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Application of ozone treatment in cooling water systems for energy and chemical conservation

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Abstract. In this study, a complete set of recirculating cooling water system and the required instruments were built in a semi-industrial-scale and a 50 g/h ozone generation plant and a chlorine system were designed for cooling water treatment. Both chlorination and ozonation treatment methods were studied and the results were analyzed during two 45-days periods. The concentrations of ozone and chlorine in recirculating water were constant at 0.1 mg/lit and 0.6 mg/lit, respectively. In ozone treatment, by increasing the concentration cycle to 33%, the total water consumption decreased by 26% while 11.5% higher energy efficiency achieved thanks to a better elimination of bio-films. In case of Carbon Steel, the corrosion rate reached to 0.012 mm/yr and 0.025 mm/yr for the ozonation and chlorination processes, respectively. Furthermore, consumptions of the anti-corrosion and anti-sedimentation materials in the ozone cooling water treatment were reduced about 60% without using any oxidant and non-oxidant biocides. No significant changes in sediment load were seen in ozonation compared to chlorination. The Chemical Oxygen Demand of the blow-down in ozonation method decreased to one-sixth of that in the chlorination method. Moreover, the soluble iron and water turbidity in the ozonation method were reduced by 97.5% and 70%, respectively. Although no anaerobic bacteria were seen in the cooling water at the proper concentration range of ozone and chlorine, the aerobic bacteria in chlorine and ozone treatment methods were 900 and 200 CFU/ml, respectively. The results showed that the payback time for the ozone treatment is about 2.6 years.

Keywords: ozone treatment; cooling tower; corrosion; energy conservation; chemical conservation

1. Introduction

Once-through and re-circulating cooling water systems (RCWSs) are used for the rejection of waste heat into the environment. Of these methods, RCWSs are by far the most common method because they can conserve freshwater and reduce thermal pollution compared with Once-through systems (Ataei *et al*. 2009, Alawadhi 2011).

Ozone is a gas that acts as a powerful oxidant and disinfectant. When ozone is injected as tiny bubbles into water, it precipitates materials such as iron, sulfur and manganese, while destroying

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bacteria at the same time.

Considering ozone unique specifications, Hertrampf (1998) introduced it as a good alternative to chlorine in cooling water treatment (Hertrampf 1998). Conner (2005) proposed the combination of ozone with other chemical inhibitors to improve corrosion resistance and then scaling reduction was reported. Viera *et al*. (2000) applied chemical inhibitors in cooling water treatment and showed that using chemicals may increase operational costs while creating environmental issues. They considered ozone as a stronger oxidant compared to chlorine, which possesses unique properties and high disinfecting qualities in cooling towers. Also, ozone can create a passive medium that causes resistance against corrosion in some metals such as carbon steel. Ataei (2008) has integrated ozone treatment with chemical inhibitors for water treatment in cooling tower his work resulted. In the reduction levels of bacterial and mineral substances in the waters discharged through blow-down decreases. Ataei *et al*. (2010) studied on application of the ozone treatment in water and energy conservation, while ozone treatment is integrated to cooling tower. This technique, accounts for the maximum cycle of concentration on the tower side and optimal configuration of coolers on the network side. The MATLAB software was used to simulate ozone treatment process in cooling water. Panjeshahi *et al*. (2009) showed that integration of ozone water treatment within the recirculation of cooling water, decreases the concentration of insoluble components both in circulating water and blow-down dramatically, which is environmentally constructive indeed. Strittmetter *et al*. (2003) used ozonation as a disinfection method to remove infectious bacteria, algae and viruses and bio-film from water.

Gaylarde and Videla (1992) showed that integration of ozone treatment with conventional biocides in cooling water treatment introduces several advantages including minimum on-site chemical inventory since ozone is used and generating simultaneously, the lowest level of toxicity risks in the downstream because ozone is a rapid decomposer and reduction of the amount of discharged water.

One of the most important problems of wet recirculating cooling towers is that they consume huge amount of make-up water. To decrease biological problems, corrosion and sedimentation, several inhibitors chemical materials, both mineral and organic have been used. It should be noted that high consumption of inhibitors and chemical materials could increase economical cost in industry.

The purpose of this research is to provide an innovative method to decrease pollution, corrosion and blow down water and substitute the conventional process in cooling tower treatment with a new one in order to decrease the consumption of chemicals and make the whole process environmentally friendly.

2. Process description

The features of the pilot cooling tower are presented in Table 1. There is variety of cooling tower pilots in the world, but in this study, using instrument control equipment and some other facilities, could enhance the acquired data and simplify the monitoring process. This invention also, utilizes an improved sealing system of electro fan with low IP which will increase the performance. This work has been recorded in Iran Patent Office as “A design for an automatic wet cooling tower with remote controlled capability at No 84442, 2014 (Ghazi and Ataei 2014a, Al-Bassam and Maheshwari 2011).

Table 1 The features of the pilot and the main cooling towers

Type: Wet cooling (counter current)	Pilot	Main
L/G	1.1	1.1
Wet temperature	12°C	12°C
System volume	1 m^3	1000 m^3
Working circulation flow	2 m^3/hr	750 m^3/hr
Cooling water return temp	42°C	42°C
Cooling water supply temp	27°C	27°C
Tower material	Wooden structure	Wooden structure
Pacing	Turbo splash	Turbo splash
Pipes and exchangers	CS and SS	CS and SS

3. Methodologies

A schematic of the pilot cooling tower is given in Fig. 1. The pilot cooling tower is shown in Fig. 2(a). Also, the ozone generator is shown in Fig. 2(b). In this pilot plant, a permanent work type ozone generator and silent corona discharge were used.

