Evaporation Enhancement from Evaporation Ponds Using Collector Plate Units

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2 Table of Contents

1 Acknowledgements 2

2 Table of Contents 3

3 Table of Figures 5

4 Table of Tables 6

5 Executive Summary 7

6 Introduction 9

6.1 Background 9
6.2 Aim 15
6.3 Key Research Questions 15
6.4 Thesis Outline 15

7 Literature Review 17

8 Materials Selection Assessment 24

8.1 Introduction 24
8.2 Collector Plate Material Options 24
8.3 Plate Material Selection 25

9 Design, Construction and Commissioning 26

9.1 Detailed Design 26
9.2 Construction 27
9.3 Commissioning 28

10 Research Methodology 31

10.1 Research Approach 31
10.2 Enhanced Evaporation Ratio 33
10.3 Brine Wastewater 34
10.4 Key Weather Parameters 35

11 Results and Discussion 36

11.1 Introduction 36
11.2 Performance of CPU for Brine at 3.5% NaCl 38
11.3 Performance of CPU for Brine at 7.0% NaCl 56
11.4 Performance of CPU for Brine at 12.5% NaCl 61
11.5 Discussion 66

12 Theoretical Evaporation 75

12.1 Brine Pan Evaporation 75
12.2 Collector Plate 78

13 Energy Balance 82

13.1 Introduction 82
13.2 Brine Pan Evaporation 83

13.3 Collector Plate Evaporation 85
14 Conclusion 87
15 Recommendations 90
16 References 92
17 Appendix 107
17.1 Abbreviations 108
17.2 Schematic Arrangement of Experimental System 109

3 Table of Figures

Figure 1 – EER vs. Air temperature – Brine 3.5% NaCl 49
Figure 2 – Collector Plate Evaporation vs. Air temperature – Brine 3.5% NaCl 50
Figure 3 – EER vs. Relative Humidity – Brine 3.5% NaCl 51
Figure 4 – Collector Plate Evaporation vs. Relative Humidity – Brine 3.5% NaCl 52
Figure 5 – EER vs. Solar Radiation – Brine 3.5% NaCl 52
Figure 6 – Collector Plate Evaporation vs. Solar Radiation – Brine 3.5% NaCl 53
Figure 7 – EER vs. Wind Speed – Brine 3.5% NaCl 54
Figure 8 – Collector Plate Evaporation vs. Wind Speed – Brine 3.5% NaCl 55
Figure 9 – CPU Evaporation vs. Air temperature – Brine 7.0% NaCl 57
Figure 10 – CPU Evaporation vs. Relative Humidity – Brine 7.0% NaCl 58
Figure 11 – CPU Evaporation vs. Solar Radiation – Brine 7.0% NaCl 59
Figure 12 – CPU Evaporation vs. Wind Speed – Brine 7.0% NaCl 60
Figure 13 – CPU Evaporation vs. Air temperature – Brine 12.5% NaCl 62
Figure 14 – CPU Evaporation vs. Relative Humidity – Brine 12.5% NaCl 63
Figure 15 – CPU Evaporation vs. Solar Radiation – Brine 12.5% NaCl 64
Figure 16 – CPU Evaporation vs. Wind Speed – Brine 12.5% NaCl 65
Figure 17 – EER Vs CPU Temperature – Brine 3.5% NaCl – Film Ht 0.15 mm – Pt A 70
Figure 18 – EER vs. CPU Temperature – Brine 3.5% NaCl – Film Ht 0.15 mm – Pt B 72

