Cremaschi et al. to achieve high LSI values for the cooling tower water and the feasibility and repeatability of the fouling measurements were demonstrated for several BPHEs geometries.

Based on that review, the effect of surface temperature and water quality on fouling characteristics of BPHEs was never completely considered, either theoretically or experimentally. This paper presents data of the fouling performance of BPHEs at two refrigerant condensation temperatures commonly found in cooling tower loops of chillers for building air-conditioning applications. Based on the methodology originally presented in Cremaschi et al. (2011), the effect of water quality was also investigated in this work by varying the water scaling conditions from moderate to severe. The propensity for fouling on brazed-plate type condensers was summarized by calculating asymptotic fouling resistance at the various operating conditions, as discussed next.

**EXPERIMENTAL METHODOLOGY**

High- and medium-water fouling potentials were developed in our laboratory to replicate the fouling mechanism of brazed-plate type condensers in cooling tower applications. A brief summary of the experimental methodology is given next and the reader can find further details in Cremaschi et al. (2011).

In this work, a new clean BPHE was used in each fouling test. Water was progressively concentrated and the dissolved minerals reached solubility limits. Water was maintained at saturated conditions while running through the test BPHE, which was run in series to a small cooling tower inside the laboratory that served primarily to concentrate the fouling minerals. During operation, the water became supersaturated near the heat transfer surfaces of the test BPHE. Here the water was rapidly heated up by the refrigerant, and thus mineral precipitation was promoted due to a local sudden drop of solubility. In the present work, the cooling tower acted more as a mineral concentrator device rather than a heat sink. It should be emphasized that the work in this paper deals with a combination of precipitation and particulate fouling because simulated cooling tower water typically contains inversely-soluble minerals, which come primarily from the makeup water source, but which may also be introduced by particles in the atmosphere (Zdaniuk et al. 2006). Precipitation fouling is expected because when water is heated up inside the test BPHE, the calcium and bicarbonate ions tend to precipitate due to the decreased local water solubility (Flynn 2009). Particulate fouling is also introduced in the water stream by fragments of deposit material that detach and depart from heat transfer surfaces of the BPHE. Suspended solids were evident in the system because they
formed a soft film layer along the connecting pipelines that were used upstream and downstream the BPHE. Clear PVC pipes were used downstream the BPHE and the accumulation of particulate were visually observed during the fouling test. During inspection of the pipelines, the BPHE, a deposit material of similar color and consistency, was also observed for the upstream and downstream pipelines. Particulate fouling was also postulated to occur because large particles, which were white and have irregular shape were observed in the water tank during the fouling test. The water-metering valve used to control the water flow rate clogged often during the fouling test period. Since water temperature was about 85°F (29.5°C) when crossing the metering valve, precipitation of the mineral is absent when considering the theory of the solubility limits, and the blockage of the metering valve was assumed to be due to particles in suspension in the water stream. We postulate that fragments of mineral deposit material detached from the heat transfer surface of the BPHE and resulted in large fluctuations of the waterside pressure drop across the BPHE. While the fouling resistance varied gradually during the heat transfer tests, particulate fouling is assumed to be the phenomena causing a sudden leap of the pressure difference across the water side of the BPHE to higher values, in case of local flow blockage of the microchannels, or to lower values in case of detachment of fragments of solid particles from the substrate deposit of fouling material on the heat transfer surface.

The effects from biological fouling and corrosion were reduced by treating the cooling tower water with a sufficient amount of chlorine and Tolytriazole, which is a chemical additive that prevented corrosion (Hollander and May 1985, Walker 1976). It should also be noted that reverse osmosis water, a few chemicals, and a small-scale cooling tower were our starting points to create low- and high-water fouling potentials.

**Experimental Apparatus and Test Conditions**

The experimental apparatus consisted mainly of two sections: a simulated cooling tower water loop and a refrigeration loop. These two loops, which are described in detail by Cremaschi et al. (2011), shared the test BPHE that acted as refrigerant condenser. About 25% of the total flow rate through the test BPHE was diverted to the small-scale cooling tower in order to evaporate the water at ambient temperature. The remaining stream flowed through the water postcooler and back to a batch water reservoir. The cooling tower progressively increased the concentration of the minerals in the water stream until saturated conditions were achieved. Makeup water was added periodically to the cooling tower water loop to replace the amount of water evaporated. Makeup water had a mineral content such that its LSI was about 0.4 to 0.8; that is, at low-fouling potential. A gear pump with a variable-speed drive circulated refrigerant R134a throughout the refrigeration loop. The refrigerant was first evaporated in the top heat exchanger and then superheated before entering the test BPHE. The pressure was taken at the inlet of the test BPHE while temperature sensors were installed before and after the test BPHE. The flow rate was measured by using a coriolis type flow meter, which was installed right after the refrigerant subcooler.

