Transport Properties of Evaporative Cooling in a Seashell Packed Bed Cooling Tower

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Abstract. This project was aimed to investigate the transport properties of evaporative cooling using seashell as packing material in a packed bed tower. Cockle shell was used as the packing material, which usually discharged as waste from marine life and fishery industry. The packing section is 15 inch high and filled with seashell which consists of 15 mm to 14 mm of equivalent diameter. The performance of cooling tower using seashell packing is compared to HDPE pipe packing. The results show that seashell packing have higher cooling water range, lower cooling approach and higher cooling tower efficiency than HDPE pipe packing. Meanwhile, cooling water range, R and cooling tower efficiency, e decrease with increasing of water to air ratio, L/G for all circulation rate. The heat transfer coefficient, KaV/L decreases with increasing of L/G ratio with lower circulation rate.

1 Introduction
Cooling towers have been widely used in large chemical industry, thermal and nuclear power plants, petroleum industry and other industrial facilities [1]. A cooling tower is a heat removal device in which involve a direct contact between two fluids, ambient air and warm water [2]. These steady flow devices are based on the combination of mass and energy transfer that used to reduce water temperature by rejecting it directly to the atmosphere [1].

Evaporation is the main mechanism in cooling tower. This process allows a certain amount of water to be evaporated into moving air stream due to vapor pressure in that gas phase is lower than the saturated vapor pressure [3]. Evaporative cooling is divided into two different types, which is direct and indirect evaporative cooling. Direct evaporative cooling is a process of air and water directly in contact with each other to cool and humidified air. While for indirect evaporative cooling, the water and air are separated to prevent adding moisture to the air by using different paths [4]. Cooling tower can operate either in cross flow or counter flow where the air flow due to mechanical arrangement of convection currents or by natural wind [5].

The packing is an essential section in cooling tower, which have major influence on the performance of the cooling tower [6]. The main function of packing material is to provide a large contact area for water and air, increase contact time and the dispersion of water droplets by distributing the water flow uniformly to enhance evaporation and heat transfer [7]. The material used in packing had great effect on the efficiency of thermal performance in the cooling tower. Nowadays, various types of packing material are design and modified as an alternative for conventional material used in cooling tower.

Selection of packing material is very important to improve the transport properties and enhance the performance of cooling tower. Seashell were used as packing material as modified and partial replacement for conventional materials packing material in packed bed cooling tower. The cooling tower efficiency was achieved by increasing contact area between the fluids in packing material and intensifying the transport of mass and energy [8]. The utilization of waste materials in packing of cooling tower could moderate the problem of excessive consumption of conventional materials as well as reduce the amount of waste generated. The use of waste will helps to provide environmental protection and cost reduction.
Urge of usage evaporative cooling that is more economical consistently rising for highly water and energy efficient due to the increasing energy costs and water scarcity [6]. Cooling towers are one of the most widely equipment used in cooling systems that represent a relatively inexpensive and dependable equipment in removing heat. Small scale cooling towers are designed to handle water streams for regular pipelines as in residence, laboratory and minor projects [9]. Laboratory scale of cooling water is used to study the principles of cooling tower operation. It serves as a conjunction of a residential size water heater to simulate a cooling tower used to provide cool water to an industrial process. The laboratory cooling tower used as recycled system to cooled water that discard from water distiller and recycled back to the process.

2 Material and methods

2.1 Materials

2.1.1 Chemicals
Hydrochloric acid, HCl were purchased from Fisher Pte Ltd and Sodium hydroxide, NaOH were purchased from Sigma Aldrich Corporation.

2.1.2 Packing materials
Cockle shells were collected from around beach area at Kuala Perlis, Perlis. The shells collected were rinsed with water to remove dirt and sand. HDPE tube was used for enhanced wettability use as packing material in countercurrent flow cooling tower.

2.2 Methods

2.2.1 Pretreatment of seashell
The surface of Cockle shells was undergoing pretreatment process before it was used as packing material. Pretreatment process used to clean the shells and remove any impurities along with collected shell [10]. The Cockle shell collected was rinse with water to remove dirt and impurities. Then, the shell was soaked in 0.5 M of HCl solution overnight and after that was rinse with distilled water for three times. Then, the shell was soaked again in 1 M of NaOH solution and leave for overnight. Then the shell was rinse with distilled water for three times and dried with room temperature. The acidic and alkaline which is HCl and NaOH solution was used for surface cleaning and neutralization of the seashell [10].

