Analysis of Evaporation Data from an Enclosed Pond Ventilated by Solar Chimney

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Abstract. Water removal from industrial effluent streams, salt cultivation farms, biodiesel conversion process from microalgae, and food drying by using pond evaporation with a higher rate of mass flux can be considered as an economical and energy saving scheme. The objective of this study is to utilize a method of enhancing the pond natural evaporation rate to improve the sustainability of industrial operations. In this study, canopied ventilation technology was employed to enhance the pond evaporation. This technology caused the natural draft enhancement by installing a wire mesh on the chimney. The unit consists of a solar irradiated solid wall chimney installed on the evaporation pan as a means to increase the evaporation rate of existing water body. Experiments were conducted in square pan at the same size as class-A pan in three configurations. The experimental result showed that the evaporation flux from configuration YY (Solar chimney with wire mesh) averaged at 13 percent more than configuration NN (Open Pond) and at 20 percent more than configuration YN (Solar chimney without wire mesh). Counter to intuition, for configuration YN the evaporation averaged at 6 percent lower than the evaporation from the open pond configuration. The pan evaporation flux was found to be predicted satisfactorily by the Rayner[5] evaporation model showing it is able to aggregate reasonably the effect of changing characteristics of the three configurations in terms of net radiation, vapor pressure deficit and natural ventilation draft.

1. Introduction
Evaporation is one of the important processes in many fields ranging from hydrology and agriculture, to food science and engineering applications. Methods of enhancing the practice of natural evaporation in industrial operations employing the process will improve sustainability. The evaporation rate can be increased through a number of mechanical and chemical means, but notably raising the water temperature, increasing the exposed surface area (Ahmed et al.[1]). Jhajharia et al.[2] examined the influence of different meteorological parameters on pan evaporation at Agartala, Bangladesh and using the linear and exponential methods concluded that the wind speed and mean temperature have a positive influence on pan evaporation. Any obstructions, near the pan, may alter the wind structure over the pan site and increase deposition of foreign matter (Pereira[3]). Roderick et al.[4] and Rayner[5] suggested that the changes in wind speed were the most important cause for the decline of pan evaporation rates. Liu et al.[6] concluded that air temperature variation dominated the change in pan evaporation, which offset the effect of wind speed and led to the increase in the pan evaporation.

This research investigates an enclosed pond evaporation by solar irradiated ventilation through an enhanced chimney in East Malaysia. The augmentation involves the incorporation of a solar chimney ventilation technique using wire mesh developed by Chu et al[7] in a test facility consisting of a solar irradiated ventilated class-A pan (SINVAP).
2. Factors influencing pond natural evaporation

Chow et al. [8] stated that the mechanism of transporting the vapor from the water surface plays a great role in the phenomenon of evaporation from open water body. To estimate evaporation properly, meteorological variables are required, such as net radiation, wind speed, relative humidity and air temperature have been widely used (Shuttleworth [9]). According to Liu and Xia [10], the rate of evaporation is most responsive to net radiation, followed by relative humidity, air temperature and wind speed. Smith and Lavis [11] indicated that water temperature is one of the most important factors for evaporation. The existing vapor pressure gradient between the water surface and air above is considered the main driving force in the evaporation process (Jackman and Yotsukura [12]). Vapor pressure deficit (VPD) is the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated.

The earliest water surface evaporation model is that of Penman [13], consisting of vapour pressure deficit and wind speed as parameters. Thom et al.’s [14] pan evaporation model added a wind function for when the wind speeds were only in the range of 0 to 3 m/s. Rayner [5], based on the field measurements in Australia, then proposed another wind function for higher wind speed.