4 Table of Tables

Table 1 – Brine Disposal Options – Advantages and Disadvantages 12
Table 2 – Bendigo Mining – Brine Disposal 13
Table 3 – Collector Plate Material Assessment Criterion 24
Table 4 – Collector Plate Unit Instrumentation 27
Table 5 – Brine Characteristics Vs Research Source Water 34
Table 6 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.3 mm 38
Table 7 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.3 mm 42
Table 8 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.2 mm 44
Table 9 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.15 mm – Pt A 47
Table 10 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.15 mm – Pt B 48
Table 11 – CPU Trial of Brine at 7.0% NaCl Film Ht 0.2 mm 56
Table 12 – CPU Trial of Brine at 12.5% NaCl Film Ht 0.2 mm 61
Table 13 – Polynomial Line of Best Fit – 3.5% NaCl – Film Ht 0.2 mm 66
Table 14 – Pan Evaporation – Brine vs. Fresh Water 67
Table 15 – Polynomial Line of Best Fit – 7.0% NaCl – Film Ht 0.2 mm 67
Table 16 – Polynomial Line of Best Fit – 12.5% NaCl – Film Ht 0.2 mm 68
Table 17 – Energy Balance – Brine Pan Evaporation 84
Table 18 – Energy Balance – Collector Plate Evaporation 85

5 Executive Summary

In this thesis research was undertaken into enhancing the rate of evaporation from evaporation ponds, used by mining industry and other industrial operators to dispose of brine wastewater.

A pilot scale collector plate unit was designed and constructed to evaluate the enhanced evaporation capabilities of an unglazed collector plate. A 14 month experimental program was undertaken to evaluate the ability of the unit under different operational parameters to enhance the rate of evaporation of synthetic brine wastewater.

The relationship between evaporation enhancement and collector plate evaporation results and the four key meteorological parameters, solar irradiation, wind speed, air temperature, and relative humidity was investigated by making parameters film height (0.15 mm, 0.2 mm and 0.3 mm) and brine concentrations (3.5% NaCl, 7.0% NaCl, and 12.5% NaCl) constant during the experimental program.

Data analysis found weather conditions low in relative humidity (less than 40%), high in total incident solar radiation (greater than 20 $MJ/m^2/d$), steady, constant wind speeds (between 1.1 and 1.3m/s), and high daily average air temperatures (greater than 25°C) would generally produce evaporation enhancement ratio (EER) results between 2.0 and 3.0 for brine solutions with concentrations up to 7.0% NaCl.

It was observed during the 12.5% NaCl brine pilot trial that despite achieving the peak EER result of 3.01, that EER results were less than expected based on the peak summer weather. The data supported the observation with EER concentrated in the range 1.5 to and 2.0 for brine at 12.5% NaCl.

The peak EER result of 3.01 (achieved during summer) equated to the collector plate unit achieving a rate of evaporation 301% higher than an equivalent surface area of evaporation pond containing similar brine wastewater and subject to similar weather conditions.

The mean EER result over the 14 month sampling period was 1.52. The research found in the scenario where 100 nr collector plate 1 m^2 units were connected to an evaporation pond covering 20,000m^2 and 1 m in depth, subject to typical Melbourne CBD weather conditions, and a testing period of 100 days. The collector plate unit had the potential to reduce the surface area by 0.44% representing an 88m^2 reduction in surface area for the 1 m deep evaporation pond.

An energy balance was developed for the collector plate unit that considered energy in and out of the unit, by way of solar radiation, convection and evaporation. It was found the collector plate lost over 49% of its energy to evaporation as compared with 76% by the evaporation pond due to evaporation under the same weather conditions.

The research found collector plate technology had the potential for augmenting existing and future evaporation ponds located in regions and countries where the meteorological conditions are favourable to evaporation.

6 Introduction

6.1 Background

Water is vital for every human activity. In the past abundant fresh water supplies were believed to be limitless. In the last two decades, dwindling reserves of freely accessible water at the surface and subsurface environments have raised community awareness about the need to ensure that industrial production operates in a sustainable way that won't constrain the development and sustainability of regional cities and towns that draw on downstream ground waters for their potable and non potable water requirements (Ahmed et al, 2000).