During ozone treatment, the concentration of the ozone diffused into cooling basin was 1.5 to 2 mg/lit, and the concentration of the ozone in cooling water supply was between 0.05 to 0.15 mg/lit. Ozone concentration was analyzed three times per week, using standard method No. 4500-O_3-B (Eatom 1995). In conventional treatments, concentration of the free chlorine is ranged from 0.3 to 0.6 mg/lit according to the standard method No. 4500-CL-G- DPD (Eatom 1995, Cortinovis *et al*. 2009). Also, ozone concentration was continually and indirectly analyzed by ORP analyzer, and the amount of ORP was shown on HMI. Residual ozone concentration should be controlled to be remained between 0.05 to 0.15 mg/lit (500-600 mv).

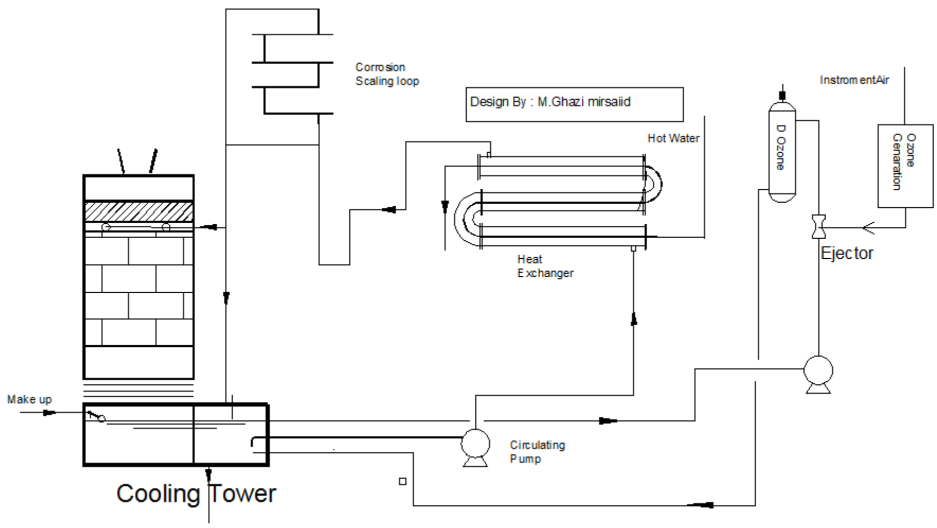

Fig. 1 Block diagram for the ozone treatment pilot plant


(a) The cooling tower pilot plant


(b) Ozone-generator package

Fig. 2 Pilot plant

Indirect ozone measurement can be conducted by using of ORP method which has already been practiced. In this invention, instrument control equipment and some other facilities could improve the monitoring process. Also, a more logical connection was developed between ORP amount and remained ozone. This invention has been recorded in Iran Patent Office as “A continues and remote controlled process for Ozone measurement in cooling towers, A novel approach based on ORP method”, at No. 83863, 2014 (Ghazi and Ataei 2014b, Heidarinejad *et al*. 2009).

In this pilot plant, a double pipe heat exchanger was used. Single phase hot water (DM water) with 80℃ temperature entered the internal pipe of the exchanger which was made of SS-304 and would leave after exchanging heat. The cooling water with a temperature of 26℃ entered the exchanger shell which was made of steel carbon.

3.1 Pilot cooling tower tests

Pilot cooling tower tests has been done in two stages. In stage one (45 days), the conventional treatment was tested while in stage two (45days), the ozonation treatment was tested.

In this pilot plant, microbial and chemical tests were carried out based on the microbial and chemical tests done in main cooling towers. Due to the corrosion stress made by chloride, the amount of chloride in circulation water should not be more than 50 mg/lit. The chemical analysis of circulating cooling water was performed two times a day. Also, TBC, SRB, and COD tests have been done three times a week. The average values are shown in Table 2. The temperature, flow rate and some chemical parameters are shown on HMI. The chemical and microbial qualities of make-up water were measured at the beginning of each period. The average values are shown in Table 2.

3.2 Corrosion and sedimentation

Carbon steel and stainless steel coupons were used for corrosion and sedimentation control, respectively. Coupons were placed via a device in accordance with ASTM D2688-05. In this study, corrosion rate was measured by means of coupon placement test through a long-term period (45 days) and a daily measurement procedure via the Corrater device (Model: 9000 plus) (Historical Standard 1983). Table 3 shows specifications of coupons. Allowed corrosion rate has great significance (See Table 4). Then Langelier Saturation Index (LSI) was calculated with respect to the obtained water chemical parameters every day.

Table 2 Chemical and microbial results of make-up water and circulation water in the two treatment methods

Parameter	Unit	Make up	Injecting ozone	Injecting chlorine
pH	-		8.65	8.7
Conductivity	μs/cm	7.76	1250	1100
Total hardness	mg/lit as $CaCO_3$	510	470	459
Calcium hardness	mg/lit as $CaCO_3$	192	248	241
Mg hardness	mg/lit as $CaCO_3$	107	222	218
Total phosphate	mg/lit as phosphate	165	3.5	7.5
Silica	mg/lit as Silica	14.0	40	30
Chloride	mg/lit as chloride	20	44	51
Sulfate	mg/lit as Sulfate	64	165	134
Turbidity	mg/lit	Trace	0.7	2.9
Total Fe	mg/lit	0.07	0.05	0.4
SRB	CFU/mL	0	0	0
TBC	CFU/mL	< 10	< 100	< 1000
Free CL_2	mg/lit	0	0	0.5
O_3	mg/lit	0	0.1	0
LSI	-	-	2.0	2.0

Table 3 Specifications of the applied coupons

Coupon type	Surface area (in^2)	Surface area (cm^2)
Bar-shape 3×0.5×1/16 in. (76×12.7×1.6 mm)	3.38	22.0
Metallurgies	Density ($g.cm^3$)	
Mild Steel (C1010)	7.86	
Stainless Steel (316)	7.98	

Table 4 The allowed corrosion rate of carbon steel (Boffardi 1995, Kern 1950)

Corrosion rate (mpy)	
Carbon steel	Description
< 1	Excellent
1 to 3	Very good
3 to 5	Good
5 to 8	Fair
8 to 10	Poor
> 10	Severe

3.3 The comparison of organic contamination

Large amount of COD in blow-down is due to the consumption of chemical inhibitors, especially anti-scaling ones. The amount of organic materials was analyzed three days a week. The evaluation of COD carried out by using of colorimetric based on the standard method No. 5000, 5220, 5-18-D (Eatom 2005).

