Experimental study of seawater evaporation using natural convection principles

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Abstract. Evaporation of seawater into the air is a phenomenon that involves heat and mass transfer. The process of evaporation of water can be divided into different categories based on the flow regime, such as natural convection. The rate of evaporation that occurs in seawater without treatment or is called natural convection method only takes into account the density difference between the existing fluids. The method has been tested in natural convection with the result that the highest rate of evaporation of water in the tub is directly proportional to the radiation received. It was found that experimental result have a good agreement.

1. Introduction

The production of salt that uses seawater as the main raw material is something that humans need to obtain consumption salt or additional raw materials for various industries. Based on data from the Coordinating Ministry for Economic Affairs, the total national salt production in Indonesia in 2019 is 2.3 million tons and it is estimated that this production output will decrease by 14.4%. North Sumatra is one of the provinces where the need for salt every year continues to increase to reach 80 thousand tons, consisting of 42 thousand tons (52.50%) iodized salt consumption, 25 thousand tons (31.25%) salt for the consumption of salted fish, salt for the food and beverage industry consumption is 4 thousand tons (5%) and salt for the consumption of the soda industry is 9 thousand tons (11.25%).

Evaporation of seawater into the air is a phenomenon that involves heat and mass transfer. This evaporation process is also very important in applications such as swimming pools, solar panels, drying systems, and air cooling. The process of evaporation of water can be divided into different categories based on the flow regime, such as natural convection. The mechanism used is the convection mechanism, namely natural convection which will affect the rate of evaporation [1].

In this study, the rate of seawater evaporation or mass transfer under study involves the effect of mass diffusivity. This effect gives a calculated result of the diffusion coefficient for salt in seawater. The main driving mechanism for mass diffusion is the concentration gradient, and mass diffusion due to the concentration gradient is known as ordinary diffusion. However, diffusion can also be caused by other effects, such as a temperature gradient in the media that can cause thermal diffusion and a pressure gradient can cause diffusion of pressure [2].
The Nusselt and Sherwood numbers are a function of the Rayleigh number which for the case of mass transfer with a vertical and horizontal cross-sectional area, is used to determine the convection mass transfer coefficient for evaporation [3]. In this research, the tool used for the testing and analysis process is in the form of a horizontal rectangle. So that the Nusselt and Sherwood numbers can be used the purposes of analysis and calculation of the evaporation rate. For the case of natural convection, the calculation uses Grashof number [5] while for the case of forced convection the Rayleigh number is used. In general, natural convection and forced convection have a big effect on the evaporation process [6].

2. Method

2.1. Theoretical basis

The rate of evaporation is formed from a boundary layer of saturated air that forms above the water surface as a result of the irregularly received heat and the different motion of water molecules. The rate of evaporation that occurs in seawater without treatment or is called natural convection method only takes into account the density difference between the existing fluids.

![Figure 1](image.png)

**Figure 1.** A simple scheme of mass transfer and rate of evaporation with direct contact of air and water.

Figure 1 shows the actual process of evaporation and mass transfer that occurs in a thin layer of saturated air and passes through the air surface in the seawater tub. The convection that occurs is natural convection, and when air enters the tub the flow will enter through the inlet and the steam produced will be disposed of directly into the environment.

Meanwhile, the factors that affect evaporation are:

- Solar radiation.
- The ambient and water temperature.
- Environmental humidity (Relative humidity).

2.2. Geometric model

The geometry model used for the three seawater tubs uses the same size. The size can be seen in figure 2. The size of the geometry model used is 3000 mm for length, 1000 mm width, and 700 mm height. In every corner and part of the tub is supported by a frame made of iron to be able to stand on the ground.
2.3. Experimental procedures.
This study is carried out by designing seawater tubs. For tub 1 the optimal time for experiment is 12 hours, with a time range of 7.20 - 17.20. Then when approaching the afternoon and solar radiation is no longer there and the sky is getting dark, tub 1 is covered with plastic so it doesn't evaporate and the test is continued the next day by opening the plastic cover again.

2.4. Apparatus and measuring point layout
From the experimental procedure described for the three tubs above, there are data taken directly for the tubs that are used every 1 hour continuously during the experiment. Table 1 presents the details of the apparatus including the wind speed sensor, salt percentage sensor, ruler, temperature sensor of atmosphere, water and tubs, radiation and relative humidity sensor. These are used to measure wind speed, the percentage of salt in seawater, seawater level, thermocouples record the temperatures of water, environment and tubs, solar radiation density, and percentage relative humidity.
Table 1. Details of measuring apparatus used in the experiment.

| Measuring apparatus | Name of measuring instrument | Type          | Measuring range |
|---------------------|------------------------------|---------------|-----------------|
| Wind speed sensor   | Anemometer                   | GM816         | 0~30 m/s        |
| Salt percentage sensor | TDS (Total Dissolved Solids)/(Salinity meter) | C-100 | 0.00-25.00% |
| Thermocouples record the temperatures of water and tubs | Agilent data acquisition | 34972A | — |
| Radiation and relative humidity sensor | HOBO Microstation data logger | — | 1-18 hour |

2.5. Experimental setup
For the sake of improving the heat and mass transfer in the seawater tub, an less airflow is always an essential accessory for fluid motion enhancement. This is interpreted by the presence of natural convection that occurs in the tub. This study was conducted in Medan, Sumatera Utara (latitude 3.43° N and east longitude 98.44° E). Figure 4 shows a schematic diagram for the experimental setup.

