Design of an economic heat-integrated distilled water pilot plant with internal water circulation cycle

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Abstract
Distilled water is widely used in many industrial processes as well as for research and development applications. There is an insufficient supply of high quality distilled water at economical rate for various industrial and academic applications. The distillation process works on the principle of the phase transformation of water by evaporation followed by condensation of steam back to liquid. Water condensation is carried out by cooling with another cold water stream in heat exchanger condensers. Coolant water line is generally wasted and sent to drain as rejected hot line. The design of a heat integrated pilot plant for production of distilled water is an innovative, cost effective and efficient alternative. In this study, part of water coming out from the jacket of the condenser is sent to the boiler chamber. The other portion is cooled in a direct contact cooling tower with ambient air. Cooled water is collected in a storage tank and reused for cooling the condenser heat exchanger. A water make-up line is used to compensate water losses in distilled water production and to humidify the air stream in the cooling tower. The current design of distilled water unit presents an economically feasible, and heat integrated distilled water pilot plant. It can be used to purify potable and raw tap water with a distilled water output of 29.2 liters per hour.

Key words: distilled water pilot plat; heat integration; cooling tower; economic design

1. Introduction
Water is considered as one of the most abundant molecules in the Universe. Nearly 70% of the surface of our planet earth is covered with water and also it is the main component of several other planets, moons and comets [1, 2]. It is a colorless, odorless liquid and classified into different types according to the degree and type of contamination. These types include hard water, boiled water, raw water, rain water, snow water, filtered water, soft water, de-ionized water, and distilled water [3]. Distilled water or Aquadest (lat. aqua destillata) is the water that has initially been transformed into vapor so that majority of its contaminants or pollutants are removed [4]. The total dissolved solids (TDS) in distilled water is below 50 mg/L and it has low mineral content. Distillation process removes over 95 per cent of the minerals from the source water. It has also very poor thirst quenching and taste characteristics [5, 6]. Distillation can also remove metals, organic chemicals and micro-organisms such as bacteria, viruses and cysts from the feed water. The carbon dioxide from the environmental air can dissolve easily in the distilled water and can lead the pH value of distilled water to be slightly acidic. Therefore, distilled water should be consumed quickly or stored under airtight conditions. Impurities having a higher boiling point than water are effectively removed during distillation and they remain as sediments or residues. Thus, one of the major operational limitation of distiller is scaling due to these sediments and lime scale built-up in the boiling chamber. Methods of pre-treatment of the feed water using water softeners are often adopted to deal with the scaling problems. Some volatile organic compounds that have a lower or the same boiling point as that of water are brought to condensation posing difficulties in controlling the quality of the distilled water. These volatile organics can be effectively removed by appropriately placing volatile gas vent, activated carbon filter or suitable membranes [7]. Despite all these, distillation is considered as the most reliable and efficient method for water purification.
compared with other methods such as de-ionization or filtration. Thus, distilled water is utilized for many industrial processes as well as for research and development activities [8]. Pilot or lab scale distilled water production units are very popular. In most of these pilot units, water condensation is carried out by cooling with a separate cold water stream. Coolant water line is wasted and sent to drain as rejected hot line. It is estimated that the requirement of coolant is almost 50 to 60 liters per one liter of distilled water produced and in some units it even exceeds this ratio. Economic feasibility of the units is not considered as a major controlling parameter in measuring the overall performance of these distilled water units. Thus, the pilot/lab scale distilled water production units are simple but not feasible and absolutely not economic. In the present investigation, an attempt has been made to design an economically feasible and heat integrated pilot plant operating with relatively large production rates of distilled water. The unit includes a cooling water circulation cycle. The system is equipped with a direct contact cooling tower to cool down the hot water line used for condensing the water vapor produced by the boiler units. The cooled water output stream from cooling tower drum is mixed with a makeup potable water line and then recycled to the heat exchanger condenser unit as coolant. To the best of our knowledge, this design is an efficient, cost effective and feasible method for distillation of water. However, the unit’s operation is diverse and can be used to purify any source of contaminated water. Besides, the distilled water production capacity can be increased using an additional external heat source.

