Article

The Development and Full-Scale Experimental Validation of an Optimal Water Treatment Solution in Improving Chiller Performances

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Abstract: An optimal solution, in combining physical and chemical water treatment methods, has been developed. This method uses a high voltage capacitance based (HVCB) electrodes, coupled with biocides to form a sustainable solution in improving chiller plant performances. In this study, the industrial full-scale tests, instead of laboratory tests, have been conducted on chiller plants at the size of 5000 RT to 10,000 RT cooling capacities under commercial operation for more than two years. The experimental results indicated that the condenser approach temperatures can be maintained at below 1 °C for over two years. It has been validated that the coefficient of performance (COP) of a chiller can be improved by over 5% by implementing this solution. Every 1 °C reduction in condenser approach temperature can yield approximately 3% increase on chiller COP, which warrants its future application potential in the HVAC industry, where T_a can degrade by 1 °C every three to six months. The solution developed in this study could also reduce chemical dosages and conserve makeup water substantially and is more environment friendly.

Keywords: optimal water treatment solution; high voltage capacitance based electrodes; condenser approach temperature; chiller COP; chemical dosage reduction; makeup water conservation; HVAC industry application

1. Introduction

In high tech and petrochemical industries, huge central air-conditioning plants are normal equipment, consisting of multiple units of chillers, with total cooling capacity ranging from 5000 RT to 15,000 RT (Refrigeration Tons) in each plant. The tremendous cooling load imposes a heavy burden on its operating cost. Many strategies can be applied to improve chiller performance. Among them, keeping the cooling water system clean for good heat dissipation is one of the most energy-efficient measures.

In HVAC industry, two indicators were selected to identify the thermal performance of a chiller, namely, the COP, and its condenser approach temperature (T_a) [1]. The COP of a chiller can be defined as in Equations (1) and (2):

$$COP = Q_e/P \tag{1}$$

$$Q_c = Q_e + P \tag{2}$$

where

- Q_e is the cooling capacity of a chiller on the evaporator side, kW;
- P is the power consumption of a chiller compressor, kW; and
- Q_c is the heat dissipation on the chiller condenser side through cooling towers, kW.

The approach temperature on the condenser side of a chiller, or T_a, can be defined as Equation (3), which is a direct indicator to evaluate the heat dissipation effectiveness of its cooling water loop.

$$T_a = T_c - T_2 \tag{3}$$

where

- T_a is the approach temperature of a chiller on the condenser side, °C;
- T_c is the refrigerant condensing temperature of a chiller, °C; and
- T_2 is the cooling water temperature leaving the chiller condenser to the cooling tower, or simply, cooling water leaving temperature, °C.

When mineral scale or biofilm begins to build up in a chiller condenser and cooling tower, T_c will rise due to poor heat dissipation, causing P to rise and Q_e to drop subsequently, resulting in lower chiller COP. Stoecker [2] analyzed that an ideal R22 compressor, with 4.5% clearance and 50 L/s displacement rate, at −20 °C evaporating temperature, every 1 °C increase of T_c will cause the Q_e to drop by approximately 1%. Further analysis shown in the ASHRAE Handbook [3] revealed that, for a condenser with a design fouling factor of 44 mm^2 K/W, an increment of scale fouling by 50% in the condenser will result in approximately 1% of P increase and 1% of Q_e drop, causing the chiller COP to decline more than 2%, as shown in Figure 1.
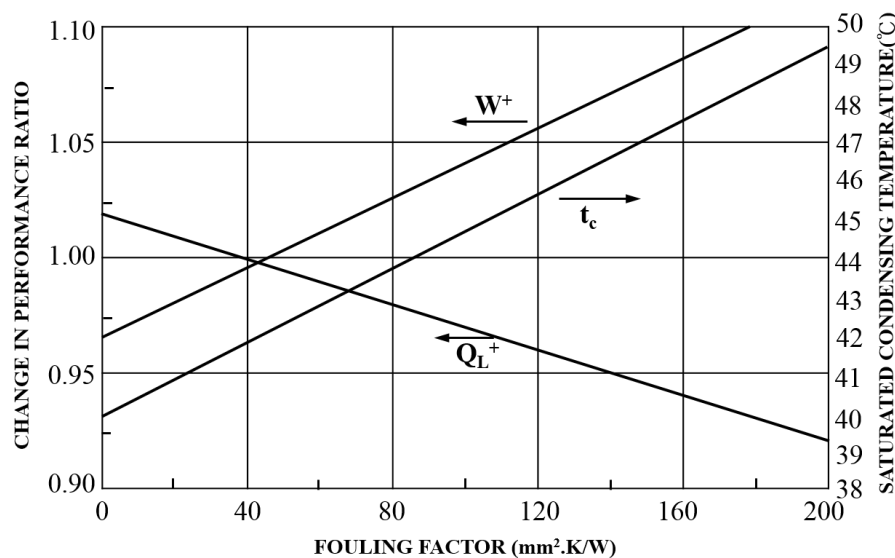

Figure 1. The impact of condenser fouling factor on chiller performances [2].

Normally, in the HVAC industry, T_a is kept below 2.2 °C level, preferably below the 1.5 °C threshold, so that chillers can run energy-efficiently. An exceedingly high T_a, such as above 3.5 °C, not only indicates that the chiller is suffering from a higher power consumption, but also posing higher risk, as the chiller might trip instantly.

On the other hand, the hot and humid weather enhances biofouling and makes it worse. Due to constant evaporation, calcium and magnesium ions in the cooling water stream accumulate, and precipitate due to a sudden drop in their solubility when heated in the condenser tubes, becoming hard mineral scales. Both biofouling and mineral scaling problems can jack up the T_c, and thus T_a. Based on cooling technology institute (CTI) reports [4], biofilm can be four times more thermal-resistant than that of mineral scales, as shown in Figure 2. A sustainable and industrial-scale methodology to handle the scaling and biofouling problems has yet to be developed, and is the main theme of our research effort.
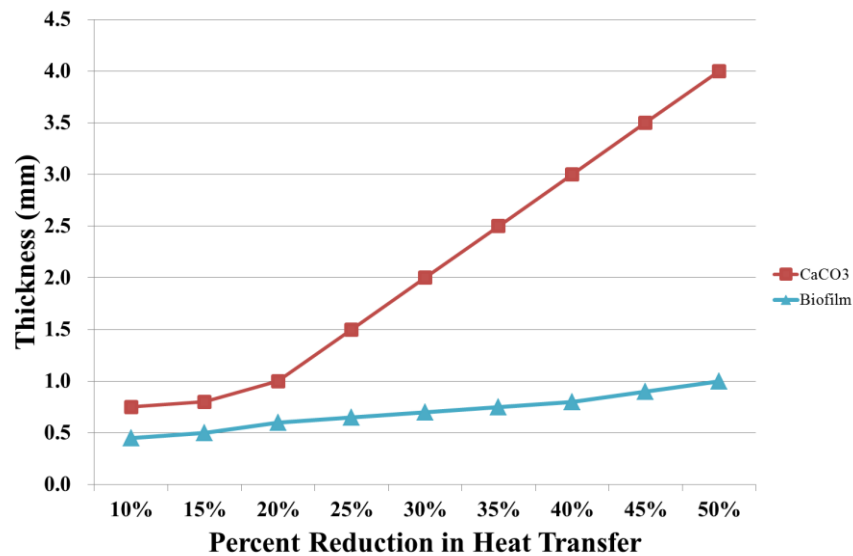
Figure 2. The influence of scale/biofouling thickness in reducing heat transfer effectiveness [4].

2. A Comparative Analysis on Existing Methods to Keep T_a Smaller

Chemical water treatment has a long history of application in the global cooling industry, starting in 1950. When the concentration of colloidal particles exceeds its solubility in the bulk water, precipitation will occur. To avoid this, chemicals can be added to alter its solubility, which changes its pH value, and are named scale inhibitors. Changing the particle size or its surface charge density is another way to keep it from settling out of the solution. Chemicals for this purpose are called dispersants. Microbiocides, or simply biocides, are added to control the proliferation rate of microorganisms. They could be oxidizing or non-oxidizing and are normally low molecular weight polymers. However, in considering that the chemicals added might corrode the galvanized components of the cooling water system, corrosion inhibitors are added to form a protective coating on metallic or alloy tube surfaces. While this "adding more chemicals" process goes on, the threat to the environment and working staff increases, as does the concern of causing premature equipment failure. On the other hand, due to constant evaporation and blowdown, make-up water will be injected to the cooling towers. A dynamic balancing among all of these factors is thus obtained to maintain a favorable water quality for long-term commercial operation of a chiller plant.

Alternatively, it can be achieved by physical water treatment. By applying magnetic [5,6] or electrostatic fields [7] externally, the characteristics of the nucleation of mineral ions and other electrically-charged submicron particles in the water can thus be altered. The mechanism of coagulation and flocculation of solid particles suspended in the water loop can be enhanced by the magnetic, electromagnetic [8] or electrostatic field imposed, increasing the crystal formation on the bulk solution, and preventing it from depositing on heat transfer surfaces [9]. For this purpose, permanent magnets, solenoid coils, and high-voltage electrodes are the most commonly applied physical water treatment devices. Theoretically, these devices all produce time-varying electric fields, which either cause the precipitation of mineral ions, becoming particulates in bulk water; or alleviate the surface tension of the colloids [10], making the scale and biofilm softened, which can easily be flushed out by cooling water stream, and settled down at the cooling water basin. Cho et al. [11] conducted a systematic study sponsored by the ASHRAE in 2002, and analyzed all three physical treatment methods. Conclusion was drawn on permanent magnets that an optimal water flow velocity, at around 2.3 m/s, is very effective for hard mineral scale prevention. Its efficiency is also very sensitive to the orthogonalization of the magnetic field introduced by the magnets and the water flow. When operation departs from these two optimal conditions, the efficiency drops quite significantly. Cho [12] further conducted tests for the solenoid coils, with water flow velocity fixed at 1.0 m/s, electric conductivity was at

3000 μs/cm, and the current ampere and frequency increased from 0.7 A, 0.5 kHz to 7.0 A, 3.5 kHz. It was found that the fouling resistance of water decreased when compared with the baseline by 20% and 53%, respectively, and is in proportion to the intensity of the electrical field imposed. The crystal size in the bulk also increases, implying that the pulsating electric field imposed causes molecular agitation to the charged mineral ions such as calcium and magnesium. They precipitate in the bulk water, instead of forming hard scale on the heat exchanger surfaces.