Inside a BPHE, alternating plates are stacked together to form a network of contact points. These contact points support the two plates and increase the intensity of turbulence. Figure 1 shows the plate geometric parameters that contribute to the heat transfer process, such as aspect ratio, L/W; corrugation angles, φ; corrugation depth, p.; and corrugation pitch transverse to the ribs, λ. The corrugation angle is known as the key variable that controls heat transfer enhancement and fouling resistance of a BPHE. In the current work, two BPHEs were selected and their geometries are summarized in Table 1. The chevron pattern of A1 yielded low pressure drop on the water side in clean conditions.

The detailed procedure to prepare the simulated cooling tower water in laboratory can be found in Cremaschi et al. (2011). Initially, the LSI of the makeup water calculated using Equation 1 resulted in the range from 0.4 to 0.8, which was considered light scaling conditions. This solution was charged into the batch tank of the cooling tower loop of the test apparatus and potassium hydroxide was added to adjust the pH to 8.6 or 9.3 to achieve LSI of medium- or high-water fouling potentials, respectively. Then the water was circulated in the test BPHE and in the cooling tower installed in series in the experimental apparatus. To avoid sudden precipitation of the dissolved minerals, the evaporation in the cooling tower took place at ambient room temperature of about 79°F (26°C). During the evaporation process, the dissolved salts are left behind in the remaining water stream. The more...
water was evaporated, the higher was the ratio of salt concentration in the remaining water inside the simulated cooling tower loop. Minerals were present in form of precipitate elements, deposit material, and dissolved compounds, and mineral precipitation was further promoted within the close proximity of the heat transfer surfaces of the brazed-plate-type condensers, where the water was heated by refrigerant and the local concentration of the minerals was brought above the solubility limits. The thermal entry length of the water stream depended on the wall surface temperature, which was controlled by the refrigerant temperature. The operating conditions during the fouling measurements were selected in a way that the test BPHEs operated in similar conditions as the ones for direct refrigerant-to-water condensers in cooling tower applications. Test conditions were also in agreement with the recommendations given in the AHRI 450 guidelines (AHRI 2007). Table 2 provides the list of independent variables that were set and accurately controlled during the laboratory fouling experiments of the present work. The degree of superheat and the water flow rate were selected from typical range of brazed-plate type condensers and within the scope of interest recommended by ASHRAE (ASHRAE 2007).

Table 1. Summary of the Brazed-Plate Heat Exchangers (BPHEs) for this Fouling Study

<table>
<thead>
<tr>
<th>Dimensions, L · W (in. · in.) [cm · cm]</th>
<th>BPHE A1</th>
<th>BPHE A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio, L/W</td>
<td>13.3 · 5.1 (33.8 · 12.9)</td>
<td>13.3 · 5.1 (33.8 · 12.9)</td>
</tr>
<tr>
<td>Number of plates</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Heat transfer area (ft²) [m²]</td>
<td>4.6 (0.43)</td>
<td>4.6 (0.43)</td>
</tr>
<tr>
<td>Corrugation angle, φ (degree from flow direction)</td>
<td>30 (referred to as soft angle)</td>
<td>63 (referred to as hard angle)</td>
</tr>
<tr>
<td>Calculated water velocity in between plates during fouling tests (ft/s) [m/s]</td>
<td>0.6 (0.19)</td>
<td>0.6 (0.19)</td>
</tr>
</tbody>
</table>

Table 2. Test Conditions for the Fouling Tests on Brazed-Plate Type Condensers

<table>
<thead>
<tr>
<th>Independent Variables Controlled During the Fouling Experiments</th>
<th>Nominal Value and Tolerances During the Fouling Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water Side</strong></td>
<td></td>
</tr>
<tr>
<td>Entering water temperature (T_EWT)</td>
<td>85.03°F ± 0.05°F (29.4°C ± 0.03°C)</td>
</tr>
<tr>
<td>Water flow rate (V_w)</td>
<td>4.65 gpm# ± 0.03 gpm (29.3 · 10⁻⁵ m³/s)</td>
</tr>
<tr>
<td>Cooling tower water LSI</td>
<td>2.1–3.5 (with modified pH at 9.3–9.6)+</td>
</tr>
<tr>
<td><strong>Refrigerant Side</strong></td>
<td></td>
</tr>
<tr>
<td>Saturation condensing temperature (T_sat,r)</td>
<td>(Condition 1: nominal heat flux) 105.5°F ± 0.5°F (41°C and ± 0.3°C)</td>
</tr>
<tr>
<td>(Condition 2: increased heat flux)</td>
<td>120.2°F ± 0.5°F (49.0°C and ± 0.3°C)</td>
</tr>
<tr>
<td>Degree of superheat for entering refrigerant (ΔT_θ)</td>
<td>65.0°F ± 0.5°F (36.1°C ± 0.3°C)</td>
</tr>
<tr>
<td>Mass flow rate of refrigerant (m_ref)</td>
<td>3.50 ± 0.02 lbm/min (26 · 10⁻³ ± 15 · 10⁻⁵ kg/s)</td>
</tr>
</tbody>
</table>