Fig. 1. Schematic representation of the distilled water unit

2. Experimental
2.1. Unit description:

The experimental apparatus shown in Figure 1, consists of two boilers (B-1 & B-2) with an internal diameter of 30cm and height of 50 cm. The two units are equipped with pressure gauges (PG-1 & PG-2), relief valves (RV-1 & RV-2), four electrical heaters of 10kW each (THE-1, THE-2, THE-3 & THE-4) 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). Cold water flowing down through the cooling tower is collected in a storage tank where it is recycled to the heat exchanger condenser (HE-1). 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 pipelines, elbows and joints are made of high grade stainless steel [C45] due to its excellent chemical and physical properties.

2.2. Insulation
Thermal insulation plays a very important role in reducing the heat losses from hot surfaces. Thermal conductivity, \( k \) (unit \( \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \)), denotes the ability of a material to conduct heat, while, thermal Resistance, \( R \), is temperature difference at steady state between two defined surfaces of a material or construction that induces a unit heat flow rate through a unit area. Thus, a material that has a low thermal conductivity \( k \) has a high insulating capability \( (R\text{-value}) \). Two insulation materials were used in the present investigation. AFICO Pre-Engineered Metal Building Insulation (PEBI) is a lightweight, highly efficient, flexible, and resilient blanket form of insulation that consists of stable, oriented and uniformly textured inorganic glass fibers that are bonded together with a non-water soluble and fire-retardant thermosetting resin. This insulator is used for pipelines and the tank under the cooling tower. \( K \) and \( R \) values of PEBI are shown in Table 1.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>( K )-Value (W·m(^{-1})·K(^{-1}))</th>
<th>( R )-Value(m(^2)·K·W(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.047</td>
<td>0.53</td>
</tr>
</tbody>
</table>

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 °C. This insulator is used for insulating the two boiler tanks and the heat exchanger condenser in the present study. \( K \) and \( R \) values of this insulator are shown in Table 2.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>( K )-Value (W·m(^{-1})·K(^{-1}))</th>
<th>( R )-Value(m(^2)·K·W(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.208</td>
</tr>
</tbody>
</table>

3. Design of equipment
3.1. Design of boiling chambers
Boilers are pressure vessels designed to heat water in order to produce steam. By careful design, efficiencies up to 95% or greater can be achieved. However, fuel costs and regular maintenance need careful monitoring [9]. Operating temperatures of boilers are generally classified into three ranges: low (< 120°C), medium (120-250 °C), and high (>250 °C). Selection of suitable heaters for boiler depends on the required temperature and heat load. Fired heaters and electric heaters are very popular [10]. Pilot distilled water units commonly use electric heaters as this has many advantages such as capability to reach very high temperatures (up to 1200 °C), absence of cross-leakage, good control, no emissions, and applicability in cyclic operations [11]. However, electric heaters have few drawbacks including high capital and operating costs and the risks associated with large voltages. Kettle reboilers are the most common reboiler types used as a steam generator [12]. Pool boiling is the mechanism adopted in kettle reboilers, in which agitation occurs through bubbling and natural convection. The vapor-liquid separator is built-in and allows for blowdown. This in turn helps to maintain the liquid level above the tube bundle. This mechanism also helps to prevent the entering liquid from mixing with the residual reboiled liquid (exiting from the bottom) [13]. Kettle reboilers are comparatively more expensive than horizontal thermos syphons fabricated for a comparable duty.

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 (1/2 inch), a drain (1/2 inch), a steam outlet (4 inch), 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.

At steady state operation after boiling, simple material and energy balance equations can be derived to calculate the amount of steam generated from the two boilers. The relief valve and drain valve were intended for emergency and the blow down valve was planned to open once per two cycles. Thus, these three lines
were not taken into account for material balance calculations. Theoretical maximum heat load of the four electrical heaters, \( Q \), was 20 kW and therefore;

\[
R_\text{heat} = M_i \times Q \times (\lambda \times CPw \times \Delta T) = 0.00811 \text{ (kg/s)} = 29.197 \text{ (kg/hr)}
\]

(1)

Where, \( R \) [kg/s] is the rate of main water feed line to boilers. This line consists of a portion of hot water from the jacket of the heat exchanger. \( M_i \)[kg/s] is the rate of steam produced and \( \lambda \) is the latent heat of vaporization of water (2257 kJ/kg). Assuming that the make-up line of water is fed at 50 \(^\circ\)C and the distilled water leaves at 40 \(^\circ\)C, distilled water produced, 29.197 kg/hr, is taken as basis for calculations needed for the design of other equipment of the current distilled water unit.