Furthermore, the same experimental set-up and test conditions were maintained to investigate the effectiveness of a high-voltage electrode system in mineral scale mitigation and prevention. It was found that the high-voltage electrodes reduced the surface tension of water samples by approximately 8% in cooling-tower applications [12]. It was suggested that more detailed and full-scale tests would have to be proceeded to draw any more conclusions, which is the main theme of our studies. Romo and Pitts [13] studied in greater details the application of a high-voltage electrodes system in the removal and prevention of redevelopment of biofouling from operating reverse osmosis equipment (RO). Successful results were obtained from field observations supported by laboratory tests. The theory lies in that, in the cooling water loop, suspended particles or colloids are balanced between the attraction force and the repulsion force acting on them. The former is known as the van der Waal's effect; the latter is introduced from surface charges, known as the electrostatic effect, which is in proportion to its zeta potential.

The installation of an insulated and sealed electrode directly inside the water stream, for example, from a piping elbow, or the cooling tower basin, will form a capacitor-based electrostatic field. This field will raise the zeta potential of the suspended colloidal and wet surfaces of the containment, causing the scale and biofilm to soften and be flushed away by the water stream. The proliferation and reproduction of the biofilm will be disrupted and prevented. Although fruitful, only small-scale tests had been performed in this study. Afterwards, Cho et al. [14] performed another study to test the effectiveness of a commercially available solenoid coil devices for mineral scale and fouling mitigation on a 500 RT chiller. The tests were run for 12 days, resulting in approximately 70% reduction of fouling resistance on the condenser tubes of the chiller.

It is this inspiration leads to the main theme of our study, to investigate the effectiveness of a high-voltage electrodes system in mitigating mineral scaling and bio-fouling on huge central chiller plants under commercial operation. Preferably, full-scale tests in the field will be conducted with results followed up on an annual basis, not just for weeks to verify the sustainability of such a solution.

To sum up, our study aims to answer the following important points, which were not found in earlier studies:

(1)　An optimal solution, in combining physical with chemical treatment, will be developed. A high tension electrodes system, namely HVCB electrodes, also used by Romo and Pitts, coupled with biocides will be experimented.

(2)　Industrial full-scale tests, instead of laboratory tests, will be conducted. Chiller plants at the size of 5000 RT to 10,000 RT cooling capacities will be selected as the test sites for experiment.

(3)　Tests will be conducted and recorded on an annual basis, to identify the sustainability of this solution for commercial operations.

In addition to the T_a data recording, the corresponding improvement of chiller COPs in energy-saving, will be analyzed to warrant its future application potential in the HVAC industry.

3. Theoretical Analysis on Chiller Performances

Mollier diagram facilitates a useful tool to perform sensitivity analysis on chiller performances subject to variations in its operating parameters, especially T_a. Here, the useful tool is briefly introduced [15]. It is a powerful calculation program for thermophysical properties. It calculates the thermodynamic substance data and transport properties of all refrigerants. It contains modules for the calculation of a total of 7 different ones and two-step cycle processes and for dimensioning

of a refrigerant's pipelines. Hence, we used it to simulate a variety of parameters of a refrigeration cycle and to get the corresponding results. Analysis was performed on a 1422 RT centrifugal chiller operating with R134a refrigerant. The chiller's actual operating data were collected as simulation inputs, resulting in Figure 3 showing its Mollier diagram.
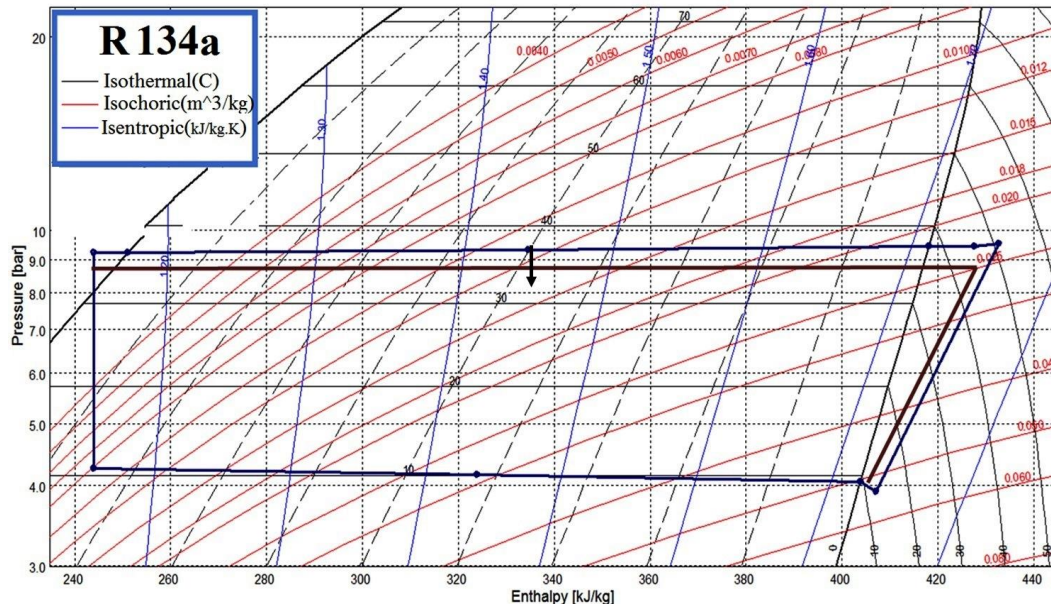
Figure 3. The Mollier Diagram [8] of a 1422 RT centrifugal chillers, operating on R134a refrigerant at 6600 V 60 Hz, Model YDHA73DD.

Table 1 further indicated the detailed sensitivity analysis of this chiller based on various reduction of T_a and its impact on COP improvement. T_a at 3 °C was selected as a comparison basis. The sensitivity was conducted by changing the condensing approach temperature T_a from 0 °C to 3 °C, with an increment of 0.2 °C. Simulation result predicts that each 1 °C of T_a reduction will yield around 3.5% of COP increase. It would be further compared with experimental results.

Table 1. Sensitivity analysis of a 1422 RT chiller based on various reduction of T_a and its impact on COP improvement.

T_a (°C)	T_c (°C)	Q_e (°C)	P (kW)	COP	kW/RT	Percentage of Increase COP	Percentage of Reduction kW/RT
3.0	37.2	3811	612	6.22	0.565	0 (Base)	0 (Base)
2.8	37.0	3842	612	6.27	0.561	0.80	−0.80
2.6	36.8	3872	613	6.32	0.556	1.61	−1.58
2.4	36.6	3903	614	6.36	0.553	2.25	−2.20
2.2	36.4	3934	615	6.4	0.549	2.89	−2.81
2.0	36.2	3965	615	6.44	0.546	3.54	−3.42
1.8	36.0	3995	616	6.49	0.542	4.34	−4.16
1.6	35.8	4026	616	6.53	0.538	4.98	−4.75
1.4	35.6	4057	617	6.58	0.534	5.79	−5.47
1.2	35.4	4088	617	6.62	0.531	6.43	−6.04
1.0	35.2	4118	618	6.67	0.527	7.23	−6.75
0.8	35.0	4149	618	6.71	0.524	7.88	−7.30
0.6	34.8	4180	618	6.76	0.520	8.68	−7.99
0.4	34.6	4210	619	6.81	0.516	9.49	−8.66
0.2	34.4	4241	619	6.85	0.513	10.13	−9.20
0.0	34.2	4272	619	6.9	0.510	10.93	−9.86

4. Experimental Investigation

The experimental set-up of the cooling water loop in a typical chiller plant is shown as Figure 4, with the electrodes and power supply installed. On the chiller side, T_a will be recorded automatically through the existing data acquisition system inherent and mounted on the chillers or from the central energy management system under commercial operation. Chiller COPs will also be measured, before and after the treatment to verify its effectiveness in improving the performances.
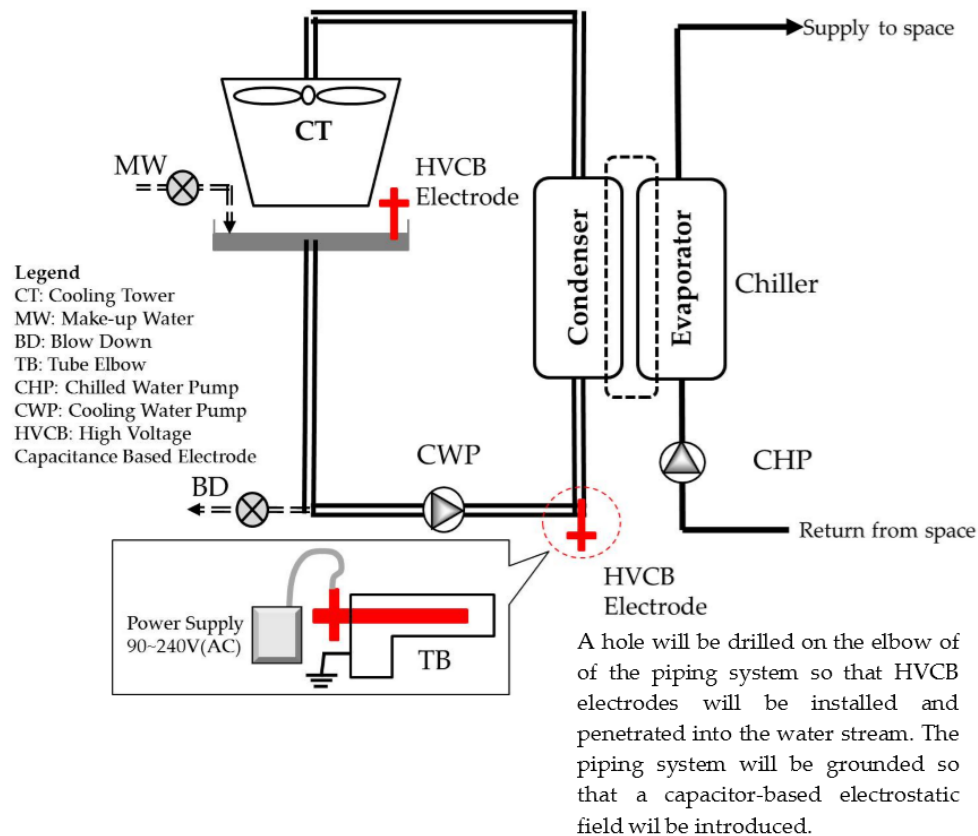
Figure 4. The experimental set-up of the cooling water loop in a typical chiller plant indicating the installation position of the electrodes system.

