Energy and Water Conservation in Tap Water Distillation Units

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Abstract

In this study pilot-scale tap water distillation unit has been constructed and operated. The special feature of this unit is its ability to save tap water used to condense steam produced in tap water distillation units. Prior to our work hot tap water was conventionally being rejected to the drain. That resulted the waste of tap water as well as heat load on the distillers. In our approach we have made a provision of recycling part of the tap water back to the boiler and part of it to the air cooling tower where it exchanges heat with the atmospheric air. The cooler tap water is then returned to the boiler. Our approach has resulted in the significant savings of tap water as well as decreased heat demand in the boilers. It is estimated that about 650 kg of tap water saved per 30 kg of steam produced. By adopting our approach distilleries around the world which produce steam for distilled water as well as for extracting essential oils and perfumes from herbs/plants can become more economical and conserve significant amount of tap water especially arid countries like Saudi Arabia where water is considered a very valuable resource.

Keywords: Distilled Water, Pilot Plant, Tap Water, Steam Production

1. Introduction

Steam production is an essential process to produce distilled water as well as to extract essential oils and perfumes (Lis-Balchin, 2006). With continuous increase in world's population the use of distilled water and hence the number of steam distillation units have been increasing steadily. According to one report the purified water industry is expected to reach US$ 334 billion by 2023 in USA, (Wood L., 2018). A number of uses of distilled water are given in the **Table 1**.

Table 1. Distilled Water Usage*

Industry	Uses
Medical	First Aid, Dental, Wounds cleaning, Sterilization, Patient's Food
Automobile	Cleaning metal components, recharging of lead batteries
Laboratories	Chemical and Biological Experiments
Humidifiers	To prevent bacterial growth and mineral deposition
Cosmetics	Shampoos, conditioners, and lotions
Cleaning	To prevent any trace on doors and windows
Tea and Coffee	1/3rd less tea or coffee is consumed when boiled in distilled water
Cooking	Boiled vegetables and eggs, baking cookies and cakes.
Soap Manufacture	To combat dirt, toxins and other chemicals come with tap water
*More uses can be found in the literature	

Distilled water can be produced through various methods like ion exchange, membrane filtration, sedimentation, coagulation, adsorption (Jennifer and Trevor, 2010; Abdulkarim et al., 2010; Ochowiak, 2007) etc. Distillation is mostly preferred when tap or salted water is to be purified. This is because the relative volatilities of tap water constituents differ widely so the separation by boiling is relatively quite easy (Jinhui, 2008).
In general, steam produced by boiling tap water is condensed by a separate cooling water stream in a condenser. Cooling water is then rejected to drain at high temperature around 50^{o}C. The requirement of this coolant is almost 50

~ 60 liters per one liter of distilled water produced. Usually, distillation units reject coolant water at higher temperature than the temperature of the distilling tap water. Therefore, both loss of mass and heat make these units uneconomical and more so in arid countries like Saudi Arabia where water is a precious commodity. Glass water distiller, Quartz water distiller and Quartz double distillation unit by Bionics Scientific Technologies (P). Ltd, Wall mounted distillation unit by Stericox sterilizer systems India, Water Stills, Bamstead water purification systems, by ThermoFisher scientific, and several models of Goel Scientific Glass Works Ltd., SDU20, SDU50, SDU100, SDU200 and SDU300, are all working in the same principal, where hot water line from the jacket of the condenser is sent as a reject line.

In the present work, an attempt is made to reconsider the design of such a distillation unit at the pilot level. To reduce the loss of hot water a provision of cooling water circulation cycle is introduced. To achieve this, a direct contact cooling tower is added to the system to cool down the exiting hot tap water from the condenser. The cooled water output from cooling tower drum stream is mixed with a makeup potable water line and then recycled to the heat exchanger condenser unit as coolant. Thus overall intake of tap water is significantly reduced. To the best of our knowledge, this new design approach is an efficient, cost effective and feasible method for the distillation of tap water. However, the unit's operation is diverse and can be used to purify any source of contaminated water with a maximum distilled water output value of 30 liters/hr.