3.4 The comparison of chemical compatibility

Does using ozone and chlorine as oxidizers in an injected concentration, lead to decomposition of chemical inhibitors and affect their performance? To address this question, in this study, anti-corrosion and anti-scaling chemical inhibitors were based on phosphate and all organic types. Samples of anti-corrosion and anti-scaling inhibitors were taken out of the barrel and were diluted as much as the water in cooling tower. During the ozonation and chlorination processes, cooling circulation water samples of the tower were extracted several times. Orthophosphate and polyphosphate amounts of the samples were measured. All has been done using standard method No. 4500-P-E (Ponce-Ortega *et al*. 2010, Eatom 1995).

3.5 The comparison of turbidity.

In this study, water turbidity value was analyzed in ozonation and chlorination treatments. These measurements were done using a spectrophotometric method based on standard method No. 2000, 2130-2-8 (Eatom 1995).

3.6 The comparison of soluble iron

Ozone and chlorine with oxidizing features could change soluble Ferro (Fe) to non-soluble Fe. The amount of Fe was measured using standard method No. 3000, 35000-Fe, and 3-77 (Eatom 1995, Rubio-Castro *et al*. 2013).

3.7 The comparison of the cycle of concentration

The cycle of concentration (π_c) is defined as the concentration ratio of a soluble component in the blow-down stream to that of make-up stream (Eq. (1)) (Heikkila and Milosavljevic 2001, Rao and Patel 2011).

$$\pi_c = \frac{X_B}{X_M} \tag{1}$$

$$\frac{X_B}{X_M} = \frac{M}{(B + D)} \tag{2}$$

Silica was considered as the index of the cycle of concentration. Silica concentration in blow-down water divided by the silica concentration in make-up water equals cycle of concentration.

3.8 The Ozone and Chlorine Disinfections

In main cooling towers, only SRB and TBC tests are conducted. Initially, the numbers of TBC and SRB were calculated according to ASTM D5465 and D4412, respectively. Total Bactria Content (TBC) was measured three days a week (ASTM International 2012). Number of SRB was measured two days a month. Culture medium was prepared for SRB microbial test, and incubated at 20℃ for 21 days. In main cooling tower, only absence or presence of SRB is important in disinfection time. Counting the number of SRB is not very common in such projects (ASTM International 2009, Jonnalagadda and Nadupalli 2014).

3.9 The comparison of saved energy

Cooling tower water must be treated to limit the growth of mineral and microbial deposits that can reduce the heat transfer efficiency of the cooling tower (U.S. Department of Energy 1995).

In this study, the efficiency of double pipe exchangers was studied through a 45-days period. The energy can be determined using Eq. (3)

$$Q = m_c C_c \Delta T_c = m_h C_h \Delta T_h = UA.LMTD \tag{3}$$

One of the factors that affect the quantity of exchanged energy is the amount of deposited bio-film on inner and outer surface of the tube. That alters the amount of U (heat transfer coefficient) and thus the Q value. The impact of these parameters on the ozonation and chlorination methods was evaluated during the experiments. At this point, by changing the exchanger input temperature and flow rate, the effects of ozone and chlorine on the performance of heat exchangers were calculated (Kern 1950, Putois *et al*. 2014).

3.10 Comparison of consumed and costs

The amounts of chemical inhibitors, energy, and water were measured in pilot cooling tower for both ozonation and chlorination methods. The changes were scaled up and applied in the main cooling tower.

Following symbols describe the chemicals used in the cooling tower:

X_1 = It is a synergistic blend of both organic and inorganic phosphate and polymers which is designed to inhibit corrosion and scale as well.

X_2 = It incorporates a polymeric factor that uses calcium phosphate scale inhibitor and permit proper phosphate concentration for corrosion inhibition of mild steel.

X_3 = It stands for a very effective biocide based on a blend of isothiazolin compounds.

X_4 = It is an aldehyde based biocide with wide spectrum bacterial properties**.**

X_5 = It shows a blend of non-ionic ingredients that were used to remove bio-films in industrial water systems.

Calcium hypochlorite = Calcium hypo chlorite is an oxidizing disinfectant.

4. Result and discussion

4.1 Corrosion result

4.1.1 Via a Corrater device

Uniform corrosion diagrams are plotted in two ways via a Corrater device in Fig. 3. Pitting corrosion diagrams are also drawn in two ways via a Corrater device (See Fig. 4).

