

Design and construction of a pilot scale heat exchanger-cooling tower system for scaling/deposition and inhibition studies

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Abstract

In this manuscript we present the design and construction of a pilot system that incorporates both a heat exchanger component and a cooling tower add-on. This prototype was constructed in order to simulate real industrial open recirculating cooling systems. Heat exchanger planning was realized using mass and energy balance. The application of mass balance was realized under permanent (static) conditions, whereas the application of energy balance was realized under non-permanent (dynamic) conditions, as it happens in a real industrial setting. Also, the necessary pump power was calculated in order for the cooling tower to function in a “cross-flow” fashion for most efficient water cooling. The pilot system allows the use of water of choice (either artificial or natural), the selection of different metallurgies for the heat exchanger, as well as monitoring of important metrics in the system (inlet and outlet temperatures, heat exchanger temperature, *etc*). The goal is to use this pilot system for sparingly-soluble salt precipitation and deposition studies.

Key words: *scale, deposit, precipitation, inhibition, pilot cooling system, heat exchanger, cooling tower.*

Received: 03.07.2013.

doi: [10.17675/2305-6894-2013-2-3-216-223](https://doi.org/10.17675/2305-6894-2013-2-3-216-223)

Introduction

Cooling systems are designed to transfer heat from a heat source and ultimately dissipate it into a heat sink [1]. In more practical terms, a cooling medium is required, this most often being water. Water absorbs heat from a “hot process” (there are several of those in an industrial setting, eg. electricity generation, chemical reactions, air-conditioning systems), thus causing the effect of “cooling” [2].

However, the “hot water” cannot be disposed off to the environment, as it is, because it will cause thermal pollution to the neighboring environmental setting. There are also additional reasons for recirculating this “spent” water, mainly due to cost, especially in arid areas. Hence, the “hot water” must in turn be re-cooled for reuse. This is achieved by cooling systems, called cooling towers [3].

There are several types of cooling towers, but of relevance to the present paper are the evaporative cooling towers [4]. In these, the “hot water” is brought to the top of a tower equipped with spray nozzles, through which it is sprayed downwards through the tower

fill. Droplet formation is critical because the water can then partially evaporate, and through this process its temperature drops to acceptable levels. Then it can be re-used in the same cooling loop.

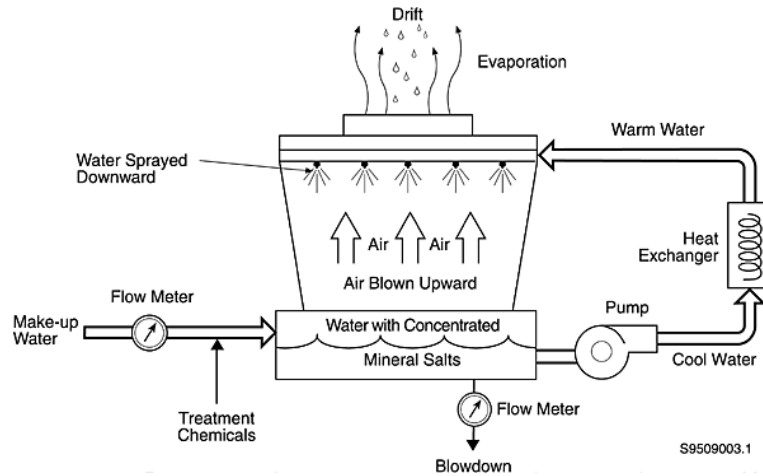


Figure 1. A schematic of a typical cooling tower/heat exchanger system. Taken from http://www.globalspec.com/learnmore/manufacturing_process_equipment/heat_transfer_equipment/cooling_towers.

Results and Discussion

Calculations

Calculation of the total heat transfer coefficient (h)

For these calculations, we need to accept a number of hypotheses:

- (a) Heat transfer occurs in a monodimensional way
- (b) Heat transfer occurs via conduction
- (c) Heat transfer occurs in a constant (not intermittent) way
- (d) Thermal conductance is constant

The total heat transfer coefficient (h) is given by the following Eq. 1.

$$h = \frac{1}{R}, \quad (1)$$

where R is the resistance.

Fourier's Law states that [5]:

$$\frac{Q}{A_{Lm}} = -k \frac{\Delta T}{\Delta r} \Leftrightarrow Q = -k A_{Lm} \frac{\Delta T}{\Delta r} \Leftrightarrow Q = -\frac{\Delta T}{R} \text{ where } R = \frac{\Delta r}{k A_{Lm}}, \quad (2)$$

where Q is the heat transferred, A_{Lm} is the surface area, ΔT is the difference in temperature, k is the heat conductance of the medium, and $\Delta r (= r_1 - r_2)$ is the tubing thickness.

A_{Lm} is given by the following Eq. 3:

$$A_{Lm} = \frac{2\pi L(r_2 - r_1)}{\ln\left(\frac{r_2}{r_1}\right)} \quad (3)$$

Replacing in Eq. 3 $\Delta r = r_1 - r_2 = 0.002$ m (tubing thickness) and $L =$ tubing length = 50 cm, we find that $A_{Lm} = 0.097$ m².