Apart from the production of distilled water our approach is equally beneficial to those who use low pressure steam to extract essential oils, produce perfumes and flavored water drinks (Beis, et al., 2000; Masango, , 2005; Usman et al., 2013; Maleky-dozzadeh, 2013; Danlami, 2014; Soto-Armenta, 2017). This is because our method of steam production with internal water circulation reduces the load on the boiler and saves significant amount of tap water from being wasted. Using our method laboratories and pilot plants around the world can contribute to appreciable water conservation and entropy minimization.

Figure 1. Pilot Plant Water Distillation Unit with Internal Circulation Line at our facility

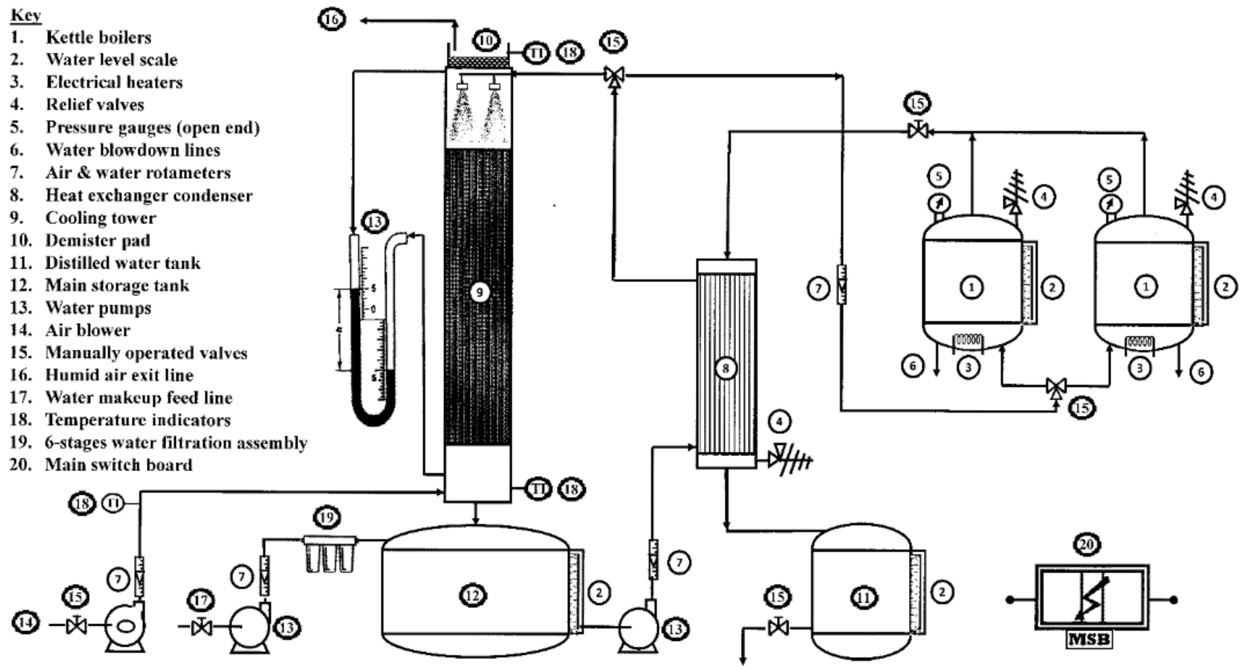

Figure 2. A schematic of tap water distillation unit

2 Experimental section: unit description, design details and installation

In the light of the above conceptual design, calculations were carried out and the pilot-plant was installed, assembled and fully operated as shown in real and schematically in **Figure 1 and Figure 2,** respectively.
It consists of two boilers with an internal diameter of 30 cm and height of 50 cm. The two units are equipped with pressure gauges, relief valves, four electrical heaters of 10 kW ach and inlet and outlet blow down valves. Water vapor flows from two boilers to a counter current vertical type heat exchanger condenser, where water vapors are cooled by water from a storage tank located under a cooling tower. The condensed vapors (distilled water) are collected in the product storage tank. Hot water line coming out of the jacket of the condenser is divided into two lines. One flows to the boilers to compensate the water evaporated and the other line flows to the cooling tower, where the hot water from the jacket of the condenser heat exchanger is cooled down by direct contact with ambient air using an air blower (Taiwan Jouning SIROCCO FAN JSD-90L industrial Blower and ventilation fan). Table 2 summarizes the operating conditions for the cooling tower.

Cold water flowing down through the cooling tower is collected in a storage tank where it is recycled to the heat exchanger condenser. A make-up line is fed to the storage tank under the cooling tower to compensate losses of water from the whole system. Water in the whole plant decreases continuously as part of it goes as distilled water product and another part of water humidifies the air stream coming out from the cooling tower. The boilers, the condenser heat exchangers and all pipelines, elbows and joints are made of high grade stainless steel due to its excellent chemical and physical properties.