4.1.2 Via corrosion coupons

Corrosion rates obtained from coupons tests (Gravity test), (See Table 5). Uniform corrosion rate was acquired based on standard method of weight loss, using Eq. (4) (Boffardi 1995, Tijing *et al*. 2010).

$$CR = \frac{W}{(A \times t \times d)} \times K \tag{4}$$

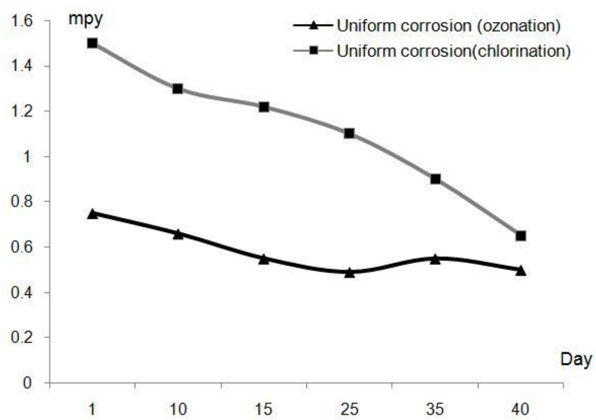

Fig. 3 Uniform corrosion plot in the two treatment methods

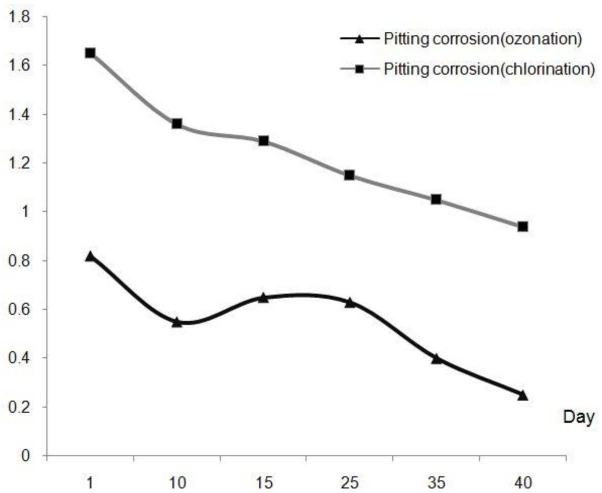

Fig. 4 Pitting corrosion plot in the two treatment methods

Table 5 The corrosion and sedimentation rates by days

	Chlorination	Ozone disinfection
Average weight loss of carbon steel coupons	54 mg	30 mg
Average weight increase of stainless steel coupons	15mg	16 mg

Corrosion rate: calculations for carbon steel during ozone:

$$CR = \frac{W}{(A \times t \times d)} \times K \frac{30}{3.38 \times 45 \times 7.86} \times 22.27 = 0.465 \text{ mpy} = 0.012 \text{ mm/y}$$

Calculations for carbon steel during chlorination:

$$CR = \frac{W}{(A \times t \times d)} \times K \frac{54}{3.38 \times 45 \times 7.86} \times 22.27 = 1.006 \text{ mpy} = 0.025 \text{ mm/y}$$

4.1.3 Via a lingerie index

The corrosion rate was mostly controlled by putting the chemical state of water in a relatively sedimentation situation (Lingerie index was 1.9 to 2.3). By regulating the amount of blow-down water and water PH, we could have LSL value in an appropriate range (See Table 2).

4.2 Sedimentation results and comparison

In general, no difference was observed in sedimentation on stainless steel for both cases (See Table 5).This issue has also been proved by coupon weighing and chemical results. This was done by inspecting inside of tubes and coupon surface. In the ozonation method, in order to control the sediment, the actual ratio of anti-corrosive to anti-sedimentation inhibitors should be 3 to 1, while it was between 2 to 1.

4.3 Organic contamination rate in cooling tower

The amount of COD of blow-down water in the ozonation method reached to one sixth of its value in chlorination, (See Fig. 5).

In conventional method, due to discharge of chemical organic inhibitor and stability of biocide material, we would face much more environmental problems than ozonation method.

Decline in COD is observed because of the following reasons:

(1) Since the oxidizing capability of ozone is higher than chlorine, larger amount of decomposable organic materials in water is decomposed.
(2) Ozone has greater capability to eliminate bio-film and microbial materials in the cooling water compared to chlorine.
(3) The amount of turbidity in the ozonation method is decreased more than in chlorination.
(4) And finally, the main reason is that the amount of decreasing or eliminating organic chemicals in ozonation is higher compared to that in chlorination.

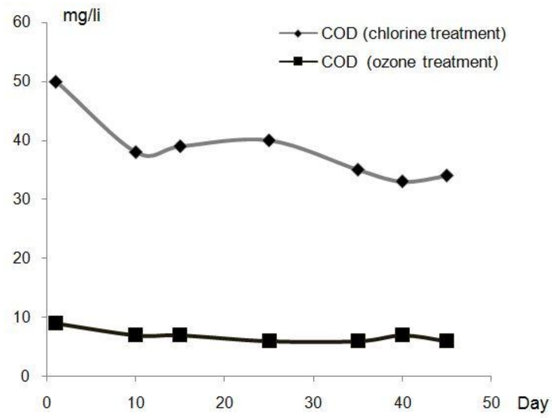

Fig. 5 Compare the amount of COD in the two treatment methods

4.4 Compatibility of chlorine and ozone with other chemical inhibitors

If the total phosphate is decomposed by ozone or chlorine, the ratio of total phosphate to Ortho-phosphate will be smaller (See Eqs. (5) to (7)).

Ratio of phosphate types:

$$\text{Inside the barrel} = \frac{\text{total phosphate}}{\text{orthophosphate}} = \frac{990\ \text{ppm}}{660\ \text{pp}} = 1.50 \tag{5}$$

$$\text{Inside the cooling water (chlorination method)} = \frac{7.5\ \text{ppm}}{4.9\ \text{ppm}} = 1.53 \tag{6}$$

$$\text{Inside the cooling water} \qquad \text{(ozonation method)} = \frac{3.5\ \text{ppm}}{2.4\ \text{ppm}} = 1.46 \tag{7}$$

Based on the above Equations, the proportion of total phosphate to orthophosphate in the sample taken from the barrel is the same as that in the sample of circulation cooling water.