4.1. Experimental Procedure

The following steps will be carried out during the experiment sequentially:

Step 1: Perform all chiller COP measurement before the treatment, as a baseline for comparison.

Step 2: Select an experimental chiller, divert the cooling load to a spare chiller, close the gate valve and drain its cooling water loop.

Step 3: Drill a hole and weld the adaptor on the chiller condenser cooling water entry pipe, preferably at the elbow, then install the electrodes on site. It will take around 4 to 8 h to complete one rod installation.

Step 4: Set up the power supply and test it, and identify that it could introduce around 30 kV to 35 kV continuous DC voltage at the site. As the electrode is not in direct contact with water, only a capacitor-based electrostatic field is introduced.

Step 5: Reverse step 2 and put the experimental chiller back on duty. Rotate in the same order, until all experimental chillers are installed with electrodes system.

Step 6: Switch on the power supply and begin all data-recording automatically.

Step 7:   Observe until the T_a begin to rise, which indicates that the first phase of scale and biofilm from the cooling tower fins is falling, causing the cooling water loop to be even dirtier than before. When the T_a reaches over 3 °C, input the biocide into the cooling tower, with 25 kg to 30 kg sodium hypochlorite (NaOCl). Close the blowdown valve, or raise its conductivity settings, of the cooling tower and keep it overnight.

Step 8:   Expect the T_a to drop significantly following the biocide input, to lower than 1 °C level on the following day. Drain the cooling tower and clean the basin.

Step 9:   Repeat Steps 7 and 8 until the T_a no longer shoots up over the 2.2 °C level, indicating the whole cooling water loop is clean.

Step 10:   Perform post-treatment chillers COP measurement to verify the energy-saving effectiveness and keep tracking it.

Step 11:   Allow the chiller plant to run under its normal commercial operation until the completion of the experimental investigation, preferably for over one or two years. Keep track on its T_a variation during the whole period of time from the automatic data acquisition system.

4.2. Measurement and Verification Methodology on the COP Improvement

In order to evaluate the thermal performance of a chiller before and after the treatment without interrupting its operation, its COP will be measured using an ultrasonic water flow meter, together with thermocouples to record its corresponding chilled water and cooling water temperatures. Furthermore, the heat balance among the Q_e, P and Q_c, that is Equation (2), shall be obeyed all the time, to validate the data collected. To this purpose, a portable real time dual-loop ultrasonic flow meter will be utilized to perform this test, which records all parameters simultaneously in both cooling water loop and the chilled water loop of a chiller, second by second, together with corresponding power readings. The chillers' COP will be measured according to the following procedure:

(1)   The circumference of one of the cooling water pipes and the circumference of one of the insulated chilled water pipes shall be measured using a measuring tape. The outer diameter of the cooling water pipe shall be computed and keyed into the portable ultrasonic flow meter.

(2)   A rectangular portion of the insulation foam, measuring 60 cm × 12 cm shall be removed from the exterior of the chilled water pipe. On the wall of each piping system chosen from the chilled water and cooling water loop, a pair of flow rate transducers of the flow meter will be installed by choosing a location of reasonable distance, normally around six pipe diameters in distance away from piping fittings, including elbows and valves to avoid flow turbulence resulting in bad readings.

(3)   Besides the chilled water and cooling water flow rates, the following parameters shall be measured every three seconds for three days, including:

    (a)   cooling water outlet temperature (T_1);
    (b)   cooling water inlet temperature (T_2);
    (c)   chilled water inlet temperature (T_3);
    (d)   chilled water outlet temperature (T_4);
    (e)   condenser output (Q_c), as shown in Equation (2); and
    (f)   evaporator output (Q_e), as shown in Equation (2).

(4)   The length of measurement time shall be extended until the following criteria are met:

    (a)   fluctuation of water flow rates to be within the range of ±5%;
    (b)   fluctuation of all inlet and outlet temperatures to be within the range of ±0.5 °C; and
    (c)   compliance with Equation (2) to stay within 5% engineering tolerances.

(5)   After 60 days, the above-mentioned procedure will be repeated for the post-treatment COP measurements.

A schematic diagram is shown in Figure 5 to indicate all the measurement parameters. As the ambient air condition could have varied quite significantly during these 60 days, the control of the cooling tower fan presents a useful means in adjusting T_2 temperature during the whole measurement period. The average value of P shall be recorded from the power analyzer or the chiller power panel accordingly so that Equation (2) can be checked for compliancy all the time.
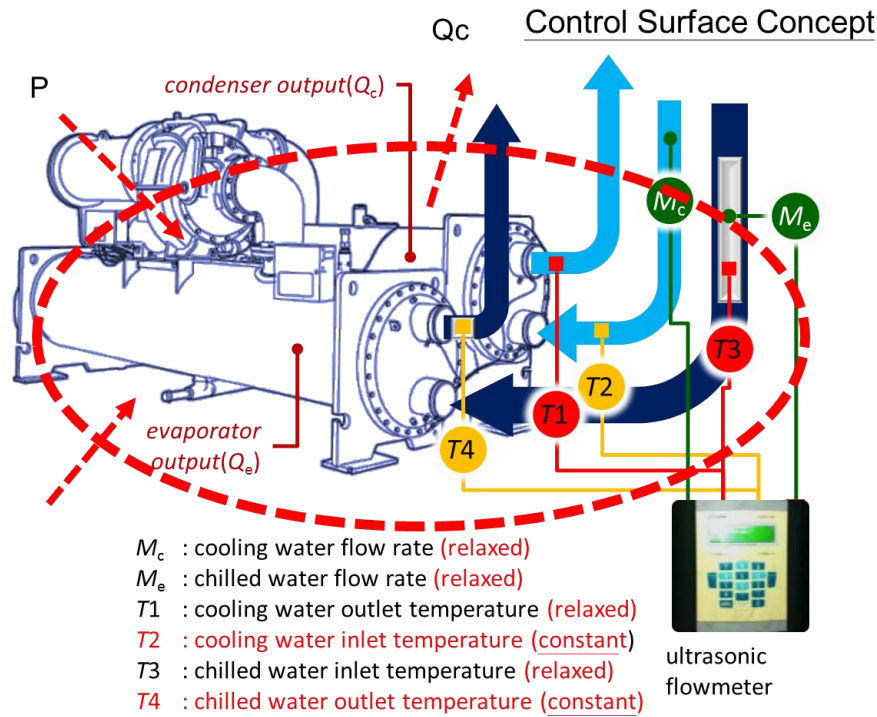
Figure 5. A schematic diagram of chiller COP measurement and verification.

Normally, the T_a value will be shown on the chiller LCD display automatically. Instead, they can be calculated readily form the readings of T_2 and T_c, as shown in Equation (3). The entire set of readings will be automatically recorded, stored, and saved in the data acquisition system described above to be analyzed and printed out afterwards.

According to Stoecker [1], the COP of a centrifugal chiller is mainly determined by the T_2, T_3, and the part load factor (L), such that:

$$Q_e = f(T_2, T_3) \tag{4}$$

$$P = f(T_2, T_3, L) \tag{5}$$

where Q_e or P can be further correlated and curve-fitted with a bi-quadratic equation.

This methodology sets up an important experimental model to compare the operation data of a chiller, before and after the renovation, and to identify the percentage of its COP improvement. That is, when comparing the chiller performances before and after the electrodes installation, data with the same T_2 and T_3 values will be selected, while L could be allowed for a minor deviation of 3%, in considering the chillers are under commercial operation with varying load most of the time.

Above all, Equation (2) is used to justify the validity of the measured data to keep the heat balance, based on the first Law of Thermodynamics. Data gathered during measurement which cannot comply with Equation (2) within 5% tolerances, will be excluded, as shown in Equation (6).

$$\text{Heat balance deviation} = \left| \frac{Q_e + P - Q_c}{Q_c} \times 100\% \right| \tag{6}$$

In some plants, more than one strategy had been implemented simultaneously on the chillers to conserve energy. For example, in some chillers, oil additives were added on its refrigerant compressor to improve its lubricity in reducing power consumption P. As the oil additives might also contribute to the COP improvement on a chiller [14], the principle of superposition will be applied to analyze the effectiveness derived solely by water treatment in that case.