For insulation we have used AFICO Pre-Engineered Metal Building Insulation (PEBI) that is a lightweight, highly efficient, flexible, and resilient blanket form of insulation consists of stable, oriented and uniformly textured inorganic glass fibers that are bonded together with a non-water soluble and fire-retardant thermosetting resin. As a result of its mineral composition, it is free from shot and coarse fibers. This insulation is used for pipelines and the tank under the cooling tower. K and R values of PEBI are shown in Table 2.

Table 1. K and R values of PEBI

At 24 °C mean Temperature	Thickness	K-Value ($W \cdot m^{-1} \cdot K^{-1}$)	R-Value($m^2.K.W^{-1}$)
	25 mm	0.047	0.53

Additionally, FIBREFRAX DURABLANKET S is a premium-grade insulator that is manufactured from spun ceramic fibers that are exceptionally strong and, as such, form very strong blankets. The strength of the fibers that the blanket is manufactured from in combination with is advanced resilience ensure that this blanket is very tough and can, therefore, be used in challenging environments at temperatures up to 1000 ^{0}C. This insulation is used for the two boiler tanks and the heat exchanger condenser in the present study. K and R values of this insulator are shown in Table 3.

Table 2. K and R values of FIBREFRAX DURABLANKET S

At 600°C mean Temperature	Thickness	K-Value ($W \cdot m^{-1} \cdot K^{-1}$)	R-Value($m^2.K.W^{-1}$)
	25 mm	0.12	0.208

Table 3. K and R values of FIBREFRAX DURABLANKET S at 600 °C mean temperature

Thickness (mm)	K-Value ($W \cdot m^{-1} \cdot K^{-1}$)	R-Value($m^2.K.W^{-1}$)
25 mm	0.12	0.208

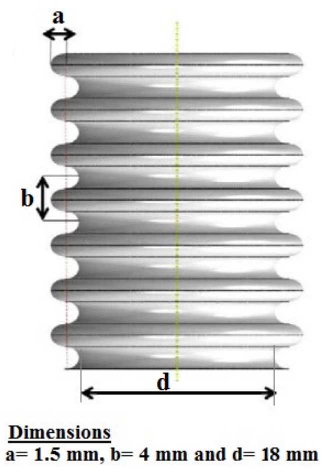

Figure 3. Corrugated tube packing

Operating temperature and heat load control the selection of suitable heaters for boilers. Broadly, fired heaters and electric heaters are used (Trinks et al., 2003). Although electric heaters have high capital and operating costs and the risks associated with large voltages, pilot distilled water units still commonly use electric heaters due to absence of cross-leakage, good control, no emissions, and applicability in cyclic operations (Dow et al., 2016; Pezo et al., 2006). Kettle reboilers of the pool boiling mechanism, in which agitation occurs through bubbling and natural convection, are commonly used and equipped with electric heaters (Bernstein, 1995; Dooley, 1996; Kohan, 1998). In this study, two identical stainless steel kettle-type boilers with four electric heaters (5kW each) were used, each boiler was provided with an inlet (0.5-inch dia.), a drain (0.5-inch dia,), a steam outlet (4-inch dia.), two electric heaters (10 kW total), a pressure gauge, a relief valve and a level indicator. Boilers were of 30 cm internal diameter with a height of 50 cm.