4.5 Impact of ozone on the turbidity of cooling water

When ozonation method is used in the research pilot, the average value of turbidity was about 0.7 NTU; while it reached to 2.5 NTU, during chlorination treatment. Since ozone is a stronger oxidizer rather than chlorine, it could eliminate bio-films and biological mass easily and oxidize several organic material and by-products (See Fig. 6).

4.6 Impact of ozone on the amount of soluble Fe

The average amount of soluble Fe in ozonation treatment and chlorination method was 0.01-0.07 and 0.2-0.4 mg/lit, respectively. Therefore, a decreasing rate of 97.5 percent in the amount of Fe is observed in ozonation method compared to chlorination method. The trends of changes in the amount of Fe in two periods are demonstrated in Fig. 7.

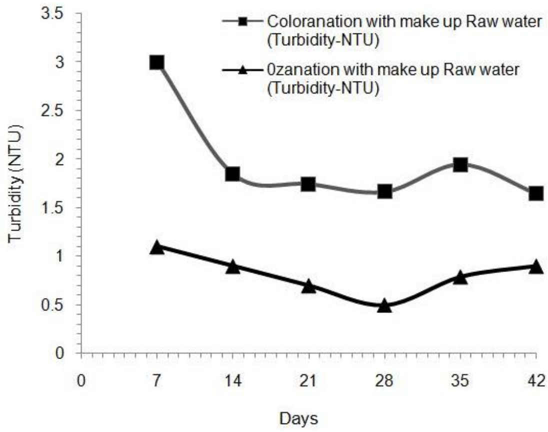

Fig. 6 Turbidity plot in the two treatment methods

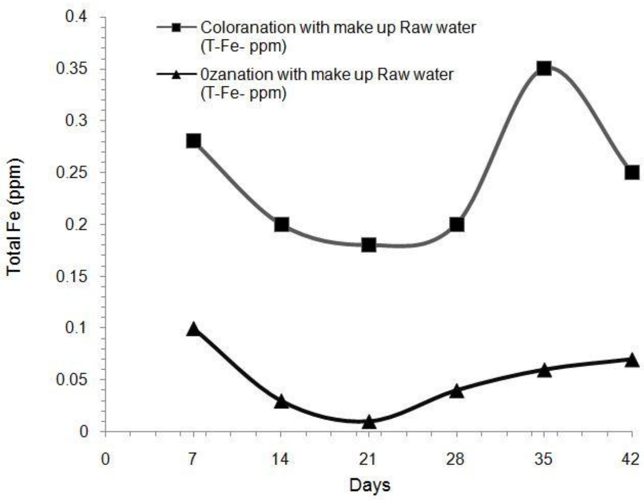

Fig. 7 Soluble Fe plot in the two treatment methods

4.7 Increasing cycle of concentration and decreasing make-up water consumption

Silica is considered as the index of the concentration cycle (See Eq. (8)).

$$\pi_c = \frac{\text{Silica concentration in Blowdown water}}{\text{Silica concentration in make} - \text{up water}} \tag{8}$$

Cycle of concentration:
Conventional method = 30 ppm / 14 ppm = 2.1
Ozone method = 40 ppm / 14 ppm = 2.8
Cycle of concentration declined to 33%. Measuring blow-down and water consumption in new method of ozonation decreased by 26%.

4.8 Microbial testing results

Number of TBC was 10^4 CFU/ml before disinfection. Average TBC was 900 CFU/ml in disinfection time, while chlorine concentration was 0.5 mg/lit. Average TBC was 200 CFU/ml in disinfection time while ozone concentration was 0.1 mg/lit.

According to the standard method No.D-5465, numbers of bacteria in cooling towers water have to be less than 10^3 CFU/ml; thus, it may be concluded that conditions in both cases were acceptable. However, disinfection capability of ozone was revealed.SRB test was conducted at the time when no disinfectant was injected into the system. The results of the test were positive. In free chlorine concentration condition, SRB test was less than 0.2 mg/lit which meant it was positive. When ozone concentration was about 0.05 to 0.15 mg/lit and free chlorine concentration was between 0.3to 0.6 mg/lit, SRB test was negative.

4.9 Calculation of energy saved

In order to compare the heat efficiency in two conventional and ozonation methods, the flow rate and temperature of the circulation water in the cooling tower were adjusted. Therefore, water condition remained constant during heating process in the double pipe heat exchanger. If the temperature of the hot water was constant, then we could measure the change in the flow rate of hot water in double pipe heat exchanger.

The two methods have been compared using heat transfer equation in heat exchanger ($Q=mc\Delta T$) (See Table 6).

(a) In ozonation method:

- At the begging of the operation:

$\dot{m}_{(\text{hot water})} = 0.36$ kg/s

- At the end of the operation:

$\dot{m}_{(\text{hot water})} = 0.35$ kg/s

$$Q = 0.35\text{kg/s} \times 4.18j/\text{kg℃} \times (85 - 65\text{℃}) = 29.3\ \text{W} \tag{9}$$

(b) In chlorination method

$\dot{m}_{(\text{hot water})} = 0.36$ kg/s

- At the end of the operation
- At the begging of the operation

$\dot{m}_{(\text{hot water})} = 0.31$ kg/s

$$Q = 0.31\text{kg/s} \times 4.18j/\text{kg℃} \times (85 - 65\text{℃}) = 25.9\ \text{W} \tag{10}$$