# Set at 3 gpm/ton of cooling capacity. Estimated capacity BPHEs was about 1.5 tons of refrigeration (5.3 kW or 18,000 Btu/h)
+ LSI representative of strong to severe scale formation conditions
* LSI representative of moderate scale formation conditions
Data Reduction and Uncertainty Analysis

Tests were conducted until near to asymptotic fouling conditions were achieved or until the waterside pressure losses exceeded the maximum pumping head available in the water loop. The data reduction for the measurements for fouling resistance in brazed-plate heat exchangers (BPHEs) was carried out according to the steps summarized in Cremaschi et al. (2011). The logarithmic mean temperature difference, LMTD, was based on the refrigerant saturation temperature in agreement with the AHRI Standard 450. This LMTD method does not consider either the degree of superheat or the degree of subcooling on the refrigerant side of the BPHE. In the current work, the degree of superheat was controlled to 65.0°F (36.1°C) in order to replicate operating conditions similar to the ones of actual condensers in cooling tower applications. However, the degree of subcooling of the refrigerant varied from test to test, depending on the heat flux and fouled conditions. This observation has important implications in the calculated fouling resistance and it will be discussed later in this paper.

Resistance temperature detectors (RTDs) were used to read the water and refrigerant inlet and outlet temperatures while the refrigerant saturation temperature was obtained from the refrigerant pressure, for which the transducer was installed at the inlet of the BPHE. A data logger from National Instruments and Labview Real Time data acquisition system was used to record and store the data. Operating conditions were closely monitored every one second at all times by the Labview Real Time control module. Data were recorded two to three hours each day with a sampling rate of two seconds and the average values of the operating parameters were then calculated from about 5000 data points taken during each recording period. The measurements samples were statistically large enough to reduce the error from noise, random fluctuations of the sensor output signals, and sensors response time. The sensors and corresponding accuracies are summarized in Table 3. The bias error was considered by calculating average values of the operating parameters directly on line during the tests. The averages were brought close to the nominal values of the operating parameters. The fouling resistance was calculated from temperature, flow rate, and heat transfer rate measurements and according to this equation:

$$R_f = A_{ht} \left( \frac{1}{(UA)_f} - \frac{1}{(UA)_{c,corrected}} \right)$$  \hspace{1cm} (3)

where $A_{ht}$ is the nominal heat transfer area. The $(UA)_{c,corrected}$ is the corrected value for the clean $(UA)_c$ factor of the BPHE and it was obtained from double linear interpolation of the $(UA)_c$ coefficients recorded during the calibration phase of the fouling test. The double linear interpolation was performed using the actual saturation pressures of the refrigerant and average water flow rates of the fouling experiments as specified in Cremaschi et al. (2011).

<table>
<thead>
<tr>
<th>Item</th>
<th>Type</th>
<th>Nominal range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water mass flow meter</td>
<td>Coriolis</td>
<td>16 to 55 lb/min (0.1 to 0.4 kg/s)</td>
<td>±0.03% of flow rate</td>
</tr>
<tr>
<td>Refrigerant mass flow meter</td>
<td>Coriolis</td>
<td>1 to 5 lb/min (0.01 to 0.04 kg/s)</td>
<td>±0.1% of flow rate</td>
</tr>
<tr>
<td>Water inlet temperature</td>
<td>In-stream Pt-RTD</td>
<td>83°F to 87°F (28°C to 30°C)</td>
<td>±0.09°F (0.05°C) <strong>+</strong></td>
</tr>
<tr>
<td>Water outlet temperature</td>
<td>In-stream Pt-RTD</td>
<td>88°F to 95°F (31°C to 35°C)</td>
<td>±0.09°F (0.05°C) <strong>+</strong></td>
</tr>
<tr>
<td>Refrigerant inlet temperature</td>
<td>In-stream Pt-RTD</td>
<td>68°F to 173°F (20°C to 78°C)</td>
<td>±0.2°F (0.1°C)</td>
</tr>
<tr>
<td>Refrigerant pressure</td>
<td>Piezo-transducer</td>
<td>2.2 to 251 psia (15 to 1,730 kPa)</td>
<td>±0.13% of full scale</td>
</tr>
<tr>
<td>Pressure difference</td>
<td></td>
<td>0 to 15 psia (0 to 103 kPa)</td>
<td>±0.10% of full scale</td>
</tr>
</tbody>
</table>