Table 4. Design and operating parameters of the heat exchanger condenser

Design/operating parameter	Value
Number of tubes	12
Tube inside diameter	10 mm
Total tube length, L	0.6 m
Square pitch type, P_t	1.25 cm
Shell diameter	7.06 cm
Steam to water heat transfer coefficient, $U_{steam\text{-}water}$	2000 W/(m^2.^{0}C) (Sinnot, 2014)
Condensate to water heat transfer coefficient, $U_{condensate\text{-}water}$	1000 W/(m^2.^{0}C) (Sinnot, 2014)
Cooling water inlet temperature	25 ^{0}C
Cooling water out let temperature	50 ^{0}C
Distilled water outlet temperature	40 ^{0}C
Distilled water production capacity	31.9 kg/hr
Cooling water circulation rate	699.7682 kg/hr

Vertical type shell and tube heat exchanger was selected for the design based on its advantages such as cost effectiveness, ability to be used in systems with higher operating temperatures and pressures, less pressure drop across the tube, and easy pressure tests (Costa and Queiroz, 2008). The current design of the one pass shell & tubes heat exchanger condenser follows the standard design methods (Richardson, 2005). Complete design specifications and operating parameters of the current shell and tube heat exchanger condenser are shown in **Table 4.**
In the present study, a corrugated tube type packing which helps to provide very large specific surface are per unit length of the tower and also provides enough void which helps to minimize the pressure drop across the top and bottom of the packing.

In the current design, water is to be cooled from 50 ^{0}C to 25^{0}C and collected in the storage tank under the cooling tower filled with a corrugated tubed, which is used for the first time in this study and showed high performance with respect to contact area and pressure drop. Dimensions of the corrugated tubed are shown in **Figure 3**. The cooled water is recycled back to the condenser where it absorbs heat. Parameters required for the design of the cooling tower are shown in **Table 5.**

Table 5. Cooling tower design data

Design/operating parameter	Value
Maas flow rate of water in	670.782 Kg/hr.
Temperature of water in	50 0C
Temperature of water out	25 0C
Maximum blower flow rate of air	1698 m3/hr
Actual operating air flow rate (85 % of the max.)	1443.3 m3/hr
Max. allowable temperature of air out	290C
Temperature of air in	230C
Relative humidity of air in, RH %	50 %
Number of tubes	69
Corrugated tube length	85 cm
Corrugated tube average diameter	~ 2.0 mm