### 3.2. Design of heat exchanger for condenser

Since applications of these exchangers are specialized, the tubular and plate construction types are widely used for several applications [14]. For tubular and plate-type exchangers, the influence of the following factors must be taken into account in exchanger design: corrections due to leakage and bypass streams in a shell-and-tube exchanger, effects due to a few plates in a plate exchanger [15]. Shell and tube heat exchanger consists of anumber of round tubes mounted in a cylindrical shell with the tube axis parallel to that of the shell. One fluid flows inside the tubes, the other flows across and along the tubes. The major components of this exchanger are tubes (or tube bundle), shell, front-end head, rear-end head, baffles, and tube sheets [16]. 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. In the present study, it is required to cool the steam from 100 \(^\circ\)C to 40 \(^\circ\)C. Water of 25 \(^\circ\)C is used for condensing 31.9 kg/s of vapors and is fed from the storage tank located under the cooling tower.

Calculations are divided into two regions. The upper region of phase change from vapor to liquid, where vapors are condensed to saturated liquid (\( T_f = 100 \) \(^\circ\)C), and second lower region, where condensed vapors is cooled down (\( T_f = 40 \) \(^\circ\)C). Cooling water is assumed to enter at \( T_i = 25 \) \(^\circ\)C and leaves at \( T_i = 50 \) \(^\circ\)C. Thus, it is heated from 25 \(^\circ\)C to an intermediate temperature, \( T_m \), then heated more to 50 \(^\circ\)C.

For the top region,

\[
M_i \times \lambda = m_w \times CPw \times (T_i - T_m)
\]

(2)

For lower region,

\[
M_i \times CPw \times (T_i - T_f) = m_w \times CPw \times (T_m - T_f)
\]

(3)

Solving equations (2) and (3) results in \( T_m = 27.503 \) \(^\circ\)C and \( m_w = 699.7682 \) kg/hr.

The hot water line from the jacket of the heat exchanger is divided into two portions. The smaller portion (29.197 kg/hr) is divided equally between the two boilers as a main feed line. The larger portion of hot water (670.5712 kg/hr) is cooled through the cooling tower.

The heat transfer area can be calculated by the equation below:

\[
Q_i = U_i A_i \Delta T_{\text{LMTD},i}
\]

(4)

For upper region, assuming 12 total number of tubes, \( N_t \), and each has 10 mm internal diameter;

\[
\Delta T_{\text{LMTD}} = \frac{(100 - 50) - (100 - 27.5)}{\ln(100 - 27.5)} = 60.5 \text{ \(^\circ\)C}
\]

(5)

\[
Q_i = M_i \times \lambda
\]

(6)

where \( Q_i \) can be obtained from steam tables, then, \( Q_i = 71998.3 \text{ kJ/hr} = 20 \text{ kW} \)

Heat transfer coefficient (\( U \)) for steam and water is 2000 W/(m\(^2\).\(^\circ\)C) [17]

Total lateral heat transfer area, \( A_{i\text{LPA}} = 0.16514 \text{ m}^2 = \pi D L_i N_i \)

(7)

Length of each tube, \( L_i = 0.43 \) m

For lower region, using water heat capacity, \( C_p = 4.199 \text{ kJ/kg.}^{\circ}\text{C} \); \( \Delta T_{\text{LMTD},ii} = \frac{(100 - 27.5) - (40 - 25)}{\ln(100 - 27.5)} = 36.5 \text{ \(^\circ\)C} \)

(8)

Heat lost is calculated using condensate cooling, \( Q_{ii} = M_i \times C_p \times \Delta t = 9850.854 \text{ kJ/hr} = 2.73 \text{ kW} \)