**Special limits from high accuracy in-house customized calibration with isothermal bath and precision thermometer**
The pressure drop in clean condition, $\Delta P_{w,c}$, was measured by using a differential pressure transducer and it was compared with the pressure drop in fouling conditions, $\Delta P_{w,f}$. The water friction factor in clean ($f_{w,c}$) and fouled ($f_{w,f}$) conditions could be calculated according to the following definitions:

$$f_{w,c} = \frac{1}{2} \frac{d_e}{L} \left( \frac{\rho_w}{G_w,c} \right) \Delta P_{w,c} \quad \text{and} \quad f_{w,f} = \frac{1}{2} \frac{d_e}{L} \left( \frac{\rho_w}{G_w,f} \right) \Delta P_{w,f}$$

(4)

where $d_e$ and $L$ are the flow channel equivalent diameter and channel nominal length, respectively (Ayub 2003). During the fouling tests, the water mass flux and inlet temperature were constant and thus, the fouling pressure drop penalty factor, $PDPF$, is reduced to:

$$PDPF = \frac{\Delta P_{w,f}}{\Delta P_{w,c}}$$

(5)

A complete and thorough uncertainty analysis was conducted according to the uncertainty propagation method suggested by Taylor and Kuyatt (1994) and details on the error propagation analysis for the fouling measurements can be found in the paper from Cremaschi et al. (2011). The outcomes from the uncertainty analysis were included in the data reduction of this work and are integrated in the experimental results discussed next.

**DISCUSSION OF THE RESULTS**

Low-fouling potential water was circulated through the test BPHE and cycled through the cooling tower. The concentration of minerals in the cooling tower water was progressively increased by evaporating the water at a controlled rate of 20–24 gallons (76–91 liters) of water per day and the dissolved minerals quickly reached solubility limits. Figure 2 shows the LSI of the cooling tower water during this process for the various tests. The mineral concentrations continuously increased and the LSI values augmented incrementally from 0.8 up to the maximum of 3.5. The water scaling conditions are reported on the right side of the plots of Figure 2. The definitions of scaling conditions reported in Figure 2 (and adopted throughout this paper) are from a commonly used range adopted by laboratories specializing in industrial water treatment. At low- and slight-scaling conditions, the water fouling potential was defined as low and the LSI was lower than 1. At moderate- to strong-scaling conditions, the LSI was between 1.0 and 2.1 and these conditions are referred throughout this paper as medium-fouling potential water (med FP). At LSI greater than 2.1, very strong to severe scaling conditions might

![Figure 2](image_url) **Figure 2** Langelier Saturation Index (LSI) during the fouling tests of BPHEs.
occur and the fouling potential was defined as high. Table 4 provides the range of the amount of minerals and water properties measured at our water chemistry laboratory during the fouling tests at low-, medium-, and high-water fouling potentials. The minerals were measured from water samples taken at regular intervals from the simulated cooling tower water loop. Water was analyzed by using a high performance optical emission inductively coupled plasma mass spectrometer. It should be noted that copper was not directly introduced in the water batch but visible changes in the water color from clear to yellow opaque and then to brown opaque were observed after one to two weeks from the beginning of each fouling test. The simulated cooling tower water was circulated in copper pipelines of approximately 6.7 m (22 ft) of length and 2.54 cm (1 in.) nominal pipe size diameter. It is likely that small copper particles from the interior walls of the water pipelines were gradually entrained in the water stream causing the color to change during the fouling test.

Minerals were present in the form of precipitate elements, deposit material, and dissolved compounds in the simulated cooling tower loop. The continuous evaporation process at the cooling tower guaranteed that the concentration of the minerals remained at the critical saturation limits. Supersaturated conditions occurred only in the close proximity of the heat transfer surface inside the test BPHE, where water was quickly heated up by the refrigerant and its local solubility limits suddenly decreased. Makeup water, which had low-fouling potential chemical characteristics, was added periodically to the system to replace the water vapor evaporated in the cooling tower.

Figure 3 shows the experimental measurements of the fouling resistance for the BPHEs A1 and A2 at two refrigerant temperatures and at high- and medium-water fouling potentials. The data at medium-fouling potential are shown by the solid points in Figure 3 and are marked as “med FP” in the legend. All other data in Figure 3 represent fouling tests with high-water fouling potential and the notation of high-fouling potential was omitted in the legend for clarity. After about 30 days with high-fouling potential water, the fouling resistance of BPHE A1 was about $9.3 \times 10^{-4} \text{ h}^{-1} \text{ °F}^{-1} \text{ ft}^2/\text{ Btu}$ (1.6 $\times 10^{-5} \text{ °C}^{-1} \text{ m}^2/\text{ W}$) while the A2 plate, with hard chevron corrugation angle of 63° had a fouling resistance of about $1.5 \times 10^{-4} \text{ h}^{-1} \text{ °F}^{-1} \text{ ft}^2/\text{ Btu}$ (2.6 $\times 10^{-5} \text{ °C}^{-1} \text{ m}^2/\text{ W}$) after 50 days. Both BPHEs had the same aspect ratio (see Table 1), identical geometry, heat transfer area and flow velocity. BPHE A1 has a soft chevron corrugation angle of 30° and the experimental results clearly showed that its fouling factor is one order of magnitude higher than the one experienced by BPHEs with hard corrugation angles. These results are in agreement with the conclusions of Thonon et al. (1999), who reported that the asymptotic fouling resistance of a plate heat exchanger with a 30° corrugation angle was almost ten times higher compared to the one with 60° corrugation angle. An increase of the refrigerant saturation temperature augmented the heat flux across the plates and a measurable increase of the fouling resistance was recorded for both BPHEs A1 and A2.