5. Experimental Results and Discussion

5.1. UH Plant Chiller Data

On 13 November 2013, 35 kV DC electrodes were implemented on the UH chiller plant, which was equipped with five units of 600 RT centrifugal chillers running on R123 refrigerant at 380 V 60 Hz, Model CVHF as shown in Figure 6. The test data in Figure 7 showed that on 22 August, T_a dropped from 3.5 °C to 1.5 °C, and then to around 1.2 °C on 30 September 2014. Chiller COP measurements are shown in Figure 8, indicating an improvement ranging from 5% to 7% on all 600 RT chillers.
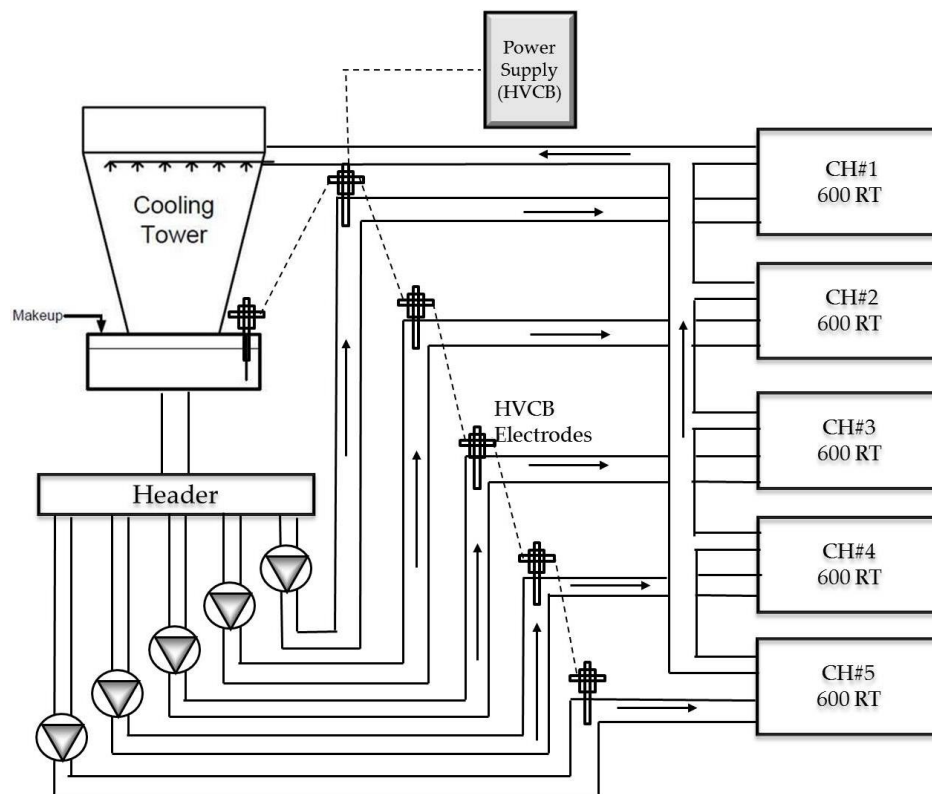
Figure 6. A schematic diagram of HVCB electrodes installed at UH chiller plant.

Visual inspection was performed after one year of operation and virtually all biofouling of the tubes as well as the cooling tower surfaces was removed, as can be seen on Figure 9. Additional observations were made with regard to bacteria counts in the system. Prior to treatment, bacteria counts measured, mainly composed of aerobic bacteria, in excess of one million colony forming units per milliliter (CFU/mL), due to the high outdoor temperature and relatively humid climate. Results after implementation were less than 100 CFU/mL. It is clear that the scaling and biofouling problem on the condenser has been mitigated quite successfully and kept sustainably for about one year of commercial operation.
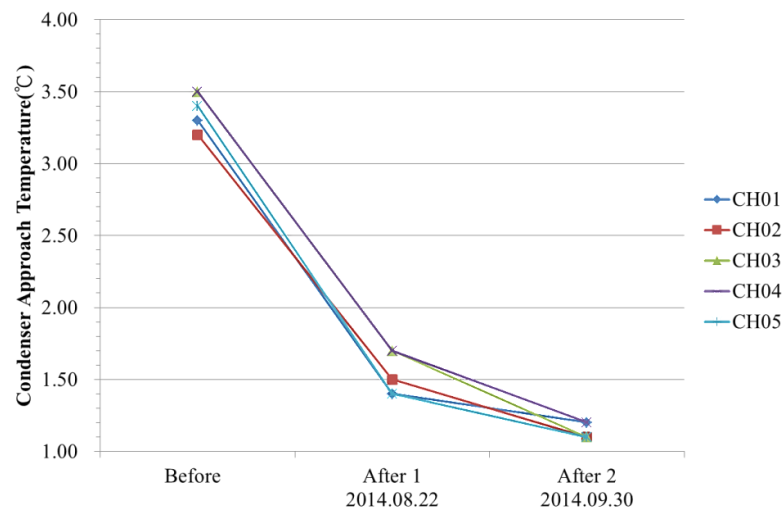
Figure 7. The T_a data in UH chiller plant before and after the electrodes treatment. All chillers were the same CVHF Models centrifugal units and with a cooling capacity of 600 RT each.
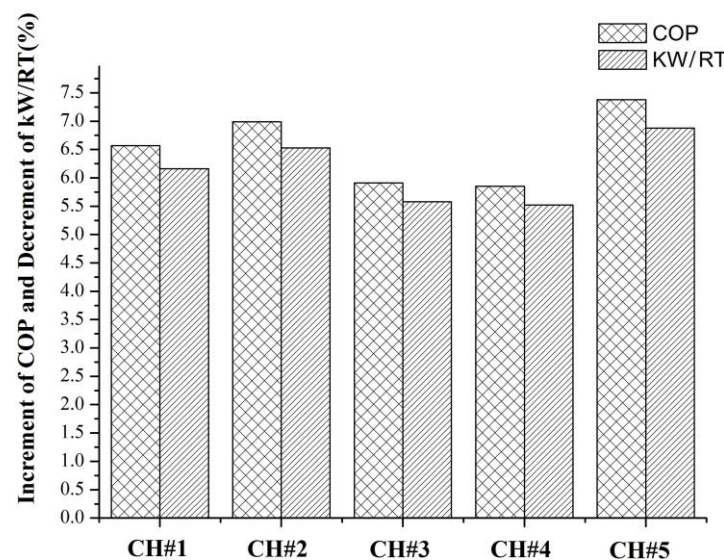
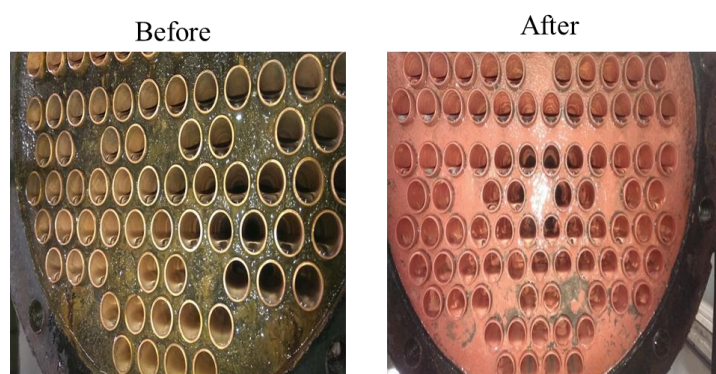**Figure 8.** The chiller performance of UH chiller plant before and after the electrodes treatment.


Figure 9. Visual inspection of the UH plant 600 RT chillers (condenser after one year of electrode installation).

5.2. GF Plant Data

As shown in Figure 10, the GF plant was equipped with eight units of 1422 RT centrifugal chillers, operating on R134a refrigerant at 6600 V 60 Hz, Model YDHA73DD with a centralized cooling water systems. In October 2013, dual energy-saving solutions were implemented on this plant. That is, oil additives were added to improve the lubrication of the compressor, and 35 kV DC electrodes were installed on the cooling water loop to mitigate scale and biofouling.
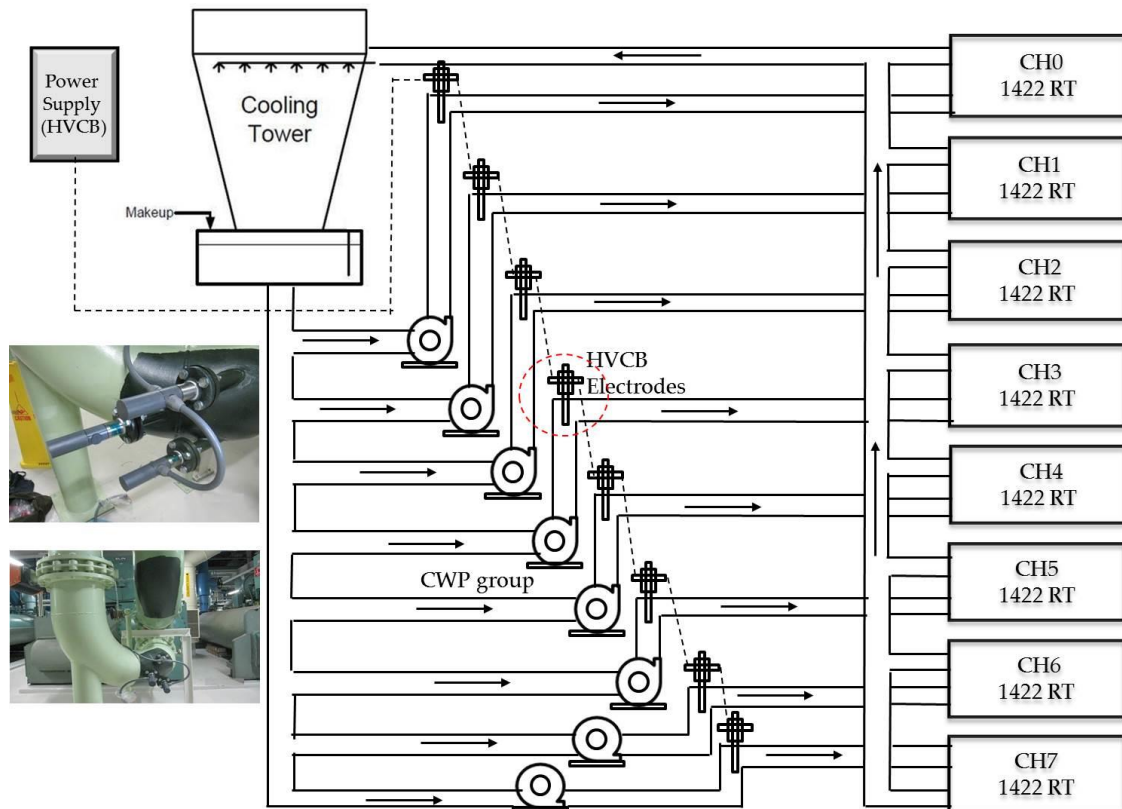
Figure 10. A schematic diagram of HVCB electrodes installed at GF chiller plant.