2.2.2 Seashell properties

2.2.2.1 Size measurements
Size measurement for seashell involved three linear dimensions which is thickness (T), length (L) and width (W). The dimensions were measured by using vernier caliper. The size of the shell can be obtained by a relationship involving equivalent diameter, \( D_e \), sphericity \( \phi \) and aspect ratio which is the ratio between widths to length of shell [11].

\[
D_e = (LWT)^{1/3} \tag{1}
\]
\[
\phi = \frac{D_e}{L} \tag{2}
\]
\[
\text{Aspect ratio} = \frac{W}{L} \tag{3}
\]

2.2.2.2 Density

In order to get the density, \( \rho \) of seashell, the true density, \( \rho_t \) and bulk density, \( \rho_b \) of shell were determined. True density of shell are obtained where sample of shell was weighed in air with mass, \( M_a \).
and emptied into a measuring cylinder containing water where $M_w$ is the weight of water used [11]. The test was repeated for at least three times and obtains the average value.

$$\rho_t = \left(\frac{M_a}{M_a - M_w}\right) \rho_w \tag{4}$$

The bulk density, $\rho_b$ of shell was determined by weighing sample shell and record value obtain as $M$ and emptied from a constant height into a measuring cylinder, a container of known volume, $V$ [11].

$$\rho_b = \frac{M}{V} \tag{5}$$

2.2.2.3 Effective porosity

The porosity is also known as the packing factor that corresponding with the true density and bulb density of shell [11]. By using following equation, porosity of shell was determined.

$$PF = 100 \left(\frac{\rho_b}{\rho_t}\right) \tag{6}$$

2.3 Working procedures of cooling tower

The laboratory scale cooling tower with seashells and HDPE pipe packing was used. Figure 1 shows the schematic diagram of laboratory cooling tower at School of Bioprocess Engineering. The structural components mainly includes cooling tower fills with seashells packing, submersible pump, electric fan, water shower, reservoir, hose, water supply, control valve, condenser, water distiller, air distribution space, thermocouple, TDS meter, thermometer, anemometer and flow meter.

![Schematic diagram of laboratory cooling tower](image_url)

**Figure 1:** Schematic diagram of laboratory cooling tower

The working procedure of cooling tower are starts when hot water from the water distiller at 90-80°C is measured as inlet water temperature, $T_{L1}$, and flows through a hose to the top of cooling tower, where it is then sprinkled onto the packed-bed material (seashells) by a water shower and flows down across the bed. Ambient air enters the unit at the bottom by a 12V 80W electric fan so that a counter current flow is established throughout the bed. The air from electric fan flows into the air distribution area through air inlet and measured as the dry and wet bulb temperatures, $T_{db1}$ and $T_{wb1}$ of the air before...
entering the packing. This air interacts with the water resulting in a net transfer of heat from the water to the air by the vaporization of some of the water [12]. Before the air is discharged into the atmosphere, the outlet dry and wet bulb temperatures, \( T_{db2} \) and \( T_{wb2} \) of the air was measured. The cooled water then flows into the reservoir and measured as outlet water temperature, \( T_{L2} \). The reservoir provides any make-up water required to replenish that lost to evaporation and connected by a hose to the water supply inside the laboratory [13]. The level of the reservoir was kept constant by a float valve which controls the flow of the make-up water from the water supply line. From the reservoir, the water flows to the pump that returns the cooled water back to the condenser of water distiller unit.

2.3.1 Cooling tower performance
2.3.1.1 Cooling tower efficiency

The cooling tower efficiency is the ratio of range to the ideal range and closely related to the range and approach of the tower [1].

\[
Efficiency (e) = \frac{Range (R)}{Range (R) - Approach (A)} \times 100\% 
\]  

(7)

2.4 Heat and mass transfer phenomena in cooling tower
2.4.1 Relationship of water to air flow rate ratio

The laboratory scale cooling tower were operated following the working procedure. The fan frequency converter is adjusted to change the inlet air flow rate. Anemometer is used to measure the wind speed of measuring points in the cross section of the outlet flow of the tower. Water to air flow rate ratio, \( L/G \) of a cooling tower is the ratio between water and the air mass flow rate [3]. The relationship between \( L/G \) ratio were determined by using the temperature of water entering and leaving the tower. The relation of \( L/G \) ratio can be derived from the equation below [1].

\[
G (H_{y2} - H_{y1}) = L_{CL} (T_{L2} - T_{L1}) 
\]  

(8)

In order to study the effect of circulation rate, the inlet air dry and wet bulb temperatures of the cooling tower were remains unchanged [12]. In this experiment, the circulation rate and outlet temperature of water was independent variables. As for outlet temperature of water, considering the convenience adjusting of parameters. The change was achieved by adjusting the fan speed and controlling circulation rate. The distilled water production rate was calculated by measuring distilled water produce over time for each outlet temperature of water. This experimental research consists of three levels circulation rate and outlet temperature of water in five levels. The circulation rate takes in 13.33 g/L, 14.44 g/L and 15.55 g/L and outlet temperature of water takes in 35°C, 36°C, 37°C, 38°C and 39°C.