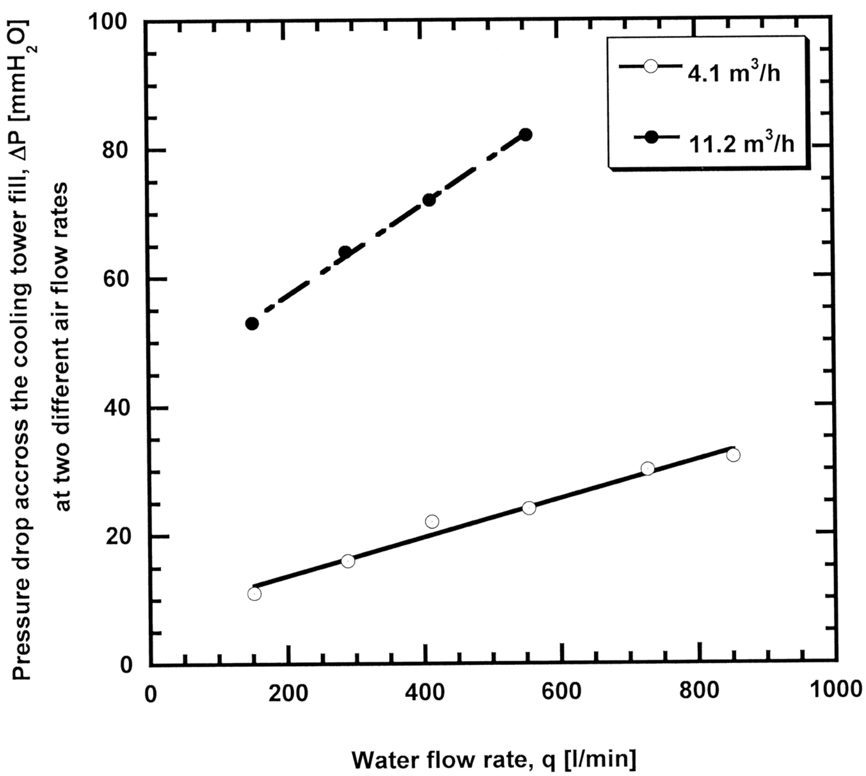

Figure 4. Variation of pressure drop at different sets of air flow rates

3. Results and discussions: performance evaluation

Several performance indicators can be used to express the overall operational and economic performance of the current distilled water unit such as boiler pressure, boiler blowdown and concentration cycles pressure drop across the cooling tower, production efficiency, cooling tower approach and range and water quality in terms of TDS, salinity, conductivity, alkalinity etc.

3.1. Boiler pressure and Pressure drop across the cooling tower

Two sets of readings were taken to measure the pressure drop across the cooling tower at variable water flow rates with time. The first set was obtained during the operation of air flow of 4.1 m^3/hr, and the second set was taken at air flow of 11.2 m^3/hr. The variation of the pressure drop across the fill of the cooling tower increased with water flow rate as shown in **Figure 4**. Pressure drop was larger at higher air flow rate. Maximum pressure drop was 82 mm.H_2O which was relatively low and sufficient for smooth operation with respect to minimum mist elutriated at the top of the cooling tower. No flooding risk appeared even at the minimum water and maximum air flow rates.

3.2 Boiler Blowdown

One of the most important operational parameters of any boiler is to keep solid content of boiler water in certain limits. The job of boiler engineer is to make boiler blowdown as less frequently as possible. This is because blowdown will reduce makeup water and chemical treatment costs. The maximum levels of solid contents possible for each specific system can be determined only from experience. The effect of water characteristics on steam quality can be verified with steam purity testing. However, the effects on internal conditions are determined during boiler shutdown periods for maintenance (ASME Codes: Zotero, 1994).