Heat transfer coefficient (\( U \)) for condensate and cooling water is 1000 W/(m\(^2\).\(^\circ\)C)

\[
Q_{ii} = U_{ii} A_{ii} \Delta T_{\text{LMTD},ii}
\]

(9)

Total tube length, \( L_t = L_1 + L_2 = 0.6 \) m

Assuming very thin tubes, the tube pitch, \( P_o \), and tube bundle diameter, \( D_b \), can be calculated as following as:

\[
P_o = 1.25 \text{ } d_t
\]

(10)
Where, $K_i = 0.215$ and $n_i = 2.207$, considering square pitch type for tube arrangement [17].

$P_t = 1.25 \text{ cm} = 12.5 \text{ mm}$, $D_b = 61.8 \text{ mm}$

Shell diameter, $D_s = D_b + \text{BDC}$

Bundle diameter clearance, BDC can be taken as 9.1 mm (for fixed tube, [17]).

Hence, shell diameter = 61.8+9.1 = 70.9 mm = 7.09 cm

4. **Design of the cooling tower**

A cooling tower is considered as a direct contact heat exchanger in which air and water are allowed to come into direct contact with each other with an aim to decrease the temperature of water. A small volume of water is evaporated during this process, thereby reducing the temperature of water circulated through the tower and leads to a cooling action [18]. Cooling towers are designed and manufactured according to the application in several types and in many sizes. These types are classified according to direction of flow of air and water into two types viz, cross flow towers and counter flow towers. Counter flow tower are again classified to natural draft and mechanical (forced or induced) draft cooling towers [19]. Natural draft cooling towers are also known as hyperbolic cooling towers and are best suited for processing large amount of water flows such as in power plant applications. In mechanical draft cooling towers, air is circulated inside the tower mechanically with the aid of propeller fans or centrifugal fans. For induced draft cooling tower, the fan is located at the top and for the latter it is located at the bottom of the tower.

The inside of an evaporative cooling tower is packed with fill, which is a type packing aimed to provide the necessary contact area and time between air and water. The efficiency of the cooling tower greatly depends on the condition of the packing material. The three basic types of fill are splash, film, and hybrid. In the present study, a corrugated tube type packing was used as shown in **Figure 2**. This type of packing helps to provide very large specific surface area 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°C to 25°C and collected in the storage tank under the cooling tower. 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 3**.

![Figure 2. Corrugated tube packing](image_url)

Table 3. Cooling tower design data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maas flow rate of water in</td>
<td>670.782 Kg/hr.</td>
</tr>
<tr>
<td>Temperature of water in</td>
<td>50 °C</td>
</tr>
<tr>
<td>Temperature of water out</td>
<td>25 °C</td>
</tr>
<tr>
<td>Maximum blower flow rate of air</td>
<td>1698 m³/hr</td>
</tr>
<tr>
<td>Actual operating air flow rate (85 % of the max.)</td>
<td>1443.3 m³/hr</td>
</tr>
<tr>
<td>Max. allowable temperature of air out</td>
<td>29°C</td>
</tr>
<tr>
<td>Temperature of air in</td>
<td>23°C</td>
</tr>
<tr>
<td>Relative humidity of air in, RH %</td>
<td>50 %</td>
</tr>
<tr>
<td>Number of tubes</td>
<td>65 tube</td>
</tr>
</tbody>
</table>

Water-19, Paris, 22-24 July 2019
4.1. COOLING TOWER DESIGN CALCULATIONS

Cooling towers are designed to reject heat from water through the natural process of evaporation. Warm water from the condenser is sent to the cooling tower for reducing its temperature. A portion of this water is evaporated into the air passing through the cooling tower. During this process, the air absorbs some heat, which leads to a reduction in temperature of the rest of the water. The cooled water is collected at the bottom of the tower, which can be sent back to the condenser. The amount of heat that can be rejected from the water to the air is directly linked with the relative humidity of the air. Air with a lower relative humidity has a higher capability to absorb water through evaporation than air with a higher relative humidity. Overall design calculations are given below.