The T_a Data Analysis

On 13 October 2013, the HVCB electrodes were installed on the chiller plant where T_a values were recorded automatically through the existing data acquisition system for two years. The T_a data, as shown in Figure 11, indicated that from 13 October to 10 November 2013, the first phase of biofilm was peeling off and falling from the cooling tower system, causing the cooling water to become much dirtier and the T_a was rising drastically. The T_a readings not only exceeded the 1.5 °C threshold, but also the 2.2 °C warning line, peaking at 3.8 °C. It depicted that, at that moment, the chiller was suffering from poor condenser heat dissipation, higher power consumption and higher risk of tripping. On 11 November, 25 kg of sodium hypochlorite was input to the cooling tower basin as biocide to circulate through the whole cooling water loop. On 12 November, the T_a dropped to less than 1 °C level instantly, as expected.
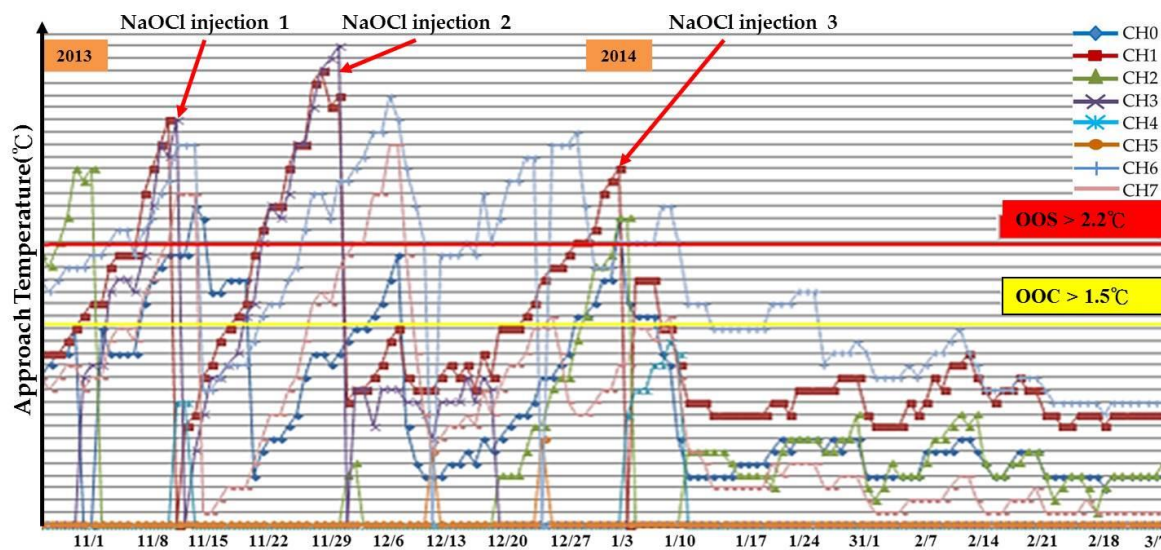
Figure 11. T_a recordings of the GF chillers from 13 October 2013 to 7 March 2014.

Beginning 13 November 2013, the second phase of biofilm reduction was coming and the T_a peaked on 30 November. Again, another 25 kg of sodium hypochlorite was input to the cooling tower basin. On 18 December, the T_a was brought down to 1 °C again.

The third phase of falling biofilm reached on 30 December 2013, but to a lesser extended, T_a peaked at around 2.5 °C, and another 25 kg of biocide was input for the third time, bringing the T_a down to 1 °C level and then maintained in that range.

In fact, the HVCB electrode system alone cannot kill bacteria, only the biocide can. Therefore, in this system, by increasing the zeta potential of the colloids, the biofilm will peel off, so that the biocide can do the job at the cooling tower basin. Afterwards, this HVCB electrode system will keep it clean sustainably, in this case, for two years. It is the merit of this study to combine a physical (HVCB electrodes) and a chemical (NaOCl biocides) solution to optimize it and become a total solution. That is how the innovation was developed and achieved in this study.

As there were eight chillers running in tandem supported by the centralized cooling tower system, they were all under the same electrostatic field effect. However, the T_a reduction in each chiller varied, as shown in Figure 12. For example, in February 2015, the T_a data showed that chiller 0, 1, 2, and 7 were all controlled under 0.4 °C. The chiller T_a was controlled at 1.2 °C, which is still under the 1.5 °C threshold value.
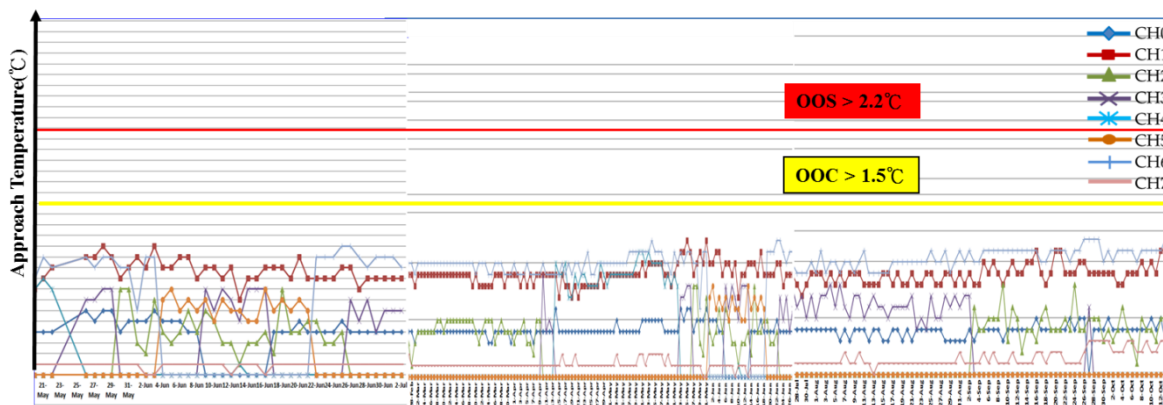

Figure 12. T_a recordings of the GF chillers from 7 March 2014 to 13 October 2015.

This tendency was maintained from 13 October 2013 to 14 October 2015, totaling two years.

This successful result indicated that the cooling water system in GF plant had been and still is operating under a well-controlled condenser approach temperature, at below 1 °C level for over two years, saving significant amount of energy and was environment friendly. After the three peaks of T_a, no more instant biocides were dosed. In addition, each 35 kV electrode consumed less than 20 watts power, considered minimal and is acceptable for this plant's applications.

(1) The Energy-Savings Effect of the GF Plant

The energy-savings effect is analyzed by comparing the COP values of chillers, before and after the electrodes installation. Chiller 0 was selected to demonstrate its detailed measurement data and analytical results. The pre- and post-measurements were conducted on 9 September and 25 October 2013 and the results are shown in Table 2. The chiller loading was fixed at 89% in both cases. The measurement result is summarized in Table 3.

Table 2. Post COP measured by flow meter and power analyzer on GF chillers, on 25 October 2013. R134a refrigerant, refrigerant condensing temperature = 30 °C–31 °C.