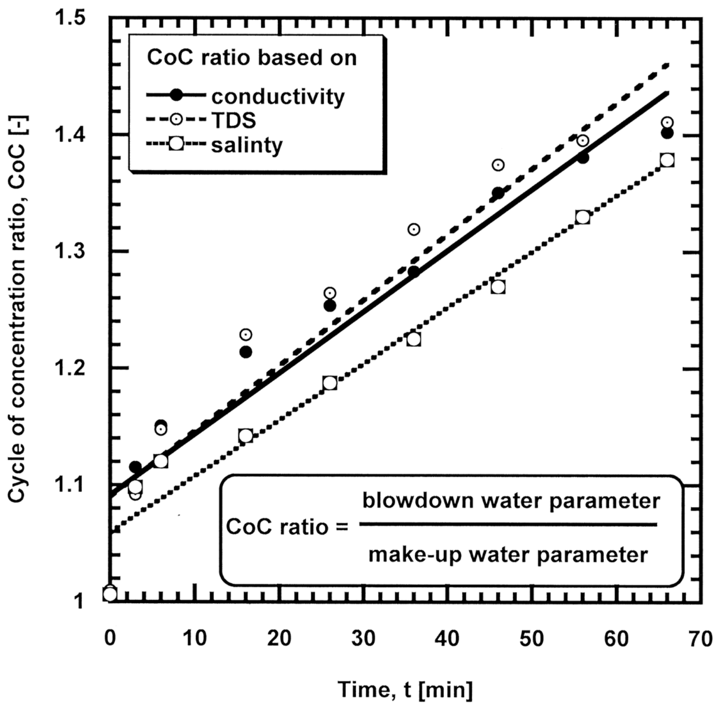

Figure 5. Variation of the cycle of concentration ratio, CoC, with time based on conductivity, TDS and salinity of water

In the current study, blowdown line is sent as a reject line to drain with a flow rate about 1.7 liter/hr (ρ_{water}= 1000 kg/m^3), the blowdown is calculated as;

$$\%\ \text{blowdown} = \frac{1.7}{26.4}\ X\ 100 = 6.4\ \% \tag{1}$$

3.3 Cycle of Concentration, CoC

Cycles of Concentration (CoC) refers to the accumulation of impurities in the boiler water and can be calculated as follows (ASME Codes: Rao, 2017)

$$\text{CoC} = \frac{\text{Blowdown Water Parameter}}{\text{Make Up Water Parameter}}\ \text{X}\ 100 \tag{2}$$

CoC is usually measured in terms of either TDS or Electrical Conductivity. Higher TDS leads to increased scale formation onto the heater surfaces which further leads to overheating of the tubes. Feed with TDS below 50 ppm are considered as soft, and over 150 ppm is considered hard. The TDS level is measured in (mg/l) by collecting samples from the bottom of the boilers blowdown sampling points. Electrical conductivity is a direct easy measure for TDS and can be used for evaluating the CoC instead of TDS. Salinity measurements can also be used for evaluating the CoC with less importance (Sinnot and Towle, 2009).

Figure 5 shows the variation of CoC ratio with time at different conductivities, TDS, and salinities of the blowdown water line and the make-up water line. CoC increased with time. In an hour, more than 40% increase was shown for CoC ratio measure using conductivity and TDS. Readings were almost identical. Conductivity is commonly used for CoC measurements.