Table 6 Comparing ozonation and chlorination methods based on the heat transfer

Ozonation method		Chlorination method		
Hot water	Cooling water	Hot water	Cooling water	Unit
$Th_{in} = 85$	$Tc_{in} = 26$	$Th_{in} = 85$	$Tc_{in} = 26$	℃
$Th_{out} = 65$	$Tc_{out} = 43$	$Th_{out} = 65$	$Tc_{out} = 43$	℃
$Flow_{(first)} = 0.36$	$Flow_{(first)} = 0.55$	Flow = 0.36	Flow = 0.55	kg/s
$Flow_{(final)} = 0.35$	$Flow_{(final)} = 0.55$	Flow = 0.31	Flow = 0.55	kg/s

Table 7 Monthly consumption and cost of the designed cooling tower

Consumption	Unit	Monthly Consumption		Consumption	Cost ($/yr)	
		Conventional	Ozonation		Conventional	Ozonation
X_1 (0.1 scale)	kg	93	37	X_1*0.1	4821	1918
X_2 (0.1 scale)	kg	40	16	X_2*0.1	1843	737
X_3	kg	90	0	X_3*0.2	726	0
X_4	kg	50	0	X_4*0.2	691	0
X_5	kg	160	0	X_5*0.2	1106	0
H2SO4 (0.1 scale)	lit	76	85	H2SO4*0.5	730	510
Ca (CLO_2)	kg	95	0	Ca(CLO)2*0.5	642	0
Raw water (0.01 scale)	m^3	216	159	Raw water*0.1	959.4	706
Energy(0.001 scale)	kJ	196	189	Energy*0.1	3536.4	3402

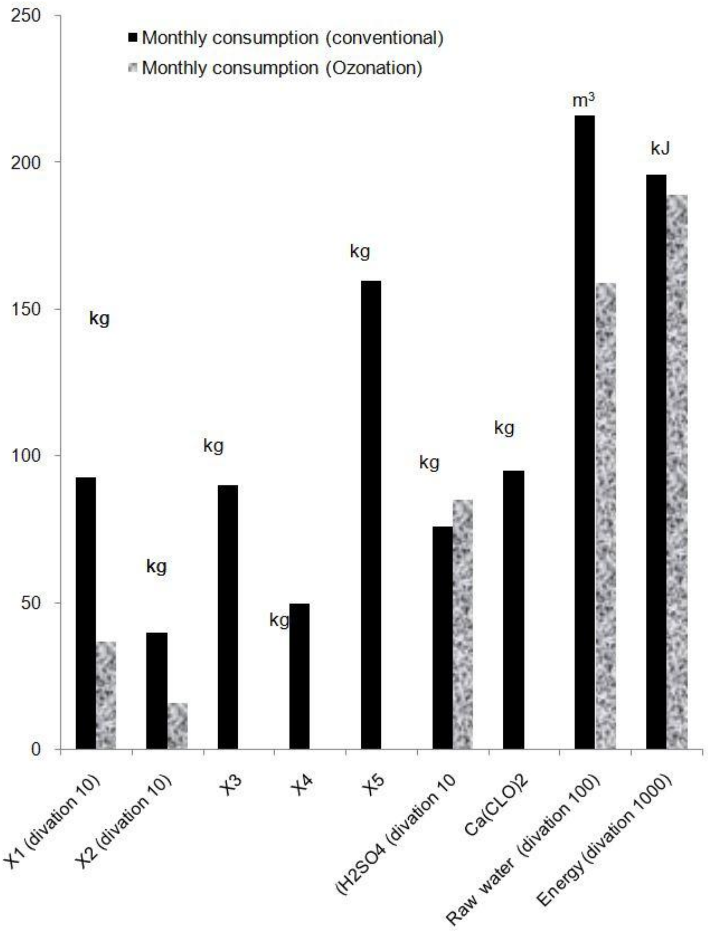

Fig. 8 Monthly consumption in the two treatment methods

By comparing the two methods and considering the Eqs. (10) and (11), it is concluded that the energy efficiency in ozonation method, increased by 11.6% due to the reduction of fouling and turbidity. It should be noted that in ozonation method, the efficiency of the bio-films layer reduction is practically higher than that of chlorination method.

4.10 Comparing two methods in terms of consumptions and economic costs.

The features of main cooling tower are shown in Table 1. For both ozonation and chlorination methods, the amounts of chemical inhibitors, energy, and water were measured in pilot cooling tower. The changes were scaled up and applied in the main cooling tower.

Table 7 and Figs. 8 and 9 present monthly consumption of water, energy and chemicals in the main tower with calculation of annual costs (US$) in both chlorination and ozonation methods.

The lower corrosion rate in ozone disinfection in comparison with chlorination method, and the reduction of inhibitors and other chemicals will be explained as follows:

(1) Both ozone and chlorine are known as powerful oxidizers which can cause destruction of a passive layer. The concentration ratio of ozone with respect to chlorine is 0.1. Also, ozone and chlorine residence time is 20 minutes and 6 hours, respectively. Therefore, ozone is more powerful than chlorine while it is more harmless indeed. Hence, uniform and pit corrosion rate of ozone disinfection are much less than chlorine.
(2) Amount of inhibitors usage, may be reduced due to decrease in corrosion. However, they cannot be eliminated to zero, due to the presence of other corrosive factors like oxygen.
(3) In order to remove bio-film bulks in chlorine method, it should be injected with the concentration of 5 mg/lit along with bio-dispersants chemicals to disperse biological and bio-film bulks. Meanwhile, the dosage of bio-dispersants used in ozonation treatment,