In this thesis, research will be undertaken into a method of augmenting the widely practiced evaporation pond approach to improve the sustainability of industrial operations employing the practice. Evaporation ponds are widely used in the Middle East and to a lesser extent in the arid regions of Australia (Glater and Cohen, 2003).

Evaporation ponds are widely used in arid and semi arid conditions because they are relatively easy to construct and operate with minimal mechanical or operator input. The ponds act to concentrate the brine effluent and reduce the liquid volume. In the Murray Darling basin of Australia, there are approx. 190 evaporation ponds or lagoons used to evaporate brine waters, with a total area of over 15, 900ha, a total storage capacity of 113,000 ML, and an annual disposal volume of over 210,000ML/yr (Mickley et al, 1993 and Hostetler & Radke, 1995).

Many of the evaporation ponds were built in decades past and met the construction standards of the day relating to embankment and spillway design, but weren't compacted or lined with impervious layers of clay or plastic. Thus, the potential remains for contaminants in the brine to seep through these older evaporation ponds and contaminant underground aquifers used by rural communities for potable water supplies (Mickley et al, 1993 and Ahmed et al, 2000). The contaminants of concern are site specific and depend on the industrial operation discharging to the evaporation pond (Gilron et al, 2004).

Evaporation ponds are generally spread over large surface areas to increase the rate of evaporation. Where the rate of evaporation could be enhanced the need for the same amount of land to achieve the same rate of evaporation would be reduced. In the case of unlined evaporation ponds, an enhanced rate of evaporation would have two advantages for industry operators. The first, is the flexibility to increase the amount of brine wastewater 'pushed' through an evaporation pond of a given footprint, and second in the case of a set brine flow rate a reduced amount of land would be required to achieve the same rate of evaporation. The environmental benefits of the later outcome for unlined evaporation ponds is reduced risk of contaminants in the brine seeping through and contaminating groundwater supplies (Ahmed et al, 2000 & Gilron et al, 2004).

The evaporation rate can be increased through a number of mechanical and chemical means, but notably by raising the water temperature, increasing the exposed surface area, and/or stirring the pond (Ahmed et al, 2000 and Gilron et al, 2004). In this research, an experimental program was undertaken to evaluate an economical and easy to operate mechanical means of increasing the rate of evaporation from evaporation ponds (Ahmed et al, 2000 & Glater and Cohen, 2003).

Evaporation ponds are widely used by the Mining Industry in Australia as a cost effective disposal option for brine wastewater. The US EPA (2008) defines 'brine' waste as "water that has a quantity of salt, especially sodium chloride dissolved in it". The Australian Minerals Industry is one of Australia's leading export industries, representing 8% of the Australian economy as measured by Gross Domestic Product (GDP) in 2004/05 (Kracman, 2007). The industry was responsible for AUS $56 billion in exports over that period, and it's estimated the 2005/06 mining industry exports would be up to AUS $68 billion (Kracman, 2007).

The industry, per annum, uses approximately 400GL or 2% of Australia's total water consumption, of which over 90% is drawn from groundwater bores (ABS, 2005). The water management techniques vary across the industry and depend greatly on the individual mining operations, quality of water required (potable versus non potable), and the quality, accessibility and volume of local groundwater. The water is mainly used by mining operations to satisfy demand for process water, fire fighting, amenities, drilling and dilution of tailings discharge (Taylor & Pape, 2006).

The water quality of groundwater in Australia is typically highly saline having regard to the geology of the aquifers where the total dissolved solids (TDS) concentrations can range to up to 100,000mg/L (Taylor & Pape, 2006). Therefore, mining operators like Australian gold miner, Bendigo Mining, who undertake extensive mine dewatering on a daily basis discharge a brine waste high in salinity, TDS, arsenic, heavy metals, turbidity, and low dissolved oxygen (Taylor & Pape, 2006 & Madin, 2007).