	Cooling Water Flow				Chilled Water Flow				Power	COP
	Outlet, T_1 (°C)	Inlet, T_2 (°C)	Flow Rate (LPM)	Q_C (kW)	Inlet, T_3 (°C)	Outlet, T_4 (°C)	Flow Rate (LPM)	Q_e (kW)	P (kW)	(kW/kW)
1	33.50	29.20	16,302.07	4890.62	18.00	13.40	13,012.11	4175.98	609.42	6.85
2	33.50	29.20	16,325.57	4897.67	18.00	13.50	13,555.80	4255.89	609.48	6.98
3	33.50	29.20	16,307.10	4892.13	18.10	13.50	13,011.36	4175.74	608.97	6.86
4	33.50	29.20	16,430.13	4929.04	18.10	13.50	13,051.68	4188.68	609.47	6.87
5	33.50	29.20	16,396.67	4919.00	18.10	13.50	13,096.96	4203.21	609.42	6.90
6	33.50	29.30	16,687.79	4889.91	18.10	13.50	13,211.78	4240.06	609.39	6.96
7	33.60	29.40	16,581.72	4858.83	18.10	13.50	13,135.57	4215.60	610.28	6.91
8	33.60	29.40	16,721.03	4899.65	18.10	13.60	13,515.12	4243.12	610.64	6.95
9	33.70	29.50	16,643.15	4876.83	18.20	13.60	13,067.73	4193.83	611.03	6.86
10	33.80	29.60	16,607.56	4866.40	18.20	13.60	13,052.15	4188.83	611.82	6.85
11	33.80	29.60	16,549.37	4849.35	18.20	13.60	13,074.49	4196.00	612.26	6.85
12	33.90	29.70	16,599.74	4864.11	18.20	13.70	13,404.31	4208.33	612.50	6.87
13	33.90	29.70	16,512.75	4838.62	18.30	13.70	13,133.01	4214.78	613.20	6.87
14	34.00	29.80	16,726.97	4901.39	18.30	13.70	13,043.96	4186.20	613.63	6.82
15	34.00	29.80	16,758.50	4910.63	18.30	13.70	13,157.07	4222.50	614.95	6.87
16	34.10	29.80	16,380.33	4914.10	18.30	13.70	13,187.04	4232.12	617.45	6.85
17	34.10	29.90	16,704.13	4894.70	18.30	13.70	13,078.86	4197.40	618.50	6.79
18	34.20	29.90	16,501.20	4950.36	18.30	13.70	13,156.35	4222.27	620.16	6.81
19	34.20	30.00	16,889.44	4949.00	18.30	13.70	13,267.21	4257.85	622.92	6.84
20	34.30	30.00	16,583.30	4974.99	18.30	13.70	13,261.79	4256.11	625.56	6.80
21	34.30	30.00	16,713.33	5014.00	18.40	13.70	13,107.31	4297.98	628.38	6.84
22	34.40	30.10	16,797.37	5039.21	18.40	13.70	13,028.57	4272.16	631.83	6.76
23	34.40	30.10	16,711.17	5013.21	18.40	13.70	13,032.45	4273.43	632.99	6.75
24	34.50	30.10	16,507.63	5067.46	18.40	13.70	13,226.56	4337.08	635.42	6.83
25	34.50	30.10	16,491.67	5062.56	18.40	13.70	13,267.09	4350.37	637.77	6.82
26	34.40	30.10	17,016.87	5105.06	18.50	13.70	12,967.55	4342.62	638.15	6.81
27	34.40	30.00	16,636.93	5107.15	18.40	13.70	13,189.01	4324.77	639.52	6.76
28	34.40	30.00	16,668.01	5116.69	18.40	13.70	13,328.14	4370.39	641.31	6.81
29	34.40	30.00	16,638.20	5107.54	18.40	13.70	13,300.78	4361.42	640.99	6.80
30	34.40	30.00	17,055.88	5235.76	18.40	13.60	13,002.60	4354.36	640.54	6.80
31	34.30	29.90	17,103.77	5250.46	18.40	13.60	12,987.10	4349.17	640.64	6.79
32	34.10	29.80	17,277.43	5183.23	18.30	13.60	13,202.37	4329.15	640.98	6.75
33	33.90	29.60	17,423.53	5227.06	18.30	13.50	13,023.18	4361.25	637.16	6.84
34	33.70	29.30	17,080.58	5243.34	18.30	13.50	13,070.90	4377.23	633.85	6.91
35	33.50	29.20	17,461.40	5238.42	18.20	13.50	13,259.71	4347.95	633.23	6.87
36	33.40	29.10	17,315.90	5194.77	18.20	13.40	12,976.86	4345.74	630.75	6.89
37	33.30	29.10	17,541.10	5139.95	18.10	13.40	13,305.05	4362.82	629.24	6.93
38	33.30	29.00	16,943.40	5083.02	18.10	13.40	13,195.39	4326.86	626.78	6.90
39	33.20	29.00	17,385.04	5094.22	18.10	13.40	13,122.81	4303.06	621.63	6.92
40	33.20	28.90	16,882.37	5064.71	18.10	13.40	13,088.62	4291.85	621.09	6.91
41	33.10	28.90	17,194.06	5038.26	18.00	13.40	13,493.24	4330.39	616.35	7.03
42	33.00	28.90	17,392.03	4974.93	18.10	13.40	13,157.27	4314.36	613.70	7.03
43	33.10	28.90	16,931.08	4961.20	18.10	13.40	13,039.64	4275.79	612.39	6.98
44	33.10	28.90	16,947.70	4966.07	18.00	13.40	13,350.07	4284.44	612.07	7.00

Table 3. The comparison of pre- and post-treatment for chiller COP and kW/RT at operating load of 89%.

	Chiller CH00	
	Pre-Treatment **9 September 2013 2:07 p.m.**	**Post Treatment** **25 October 2013 1:38 p.m.**
Loading %	89	89
Power Consumption (kW)	612.58	618.89
Refrigerant Capacity, Q_e	3810.55	4271.50
COP	6.22	6.90
kW/RT	0.565	0.509
Change in COP (Improved)		10.95%
Change in kW/RT (Reduced)		−9.87%

The pre- and post-treatment evaluations depicted that the chiller COP has increased from 6.22 to 6.90, or an increment of 10.95%. In other words, the chiller reduced its power consumption by 9.87% for each refrigeration ton it produced. Similarly, the experimental result of the COP measurement of all chillers is shown in Figure 13, ranging from an increment of 7% to 12%.
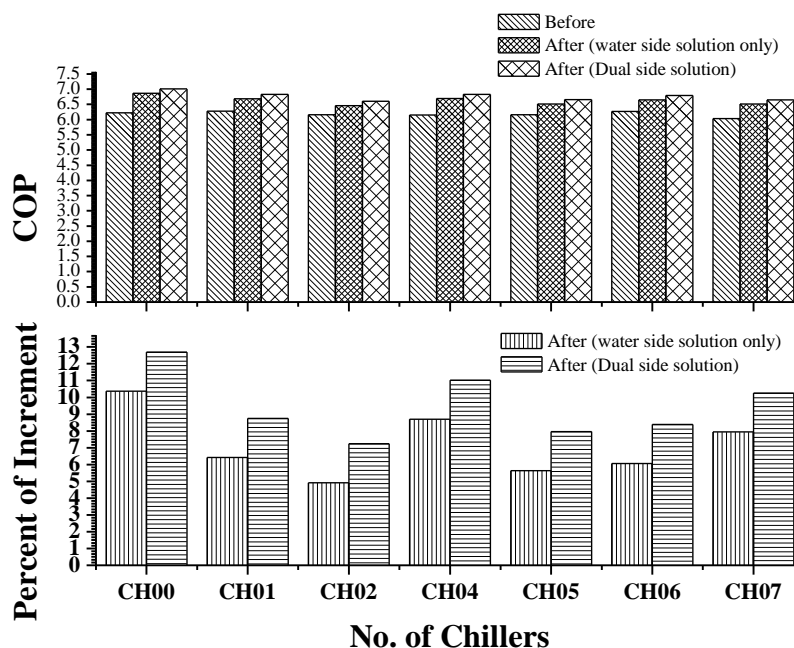
Figure 13. The experimental result of the COP measurement of all chillers on pre and post-treatment.

As the cooling tower system was centralized, electrodes installed on chillers Ch05, CH06, and CH07 provided an effective electrostatic field, which benefitted the whole cooling water system.

(2)   To Identify the Energy Savings Contribution by the Electrodes Alone

However, as these COP improvements in GF plant chillers were obtained by the application of both the oil additives and the electrodes, it should be further analyzed by the principle of superposition to verify the effectiveness provided by the electrodes alone.

In July 2013, a full-scale test was conducted on a 1250 RT model CVHF 1280 Centrifugal chiller running on R123 refrigerant, with oil additives added on the refrigerant side alone. The pre-treatment COP test was conducted on 7 July 2013 as a comparison baseline vs. the post-treatment test conducted on 1 September, under normal commercial operation conditions. These data were directly downloaded from the Supervisory Control and Data Acquisition System (SCADA) of the chiller plant.

Based on Stoecker's Measurement and Verification (M & V) methodology stated above, among the six parameters measured, namely, the condenser cooling water and chilled water flow rates, inlet and outlet water temperatures of the condenser and the evaporator, only data with the same T_2 and T_3 should be selected for pre- and post-comparison, as shown in Equations (4) and (5). The pre-treatment data recorded on 4 July 2013 7:48:42 a.m. and the post-treatment data on 1 September 2013 1:17:52 a.m. are listed in Table 4 for comparison.

Table 4. The chiller performance comparisons between pre- and post-treatment using Stoecker's M & V methodology.

Name of Item	Before	After
Date	4 July 2013	1 September 2013
Time	07:48:42 a.m.	01:17:52 a.m.
Cooling Water Flow Rate (LPM)	3193.06	3196.19
T_1 (°C)	33.7	33.6
T_2 (°C)	28.5	28.5
Q_c (kW)	533.52	533.56
Chilled Water Flow Rate (LPM)	2586.83	2590.16
T_3 (°C)	12.7	12.7
T_4 (°C)	6.2	6.2
Loading (%)	59%	59%
Q_e (kW)	339.89	339.34
Power Consumption	508.7	497.8
COP	5.09	5.20
kW/RT	0.69	0.68
Improvement of COP	2.32%	
Reduction of kW/RT	2.26%	

Table 4 shows that the six parameters were almost identical at that very moment, which constructed an excellent condition for chiller performance comparisons. Table 4 shows that the contribution of adding the oil additives alone increased the chiller COP by 2.32%. Therefore, all of the boost on COPs at the GF plant, by subtracting this figure, should yield a good estimation of the credit contributed by the installation of electrodes system alone, as shown in Figure 13.

Further comparison among the Mollier diagram analysis, Figure 1 by ASHRAE Handbook, and the experimental results revealed that for every 1 °C reduction of T_a contributed to around 3% increment of a chiller COP.

5.3. Cooling Tower System for Scaling Mitigation and Chemical Reduction

5.3.1. The Chemical Reduction Issue

In recent years, more and more concerns have been raised on chemical reduction and water conservation in performing cooling water treatment.

A systematic experimental investigation was conducted in this study to address this issue using the electrode system, as per the following steps:

(1) To record the accumulated fallen deposit amount on the cooling tower basin and the side filter screen after the 35 kV DC electrodes' implementation.

(2) To perform a systematic chemical dosage reduction phase, sampling the water for quality analysis in due course. Optimize between the chemical dosage and the acceptable water quality.

