Modelling of Saltwater Evaporation using WAIV

Henrietta¹, H Santoso¹ and J R Witono¹

¹Department of Chemical Engineering, Parahyangan Catholic University, Jalan Ciumberuit 94, Bandung 40141, INDONESIA

E-mail: hsantoso@unpar.ac.id

Abstract. Indonesia as a country, which has the second longest coastline in the world, has a big opportunity to improve its salt production. The productivity of salt production in Indonesia from 2011 to 2014 was around 67, 92, 40, and 90 tons/ha/year, respectively. This low productivity was mainly due to the method of salt production used, which was very traditional and depended mainly on the availability of solar energy for evaporation. The longer the dry season was, the higher the salt production would be in that year, and vice versa. Since the performance of evaporation process holds the key to the improvement of productivity of salt production, it is important to study a method that can speed up the evaporation process in the salt production. One of the recent methods that can be used to achieve that purpose is the Wind Aided Intensified Evaporation (WAIV) process. In this study, a model for saltwater evaporation in a WAIV unit using Harbeck equation is proposed. Two set of data for saltwater evaporation in a WAIV unit was extracted from literature. The first set of data was used to obtain the parameters of Harbeck equation by minimizing the sum of error squares of the cumulative evaporation rate in a WAIV unit compared to its model. The second set of data was used to validate the model. It is found that the proposed model can estimate the evaporation rate in a WAIV unit based on the surrounding climate data reasonably well.

1. Introduction

Indonesia has the second longest coastline in the world. With this geographical resource, Indonesia is expected to be able to fulfil its domestic demands for salts. However, until now Indonesia still imports salts from overseas. The main reason for this problem is the low productivity of salt production in Indonesia. Table 1 shows the salt production data from 2011 to 2014 [1].

| Year | 2011       | 2012       | 2013       | 2014       |
|------|------------|------------|------------|------------|
| Production (tons/year) | 1,623,786  | 2,473,716  | 1,163,608  | 2,502,891  |
| Land areas (ha)     | 20,066     | 22,632     | 25,098     | 23,411     |
| Productivity (tons/ha/year) | 67.27      | 91.70      | 39.62      | 89.72      |
| Dry season (months) | 4          | 5          | 2          | 5          |
| Demands (tons)      | 3,228,750  | 3,270,086  | 3,573,954  | 3,611,990  |

Table 1. Salt production in Indonesia from 2011 to 2014.
From Table 1, the domestic demands for salts in Indonesia increased every year while the productivity of salt production was low and unstable. This low and unstable productivity was due to the very traditional method used in the salt production, which relied heavily on the weather conditions for evaporating the seawater. Hence, the longer the dry season was in a particular year, the higher the salt production would be, and vice versa.

In general, the evaporation rate of saltwater is affected by the climatic conditions (i.e. temperature, humidity, solar radiation and wind speed), the properties of saltwater (i.e., concentration and composition of saltwater) and the size of saltwater body [2]. The climatic conditions and the properties of saltwater depend on the geographical location and the nature of saltwater available in that location. These factors are practically given by nature and cannot be modified easily. On the other hand, the size of saltwater body is a factor that can be modified using a certain method which in turn can increase the evaporation rate significantly. One of the recent methods that can be used to achieve that purpose is the Wind Aided Intensified Evaporation (WAIV) process.

The Wind Aided Intensified Evaporation (WAIV) process is a process that uses wind energy to increase the evaporation rate of liquid. The WAIV unit consists of a structure that holds several vertically hung hydrophilic sheets that serve as an enhanced surface area for evaporation. As the liquid flows down and spreads slowly on the hydrophilic sheets, it contacts with the wind blowing pass the sheets and evaporates with a significantly higher evaporation rate per footprint area compare to the traditional evaporation pond [3].

In this study, a model for saltwater evaporation in a WAIV unit using Harbeck equation is proposed. Two set of data for saltwater evaporation in a WAIV unit was extracted from literature. The first set of data was used to obtain the parameters of Harbeck equation by minimizing the sum of error squares of the cumulative evaporation rate in a WAIV unit compared to its model. The second set of data was used to validate the model.