2.4.2 Cooling characteristic coefficient

The heat transfer rate in cooling tower was determined by the difference between enthalpy of air in bulk water temperature and enthalpy of air [3]. The heat dissipating capacity of water is equal to the heat absorbing capacity of air in the packing. The integration of following equation is solved numerically in order to obtain cooling characteristic coefficient, \( KaV/L \) where \( K \) is mass transfer coefficient, \( a \) is the area of heat and mass transfer and \( V \) is volume of exchange core [12].

\[
\int_{0}^{V} \frac{KaV}{L} dt = \int_{T_{1}}^{T_{2}} \frac{c_{p}}{H_{y2} - H_{I}} dt = \frac{KaV}{L} 
\]  

(9)
\[
\frac{K\alpha V}{L} \cong \frac{T_1 - T_2}{4} \left( \frac{1}{\Delta h_1} + \frac{1}{\Delta h_2} + \frac{1}{\Delta h_3} + \frac{1}{\Delta h_4} \right) 
\]

(10)

3 Result and discussion

3.1 Seashell properties

Table 1 shows the physical properties of cockle shells used as packing material inside cooling tower. A few samples were chosen and selected according to the average range size of shell. The equivalent diameter is within the range of 14 mm to 15 mm. According to the population of cockle found in marine coast Malaysia, the cockle shell can grew to 37 mm but the average size usually found were within the range of 15 mm to 16mm in size [14]. Cockle shell used inside the cooling tower were chosen within the average size of cockle shell found in Malaysia due to wide range of shell that can be found and collected. Larger size of shell was considered as unsuitable since of the less population of shell causing for high demand.

Based on Table 1, the calculation for sphericity (\(\varnothing\)) and aspect ratio of shell shown almost the same result for each of the sample tested. The table indicated that the highest sphericity (\(\varnothing\)) is 0.380 for sample 4 but the highest aspect ratio is 0.885 for sample 6. Theoretically, the result were influenced by the length, L of shell thus the shortest length of shell, 40.0 mm for sample 4 gives the highest sphericity (\(\varnothing\)) while the longest length of shell, 42.5 mm for sample 6 gives the highest aspect ratio.

Table 1: Size parameter of cockle shell

| Sample | Equivalent diameter, \(D_e\) (mm) | Sphericity, \(\varnothing\) | Aspect ratio |
|--------|----------------------------------|--------------------------|--------------|
| 1      | 14.871                           | 0.366                    | 0.798        |
| 2      | 14.765                           | 0.362                    | 0.841        |
| 3      | 14.658                           | 0.358                    | 0.856        |
| 4      | 15.182                           | 0.380                    | 0.875        |
| 5      | 15.451                           | 0.364                    | 0.821        |
| 6      | 14.972                           | 0.352                    | 0.885        |

3.2 Cooling tower performance

The laboratory cooling tower was set up and conducted using two different packing materials. The performance parameters of cooling tower operation including the inlet and outlet temperature of water, wet bulb and dry bulb temperature, cooling range, approach and efficiency of tower were calculated.

Figure 2: The outlet temperature of water with time for HDPE pipe and seashell packing
Besides that, the outlet temperature of water for treated seashell packing is much lower as compared to the outlet temperature of water for treated HDPE pipe. Seashell packing undergoes acid and alkali treatment for surface cleaning and neutralization [10]. After treatment process, seashell packing shown improvement in cooling and increase the dispersion of water droplets thus reduces the outlet temperature of water. Nevertheless, outlet temperature of water for HDPE packing also showed decreasing after etching treatment using chromic acid. The treatment proven to enhance hydrophilic and wettability surface of pipe thus increased the dispersion water droplets [16]. However, treated seashell packing had lower cooling water temperature than treated HDPE pipe packing. Hence, the overall performance shows that seashell is more effective than HDPE pipe as packing material of packed bed cooling tower.

Figure 3 shows the cooling range, R with time for both packing materials. The figure shows that the cooling range for treated seashell is the highest compared to other packing materials. The average value of cooling range, R for untreated and treated seashell packing is 38.29°C and 46.16°C while for untreated and treated HDPE pipe packing is 33.83°C and 37.97°C respectively. The higher cooling water range indicated that higher inlet temperature of water and lower outlet temperature of water. The average inlet temperature of water using untreated and treated seashell packing is 74.46°C and 81.69°C while for untreated and treated HDPE pipe packing is 75.35°C and 76.07°C respectively. Thus, higher cooling range proves as better cooling to reduce water temperature.