3. Experimental Facility

The evaporation process took place in a Class-A pan as specified by the National Weather Service, U.S.A., modified with a square instead of a round shape. The pan evaporation data were completed for three configurations during 26th May to 7th July, 2015 at UMS. A square shaped pan was used to observe the water evaporation at 6.0367°N; 116.1186°E. This latitude locates Universiti Malaysia Sabah (UMS). The observation had been carried out daily 8:00am to 5:00pm. The summary of the experimental pan configuration is shown in Table 1.

| Conf. | Pan structure | Solar Chimney Ventilation | Wire mesh |
|-------|---------------|----------------------------|-----------|
|      | G.I. sheet    | Length (mm) | Height (mm) |                      |            |
| NN    | 0.7mm         | 600         | 254         | No                    | No         |
| YN    | 0.7mm         | 600         | 254         | Yes                   | No         |
| YY    | 0.7mm         | 600         | 254         | Yes                   | Yes        |

NN = No Chimney and no Wire Mesh, Open Pan
YN = With Chimney but no Wire Mesh
YY = With Chimney and with Wire Mesh

The experimental pans were installed on a 150 mm height wooden platform set on the ground in a grassy location at the Faculty of Engineering in Universiti Malaysia Sabah to reduce the heat exchange between the bottom wall of the pan and the soil. The photograph of the configuration NN is shown in Figure 1.

A solar chimney was used to ventilate vapor from the enclosed pan of configuration YN and configuration YY (Figure 1). A square pan was placed inside an enclosure. The topside of the enclosure was covered with a transparent plastic sheet to transmit solar energy of the radiation to the pan water. The parallel sides of the enclosure were covered by the polymer sheet to make it prevent air ventilation to the surrounding. An inlet opening of 10.5-inch diameter was installed at the front end of the enclosure to supply fresh air from the ambient into the enclosed pan. A duct was used to convey the moist air from the enclosed pan into the solar irradiated chimney as air rose through the latter by natural convection. The schematic diagram and photograph of the configuration YN and configuration YY are shown in Figure 1 and Figure 2 respectively.
4. Experimental procedure

The pan was filled with fresh water to the datum of the pan, where the water height in the pan was 200 mm for each run of all configurations. Referring to Figure 1, the ambient cold air entered in the enclosed pan by the combined effect of wind and buoyancy pressure through the inlet opening. When the ambient air passed over the pan water, the air would be heated by solar irradiation bringing the vapor to a higher temperature. Hereafter the moist air was ready to enter the duct junction that was connecting the enclosed pan to the solar chimney. The heated moist air would rise up in the direction of the outlet opening of the chimney by natural convection. The chimney wall was made of hollow polymer sheets and could therefore insulate effectively the warm moist air rising from the evaporation pan. Due to the buoyancy effect of moist air in the chimney there was a negative pressure difference across the working height between the moist air outlet and the entry, with the consequence of the flow direction towards the chimney outlet opening.

A Kestrel 4000 pocket Weather & Environment meter, a vane anemometer (Airflow LCA 30 VA), a CMP3 Pyranometer, an Infrared thermometer, K-type thermocouples, an eight channel Cole Parmer data logger, a multi-meter and a digital depth gauge were the principal instruments. A Kestrel 4000 pocket Weather & Environment meter was installed at the 65cm height above the ground surface to measure the local wind speed over the evaporation pan. The Kestrel 4000 Weather & Environment meter also was used to collect local air temperature, local relative humidity, local atmospheric pressure and local elevation. The vane anemometer was installed at the inlet duct of the enclosed pan to measure the average air flow through the enclosed pan. A CMP3 Pyranometer was used to measure the net solar energy incidence to the pan water. The change of water level in the pan through evaporation was measured by a digital depth gauge. The infrared thermocouple was used to measure the water surface temperature. Two sets of combination of four thermocouples were located at the outlet of chimney to measure the average outlet air temperature covering approximately equal segments of the cross-sectional flow area.
### Table 2: Instruments range and accuracy

| Instrument                  | Parameter            | Range         | Resolution | Accuracy                  |
|-----------------------------|----------------------|---------------|------------|---------------------------|
| Kestrel 4000                | Wind speed           | 0.6 to 60 m/s | 0.1 m/s    | 3% of reading             |
|                             | Ambient temperature  | -10 to 55 °C  | 0.1 °C     | 0.5 °C                    |
|                             | Relative humidity    | 0 to 100%     | 0.1%RH     | 3% RH                     |
|                             | Pressure             | 10 to 1654.7 mbar | 0.1 mbar | 1 mbar                   |
| Anemometer (LCA30 VA)       | Flow velocity        | 0.25 to 30 m/s | 0.01 m/s  | 1% of reading             |
| K-type thermocouple         | Temperature          | -200 to 1250 °C | 0.01 °C   | 0.75% above 0 °C & 2% below 0 °C |
| Depth gauge                 | Water level          | 0 to 450 mm   | 0.01 mm    | Counting value composition error |
| Infrared thermometer        | Water temperature    | -32 to 380 °C | 0.1 °C     | 5% below 0 °C & 2% above 0 °C |
| CMP3 Pyranometer            | Solar radiation      | Max. irradiance 2000 W/m² | 10% of daily sums |