4.1.1. Calculation of the dry density of air (\(\rho_{air}\))

Density of air, \(\rho_{air}\), is calculated based on the ideal gas law [20].

\[
\rho_{dry\ air} = \frac{P \cdot M}{(R \cdot T)} = 1.1873 \text{ Kg/m}^3
\]

where; \(P\) = pressure (101.3 kpa), \(R\) = universal gas constant (8314.32J/mol. K), \(T\) = temperature (23°C + 273 = 296 K), \(M_{air}\) = molar mass of air (28.836 Kg/Kmol)

Compressibility of non-ideal gas and vapor pressure are not considered for water due to its negligible aspects. The density of a mixture of dry air and water vapor can be simply written as:

\[
\rho_{moist\ air} = \frac{\rho_{dry\ air} + P_v}{R_D T} + \frac{P_v}{R_v T}
\]

This, with some substitutions and rearranging, may also be written as

\[
\rho_{moist\ air} = \frac{\rho_{dry\ air}}{R_D T} \times (1 - \frac{0.378 \times P_v}{P_{tot}})
\]

where, \(\rho\) = density, kg/m\(^3\), \(P_{dry\ air}\) = pressure of dry air, Pascal, \(P_v\) = pressure of water vapor, Pascal, \(P_{tot}\) = \(P_d\) + \(P_v\) = total pressure air, Pascal, \(R_D\) = gas constant for dry air, J/(kgK) = 287.05 = R/Mv, \(R_v\) = gas constant for water vapor, J/(kgK) = 461.495 = R/Mv, \(M_v\) = molecular weight of water vapor = 18.016 g/mol, and \(T\) = temperature, in K

In order to apply these equations for the determination of density of air, parameters such as the actual air pressure (absolute pressure or total pressure of air), water vapor pressure, and the temperature must be known.

It is possible to obtain an approximation of absolute pressure by setting the altimeter to read zero altitude and by setting the value in the Kollsman window as the actual air pressure. The water vapor pressure can easily be determined from dew point or relative humidity, and the ambient temperature can be measured in a ventilated place away from direct sunlight.

4.1.2. Vapor Pressure:

The first step to calculate the water vapor pressure is calculation of the saturation vapor pressure. Many algorithms are available for determination of the saturation vapor pressure. For the sake of simplicity, the following curve fitting algorithm in the form of a polynomial developed by Hermann et al. [20] was used:

\[
P_v = \frac{\rho_{dry\ air}}{M} \times \frac{M}{6.1078} \times \frac{6.1078}{M} \times \frac{6.1078}{N} = 31.67008 \text{ mb} = 3167.008 \text{ Pa}
\]

Where, \(P_v\) = saturation pressure of water vapor, mb, \(\epsilon_{sat}\) = 6.1078, and \(T\) = temperature, °C

\[M = (c_0 + T^8(c_1 + T^7(c_2 + T^6(c_3 + T^5(c_4 + T^4(c_5 + T^3(c_6 + T^2(c_7 + T^1(c_8 + c_9)))))))
\]

\[c_0 = 0.999999683, c_1 = 0.90826951 \times 10^{-2}, c_2 = 0.78736169 \times 10^{-4}, c_3 = -0.61117958 \times 10^{-6}, c_4 = 0.43884187 \times 10^{-8}, c_5 = -0.29883885 \times 10^{-10}, c_6 = 0.21874425 \times 10^{-12}, c_7 = -0.17892321 \times 10^{-14}, c_8 = 0.11112018 \times 10^{-16}, c_9 = -0.30994571 \times 10^{-18}
\]

Other methods such as Tetens’ Formula [21] and Antoine equation [22] can also be used. Next step is the determination of real value of vapor pressure. Relative humidity is defined as the ratio of the actual vapor pressure to saturation vapor pressure at a given temperature, which is expressed as a percentage. Therefore, the actual vapor pressure can be calculated as

\[
P_v = R_h \cdot P_v
\]