Figure 3: Cooling range with time for HDPE pipe and seashell packing

Figure 4 shows the cooling tower efficiency, e with cooling water range, R of tower using treated HPDE pipe and seashell packing. The cooling tower efficiency was calculated and results shown that cooling tower efficiency increased gradually with increases of cooling water range. It is observed that treated seashell packing provided higher efficiency at 84% with higher cooling range of 47.5°C compared to treated HDPE pipe packing which 81% cooling efficiency with 40°C of cooling range temperature. This results is affected due to the large contact area for seashell packing which provide longer contact time between air and water causing the heat and mass transfer more intense which resulting in a better efficiency of cooling tower [12].
Figure 4: Efficiency with range treated HDPE pipe and seashell packing

Figure 5 shows the total dissolved solid (TDS) of water in cooling tower operation using treated seashell and HDPE pipe packing. It is apparent that the value of TDS measurement increased gradually with time for both packing material. This indicated that seashell packing have same effect of TDS value as HDPE pipe. As a portion of water flow from condenser are lost by evaporation through cooling process, the concentration of dissolved solids increases because of the solids are left behind as the liquid evaporates [17].

The optimum TDS value for water hardness is less than 180 ppm [18]. The highest TDS value for seashell and HDPE pipe packing is 406 ppm and 469 ppm respectively. Based on the figure, TDS value exceed 180 ppm within 4 hours and replenishment for water reservoir every 4 hours is required to control and reduces the TDS of water.

Figure 5: Total dissolved solid (TDS) with time using treated packing

3.3 Effect of circulation rate and cooling water temperature

Figure 6 shows the distilled water production rate with cooling range using treated seashell as packing material. It is observed that the cooling ranges are increasing as the distilled water production rate increase. The higher distilled water production rate is at 13.33 g/s of circulation rate which is 1.244 g/s with higher cooling range at 45.1°C. The production rate of distilled water gradually increase
for both 14.44 g/s and 13.33 g/s of circulation rate, however 13.33 g/s is more consistency produce distilled water. In the other hand, it can be observed that there is some degree of difficulty in production of distilled water at 15.55 g/s of circulation rate. The distilled water production rate reached at 1.232 g/s however; there is a reduction in distilled water production rate as the cooling range increasing. The water flow rate is faster causing the evaporation rate of water inconsistently increase and lower the cooling range. Thus, 13.33 g/s and 14.44 g/s circulation rate give stable trend if compared to the 15.55 g/s due to the rate flow of cooled water enter to the condenser effect to the cooling range.

**Figure 6:** Distilled water production rate with cooling range using treated seashell packing

Figure 7 shows the cooling tower efficiency with cooling range using treated seashell as packing material. It is apparent from the figures that the cooling tower efficiency are increasing with increase of cooling range for 13.33 g/s and 14.44 g/s of water circulation rate. The highest efficiency is 85.09% at 13.33 g/s of water circulation rate. It is found that cooling tower efficiency for 15.55 g/s have degradation at higher cooling range due to lower inlet temperature of water. The cooling tower efficiency is mainly influenced by inlet temperature of water and web bulb temperature entering the tower [12]. Thus, the lower the inlet temperature of water, the lower cooling tower efficiency. The overall, water circulation rate at 13.33 g/s is most suitable flow used for the condenser in water distiller.

**Figure 7:** Cooling tower efficiency with cooling water range using treated seashell packing
4 Conclusions
In this study, transport properties of evaporative cooling using seashell packing in packed bed cooling tower have been investigated. Lab scale cooling tower were filled with seashell and HDPE pipe packing and cooling performance were compared before and after treatment of packing material. The results show that, seashell packing have large surface area and provided wide contact area and longer retention time during cooling tower operation compared to HDPE pipe packing. The range of equivalent diameter is between 14 mm to 15 mm. The percentage of porosity was low which is 20.35%, 21.45% and 22.16%. Treated seashell packing has better and more effective cooling compared to untreated and both untreated and treated HDPE pipe packing. The outlet temperature of water achieved is between 32.7°C to 37.9°C. It had higher cooling water range and lower cooling approach. Seashell packing provided higher efficiency with higher cooling range than HDPE pipe packing. The results obtained at different circulation rate, 13.33 g/s, 14.44 g/s and 15.55 g/s. The cooling water range (R) and cooling tower efficiency (e) decrease with increasing of L/G ratio. The higher cooling water range, R and efficiency, are obtained at lower L/G ratio. Circulate water rate for 13.33 g/s have the highest cooling water range and efficiency of 45.1°C and 84.93% respectively at 0.67 of L/G ratio compared to other circulation water rate. The heat transfer coefficient, Ka/L decreases with increasing of L/G ratio with lower circulation rate. The highest cooling characteristic coefficient is 1.389 with 0.67 of L/G ratio at 13.33 g/s circulation water rate. Circulation rate of 13.33 g/s is most suitable circulate water flow rate used to recycle water back to condenser. As a conclusion, the cooling tower filled with treated seashell packing is more effective and provided a greater water cooling capacity which leads to better performance of heat and mass transfer characteristics than HDPE pipe as packing material of packed bed cooling tower. Thus, this operation can contribute significantly for water saving and economics.

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