2. Methodology
In this study the saltwater evaporation in a WAIV unit was modelled using the mass transfer model. The mass transfer model is one of the oldest models that are commonly used to model water evaporation. This model has a simple form. The parameters of model can be easily determined. The model also can provide a reasonably good result. The mass transfer model for free water surface can be written as follows [4]:

$$ E = C (e_s - e_a) $$

where $E$ is the free water surface evaporation rate (mm day$^{-1}$), $e_s$ is the saturated vapour pressure at the temperature of the water surface (mbar), $e_a$ is the vapour pressure in the air (mbar), and $C$ is a coefficient that is dependent on the wind speed, the size of water body, the roughness of water surface, the thermally induces turbulence, the atmospheric stability, the barometric pressure, the density and the kinematic viscosity of the air [4, 5, 6].

The mass transfer driving force for evaporation is due to the higher vapour pressure of the water surface compared to the vapour pressure of the surrounding air [7]. If the evaporation rate can be assumed to be proportional to the wind speed $u$ (mm day$^{-1}$) [5], Equation 1 can be expressed as:

$$ E = N u (e_s - e_a) $$

where coefficient $N$ is given by the following correlation:

$$ N = 3.367 \times 10^{-9} \times A^{-0.05} $$

where $A$ is the size of water body ($m^2$). Equation 2 is known as Harbeck equation. The correlation given in Equation 3 holds for water body of the size between 4000 m$^2$ and 120 km$^2$ [7].
Saturated vapour pressure $e^* \text{(mbar)}$ at the temperature of the water surface and at the temperature of the air can be calculated using the modified Clausius-Clapeyron equation where temperature $T$ are expressed in degree Kelvin [8]:

$$\ln e^* = 53.67957 - \frac{6743.769}{T} - 4.8451 \ln (T) \quad (4)$$

For evaporation of saltwater in the WAIV process, the mass transfer driving force for evaporation is the difference between the saturated vapour pressure of the saltwater at the wetted surface and the vapour pressure of the surrounding air blowing pass the wetted surface. The temperature at the surface of the falling saltwater can be estimated using the wet bulb temperature of the air moving through the WAIV array. The mass transfer driving force for evaporation ($e_s - e_a$) then can be calculated using the following equations [8]:

$$(e_s - e_a) = \left[ (e^*_{T_{WB}}) \left( \frac{e}{e^*} \right)_{T_{WB}} - (e^*_{T_a})(RH) \right] \quad (5)$$

$$\left( \frac{e}{e^*} \right) = a_W \quad (6)$$

where $T_a$, $RH$, and $T_{WB}$ are the temperature, the relative humidity, and the wet bulb temperature of the air moving through the WAIV array, respectively while $a_W$ is the water activity of the saltwater.

The WAIV data used in this study was taken from the demonstration trial conducted on the WAIV module at Queensland, Australia [3]. The WAIV module uses around 2850 m$^2$ sheets, thus has approximately 5700 m$^2$ wetted surface for evaporation. The dimensions of the full scale WAIV module is illustrated in Figure 1.

![Figure 1: The WAIV module [3](image)](image)

The feed water for the WAIV unit was taken from the reverse osmosis reject saltwater of desalination plant. The composition of the feed water was shown on Table 2. The evaporation performance of the WAIV unit were observed for 24 hours. The results from February 21$^{st}$, 2013 and and November 20$^{th}$, 2012 were plotted in the graphs shown in Figure 2 and Figure 3 [3].
Table 2. The feed water composition for WAIV unit [3].