### 5. Results and Discussion

The prevailing ambient conditions comprising of net radiation, air temperature, wind speed, relative humidity and atmospheric pressure are typical of an equatorial climate where the net radiation ranged from 7.96 to 435 Wm⁻², air temperature from 23.6 to 37.7°C, atmospheric pressure from 100.45 kPa to 101.17 kPa, wind speed from 0.71 ms⁻¹ to 1.31 ms⁻¹ and relative humidity (RH) from 50.8% to 95.2%. The vapour pressure deficit and maximum air temperature values were always in the descending order of YY, YN and NN. Evaporation rate however, had a descending order of YY, NN and YN.

![Comparison of Evaporation Rates between YY and YN configurations](image)

The net radiation in the enclosed pan was slightly below that of the net radiation in the open ambient pan water although the trend were closely mimicking each other. The cause for the difference in net radiation values between the open pan and the YY and YN configurations was the YY and YN material radiation transmissivity. The evaporation pan in the open atmosphere received direct solar...
radiation; in contrast, the evaporation pan in the YY and YN configurations was receiving transmitted rays. This caused a small amount of radiation rays to be reflected from the transparent plastic sheet. Therefore, net radiation contribution in this study was based on the transmitted radiation.

The comparison of evaporation rates between each pan is shown in Figure 3. According to Liu and Xia [10], Chu et al [15] and Goyal [16] study, the evaporation flux from the free surface of water increased with the higher air vapor pressure deficit, higher air temperature and higher wind speed.

Figure 4 shows the Penman [13] model apparently over-predicting the evaporation rate for all configurations. Rayner [5] has performed better by far. It seems Rayner model could cope with the aggregated change of characteristics of all three configurations with the minimum percentage difference ranging between 0.6 to 52.4 while Penman was from 2.7 to 91.5. The maximum percentage difference in prediction for both models were for the YN configuration, implying that this was the least stable of all configurations, since flow reversal at the chimney exit was detected by smoke flow visualization and CFD analysis.

The plot of predicted and measured evaporation rates of all three configuration on the same graph in Figure 4 shows that the Rayner [5] model appears to predict the data of all configurations satisfactorily and a recent work Li et al [17] has confirmed its satisfactory performance. While this is helpful for design purposes, the model’s accuracy copes with effects and does not explain the cause between the difference of configurations YY and YN if one is not given the knowledge of the different geometrical arrangements.

6. Conclusion
This study assessed the ability of canopied solar irradiated natural ventilation to enhance the evaporation of free surface water in pans data collected under the East Malaysian’s hot and humid climate. It also investigated the influence of the meteorological parameters including the net solar radiation on the free surface of water, the vapor pressure deficit, and ability to transfer vapor from the free surface of water. The observation results concluded that:

- The evaporation rate for all three evaporating configurations could be predicted satisfactorily by Rayner [5] but not Penman [13].
- the configuration YY, where natural draft and vapor pressure increased 13% higher evaporation rates than configuration NN, was because as the vapor pressure deficit rises, the water molecules begin moving amount more rapidly.
the configuration YY, where natural draft and vapor pressure increased 20% higher evaporation rates than configuration YN, was not characterized by any one of thermodynamic or flow parameters but an aggregate of them according to Rayner [5], and possibly due to the increase of surface air velocity and hence reduction of pressure for the same energy input.

Acknowledgements
The authors would like to thank the Ministry of Higher Education for providing a fundamental research grant with number and Universiti Malaysia Sabah for the facility and laboratory support FRG0352-TK-1/2013 to carry out the experimental research.

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