The brine discharged from mining operations typically contain higher than acceptable water quality levels under current environmental standards for discharge to watercourses. Hence, the requirement for brine to be kept on site and transferred to either RO treatment plant or evaporation ponds and dewatered over time due to evaporation, and where the ponds are sited in a sequence, the last pond can be used to dry and harvest the salt (Kedem, 2004).

The brine disposal approach employed by every industrial operation is a site specific issue. According to Mickley et al (1993), the issues are the volume of brine wastewater, brine water quality, brine discharge point, statutory approvals required for discharge, capital and operating costs, and ability to expand in the future.

The disposal of brine wastewater by evaporation ponds is a widely used technique along with mechanical treatment options – reverse osmosis (RO), groundwater injection, deep well/ mine injection, irrigation, and crystallation (Ahmed,2001; Coliban

Water, 2007; Kedem, 2004; Khordagui, 1997 and Muirhead, 1997). The advantages and disadvantages of the different brine disposal techniques are outlined below:-

Table 1 – Brine Disposal Options – Advantages and Disadvantages

Disposal Method	Advantages	Disadvantages
Evaporation Ponds	Low tech solution Provides storage until alternate solution found Minimises impact on surrounding waters	Large surface areas required Needs favourable weather conditions High volumes of salt require disposal
Groundwater injection	Low tech solution	Brine heavy metals may contaminate the aquifier
Deep well / mine injection	Low tech solution	Brine heavy metals may contaminate the aquifier
Irrigation	Cheap low tech solution	Brine heavy metals may affect fauna and flora
Crystallation	High salt / solid recovery	Capital intensive Technically complex process
Reverse Osmosis	High salt / solid recovery	Technically complex process Capital intensive

The various brine disposal options were recently considered by Australian gold miner, Bendigo Mining following a decision to resume working previously submerged mine shafts (Buerger, 2003).

After a site specific review, Bendigo Mining selected mechanical treatment option, RO to dispose of the brine waste discharged from the mine shafts. It was concluded the combination of low pan evaporation and lack of available land for evaporation ponds, meant RO was the most appropriate solution (Buerger, 2003). The permitted uses of the treated effluent include irrigation, livestock drinking water, dust suppression, and car wash facilities ([1] Buerger, 2003, [2] Coliban Water, 2007 and [3] Victorian State EPA, EPA Discharge Licence No. ES52878).

Table 2 – Bendigo Mining – Brine Disposal

Bendigo Mining - Brine Disposal - Mechanical Treatment Option		Dewatered Brine Effluent [1]	Bendigo Mining WTP [2]	Percent Removal	Bendigo Mining - EPA Discharge Licence [3]
Parameter	Units	Max	Max	%	Max
Flow	ML/d	1.1	1.1	-	-
TDS	mg/L	4960	378	-	1000
TDS	kg/d	5456	416	92.38%	-
Salinity (EC)	ms	7.9	7.9	-	-
Arsenic (As)	µg/L	4880	2	-	50
Arsenic (As)	kg/d	5	0.002	99.96%	-
Sulphate (SO_4)	mg/L	294	-	-	-
Sulphate (SO_4)	kg/d	323	-	-	-
Iron (Fe)	mg/L	0.7	0.060	-	0.3
Iron (Fe)	kg/d	0.7	0.066	91.18%	-

Where evaporation ponds are selected by mining or other industrial operators for the disposal of brine waste the ponds act to concentrate the brine effluent for off-site discharge, and reduce the volume and surface area of the evaporation ponds. Typically, the evaporation ponds are arranged in cascade sequence, and occasionally a crystallizer is positioned in the final pond to recover the salt for sale for uses other than non human consumption (Ahmed, 2000 & Coliban Water, 2007).

However, the disposal of brine effluent by evaporation ponds can have severe affects on the environment, especially those that are not lined with clay soils or impermeable layers where there is the potential for groundwater contamination through seepage.