Where, \(P_v\) = pressure of water vapor (partial pressure), \(R_h\) = relative humidity, and \(P_v\) = saturation vapor pressure. The total measured atmospheric pressure is the sum of the pressure of the dry air and the vapor pressure. Hence,

\[
P_d = P - P_v
\]

where, \(P\) = total pressure, \(P_d\) = pressure due to dry air, and \(P_v\) = pressure due to water vapor

\[
\rho_{moist\ air} = \frac{\rho_{dry\ air} \times P_{wet\ air}}{RT} + \frac{P_v \times \rho_{wet\ air}}{RT} = \frac{\rho_{dry\ air} \times P_{wet\ water}}{RT} \times (1 - \frac{0.378 \times P_v}{P_{tot}}) = 1.16051 \text{ Kg/m}^3
\]

From psychrometric charts at 23 °C, humidity, \(h_1 = 0.01 \text{ [g/g dry air]}\) and enthalpy, \(H_1 = 52 \text{ [kJ/kg dry air]}\).
Mass fraction of water, $w_{wat} = \frac{h_1}{h_{1+1}+1} = 0.0099$, while mass fraction of air, $w_{air} = 1 - \frac{h_1}{h_{1+1}+1} = 0.9901$

Mole fraction of water vapor and air are $y_{wat} = 0.01577$, $y_{air} = 0.98423$, respectively.

From material balances, gas flow rate entering the cooling tower can be calculated as follows:

\[ Q_1 = Q_{2} \rho_{2|a} = 1443.4(\text{m}^3/\text{hr}) \times 1.16051(\text{Kg/m}^3) = 1674.964 \text{ Kg/hr}, \text{ where, } Q_1 = 1443.3 \text{ m}^3/\text{hr}. \]

Mass flow rates of water and air can be calculated as follows;

Mass flow of dry air in, $M_{dry \ air} = G_i \ w_{air} = 1658.382 \text{ Kg/hr}$

Mass flow of water in = $G_1 \ w_{wat} = 16.582 \text{ Kg/hr}$

From psychometric charts at 28 °C and assuming air out is saturated; humidity, $h_2 = 0.025 \text{ [g/g dry air]}$ and enthalpy, $H_2 = 93 \text{ KJ/kg dry air}$

mass fractions of water and air are $w_{wat} = \frac{h_2}{h_{2+1}} = 0.02439$, $w_{air} = 1 - \frac{h_2}{h_{2+1}} = 0.97561$, respectively.

\[ G_2 x (1 - \frac{h_2}{h_{2+1}}) = G_1 x (1 - \frac{h_1}{h_{1+1}}), \ \text{G}_2 = 1699.841 \text{ Kg/hr} \]

Mass flow of water in = $G_2 x w_{wat} = 41.4591 \text{ Kg/hr}$

Mass flow of dry air out, $M_{dry \ air} = G_2 x w_{air} = 1658.382 \text{ Kg/hr}$

The amount of water evaporated can be calculated by:

\[ \Delta W = G_2 - G_1 = 39.8055 - 16.582 = 23.2235 \text{ Kg/hr} \]

\[ \Delta W \text{ can be re-calculated using the following equation. } \]

\[ \Delta W = \text{mass of air in } (x_h - x_h) = 24.8771 \text{ kg/hr} \]

Water outlet temperature can be calculated as follows,

\[ T_{w \ out} = \text{25.75°C} \]

Calculations of heat transfer coefficient, $h_c$, mass transfer coefficient, $K_m$, heat transfer area, $A_w$, overall heat transfer coefficient, $U$, and the packing height, $L_c$, are carried out based on adiabatic cooling tower intended for closed wet cooling [23].