(3) To Record the blowdown and make-up water quantity during treatment and identify the water conservation effectiveness.

5.3.2. Results and Discussions for Step 1

ML utility Plant A with 24,000 m^3/h circulating cooling tower system was installed with 35 kV DC electrode system, and compared with EG plant B with 20,000 m^3/h water flow rate, without installing any physical water treatment device. Weight of deposits, both at the cooling tower basin and trapped by the filter, were recorded and compared on a monthly basis resulting in Table 5.

Table 5. A comparison between the plants A and B, on collected deposit weights, with and without the electrode installation.

Total Weight of Colloids Collected			Utility Plant A 24,000 RT With Electrodes	EG Plant B 20,000 RT Without Electrodes
Cleaning Time	**Weight Collected at the Cooling Tower Basin, kg Per Month**	**No. of Weeks**	**Weight Collected at the Filter, kg/week**	**Weight Collected at the Filter, kg/week**
1st month	Negligible, in either plant A or plant B	1	0.5	0
		2	2.3	0
		3	0.6	0
		4	1.3	0
2nd month	500 kg at Plant A	5	1.8	0
		6	2.0	0
		7	1.2	0
		8	1.4	0
3rd month	550 kg at Plant A	9	1.2	0
		10	2.0	0
		Average	1.43 kg per week	negligible

It indicated that during the first month, either plant A or plant B cooling tower basins did not observe significant deposits. Only 0.5 kg to 1.3 kg of deposits were found in plant A filters. Within the second month, plant A basin accumulated 500 kg of fallen deposits and had to be shoveled off manually while plant B still remained intact. In the third month, plant A basin deposits reached 550 kg, while plant B basins still remained negligible. The deposits on the side filter in plant A averaged 1.43 kg per week versus plant B where no observable deposit was found. Water quality analysis depicted that the composition of deposit found was mainly calcium carbonate, as shown in Table 6. The data in Table 6 indicate that the calcium carbonate (CaCO$_3$) concentration differs by 7.7 to 8.5 times more in plant A vs. plant B, indicating the massive fallen-off deposits accumulated quickly when the electrodes system was in effect.

5.3.3. Results and Discussions for Step 2

In NY plant C, a 6000 m^3/h re-circulating cooling tower system with electrodes installed was chosen to conduct chemical reduction phase. Originally, the plant was equipped with a chemical auto-dosing system with dosages and controlled water quality thresholds, as shown in Table 7. Sensitivity analysis was performed in developing the chemical reduction phase, as shown in Table 8. After six months, on 4 October, the sodium hypochlorite biocide and corrosion inhibitors had been reduced to 75%, 20%, and 0% of their original dosage while maintaining an acceptable water quality, except the corrosion level, as shown in Table 8. Therefore, on 9 November, modification was made to regain 25% of corrosion inhibitor, while reducing the sulfuric acid by another 25% simultaneously. On 23 December, the sulfuric acid dosage was further reduced to 0%. The plant was then operating for nine months, with the water quality maintained in an acceptable level, as shown in Table 9 and Figure 14.

Table 6. Water quality analysis of plants with and without electrodes installation.

| Sample	1		2			
Test Data	4 March 2002		2 May 2002			
Composition	Plant A Cooling Towers (With Electrodes)	Plant B Cooling Towers (Without Electrodes)	Plant A Cooling Towers (With Electrodes)	Plant B Cooling Towers (Without Electrodes)	BAP Plant Cooling Tower (Without Electrodes)	EPOXY Plant Cooling Tower (Without Electrodes)
S (SO_3)	0.856	1.712	0.579	1.423	0.661	0.578
Fe (Fe_2O_3)	1.391	1.59	0.18	1.32	2.662	2.026
Ni	<0.003	>0.009	0.003	0.009	0.019	0.007
Al (Al_2O_3)	1.893	2.984	0.231	1.961	1.262	2.869
Ca ($CaCO_3$) ▲	19.324	2.492	17.572	2.071	1.391	8.201
Si (SiO_2)	12.051	18.951	11.2	16.094	5.704	15.928
Cu (CuO)	0.038	0.097	0.019	0.014	0.042	0.01
Cl	0.077	0.11	0.082	0.138	0.143	0.144
Na (Na_2O)	0.465	0.143	0.383	>0.143	0.663	0.44
Ba	<0.001	>0.001	<0.001	0.091	0.053	0.18
Mg (MgO)	0.813	1.055	1.047	3.095	0.241	2.886
Y (Y_2O_3)	>0.001	>0.001	<0.001	0.001	>0.001	0.002
Cr (Cr_2O_3)	0.012	0.277	0.004	0.017	0.039	0.046
Mn (MnO)	0.035	0.053	0.026	0.03	>0.030	0.035
Br	0.016	0.143	0.014	0.054	0.008	0.002
K (K_2O)	0.352	0.43	0.169	0.667	0.682	1.045
Zr (ZrO_2)	0.008	0.009	<0.007	0.012	0.007	0.021
Rb	<0.003	>0.003	<0.003	>0.003	0.003	0.006
P (P_2O_5)	0.125	0.715	0.051	0.235	0.986	1.919
Zn (ZnO)	0.357	6.494	<1.800	3.112	1.814	0.114
Ti (TiO_2)	0.164	0.257	0.031	0.015	0.013	0.038
As (As_2O_3)	0.009	0.228	0.006	0.023	0.024	0.004

Note: the symbol of a solid triangle is highlighted a prior comparison with the other compositions in the analysis of water quality.
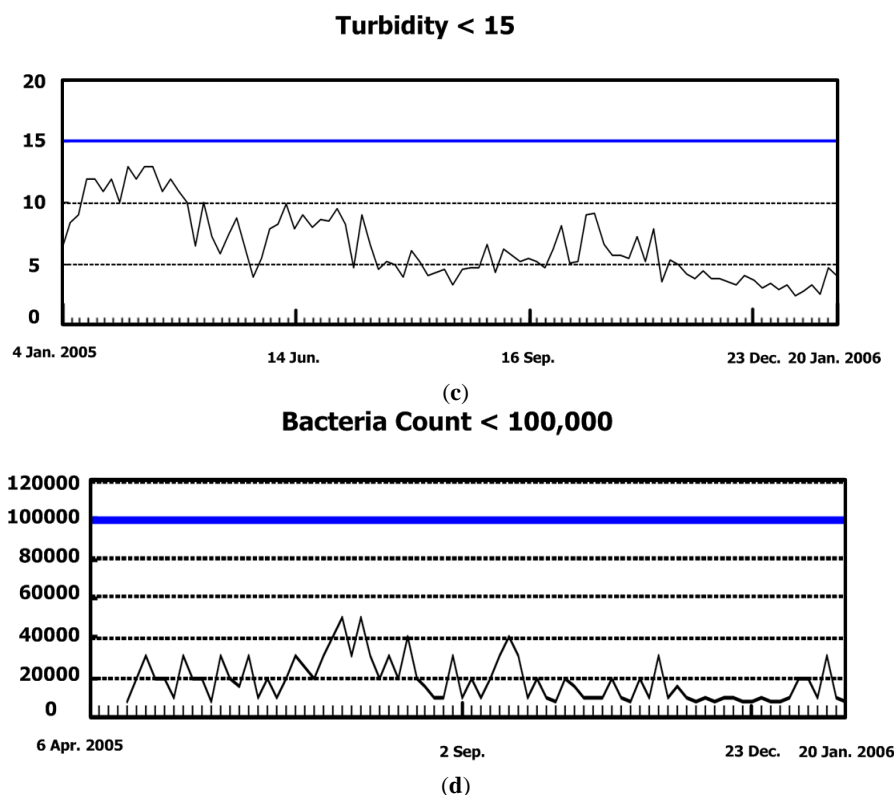

(**a**)

(**b**)

Figure 14. *Cont.*

Turbidity < 15

(**c**)

Bacteria Count < 100,000

(**d**)
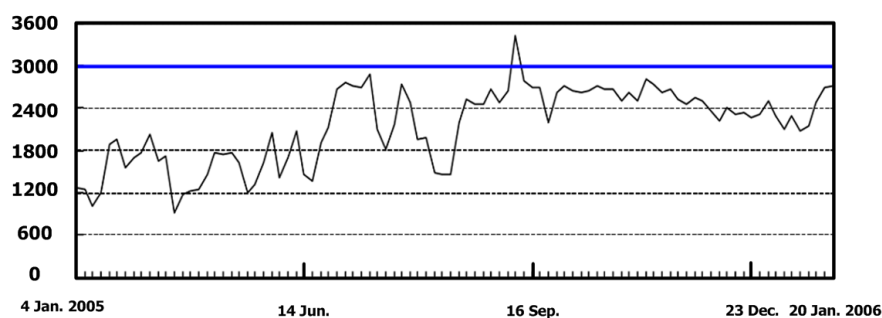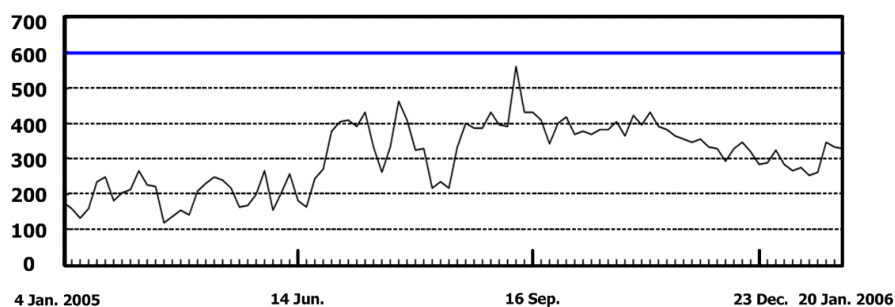
Figure 14. The water quality variations of plant C under commercial operation for nine months. (**a**) conductivity; (**b**) Calcium Hardness; (**c**) Tubidity; (**d**) Bacteria Count.