<table>
<thead>
<tr>
<th>Fouling Potential</th>
<th>Total Hardness (as CaCO$_3$)</th>
<th>Calcium (as CaCO$_3$)</th>
<th>Magnesium (as CaCO$_3$)</th>
<th>M-Alkalinity (as CaCO$_3$)</th>
<th>P-Alkalinity (as CaCO$_3$)</th>
<th>Chloride (ppm)</th>
<th>Sulfate (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>207–347</td>
<td>13–92</td>
<td>22–53</td>
<td>55–91</td>
<td>10</td>
<td>142–212</td>
<td>88–101</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fouling Potential</th>
<th>Sodium (ppm)</th>
<th>Iron (ppm)</th>
<th>Copper* (ppm)</th>
<th>pH</th>
<th>Total dissolved solid (ppm)</th>
<th>EC (μS/cm)</th>
<th>LSI (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>44–77</td>
<td>&lt;0.1</td>
<td>NA</td>
<td>8.2–8.4</td>
<td>524–643</td>
<td>793–974</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Medium</td>
<td>150–330</td>
<td>&lt;0.1</td>
<td>NA</td>
<td>8.4–8.6</td>
<td>1251–2746</td>
<td>1895–4106</td>
<td>1.1–2</td>
</tr>
<tr>
<td>High</td>
<td>192–741</td>
<td>&lt;0.1</td>
<td>NA</td>
<td>9.3–9.6</td>
<td>2158–7971</td>
<td>3270–11690</td>
<td>2.1–3.5</td>
</tr>
</tbody>
</table>

*Water is circulated in a copper pipe of about 6.7 m (22 ft) of length and 2.54 cm (1 in.) nominal pipe size diameter. Copper particles were observed in the water changing its color after about 1–2 weeks.
The triangles data of Figure 3 show some scattering during the first 20 days of the fouling test and a sharp increase of the fouling resistance occurred at about 30 days from the beginning of the fouling test. This phenomenon could be explained if one considers the effects due to flow blockage caused by particulate fouling, in which suspended particles might have been trapped in between the channels of the BPHE. Suspended solids are introduced into the water stream by precipitation within the water and/or removed particles from surface deposits. Suspended solids were evident in the system for each experiment, forming a soft white-colored film on surfaces throughout the system wherever they settle out, including the BPHE. Thus, it seems inevitable that both precipitation fouling and particulate fouling occurred in each experiment. Suspended particles interfered with the water channel flow within the inlet and outlet regions of the plates, that is, between the BPHE water connecting ports and the central sections of the corrugated plates. For a soft chevron corrugation angle of 30°, the suspended particles produced a blockage of the water flow within the plate channels more severe than the one in case of a hard chevron corrugation angle.

It should be also noted that the definition of fouling resistance in Equation 3 does not account for the actual degree of subcooling of the refrigerant at the exiting ports. The calculated fouling resistance was in agreement with the procedures recommended by the standards and AHRI guidelines but, while the degree of superheat of the refrigerant at the inlet of the BPHEs A1 and A2 was kept constant to 65°F (−36°C) for all tests, the refrigerant outlet conditions varied greatly and was dependent on the chevron angle, heat flux conditions, and fouled conditions of the plates. The degree of subcooling for the refrigerant during the condition 1 of nominal heat flux ($T_{sat} = 105.5°F$ (41°C))and condition 2 of increased heat flux ($T_{sat} = 120.2°F$ (49°C))are shown in Figure 4. The refrigerant circulating in the BPHE A1 with a soft chevron angle of 30° was subjected to practically no subcooling at the outlet refrigerant port, suggesting that refrigerant exits the BPHE A1 in two-phase liquid and vapor mixture form if the heat flux is close to nominal design value. The refrigerant in the plate A2 with a hard chevron angle of 63° had about 15°F to 35°F (8°C to 19°C) of subcooling at the outlet refrigerant port for the heat flux conditions 2 and 1, respectively. While the refrigerant was always subcooled at the outlet port for the plate A2, the degree of subcooling was quite different for the fouling tests of the plate A1. At high heat flux condition of $T_{sat} = 120.2°F$ (49°C) the refrigerant in the A1 plate had initially about 8.5°F (~4.7°C) degree of subcooling and it became saturated after about 25 days of run. The difference in the refrigerant degree of subcooling is

Figure 3  Effect of refrigerant condensation temperature on fouling resistance.
not accounted for in the definition of the fouling resistance in Equation 3 and in the plots of Figure 3.