Calculation of $h_c$, $K_m$, $U$, $A_w$, and $L_c$, based on air flow streams:

Calculation of the heat transfer coefficient ($hc$)

\[ q_1 = 1443.3 \text{ m}^3/\text{hr}, q_2 = \frac{G_2}{\rho} \times 1464.7362 \text{ m}^3/\text{hr}, \text{ and } q_{avg} = \frac{1443.3 + 1464.7362}{2} = 1454.0181 \text{ m}^3/\text{hr} \]

\[ q_{tube} = \frac{q_{avg}}{n_{tube}} = 22.5364 \]

\[ d_{narrow} = 0.018 \text{ m}, d_{wide} = 0.021 \text{ m}, \text{ and } d_{avg} = \frac{0.018 + 0.021}{2} = 0.0195 \text{ m} \]

Characteristic length, $L_c = \frac{4 x A_{avg}}{\pi x d_{avg}} = \frac{4 x 2.98 \times 10^{-4}}{\pi x 0.0195} = 0.0194 \text{ m} \]

\[ n_{tube} = \frac{\text{tube cross-sectional area}}{\text{tower cross-sectional area}} = 65 \text{ tubes} \]

\[ V_{tube} = \frac{\text{tube cross-sectional area}}{\text{avg}} = \frac{22.5364}{\pi x 0.0195} = 75460.5211 \text{ m/hr} \]

\[ \text{Re} = \rho_{air} d_{avg} V_{tube}/\mu_{air} = 25794.0231 \text{ (dynamic viscosity of air, } \mu_{air} = 0.066204 \text{ kg/m/hr)}, \]

\[ \text{Pr} = \mu_{air}/K_{air} = 0.7 \text{ (thermal conductivity of air, } K_{air} = 0.09434 \text{ kJ/hr.m.K}) \]

\[ \text{Nu} = h_c L_c / K_{air} = 0.27 (\text{Re})^{0.6} \text{(Pr)}^{0.36} = 142.8421 \]

Convective heat transfer coefficient, $h_c = 694.625 \text{ KJ/m}^2\text{hrK}$

\[ 4.1.3. \text{ Calculation of the mass transfer coefficient, } K_m \]

Mass transfer coefficient, $K_m$ is calculated by using the analogy shown in (21);

\[ \text{Sc} = (\mu_{air} \rho_{air} D_{air-water}) = 0.79232 \text{ (Diffusivity of air in water, } D_{air-water} = 0.072 \text{ m}^2/\text{hr}, [24]) \]

\[ \text{Sh} = K_m L_c / D_{air-water} = 0.27 (\text{Re})^{0.6} (\text{Sc})^{0.36} = 149.3568 \]

Convective mass transfer coefficient, $K_m = 554.31391 \text{ m/hr}$

\[ 4.1.4. \text{ Calculation of the overall heat transfer coefficient (U)} \]

\[ U = K_m x \lambda (\text{water mass flow rate in} = \text{water mass flow rate out}) + h_c = 1570.77614 \text{ KJ/m}^2\text{hrK} \]

\[ 4.1.5. \text{ Calculation of the wetted area} \]

\[ Q = M_{dry \ air} (H_2 - H_1) = U x A_w x \Delta T_{lm} \]

\[ \Delta T_{lm} = \frac{(50-28) - (25.7-23)}{\ln(50-28)} = 9.2002^\circ \text{C} \]

\[ A_w = 3.337531 \text{ m}^2 \]
4.1.6. Calculation of the actual length of tube

\[ A_w = n_{\text{tube}} \times \pi \times d_{\text{avg}} \times L_{\text{act}} \]  

(24)

\[ L_{\text{act}} = 0.839 \text{ m} \] and operating value for actual length was taken as 85 cm.

5 Results, startup and Overall Performance

5.1. Pressure in the boiler tanks and pressure drop across the cooling tower fill

The boilers were operated under atmospheric pressure. Figure 3 shows the measured pressure at the top of the two tanks using an open-end U-tube manometer. The pressure readings at the top of the two boilers were identical and showed a 40 mm.H₂O water level. This reading represents pressure of 0.00387 atmospheres, which is very low and safe for operation.

Two sets of readings were taken to measure the pressure drop across the cooling tower with time. The first set was obtained during the operation of only the small blower at its maximum load (4.1 m³/hr), and the second set was taken with both blowers operational at their maximum load (11.2 m³/hr). The variation of the pressure drop with water flow rate is shown in Figure 4.