Also, we can take the value of k from the literature for iron, $k = 45$ W/m K. Then, from Eq. 4

$$R = \frac{\Delta r}{k A_{Lm}} \quad (4)$$

we can calculate R to be

$$R = \frac{0.002 \text{ m}}{45 \text{ J/m K s} \cdot 0.097 \text{ m}^2} = 0.00046 \frac{\text{K s}}{\text{J}}.$$

Then, finally, from Eq. 1, we have

$$h = \frac{1}{R} = \frac{1}{0.00046 \text{ K s/J}} \Leftrightarrow h = 2174 \frac{\text{J}}{\text{K s}}.$$

Calculation of mass and energy balance

For the design of the heat exchanger, we need to take into account the following:

- The water mass supply at the inlet and outlet of the exchanger is $m_1 = m_2 = 40$ kg/min.
- Inlet temperature $T_1 = 18^\circ\text{C}$.
- Outlet temperature $T_2 = 40^\circ\text{C}$.
- Water density $\rho = 1000$ kg/m³.
- Water volume in contact with the heat exchanger $V = 10$ L = 0.01 m³.
- Exchanger temperature $T_{\text{exchanger}} = 90^\circ\text{C}$.
- Inlet and outlet heat capacities, $c_{p1} = 4184 \frac{\text{J}}{\text{kg K}}$, $c_{p2} = 4179 \frac{\text{J}}{\text{kg K}}$, respectively.

Mass balance

We assume that there is no water mass accumulation on the heat exchanger, so $m_1 = m_2$.

Energy balance

For the energy balance at the heat exchanger, the following Eq. 5 applies.

$$\text{Accumulation} = \text{inlet} - \text{outlet} + \text{heat production} \quad (5)$$

The reference temperature $T_{\text{ref}} = 18^\circ\text{C}$, so we have Eq. 6.

$$\text{Accumulation} = \left[m_{\text{container}} c_{p2} (T_2 - T_{\text{ref}}) \right]_{t+\Delta t} - \left[m_{\text{container}} c_{p2} (T_2 - T_{\text{ref}}) \right]_t \quad (6)$$

$$\text{At the inlet: } m_1 c_{p1} (T_1 - T_{\text{ref}}) \Delta t = 0 \quad (7)$$

$$\text{At the outlet: } m_2 c_{p2} (T_2 - T_{\text{ref}}) \Delta t \quad (8)$$

$$\text{heat production: } Q = h (T_{\text{exchanger}} - T_2) \Delta t \quad (9)$$

Therefore, the energy balance becomes, after substituting the numerical values in Eqs. 6–9, and the value for the total heat transfer coefficient (h),

$$\begin{aligned} m_{\text{container}} c_{p2} \frac{\partial T}{\partial t} &= h(90 - T) - m_2 c_{p2} (T - 18) \Leftrightarrow \\ 10 \text{ kg} \cdot 4179 \frac{\text{J}}{\text{kg K}} \frac{\partial T}{\partial t} &= 2174 \frac{\text{J}}{\text{K s}} (90 - T) - 0.67 \frac{\text{kg}}{\text{s}} \cdot 4179 \frac{\text{J}}{\text{kg K}} (T - 18) \Leftrightarrow \\ 41790 \frac{\partial T}{\partial t} &= 195660 - 2174T - 2800T + 50400 \Leftrightarrow \\ 41790 \frac{\partial T}{\partial t} &= 5.9 - 0.12T \end{aligned} \quad (10)$$

By integrating the differential Eq. 10, we have:

$$\int_{18}^{40} \frac{1}{5.9 - 0.12T} dT = \int_0^t dt \quad (11)$$

where

$$A = \int_{18}^{40} \frac{1}{5.9 - 0.12T} dT \quad (12)$$

Integral A can be solved by the substitution method, so we set

$$\theta = 5.9 - 0.12T$$

and

$$d\theta = -0.12dT \Leftrightarrow dT = -\frac{1}{0.12}d\theta$$

with the integration limits being: $\theta_1 = 3.74$ and $\theta_2 = 1.1$, hence integral A becomes:

$$-\frac{1}{0.12} \int_{3.14}^{1.1} \frac{1}{\theta} d\theta = -\frac{1}{0.12} [\ln \theta] = -\frac{1}{0.12} [\ln(1.1) - \ln(3.74)] = -\frac{1}{0.12} (0.095 - 1.32) = -8.33 \cdot (-1.225) = 10.20$$

Therefore Eq. 11 becomes:

$$\int_0^t dt = 10.20 \Leftrightarrow t \approx 10 \text{ s} \quad (13)$$

The physical significance of this result is that it represents the time needed for the water surrounding the heat exchanger (container) to acquire temperature from 18°C to 40°C, when the resistance (heat exchanger) has a temperature of 90°C.