2.6. Governing equations
Some of the equations used to calculate the rate of evaporation or mass transfer, the rate of heat transfer due to evaporation, the convection heat transfer coefficient, and other calculation parameters can be seen below. The steam due to evaporation originating from seawater is considered an ideal gas in the calculation. The error given for this assumption is 2%. Then the equation is given as follows [2]:

\[ \text{Equation} \]
At the surface

\[ \rho_{v,s} = \frac{P_{v,s}}{R_v T_w} \]  
\[ \rho_{a,s} = \frac{P_{a,s}}{R_a T_w} \]  
\[ \rho_s = \rho_{v,s} + \rho_{a,s} \]  

Away from the surface

\[ \rho_{v,\infty} = \frac{P_{v,\infty}}{R_v T_\infty} \]  
\[ \rho_{a,\infty} = \frac{P_{a,\infty}}{R_a T_\infty} \]  
\[ \rho_\infty = \rho_{v,\infty} + \rho_{a,\infty} \]  

In the above questions, \( \rho_{v,s}, \rho_{a,s}, \rho_s, \rho_{v,\infty}, \rho_{a,\infty}, \rho_\infty \) are densities of the water vapor, dry air, mixture at the water-air interface, vapor away from the surface, mixture at the water-air far from the surface in [kg/m\(^3\)], \( P_{v,s}, P_{a,s} [kPa] \), is vapor pressure at the surface, \( P_{a,\infty} [kPa] \), is dry air pressure at the surface, \( P_{v,\infty} [kPa] \), is vapor pressure of air far from the surface, \( R_v [0.4615 \, kPa \cdot m^3/kg \cdot K] \), \( R_a [0.287 \, kPa \cdot m^3/kg \cdot K] \), \( T_w [K] \) and \( T_\infty [K] \), is gas constant for steam-water, gas constant for dry air, temperature water and temperature ambient.

The vapor pressure (\( P_{v,\infty} \)) of air far from the water surface is calculated using the correlation.

\[ P_{v,\infty} = \phi P_{sat} \]  

where, \( \phi \) and \( P_{sat} [kPa] \), are relative humidity and saturation pressure.

Then using densities (instead of temperatures) since the mixture is not homogeneous, the Grashof number is determined to be.

\[ Gr = \frac{g(\rho_\infty - \rho_s) L^3}{\rho v^2} \]  

where, \( g [9.81 \, m/s^2] \), \( L \) (m), \( \rho \) [kg/m\(^3\)], and \( v \) [m\(^2\)/s], are gravitational acceleration, length of the geometry, average of density and kinematic viscosity. Recognizing that this is natural convection problem, the Nusselt number (Nu) and the convection heat transfer coefficients (h\(_{conv}\)) are determined to be.

\[ Nu = 0.15 \left( Gr Pr \right)^{1/3} \]  
\[ h_{conv} = \frac{Nu k}{L} \]  

where, \( k \) [W/m \cdot °C] and \( Pr \) are thermal conductivity and Prandtl number.

Then the heat transfer of convection (\( Q_{conv} \)) and mass diffusion (\( D_{AB} \)) are given by equations below.

\[ Q_{conv} = h_{conv} \times A_s \left( T_w - T_m \right) \]  
\[ D_{AB} = D_{salt-water} = 1.87 \times 10^{-10} \times \frac{T^{2.072}}{\rho} \]  

where, \( h_{conv} \) [W/m \cdot °C] and \( A_s \) [m\(^2\)] are convection heat transfer coefficients and area.

The corresponding quantity in mass convection is the dimensionless Schmidt number (Sc), defined as.
The corresponding quantity in mass convection is the dimensionless Sherwood number \((\text{Sh})\), defined as:

\[
\text{Sh} = 0.15 (\text{Gr} \cdot \text{Sc})^{1/3}
\]

The mass transfer coefficient \((h_{mass})\) defined as:

\[
h_{mass} = \frac{\text{Sh} \cdot D_{AB}}{L}
\]

Finally, the evaporation rate \((\dot{m}_v)\) and the rate of heat transfer by evaporation \((Q_{evap})\) become:

\[
\dot{m}_v = h_{mass} \cdot A_s \left( \rho_{v,s} - \rho_{v,\infty} \right)
\]

\[
Q_{evap} = \dot{m}_v \cdot h_{fg}
\]

where, \(h_{fg} \) [kJ/kg] and \(h_{mass} \) [m/s] are latent heat of water and mass transfer coefficient.

3. Result

3.1 Evaporation rate of tub

The result of evaporation rate of water for tub is shown in figure 5. Figure 5(a) show the evaporation rate of water for first day and figure 5(b) show the evaporation rate of water in the second days.

\[S_c = \frac{\nu}{D_{AB}}\] (13)

\[
\text{Sh} = 0.15(\text{Gr Sc})^{1/3}
\] (14)

\[
h_{mass} = \frac{\text{Sh} \cdot D_{AB}}{L}
\] (15)

\[
\dot{m}_v = h_{mass} \cdot A_s \left( \rho_{v,s} - \rho_{v,\infty} \right)
\] (16)

\[
Q_{evap} = \dot{m}_v \cdot h_{fg}
\] (17)

3.2 Radiation

Radiation intensity carved based on the HOBO measuring instrument for 2 days vs radiation per hour is shown in figure 6.
3.3 Water level for tub

Water level for tub during 2 days shown in figure 7.

4. Conclusion

In the present study concluded that. The highest rate of evaporation of water in the tub is directly proportional to the radiation received. In the method, to find out that how much seawater evaporation rate is obtained in one hour. The main conclusion is that the proposed method can be used to solve heat and mass transfer (evaporation rate) problem for seawater. It is suggested to employ the following method to solve experimental solution for evaporation rate of seawater with use the tub.

References

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