![Fig. 3. Pressure at the top of the boilers, P, measured by an open-end U-tube manometer](image)

![Fig. 4. Variation of the pressure drop, ΔP, across the cooling tower fill at different water flow rates](image)

5.2 Change of total dissolved solids, TDS, and water conductivity, \( \kappa \), in boiler blowdown and storage tank

An increase in the TDS in boiler operation leads to increased scale formation or deposition into the inner surfaces, specifically the heater surfaces. This would result in an excessive resistance for heat transfer from flue gases to the water, which further leads to overheating of the tubes. Feed with TDS below 50 ppm are considered as soft, and over 150 ppm is considered as hard. The TDS level is measured (in mg/l) by collecting samples from the bottom of the boilers blowdown sampling points. The TDS is plotted against time and is shown in Figure 5. Sharp increase in TDS was observed for the blowdown samples due to rapid evaporation of water vapors which results in rapid increase in the total solids dissolved in water. Very slow gradual increase of TDS was observed for the samples from tank due to large water reservoir in the tank. The main makeup line, which is fed to this tank also contributes for this gradual increase. However, some water is lost due to humidification of air stream used for cooling. Electrical conductivity of water increases with increasing TDS of water as shown in Figure 6. As a result, resistance of water to electricity decreases which favors good boiling. For the boiler tanks, electrical resistance decreased from 2.2 ohm to 1.4 ohm with almost 65 minutes from initial boiling point. This decrease in resistance represents almost 36.5 % from the initial resistance in the boiler tanks.

5.3 Product conductivity and production efficiency

Conductivity of the produced distilled water was 5 μS/cm which is very acceptable and much closer to the worldwide standards shown in the Table 4 below [25]. Little increase in conductivity compared to international standard was believed to be due to the use of carbon steel for the boiler body.
Table 4. Conductivity values for pure water according to various standards

<table>
<thead>
<tr>
<th>Measurement (unit)</th>
<th>ASTM D1193</th>
<th>ISO 3696</th>
<th>US Pharmacopeia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type I</td>
<td>Type II</td>
<td>Type III</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>‹ 0.056</td>
<td>‹ 1</td>
<td>‹ 0.25</td>
</tr>
</tbody>
</table>

Fig. 5. Change of TDS in the main storage tank and the boiler blowdown water with time

Fig. 6. Change of water conductivity, κ, in the main storage tank and the boiler blowdown with time

Actual production rate of distilled water was 26.4 kg/hr using a 20 kW heater, while the theoretical calculation yielded 29.197 kg/hr of distilled water (eq. 1). The production efficiency was calculated as follows:

**Production efficiency = \( \frac{\text{Condensate produced}}{\text{Steam theoretically generated}} \times 100 = \frac{26.4 \text{ kg/hr}}{29.197 \text{ kg/hr}} \times 100 = 90.42 \% \)**

The condensate produced was 90.42 % of the total steam produced. For safety considerations, small portion 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). 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. When the size of the tower is predefined, then the approach is significant, followed by the flow rate. In these situations, the range and wet bulb are of less significance. For the current operating conditions, the wet bulb temperature of air entering the column was 17 °C. The temperature of the water stream leaving the column was measured as 26 °C. Water in a relatively large storage tank located under the cooling tower will help to cool water closer to 25 °C which is recycled to cool the condenser heat exchanger.

**Approach = CWT – WBT**

**Range = Tw1 – Tw2 =50-26=24 °C and Approach = Tw2 –WBT of air inlet stream = 26 – 17 = 9 °C**

**Thermal efficiency = (Range/ (Range+Approach)) \times 100 = 72.73 \%**

6. **CONCLUSIONS**

An economically feasible heat integrated distilled water unit was designed, fabricated and successfully operated for the production of 26.4 kg/hr of distilled water. Detailed design calculations for the heat
exchanger and the cooling tower as well as the overall process calculations were performed. The overall production efficiency was 90.42% and thermal efficiency, in terms of range and approach, was 72.73%. Total dissolved solids and conductivity of the obtained distilled water were within the acceptable limit as prescribed by various international standards. The designed pilot unit can be considered as highly energy saving design due to the closed loop re-circulation of the condenser cooling water through a water cooling tower. To the best of our knowledge, such an energy efficient distilled water production unit and design considerations are reported for the first time.

References