Calculation of the resistance

The resistance is given by the Eq. 14.

$$P = \frac{W}{t} \quad (14)$$

where W is the work produced by the resistance, which is given by Eq. 15.

$$W = V \cdot I \cdot t \quad (15)$$

where V is the voltage, I is the electrical current intensity and t is the time. Substituting $V = 220$ Volts, $I = 20$ Ampere, and $t = 10$ seconds (from Eq. 13), we find that $W = 44$ kJ.

Hence, the resistance is $P = \frac{W}{t} = \frac{44 \text{ kJ}}{10 \text{ s}} = 4.4 \text{ kW}$.

Calculation of the exchanger dimensions

The water volume inside the container surrounding the exchanger is $V = 10$ L or 0.01 m^3 . This volume can be expressed as in Eq. 16.

$$V = A \cdot h \quad (16)$$

where h = the exchanger length and A = the surface area of the heat exchanger. By taking into account that the steel tube's inner diameter is 0.0175 m and the outer diameter is 0.096 m, we can calculate that $h = 40$ cm.

Finally, we can calculate (not shown here) the Reynolds number which is related to the type of flow. It was found that $Re = 7.5 \times 10^3$. This implies that we have turbulent flow.

We used the software AutoCAD 2009 to design the pilot cooling system. Figures 2–6 show some of the important system components.

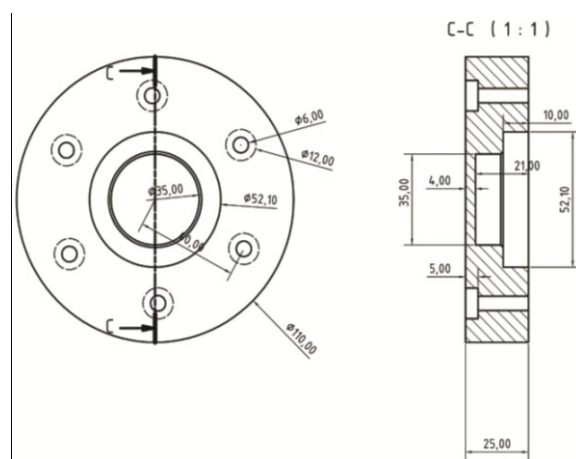


Figure 2. Side cap of the heat exchanger container.

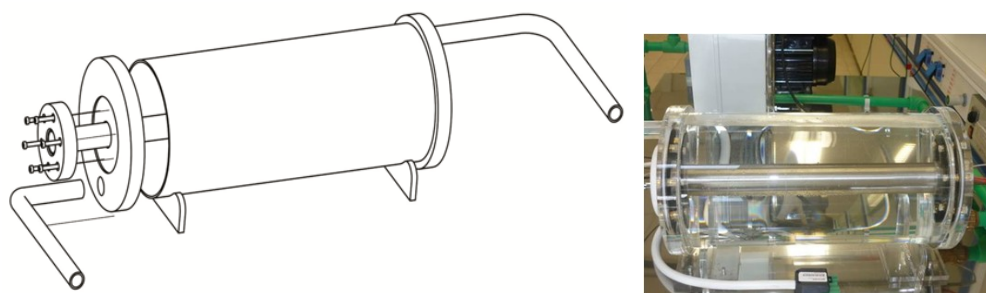


Figure 3. Plexiglass container surrounding the heat exchanger.



Figure 4. Various views of the pilot system.

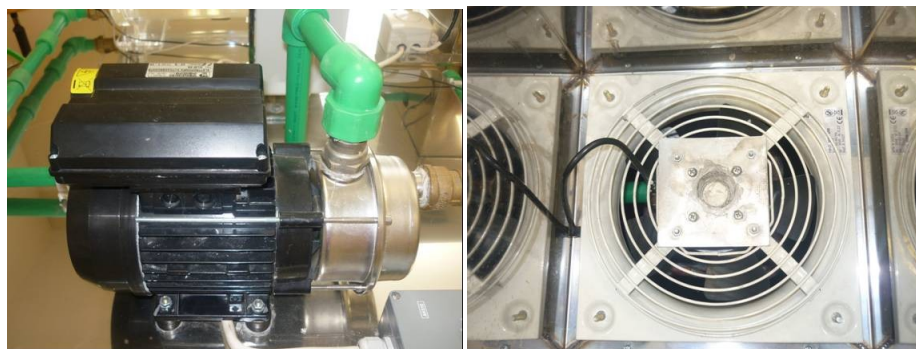


Figure 5. Views of the pump (left) and the cooling tower fan (right).



Figure 6. Views of the control panel (left), the cooling tower basin (middle) and the pilot system in operation (right).

By having this system available, we can design experiments in order to study precipitation of sparingly-soluble salts, and also monitor their propensity to deposit on a heated surface. In the following paper, we will present several of those results.

Conclusions

In this paper we designed and constructed a pilot prototype that combines a heat exchanger set-up with an evaporative cooling tower. This is an easy-to-use and operate system, that can run either short-term (a few hours) or long-term (a few days) experiments. We are planning to utilize this pilot system to study precipitation and deposition of sparingly-soluble salts (such as calcium carbonate, calcium sulfate, silica and metal silicates, *etc.*) and also to test several scale inhibitors [6].

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