Simmons et al (2000) submits a relationship exists between the risk of leakage from unlined basins, and the risk that it will impact on the underground aquifers in the surrounding areas. The key mechanism driving the lateral seepage through unlined evaporation ponds is the permeability of the aquifer material and the salinity difference between the evaporation pond of higher salinity and the groundwater of lower salinity.

To mitigate the risk of leakage from unlined ponds, a clay barrier can be formed approx. 3m deep to accommodate an acceptable seepage rate (not exceeding 3mm a day) (Muirhead, 1997). The other typical sealing options are PVC or Hypalon, but are generally more cost prohibitive than clay barrier. In the cases, where evaporation ponds are not lined for a range of economic or technical reasons, the risk of groundwater and / or aquifer contamination remains.

This research investigates an innovative approach to augmenting the current evaporation pond disposal approach used in Australia, and other regions around the world. The augmentation involves the incorporation of solar plate collector technology. The technology is widely used across the world to collect solar power to drive a range of commercial and domestic applications, most commonly solar hot water systems.

The technology referred hereon as unglazed transpired collectors (UTCs), which are relatively inexpensive, and efficient in warm and sunny climates (Summers et al, 1996). Most commonly UTCs are used in North America, and Europe where they are mounted on large south walls to maximize solar exposure. Different to most solar collector plates, they are not covered by glazing units (Summers et al, 1996). It is widely accepted UTCs have high thermal gains during summer periods, with no reflection losses due to glazing, but during winter months, the lack of glazing contributes to high thermal losses. The solar technology to be tested is considered a hybrid concept because it’s a UTC but inclined like a typical solar collector plate.

It is believed this investigation will extend the research field’s collective understanding of low cost technology (i.e. unglazed collector plate) for enhancing evaporation from evaporation ponds. The pilot unit will consist of a mechanical pump driven by mains power, connected to sample evaporation ponds as a means of determining the potential to increase the evaporation rate of existing unlined evaporation ponds.

6.2 Aim

The aim of the research to assess the ability for collector plate technology to enhance the rate of evaporation from brine filled evaporation ponds. To realise the project aims, the research will investigate the relationship between the four key meteorological parameters, solar irradiation ($MJ/m^2/d$), wind speed (m/s), ambient air temperature (°C), and relative humidity (%), and evaporation from the collector plate unit connected to a sample evaporation pond. The experimental program will modify the collector plate units operating parameters, water film heights and brine (NaCl) concentration's to realize the project aims. The level of evaporation achieved by the collector plate unit will be considered hereon as 'enhanced evaporation'.

6.3 Key Research Questions

The specific research questions to be answered are as follows:-

1. What is the highest rate of evaporation enhancement possible from the collector plate unit?
2. Investigate the relationship between four key weather parameters, solar irradiation ($MJ/m^2/d$), wind speed (m/s), ambient air temperature (°C), and relative humidity (%) and the evaporation rate from the collector plate. Determine, if a relationship exists between all or a number of weather parameters, and the rate of enhanced evaporation?
3. What percentage reduction in evaporation pond surface area can be achieved with collector plate units?
4. What potential is there for collector plate units to improve the existing evaporation ponds approach?

6.4 Thesis Outline

A review of the literature follows seeking to provide an overview of all published literature relating to the research. The review evaluates the use of collector plate technology, and its ability to enhance the rate of evaporation from ponds containing brine wastewater.

The experimental design section follows outlining the concept of evaporation enhancement, the water quality characteristics of brine wastewater, and the four key meteorological parameters that affect evaporation.

The materials characterisation study begins with a review of the collector plate material options, and outlines the desired plate thermal properties. The study then describes the types of plate materials, the rationale for selecting the plate material, and finishes with the recommended plate material.