| Parameter                      | Unit | Min  | Max  | Average |
|--------------------------------|------|------|------|---------|
| pH                             |      | 9.37 | 9.62 | 9.49    |
| Temperature                    | °C   | 18.8 | 30.9 | 25.1    |
| Total Alkalinity (as CaCO₃)    | mg/L | 2160 | 3110 | 2593    |
| Calcium (Ca)                   | mg/L | 3    | 13   | 7       |
| Magnesium (Mg)                 | mg/L | 2    | 6    | 4       |
| Sodium (Na)                    | mg/L | 2820 | 4430 | 3513    |
| Potassium (K)                  | mg/L | 50   | 89   | 65      |
| Chloride (Cl)                  | mg/L | 2970 | 5260 | 3995    |
| Sulfate (SO₄²⁻)                | mg/L | 85   | 524  | 275     |
| Boron (B)                      | mg/L | 0.75 | 1.02 | 0.87    |
| Fluoride (F)                   | mg/L | 4.9  | 9.7  | 8.6     |
| Total Dissolved Solid (TDS)    | mg/L | 8230 | 11200| 9648    |
| Electrical Conductivity (EC)   | mS/cm| 13000| 18500| 15300   |

Figure 2. Evaporation performance of the WAIV unit on February 21st, 2013 [3].

Figure 3. Evaporation performance of the WAIV unit on November 20th, 2012 [3].
The evaporation performance data of the WAIV unit on February 21st, 2013 was used to obtain the parameters of Harbeck equation by minimizing the sum of error squares of the cumulative evaporation rate in a WAIV unit compared to its model. The evaporation performance data of the WAIV unit on November 20th, 2012 was used to validate the model.

3. Results and discussion
The parameters of Harbeck equation obtained by minimizing the sum of error squares of the cumulative evaporation rate of the WAIV unit on February 21st, 2013 is given in Equation 7.

$$N = 3.719 \times 10^{-9} \times A^{-0.0459}$$  \hspace{1cm} (7)

The coefficient of determination ($R^2$) for the model is 0.9074.

![Figure 4](image1.png)

**Figure 4.** The comparison between the actual cumulative evaporation rate on February 21st, 2013 (blue dot) and Harbeck model calculated using the parameters given by Equation 3 (red line) the parameters given by Equation 7 (black line).

![Figure 5](image2.png)

**Figure 5.** The comparison between the actual cumulative evaporation rate on November 20th, 2012 (blue dot) and Harbeck model calculated using the parameters given by Equation 3 (red line) the parameters given by Equation 7 (black line).
Figure 4 shows the comparison between the actual cumulative evaporation rate in the WAIV unit on February 21st, 2013 shown as blue dot with the predicted cumulative evaporation rate calculated using Harbeck model. The red line is the cumulative evaporation rate calculated using Harbeck equation with the parameters given by Equation 3 while the black line is the cumulative evaporation rate calculated using Harbeck equation with the parameters given by Equation 7. It can be seen that the Harbeck model calculated using the parameters given by Equation 7 is slightly better that the Harbeck model calculated using the parameters given by Equation 3.

The parameters of Harbeck model given in Equation 3 and 7 are then tested to predict the cumulative evaporation rate in the WAIV unit on November 20th, 2012. Figure 5 shows the comparison between the actual cumulative evaporation rate in the WAIV unit on November 20th, 2012 shown as blue dot with the predicted cumulative evaporation rate calculated using Harbeck model with the red line represents the cumulative evaporation rate calculated using the parameters given by Equation 3 and the black line represents the cumulative evaporation rate calculated using the parameters given by Equation 7. The Harbeck model calculated using the parameters given by Equation 7 again is slightly better that the Harbeck model calculated using the parameters given by Equation 3.

The Harbeck model calculated using the parameters given by Equation 3 tends to give an underestimate prediction of the cumulative evaporation rate in the WAIV unit. In the WAIV unit, the evaporating saltwater is not static but continuously flowing. Therefore, the evaporation rate is slightly higher than the evaporation rate for conventional pond with a similar size of evaporation surface.

4. Conclusion
A model for saltwater evaporation in a WAIV unit has been developed. This model is based on Harbeck equation. The parameter for this model is obtained by minimizing the sum of error squares of the cumulative evaporation rate in a WAIV unit. When tested using the actual cumulative evaporation rate in the WAIV unit, the proposed model can estimate the evaporation rate in the WAIV unit reasonably well using the surrounding climate data.

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