The hydraulic performance of the BPHE is presented in the form of pressure drop penalty factors (PDPF) in Figure 5. These PDPFs were calculated according to Equation 5 and they represent the ratio of the waterside pressure drops measured in fouled conditions to the corresponding ones measured in clean conditions. E.g., a pressure drop factor of 1.31 corresponds to a 31% increase of pressure drop in fouled conditions. The pressure drops in clean conditions are also shown in Figure 5. BPHE A1 with a soft corrugation angle of 30° experienced a large pressure drop during the fouling tests. An increase of the refrigerant saturation temperature ultimately led to warmer plates and promoted local precipitation and particulate fouling on the heat transfer surface, especially on the waterside plate sections in direct opposite side of the superheated refrigerant section. The effect of particulate fouling is visible in the triangles data points shown in Figure 5, which were measured in high-water scaling conditions during the experiments. The PDPF increases by about 50% during the first week and by more than 11 times with respect to clean conditions in only 30 days of fouling operation of the BPHE A1. The authors speculate that this pressure drop behavior was due to severe localized flow blockages of the mini channels generated within the plates stack inside the BPHE A1. After 20 days of fouling operation, the particulate fouling mechanism accelerated the flow blockage and the pressure drop increased drastically until it exceeded the maximum pumping head of the test set up in about 31 days during the fouling experiment. For the BPHE A2, the increase of the refrigerant saturation temperature from 105.5°F to 120.2°F (41°C to 49°C) produced a measurable effect on the waterside pressure drop and the condenser experienced a pressure drop that was about 94% higher in fouled conditions with respect to initial pressure drop in clean conditions. From the data in Figure 5 one could observe that particulate fouling blocked the flow in between the mini channels of the A2 exchanger and small but finite increments of the pressure drop were recorded during the fouling tests. However, the flow blockage of the mini channels inside the plate stack for BPHE A2 was not as severe as the one that occurred for the BPHE A1.

The heat transfer rate degradation can also be analyzed from the water temperature difference across BPHE (ΔT) of the plate-type condenser. Figure 6 shows the water temperature difference versus time, in days, for the tests performed in this work. Since the entering water temperature and the water flow rate were controlled to constant for all tests, a decrease of water-leaving temperature is equivalent to a decrease in the heat flux in the heat exchanger due to fouling. BPHE A1 with high-scaling potential water showed a sharp
Figure 5  Effect of refrigerant condensation temperature on pressure drop penalty factor.

Figure 6  Reduction of water-leaving temperature in the condenser due to precipitation and particulate fouling.
The average heat fluxes in clean conditions were about 3424 Btu/h–ft² (~11kW/m²) at high heat flux conditions, and after 30 days of fouling operation, the heat fluxes decreased by 28%. A similar trend was observed for the A1 plate with low heat flux condition (see solid and hollow diamond data points in Figure 6). At this water scaling condition, the water temperature decreased by 1.0°F (~0.5°C) in 30 days, suggesting that particulate and precipitation fouling mechanisms occurred. The BPHE A2, with a hard chevron angle of 63°, also experienced a small decrease in the heat flux across the plate, and in fouled conditions the heat flux degradation was within 5% with respect to heat flux in clean conditions. Both fouling experiments at low and high heat flux conditions showed similar behaviors and the leaving-water temperature from the A2 plate decreased by no more than 0.5°F (~0.3°C) in 60 days of fouling operation with both medium and high fouling potential of the cooling tower water. From the heat transfer data of Figure 6 and the waterside pressure drop data previously discussed in Figure 5, the authors concluded that the fouling phenomenon is more of a localized type and it impaired the water flow to the channels of the BPHEs rather than the heat transfer rate across the plates. The localized fouling deposit is more likely to occur at the water outlet region of the plates, where the water is warmer and the surfaces are hotter. However, this hypothesis could not be confirmed at this time since it was not possible to take a cross section of the BPHEs without destroying the internal stack of plates and removing the deposit material on the surfaces.

The asymptotic fouling resistances were calculated using the following expression, which was originally proposed by Grandgeorge et al (1998):

\[ R_f(t) = R_{f,\infty} \left(1 - e^{-\frac{t}{\tau_c}}\right) \]  

where \( R_f \) is the fouling resistance at time \( t \), \( R_{f,\infty} \) is the asymptotic fouling resistance, and \( \tau_c \) is the time constant. The asymptotic fouling resistances were calculated from the measured fouling resistances and the results are shown in Figures 7 and 8. Asymptotic values of the fouling resistance with high-fouling potential water in the case of 105.5°F (~41°C) condensing temperature were estimated to be 1.1·10^{-5} h–°F–ft²/Btu (1.9·10^{-5} °C–m²/W) and about 1.7·10^{-4} h–°F–ft²/Btu (2.9·10^{-5} °C–m²/W) for BPHEs A1 and A2 with soft and hard corrugation angles, respectively. These asymptotic values would be achieved after about 39 days for the A1 and after about 118 days for the A2 at refrigerant saturation temperature of 105.5°F (~41°C) and at high-water fouling potential (LSI ~ 2.1 to 3.5). The measured fouling resistances at the end of our tests represented about 85% of these asymptotic values.