Table 7. The chemical dosages and controlled water quality thresholds in plant C.

pH Value	Conductivity µs/cm	Ca Hardness ppm	Suspended Solid ppm	Turbidity NTU
7–9	<2500	<450	<10	<15
Free Cl ppm		Bacteria Count CFU/100 mL	Cycles of Concentration	Corrosion rate mpy (Fe)
0.1–0.2		<100,000	<5	<2

Daily dosage: 1. Sulfuric acid: 140 kg/day; 2. Sodium Hypochlorite (NaOCl): 150 kg/day; 3. Biocide: 17.8 kg/day; 4. Corrosion inhibitor: 11.5 kg/day.

Table 8. The development of the chemical reduction phase in plant C, following the sensitivity analysis procedure.

| Chemicals Added	Existing Dosage	Adjustment Stages								
		1					2		3	4
		1 Apr. to 31 May	1 Jun. to 30 Jun.	1 Jul. to 31 Jul.	1 Aug. to 31 Aug.	1 Sept. to 30 Sept.	1 Oct. to 31 Oct.	1 Nov. to 30 Nov. (Originally Planned)	9 Nov. (Actually Executed)	23 Dec.
Sulfuric acid	100%	100%	100%	100%	100%	100%	100%	100%	75%	0%
Sodium Hypochlorite	100%	75%	75%	75%	75%	75%	75%	75%	75%	75%
Biocide	100%	75%	75%	75%	75%	50%	25%	0%	0%	0%
Corrosion inhibitor	100%	75%	50%	25%	0%	0%	0%	0%	25%	25%

Table 9. The water quality reports of plant C under commercial operation over nine months.

Year	Date	pH Value	Conductivity μs/cm	Ca Hardness ppm	Suspended Solid ppm	Turbidity NTU	Free Cl ppm	Bacteria Count CFU/100 mL	Cycles	Weekly Water Discharge Rate LPM	Corrosion Rate mpy (Fe)
		7–9	<3000	<600	<10	<15	0.1–0.2	<100,000	<6		<2
2005	21 Apr.	8.2	1222	155	7.0	11	0.10	8000	2.5		0.64
	3 May	8.4	1471	208	4.6	6.5	0.10	8000	2.9	NA	0.72
	17 May	8.3	1622	218	4.2	7.4	0.05	20,000	3.8		
	21 Jun.	8.5	1921	244	5.2	8.0	0.10	10,000	3.8	26	1.02
	1 Jul.	8.3	2760	403	4.8	9.6	0.10	20,000	6.2	797	1.40
	5 Aug.	8.2	1982	327	2.6	5.2	0.10	20,000	4.4	NA	3.28
	2 Sept.	8.3	2480	394	3.3	4.3	0.10	10,000	5.7	432	3.71
	7 Oct.	8.3	2620	377	3.8	5.3	0.10	8000	5.2	692	4.04
	4 Nov.	8.3	2800	431	3.8	5.2	0.10	8000	6.7	515	2.78
	2 Dec.	8.4	2370	329	2.6	3.8	0.15	10,000	4.8	44	1.50
2006	17 Jan.	8.5	2480	345	1.8	2.6	0.05	30,000	5.2	NA	1.10
	21 Feb.	8.6	2630	319	1.2	3.1	0.05	10,000	4.6	243	0. 81
	24 Mar.	8.4	2980	413	1.8	2.6	0.05	10,000	5.9	295	1.20
	21 Apr.	8.7	2890	340	3.6	6.8	0.10	30,000	5.4	433	2.01
	5 May	8.6	2810	368	1.3	3.7	0.10	20,000	5.7	135	2.39
	20 Jun.	8.8	2920	431	4.2	6.3	0.10	10,000	5.2	387	2.69
	18 Jul.	8.7	2760	435	1.3	3.5	0.05	10,000	5.3	NA	1.83
	22 Aug.	8.7	3050	489	1.3	4.5	0.05	20,000	5.9	821	1.06

Note: Cycles is the abbreviation of cycles of concentration.

5.3.4. Results and Discussions for Step 3

Due to higher concentration level allowed, the blowdown water quantity was reduced significantly, as shown in Figure 15. The blowdown water quantity reduced significantly in plant C following the chemical dosage reduction phase. To sum up, the installation of electrode system in plant C enabled reduction of sulfuric acid, sodium hypochlorite, biocide and corrosion inhibitor by 100%, 25%, 100% and 75%, respectively, and achieved water conservation of 60%.
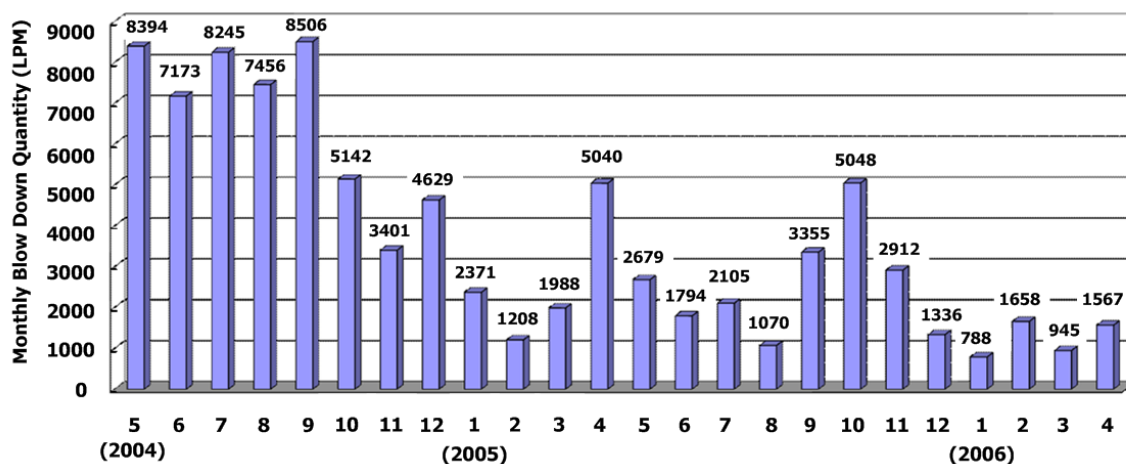
Figure 15. The blowdown water quantity reduced significantly in plant C following the chemical dosage reduction phase.

6. Conclusions and Recommendations

In this study, it has been verified that the combination of physical and chemical water treatment methods could reach an optimal solution for an open-type re-circulating cooling water system. By using electrostatic field combined with sodium hypochlorine to treat the cooling water loop of a chiller plant, it has been demonstrated that the condenser approach temperature of a chiller can be kept stable, to within 1 °C, for over two years of commercial operation. Correspondingly, the chillers' COP were increased by 5% to 6%, respectively, creating tremendous amount of energy savings effect. For example, the CH00 in GF plant was able to obtain power savings from 3.2 kW to 3.8 kW. Furthermore, significant

chemical and make-up water savings was realized, with chemical dosage reduction ranging from 75% to 25%, and water conservation quantity reaching 60%.

The effectiveness of this optimal solution lies in the electrostatic field in removing the scale and biofilm continuously by the electrodes, taking them to the cooling tower basin where biocides can be applied effectively. The power consumption of such an electrode was less than 20 watts, considered minimal, especially when compared with the significant power savings on chillers, which makes it a good and practical solution for energy savings.

The pH value is crucial during this biocide implementation process and should be controlled within the range of 6 to 8. Physical water treatment could be applied as a corrective measure, and yet, could even be better as a preventive measure. In other words, a chiller condenser can be cleaned first, then a physical water treatment be applied to keep it clean sustainably. A physical water treatment device could be effective in peeling off existing scales and biofilm, which can be observed readily by a sharp increase of the condenser approach temperatures. It would be a good timing to apply biocides to kill the biofilm and microbes simultaneously. Conventionally, this is difficult to achieve by applying chemical treatment alone, as the biofilm was normally hiding below a protective layer of mineral scales and nourished by nutritious aerobic or anaerobic layers. To develop an effective chemical treatment plan, complicated auto-dosing and online monitoring system should be adapted, or exceedingly high chemical dosages should be applied, creating health and environmental concerns. On the other hand, a physical device can soften the biofilm by raising the zeta potential of colloids in this case, surpassing its van der Waal's adhesion effect so they can be flushed to the tower basin where biocide can be applied effectively. That is how the optimal solution was developed in this study.

During water treatment process, the corrosion of cooling water circulating system parts and components remains an important issue. It is recommended that corrosion inhibitors should be applied first, immediately following the cleaning of tubes and before heavy dosages of biocide was inserted. The methodology developed and results obtained in this study may be duplicable in other plants with significant energy savings potential. However, care should be taken that each plant could have its own constraints and restrictions where an optimal solution should be developed.

Author Contributions: Chen-Yu Chiang took charge of measurement and verification of chiller COP for UH and GF plants. At the same time, he also did a simulated work for lowering cooling approach temperature. Ru Yang analyzed the cooling water quality variations and arranged everything for the experiment of COP. Kuan-Hsiung Yang helped with writing and revision of the paper and provided guidance, supervision, support. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

COP	Coefficient of performance
CFCs	Chlorofluorocarbons
HVAC	Heating, ventilation and air conditioning
HVCB	High voltage capacitance based
CH	Chiller
DC	Direct current
M & V	Measurement and verification
SCADA	Supervisory control and data acquisition system
L	Part load factor
P	Power consumption of a chiller compressor
Q	Cooling capacity or heat dissipation on the chiller
T	Temperature

Subscripts

a	approach temperature
c	condenser
e	evaporator
1	leaving condenser
2	entering condenser
3	entering evaporator
4	leaving evaporator

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