The collector plate unit design, construction and commissioning section follows with an outline of the detail design for the collector plate unit, discusses the methods involved in construction and finishes with an outline of the issues involved in commissioning the unit. The issues include plate orientation, plate area, pump operational time, plate inclination angle, tank water height, trial period duration, rainfall, and plate rainfall runoff and surface tension. The research methodology section discusses the collector plate unit orientation, the unit flow velocity and collector plate surface area, daily operating hours, collector plate inclination angle, the approach to measuring rainfall and plate runoff, and overcoming surface tension.

The results from the pilot trials will be presented in terms of evaporation enhancement and collector plate evaporation relative to the four key meteorological parameters. The data will be assessed to find the evaporation capabilities of the collector plate against brine concentration (NaCl %) and film height (mm).

An energy balance will be developed to analyse and compare the empirical data collected during the pilot trial with theoretical approaches of best fit from literature. The key research findings from the pilot trial and the energy balance will follow, before moving to detail the research conclusion and project recommendations.

7 Literature Review

Background

Evaporation ponds have been used for centuries to store final effluent waters high in salinity, heavy metals and total dissolved solids (TDS). The effluent is commonly known by the term 'brine'. The US EPA (2008) defines 'brine' as "water that has a quantity of salt, especially sodium chloride dissolved in it".

Evaporation ponds are widely used in the Gulf region and to a lesser extent in regions across Australia, Mediterranean Europe, North Africa, and the west coast of the United States where the climate is characterised by high air temperatures, low humidity, low rainfall and high solar radiation (Glater and Cohen, 2003, & Shumilin et al, 2002).

Evaporation ponds range in surface area, from tens of hectares to a couple of hundred square metres with depths varying ranging for 0.5 m to 2.0 m (Tanji et al, 1993). In the Murray Darling basin of Australia, there are approx. 190 evaporation basins used to evaporate brine, with a total area of over 15, 900 ha, a total storage capacity of 113 000 ML, and an annual disposal volume of over 210 000 ML/yr (Mickley et al, 1993 and Hostetler & Radke, 1995).

Evaporation ponds are commonly used to detain brine waters from a range of industrial activities like mining, agriculture, tanneries, smelting and metals related processing activities. The ponds in decades past were very easy to construct being unlined, with little maintenance required, and being very cost effective especially in regions with high evaporation rates and abundance of cheap land (Ahmed et al, 2000).

While, those ponds met the construction standards of the day relating to embankment and spillway design, they weren't compacted or lined with impervious layers of clay, concrete or with HDPE liners. Thus, the risk remained for constituents in the brine to seep laterally through the evaporation pond and soil strata and into underlying ground waters or aquifers. The severity of the environmental affect increasing where rural communities are accessing the water supply at risk for potable or domestic water needs (Mickley et al, 1993 and Ahmed et al, 2000).

Evaporation ponds are commonly arranged in a sequence, with brine flowing sequentially from pond to pond becoming more concentrated until reaching the final pond, where a crystallizer maybe in place to recover the salt, and the liquid depending on the water quality may either be returned to the head of the ponds, or allowed to discharge off site subject to satisfying water quality requirements. However, there are evaporation ponds which are left to stand where the objective is solids sedimentation and evaporation of the free liquid (Gilron et al, 2004). The hydraulic retention time (HRT) can range from 50 to 500 days depending on the volume of flow, land available, water quality requirements (if any), and rates of daily evaporation (Barranco et al, 2001, & Coliban Water, 2007).

Sustainability of Evaporation pond approach

In recent years concerns in Australia about the sustainability of brine disposal by evaporation, lead to the issue of guidelines for agricultural producers in Australia that use evaporation ponds calling for any leakage from evaporation basins to not pollute groundwater used or likely to be used in the future for potable or non potable water uses (Jolly et al, 1999).

The use of unlined evaporation ponds for many decades by the olive industry in California, USA lead to increased salinity levels in the groundwater. As a result, the use of evaporation ponds was discontinued, but they are still allowed in Spain and other European countries (Barranco et al, 2001).