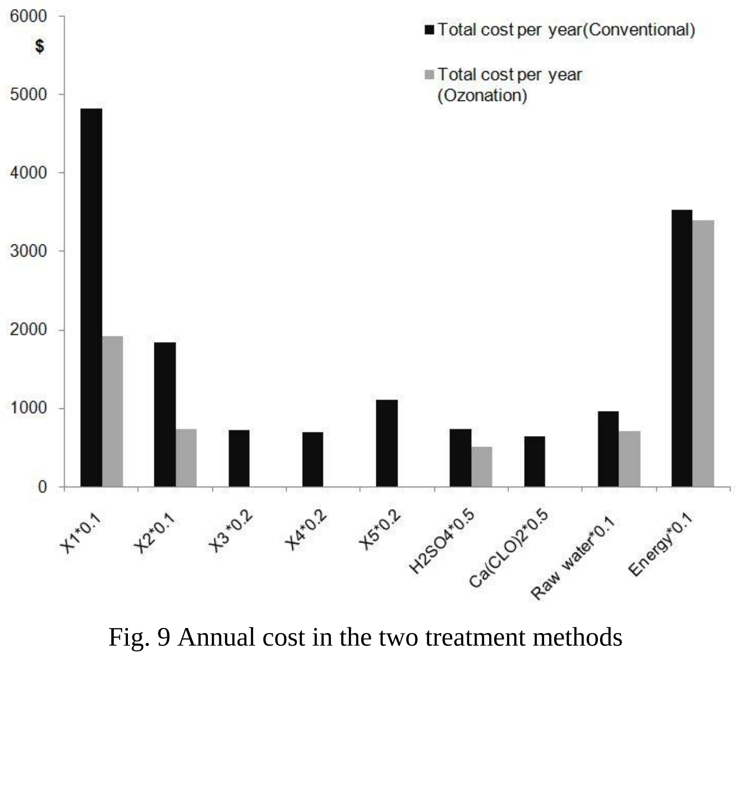

Fig. 9 Annual cost in the two treatment methods

could be eliminated or reduced down to 2 mg/lit.

(4) Non-oxidizing biocides could not be used in the ozonation treatment, since ozonation method is much more powerful than chlorination.

(5) Most inhibitors demonstrate high acidic property except solid chlorine. Therefore, PH increases during ozone disinfection while decreasing the inhibitors usage.

4.11 Economical calculation of the project for the main cooling towers

Based on Table 7 and Figs. 8 and 9, the following calculation is done.

- The total current expense in the conventional method is $ 126,953.
- The total current expense in the ozonation treatment is $ 68,649.
- The difference between the two methods is $ 58,304.
- Ozone generator capacity is: 1 kg/hr
- Generator cost is $ 150,000
- The calculating capital return
- 150,000 / 58,304 = 2.57yr

Since it takes 2.57 years for the capital to return, the project considered economical.

5. Conclusions

Ozone has been used to purify water since the late 19th century, but Ozone cooling water treatment systems are state-of-the-art ways to purify the recirculating cooling water for energy conservation. It this study, Ozone cooling water treatment was investigated and the results were compared to conventional methods for open cooling water treatment. The unique features of Ozone which make it a good alternative in our study are as follows:

(1) High disinfecting capability
(2) High toxicity when used for circulation water treatment
(3) Non-toxicity in blow-down water, making it environmentally friendly.
(4) Lower dosage of injection compared to chlorine
(5) Moderate passivation of carbon steel.
(6) Stronger oxidizing features

Considering features which are mentioned above, the following consequences were drawn in this study:

(a) Dramatic reduction of organic contamination load in blow-down water
(b) Reduction in the consumption of make-up water
(c) Dramatic reduction of soluble Fe and turbidity in circulation cooling tower
(d) The compatibility of the ozone and chlorine in proper concentrations, with chemical inhibitors of circulation water
(e) Elimination of some chemical inhibitors and reduction of some others
(f) Dramatic reduction of TBC and full elimination of SRB
(g) A more moderated passive behavior of corrosion resistance seems to be seen in ozonation treatment, taking to account the decrease in corrosion
(h) In this work, the time of capital return is less than three years.

Based on the results of this study, it was concluded that pure ozone cannot be used for cooling water treatment. Therefore, it is recommended to combine it with some other chemical inhibitors.

The moderate passive mechanism in ozonation, the effect of ozone and its compatibility with various conventional inhibitors, will be studied deeply in our future studies.

References

Alawadhi, E.M. (2011), "Cooling process of water in a horizontal circular enclosure subjected to non-uniform boundary conditions", *Energy*, **36**(1), 586-594.

Al-Bassam, E. and Maheshwari, G.P. (2011), "A new scheme for cooling tower water conservation in arid-zone countries", *Energy*, **36**(7), 3985-3991.

ASTM D4412-84 (2009), Standard Test Methods for Sulfate-Reducing Bacteria in Water and Water-Formed Deposits; ASTM International, West Conshohocken, PA, USA. www.astm.org

ASTM D5465-93 (2012), Standard Practice for Determining Microbial Colony Counts from Waters Analyzed by Plating Methods; ASTM International, West Conshohocken, PA, USA. www.astm.org

Ataei, A. (2008), "Combined pinch analysis for process industries", Ph.D. Thesis; Science and Research Branch, Islamic Azad University, Tehran, Iran.

Ataei, A., Panjeshahi, M.H., Parand, R. and Tahouni, N. (2009), "Application of an optimum design water system by regeneration concept and pinch technology for water and energy conservation", *J. Appl. Sci.*, **9**, 1847-1858.

Ataei, A., Gharaie, M., Parand, R. and Panjeshahi, E. (2010), "Application of ozone treatment and pinch technology in cooling water systems design for water and energy conservation", *Int. J. Energ. Res.*, **34**, 494-506.

Boffardi, B.P. (1995), "Water treatments in corrosion tests and standards – Application and interpretation", American Society for Testing and Materials; Philadelphia, PA, USA, 699 p.

Conner, A. (2005), "Reducing cooling towers cost with the ozone technology", Clean Water Ozone Systems Inc.