Figure 7 shows the impact of refrigerant saturation temperature on the asymptotic fouling resistance of the BPHEs A1 and A2. Our instrumentation allowed to measure fouling resistances greater of at least 1.0·10^{-5} h–°F–ft²/Btu (1.8·10^{-6} °C–m²/W) and we assumed that this value was the lower limit of fouling resistance in case of little or no scaling conditions of the water. An increase of refrigerant temperature from 105.5°F to 120.2°F (41°C to 49°C) produced an increase of the asymptotic fouling resistance to 4.5·10^{-4} h–°F–ft²/Btu (8.0·10^{-5} °C–m²/W) for the A2 plate and this asymptotic value would be achieved in only 62 days instead of 118 days. The asymptotic fouling resistance for the plate A1 at high saturation temperature was taken to be the maximum value of the resistance measured during the fouling test at heat flux condition 2 since the trend for this case was not of asymptotic type. The A1 plate reached a 2.72·10^{-3} h–°F–ft²/Btu (4.8·10^{-4} °C–m²/W) in about 31 days of operations. It should be noted the high-fouling potential water represent severe scaling conditions which should be avoided by proper water treatment of the cooling tower water. At moderate to strong scaling conditions the asymptotic fouling resistance was reduced to 3.3·10^{-4} h–°F–ft²/Btu (5.8·10^{-5} °C–m²/W) for the A1 plate, as shown in calculated asymptotic fouling resistance of Figure 8. For the plate A1, an increase of the fouling potential augmented the asymptotic fouling resistance by as much as 69%, that is, from 3.3·10^{-4} h–°F–ft²/Btu (5.8·10^{-5} °C–m²/W) to 1.1·10^{-3} h–°F–ft²/Btu (1.9·10^{-4} °C–m²/W) for medium- and high-fouling potential, respectively. For the plate A2, the asymptotic fouling resistance at medium-fouling potential was about 8.5·10^{-5} h–°F–ft²/Btu (1.5·10^{-5} °C–m²/W). For the plate A2, with hard corrugation angle, an increase of water fouling potential from medium to high level caused an increase of the fouling resistance by about 50%. Figure 8 shows the trends of the asymptotic fouling resistances for the two BPHEs and for the case of nominal heat flux condition 1 at refrigerant saturation temperature of 105.5°F (~41°C). The trends indicate that water fouling potential has a measurable effect on the fouling performance of the brazed plate-type condensers.

CONCLUSIONS

This paper presents experimental data of waterside fouling performance of brazed-plate heat exchangers (BPHEs) used in direct refrigerant-to-water condensers in cooling tower applications. The effects of refrigerant condensation temperature and water quality were experimentally investigated and asymptotic values of the fouling resistance were determined. Two saturation temperatures of 105.5°F and 120.2°F (~41°C and ~49°C) were set in extensive controlled laboratory fouling experiments and they were representative of two heat flux conditions across the plates of the brazed-plate type condensers. Both heat flux and wall plate surface temperature were responsible for mineral scaling and particulate fouling of the BPHEs. Soft chevron corrugation angles of the plates were quite sensitive to these factors and an increase of the condensation temperature critically impaired the operation of this type of heat exchanger when soft corrugation angle was adopted. For BPHEs with hard corrugation angle, the fouling...
Figure 7  Effect of refrigerant saturation temperature on asymptotic fouling resistance (high-water fouling potential, LSI 2.1 to 3.5).

Figure 8  Effect of water quality (measured as water fouling potential and LSI) on asymptotic fouling resistance (refrigerant saturation temperature of 105.5°F [41°C]).
resistance was still a function of refrigerant saturation temperature and water quality but the degradation of the heat flux was only a few percents. We observed that the fouling of the BPHEs affected the waterside pressure drops and might cause a severe flow blockage of the mini channels formed within the plate stack inside the heat exchanger. Measured pressure drops in fouled conditions were from 10% to 11 times higher than the corresponding pressure drops in clean conditions. Finally, water quality, measured by the Langelier saturation index to define a fouling potential of the cooling tower water, had a measurable effect on the fouling resistance of the BPHEs. High-fouling potential water, which is representative of strong to severe scaling conditions, increased the asymptotic fouling resistance by as much as 69% compared to asymptotic fouling resistance derived for the cases of medium-fouling potential of the cooling tower water.