The water characteristics of brine waste differs from other liquid waste streams because of two key reasons, there is no way to reduce brine to simpler and harmless compounds, and the difficulty to recycle the waste because of the high dissolved solids concentration (Koening, 1958). The optimization of evaporation ponds through increased levels of daily pan evaporation has been identified as a means of mitigating the risk associated with operating evaporation ponds in an environmentally sustainable manner.

The evaporation rate can be increased through a number of mechanical and chemical means. Ahmed et al (2001) found evaporation ponds could be retrofitted with heaters to deliver higher rates of pan evaporation. In this research, we investigate the ability for unglazed transpired collectors (UTCs), to warm the temperature of evaporation ponds by recycling water across exposed collector plates. The collector plates would be enclosed within units and be located immediately adjacent to the evaporation ponds.

UTCs were first introduced in the early nineties, and were used on several large buildings in North America and Europe, to reduce the requirement for mechanical heating. The update of UTC technology was limited for two key reasons, high installation costs, and sensitivity to inclement weather conditions.

UTCs generally comprise a dark coloured metal plate to act as a solar absorber and is fixed to wall or parallel surface with a gap of approx. 10 to 15cm between them with all sides closed and sealed (Leon et al, 2007). There are perforations in the plate to allow ambient air to pass through to the plenum between the plate and wall or parallel surface. The air absorbs heat passing through the plate and is withdrawn in the direction of air flow by a blower. The two plate option allows for the elimination of glazing which saves the material cost and minimizes optical reflectance (Leon et al, 2007).

The potential for UTCs to increase the pan evaporation rate of evaporation ponds will be investigated as part of optimizing the performance of evaporation ponds. In this thesis, UTCs will be referred to as collector plate units because of their incorporation of hybrid UTC along with other innovations to optimizing the evaporation rate.

Collector Plate Evaporation

The evaporation of brine waste overflowing the inclined collector plate unit essentially is the separation of water from a saline solution. Water is typically vaporized from the solution, where the salt in solution remains in its non-soluble and non-volatile state under normal operating conditions (Treybal, 1980).

Many researchers have sought to find direct relationships between rates of evaporation and rates of change in heat and wind transfer co-efficients, and differences in vapor pressure between air and water temperatures (Gilron et al, 2003). A literature review found that relationships vary with conditions and across regions to the extent that research is commonly presented in terms of standard laboratory conditions. Linsley et al (1992) found that "dissolved salts reduce the vapor pressure of a water surface. Hence, saline water will evaporate less readily than fresh water, the reduction being about 1 percent for each percent of dissolved solids".

Ahmed et al (2000), Fahey (1999), and Mickley et al (1993) all found salinity influences the evaporation rate to the extent that a ratio of 0.70 was appropriate for relating pan evaporation of fresh water to saline water. Mani et al (1994) found the optimum inclination angle for year round optimal performance was approx. equal to their latitude location in India (β = 12.68). However Solahart believes inclination angles do not need to reflect the latitude of the subject location, rather the typical Australian house roof pitch (22.5 degrees) being at or near optimal (verbal conversation, Mike Williams, 2005).

The emissivity and absorption capabilities of a plate material can have a major effect on plate performance. Emissivity relates to the level of incoming heat re-radiated or reflected back to the atmosphere, where absorption relates to the level of heat absorbed by the plate (Mani et al, 1994).

Srithar and Mani (2006) reported pilot trial results for experiments involving soak liquors, comprising NaCl concentration's from 5 to 20%, and mass flow rates between 200 and 500 L/hr. It was found for every $1m^2$, the collector plate on average achieved 6.3 mm/d as compared with the average pan evaporation level of 4.5mm/d. The result equates to an evaporation enhancement ratio (EER) of 1.4, when dividing the level of pan evaporation into the level of collector plate evaporation (unit less).

Before moving to consider the theoretical nature of how evaporation occurs from collector plates and evaporation ponds, the accepted physical method of measuring pan evaporation on a daily basis will be considered.