Cortinovis, G.F., Paiva, J.L., Song, T.W. and Pinto, J.M. (2009), "A systemic approach for optimal cooling tower operation", *Energ. Convers. Manage.*, **50**(9), 2200-2209.

Eatom, A.D. (1995), Standard methods for the examination of water and wastewater.

Eatom, A.D. (2005), Standard methods for the examination of water and wastewater.

Gaylarde, C.C. and Videla, H.A. (1992), "Biocide action on metal bio films", *Proceedings of the Pan-American Congress on Corrosion and Protection*, NACE International; Mar del Plata, Argentina, Houston, TX, USA, pp. 371-378.

Ghazi, M. and Ataei, A. (2014a), "A new design for an automatic wet cooling tower with remote controlled capability", Iranian Patent No. 84442.

Ghazi, M. and Ataei, A. (2014b), "Continues and remote controlled process for Ozone measurement in cooling towers: A novel approach based on ORP method", Iranian Patent No. 83863.

Hertrampf, J. (1998), *Cooling Water Treatment by a Combination of Ozone and Chemicals*, GmbH Krefeld, Germany.

Heidarinejad, G., Karami, M. and Delfani, S. (2009), "Numerical simulation of counter-flow wet-cooling towers", *Int. J. Refrig.*, **32**(5), 996-1002.

Heikkila, P. and Milosavljevic, N. (2001), "A comprehensive approach to cooling tower design", *Appl. Therm. Eng.*, **21**(9), 899-915.

Historical Standard (1983), ASTM D2688-05 Standard Test Methods for Corrosively of Water in the Absence of Heat Transfer (Weight Loss Methods), Annual Book of ASTM Standards; D2688-05; Volume 03.01, PA, USA.

Jonnalagadda, S.B. and Nadupalli, S. (2014), "Chlorine dioxide for bleaching, industrial applications and water treatment", *Indian Chem. Eng.*, **56**(2), 123-136.

Kern, D.Q. (1950), *Process Heat Transfer*: *Heat Exchanger Design*, New York, NY, USA.

Panjeshahi, M.H., Ataei, A., Gharaie, M. and Parand, R. (2009), "Optimum design of cooling water systems for energy and water conservation", *Chem*. *Eng*. *Res*. *Des*., **87**, 200-209.

Ponce-Ortega, J.M., Serna-González, M. and Jiménez-Gutiérrez, A. (2010), "Optimization model for re-circulating cooling water systems", *Comput*. *Chem*. *Eng*., **34**(2), 177-195.

Putois, T., Guittonneau, S., Chaabna, Z., Viboud, S., Zydowicz, P., Bayle, X. and Fontvieille, D. (2014), "Advanced oxidation processes for disinfection treatment of cooling waters", *Ozone-Sci*. *Eng*., **36**(5), 440-450.

Rao, R.V. and Patel, V.K. (2011), "Optimization of mechanical draft counter flow wet-cooling tower using artificial bee colony algorithm", *Energ*. *Convers*. *Manage*., 52(7), 2611-2622.

Rubio-Castro, E., Serna-González, M., Ponce-Ortega, J.M. and El-Halwagi, M.M. (2013), "Synthesis of cooling water systems with multiple cooling towers", *Appl*. *Therm*. *Eng*., **50**(1), 957-974.

Serna-González, M., Ponce-Ortega, J.M. and Jiménez-Gutiérrez, A. (2010), "MINLP optimization of mechanical draft counter flow wet-cooling towers", *Chem*. *Eng*. *Res*. *Des*., **88**(5), 614-625.

Strittmatter, R., Yang, B. and Johnson, D.A. (2003), *Application of Ozone in Cooling Water Systems*, Nalco Chemistry.

Tijing, L.D., Kim, H.Y., Lee, D.H., Kim, C.S. and Cho, Y.I. (2010), "Physical water treatment using RF electric fields for the mitigation of $CaCO_3$ fouling in cooling water", *Int*. *J*. *Heat Mass Tran*., **53**(7), 1426-1437.

Viera, M.R., Guiamet, P.S., de Melle, M.F.L. and Videla, H.A. (2000), "Use of dissolved ozone for controlling plank tonic and sessile bacteria in industrial cooling systems", *Int*. *Biodeter*. *Biodeg*., **44**(4), 201-207.

U.S. Department of Energy (The Pacific National Laboratory) (1995), Ozone treatment for cooling tower.

WL

Nomenclature

Parameters	Description	Unit
A	Surface	cm^2
	Area of heat	m^2
B	Blow-down water	m^3/hr
C	Specific heat of water	J/kg. ℃
CFU	Colony Formation Unit	CFU/ml
COD	Chemical Oxygen Demand	mg/lit
CR	Corrosion Rate (by weight loss)	mm/yr
d	Density	gr/cm^3
DM	Dematerialized Water	-
HMI	Human Machine Interface	-
IP	Ingress Protection	-
K	Constant value (depending on measurement unit)	-
L/G	Liquid/Gas	-
LPR	Linear Polarization Resistance	-
M	Make up water	m^3/hr
m	Mass flow rate	kg/s
mpy	Corrosion Unit	min/yr
NTU	Nephlometric Turbidity Unit	-
ORP	Oxidation Reduction Potential	mv
Q	Heat transfer	J/s
SBR	Sulphate Reduction Bacteria	-
t	Time	yr
TBC	Total Bacterial Content	CFU/ml
T_{in}	Cooling tower inlet water temperature	℃
T_{out}	Cooling tower outlet water temperature	℃
T	Temperature difference	℃
U	Overall heat transfer coefficient	$J/m^2.s.$℃
W	Weight loss (after cleaning)	g
X_M	Concentration of a soluble component in make-up water	mg/lit
X_B	Concentration of a soluble component in blow-down	mg/lit

Greek letters	Description
π_c	Cycle of concentration