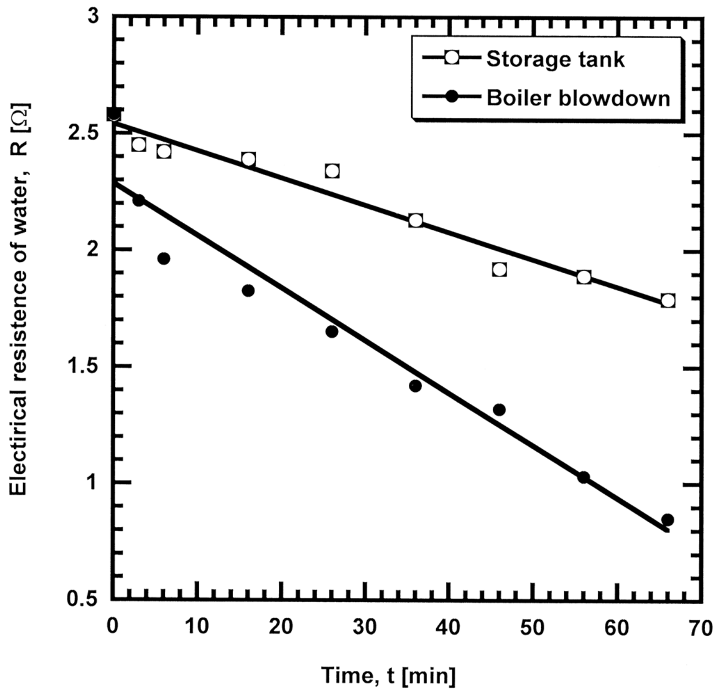

Figure 6. Water electrical residence with time in the main storage tank

3.4. Electrical properties of system water

Electrical properties such as conductivity and/or electrical resistance is a direct measure for TDS, contents in water (Rafael, 2011). Electrical resistance is inversely proportional with TDS contents in water. Storage tank located under the cooling tower is rather important as make-up line water is withdrawn from this tank. The two boilers are very sensitive to increased contents of salts in water and as it decreases the heat loads and heat transfer rates to the boiling water. Variation of electrical resistance as shown in **Figure 6** measures the change of electrical resistance with time in both the storage tank and the two boiler vessels. Decrease of the residence was smaller and sharper for the two boilers due to rapid loss of water which leads to faster accumulation of TDS in water, which in turn decreases the resistance to current flow. Besides, volume of water in storage tanks is four times larger than the volume of water in the two boilers vessels.

3.5. Cooling Tower Efficiency

The cooling tower efficiency is calculated by the following formula;

$$\eta_{CT} = \frac{\text{Approach}}{\text{Approach} + \text{Range}} \tag{3}$$

Approach is defined as the difference between the cold water stream leaving the tower and the WBT at the same exit point. In general, the closer the approach is aligned with the wet bulb, the more expensive the tower becomes, as this requirement increases the size of the tower. The lowest value of the temperature of water that a cooling tower can produce cannot be below the WBT. For the current operating conditions, the wet bulb temperature of air entering the column was 15 ℃. The temperature of the water stream leaving the column was measured as 26 ℃. Water in a relatively large storage tank located under the cooling tower will help to cool water closer to 25 ℃ which is recycled to cool the condenser heat exchanger.

$$\text{Approach} = \text{CWT} - \text{WBT Approach} = \text{CWT} - \text{WBT} \qquad 4$$
$$Range = T_{w1} - T_{w2} = 50\text{-}26 = 24\ ℃ \qquad 5$$
$$Approatch = T_{w2} - \text{WBT} = 26 - 15 = 9\ ℃ \qquad 6$$
$$\text{Thermal e}fficiency = (Range / (Range + Approatch)) * 100 = 72\% \qquad 7$$

Thermal efficiency of 72% is within acceptable range between 40 – 75 % for most of the cooling towers (Hensley, 2006).

3.6. Production Efficiency

Actual production rate of distilled water was 26.4 kg/hr using a 20 kW heater, while the theoretical calculation yielded 29.2 kg/hr of distilled water. The production efficiency was calculated as follows:

$$\text{Production efficiency} = \frac{\text{Condensate produced}}{\text{Steam theoretically generated}} * 100 = \frac{26.4\ \text{kg/hr}}{29.2\ \text{kglhr}} * 100 = 90.42\ \% \qquad 8$$

The condensate obtained was 90.42 % of the total steam produced. For safety considerations, some of the steam was vented to the atmosphere through the top release valves present at the top of the boiling chambers. Thermal efficiency was evaluated using the two terms: range and approach. The range is a function of the heat load and the circulated flow through the system. It is defined as the difference in temperature of the hot water stream and the cold water stream. Cooling towers are typically set to cool a given flow rate from one temperature to another at the required wet bulb temperature (WBT).

3.7 Distilled water quality

Conductivity of the produced distilled water was 5 µS/cm which is very acceptable and much closer to the worldwide standards.

4. Conclusions

We have discussed an approach to save energy and water in tap water distillation units. Instead of rejecting hot water to the drain part of it is recycled back to the distillation after cooling down in air cooling tower. With this approach we were able to save appreciable amount of tap water. In this paper we have also discussed several boiler operating parameters such as boiler blow down, cycle of concentrations, and electrical resisteance. The distilled water quality at our facility was checked and was found satisfactor for laboratory and other uses. It was estimated that this new approach saved about 697 kg of tap water per hour.

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Biographies

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