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NOMENCLATURE

\[ A = \text{area (ft}^2 \text{ or m}^2) \]
\[ Ca = \text{calcium concentration (ppm as CaCO}_3\text{)} \]
\[ d = \text{equivalent diameter (in) or (m)} \]
\[ f = \text{friction factor (dimensionless)} \]
\[ G = \text{mass flux (lbm/ft}^2\text{–s) or (kg/m}^2\text{–s)} \]
\[ k = \text{thermal conductivity (Btu/h–ft–°F) or (W/m–°C)} \]
\[ L = \text{length (in.) or (m)} \]
\[ LSI = \text{Langelier Saturation Index (dimensionless)} \]
\[ M_{alkalinity} = \text{“M” alkalinity (ppm as CaCO}_3\text{)} \]
\[ m = \text{mass flow rate (lbm/min) or (kg/s)} \]
\[ med = \text{medium} \]
\[ \rho = \text{pressure (psi) or (kPa) or corrugation depth (in) or (m)} \]
\[ \text{PDPF} = \text{pressure drop penalty factor (dimensionless)} \]
\[ \dot{Q} = \text{heat transfer rate (Btu/hr) or (W)} \]
\[ R = \text{heat resistance (h–°F–ft}^2\text{/Btu) or (m}^{-2}\text{–°C/W)} \]
\[ R_{f,\infty} = \text{asymptotic fouling resistance (h–°F–ft}^2\text{/Btu) or (m}^{-2}\text{–°C/W)} \]
\[ T = \text{temperature (°F) or (°C)} \]
\[ t = \text{time (s)} \]
\[ TDS = \text{total dissolved solid (ppm)} \]
\[ UA = \text{overall heat transfer coefficient (Btu/h–°F) or (W/°C)} \]
\[ \dot{V} = \text{volumes flow rate (gpm) or (m}^3\text{/s)} \]

Subscripts

\[ c = \text{clean, constant} \]
\[ e = \text{equivalent} \]
\[ EWT = \text{entering water temperature} \]
\[ LWT = \text{leaving water temperature} \]
\[ f = \text{fouling or fouled} \]
\[ ht = \text{heat transfer} \]
\[ r = \text{removal or refrigerant} \]
\[ ref = \text{refrigerant} \]
\[ sat = \text{saturation} \]
\[ SH = \text{superheat} \]
\[ w = \text{water} \]

Greek Symbols

\[ \phi = \text{corrugation angle (degree from flow direction)} \]
\[ \lambda = \text{corrugation pitch (inch) or (m)} \]
\[ \rho = \text{density (lbm/ft}^3\text{) or (kg/m}^3\text{)} \]
\[ \tau_c = \text{time constant (day)} \]

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**DISCUSSION**

**Noma Park, Chief Research Engineer, LG Electronics:** 1) What is the definition of Langelier Saturation Index? 2) How severe is the fouling resistance when it reaches the asymptotic value as compared to other heat transfer resistance?

**Lorenzo Cremaschi:** 1) The Langelier Saturation Index (LSI) is defined as $\text{LSI} = \text{pH} - \text{pH}_c$. LSI is a parameter that describes the status of the water for mineral scaling. It ranges from 0.5 to 3.5; 3.5 means that severe scaling formation conditions are expected and 0.5 means little or no scale formation is expected in the water stream flowing inside the heat exchangers. LSI can assume values in between these two extremes. LSI is defined as the algebraic difference between actual (measured) pH of a water sample and its corresponding pH calculated assuming saturated conditions (pH$_c$). The pH$_c$ is the computed pH at which the calcium concentration in given water sample is in equilibrium with the total alkalinity. In our work, pH$_c$ was computed based on the total dissolved solid, water temperature, Ca concentration and water alkalinity. 2) According to the definition of total resistance, $R_{tot} = 1 / U$ and it is calculated as follows: $R_{tot} = R_w + R_{ref} + R_t + R_{conduction}$. When asymptotic fouling resistance is reached, the fouling resistance $R_t$ was up to 68% of the total heat transfer resistance.

**James Schaefler, Project Engineer, HTRI:** Did adiabatic point (85°F) have fouling?

**Cremaschi:** 85°F was the water inlet temperature in our heat exchangers during the fouling tests. If the refrigerant condensation temperature is also at 85°F, we obviously have an adiabatic condition and no heat transfer across the plates. In this case, the definition of fouling resistance is meaningless. However, if a small heat transfer occurs between the water side and the refrigerant side, say because $T_{sat}$ refrigerant is 85.2°F, we expect some fouling to occur in the water stream. We decided to adopt the fouling resistance at 85°F refrigerant saturation temperature as the minimum fouling thermal resistance that can be detected with our instrumentation sensitivity. This value was very small that is practically considered as zero in actual applications.