Pan Evaporation

The process of evaporation is commonly measured over a daily time period in a standard size pan. The 'pan' is 'Class A' cylindrical pan situated at natural ground level with a diameter of 1210mm and a depth of 250mm (BOM, 2006). The Australian Bureau of Meteorology (BOM) practices this approach at base stations across the country.

The rate of evaporation from the pan can be affected by a range of meteorological conditions, from solar radiation, air temperature, wind speed, wind direction, relative humidity, rainfall, water temperature, to cloud cover. However, the variables identified by Penman (1948), and Ferguson (1952) were relative humidity, air temperature, solar radiation and wind speed (Ahmed et al, 2000 & Gilron et al, 2004).

The total solar energy received at ground level can be measured accurately and reliably by a pyranometer in units of kilo joules of solar radiation per square metre for a particular latitude and longitude (Australian Bureau of Meteorology, 2004).

As part of considering the combined effect of solar radiation and other key climate elements on the rate of evaporation from solar collector plates and evaporation ponds, the review will next consider the empirical approach for finding the evaporation rate of fresh and brine wastewaters.

The Penman equation is one of the most widely accepted approaches for determining evaporation rates from fresh water bodies (Oroud, 1999). However, a modified Penman model has been developed to account for the variation in the density and ionic composition between fresh and saline water bodies (Oroud, 1999, Meyer, 1999 & Reid, 1996). The Dalton equation can similarly be used to determine the evaporation rate of fresh water. A modified version of the Dalton approach has been developed to find the evaporation rate from saline water bodies (Oroud, 1999).

The modified Penman and Dalton models express evaporation as a function of air temperature and wind speed, but place varying levels of dependence on certain variables. The Penman model has a greater dependence on solar radiation than the Dalton Model, where the former has less regard to the effect of salinity on the water activity co-efficient (Asmar & Ergenzinger, 1999).

Zu et al (2004) found "countless number of papers and equations on evaporation mean that none of them is universally acceptable and each equation is valid only for particular circumstances and climates similar to those where the measurements were made". Similarly,

Sartori (2000) found there had been no consensus on which equations were better to employ for fresh water conditions, because of the large degree of scatter in evaporation results.

The scatter in evaporation rate predictions derives from both the complex interplay of climate and atmospheric variables, as well the uncertainties in the measurement of the variables themselves. Calder and Neal (1984) argue in most instances, the errors in measurement can vary by 10 to 15% and as such, the errors in predicted evaporation rates could vary by the same degree.

Heat Transfer

To better understand the evaporation process, literature regarding heat transfer will be considered. Heat transfer is generated by two key mechanisms. The first is radiation, where solar energy travels through space as electromagnetic waves. The second is convection, where molecules in the moving fluid gain or loss heat by conduction/ radiation in their movement from warmer to cooler places or vice versa (Geankoplis, 1983, & Sayigh, 1987).

The convective mechanism of heat transfer can be represented by the equation:-

$$Q = h_w A \left(t_w - t_f\right) dr$$

Where Q is per unit time, h_w is the wind heat transfer co-efficient, A is the surface area, r is directly proportional to the temperature difference between the wall, t_w and fluid, t_f for an available heat transfer area (Cheremisinoff, 1984 & Mani & Murthy, 1994). The research by Mani et al (1994) found the wind heat transfer coefficient, h_w to be:-

$$H_w = 5.7 + 3.8 \times V_o$$

where V_o = wind velocity (m/s)

Energy Balance

Mani et al (1994) in their research estimated brine evaporation from an inclined collector plate, and proposed an energy balance. The empirical conditions employed were universal, with no site specific correction factors to reflect its location in India. The energy balance consisted of accounting for energy inputs as radiation and convection, and the energy outputs as radiation, and evaporation. However, the accuracy of the models is dependent on the data tested, with Srithar and Mani (2003) submitting there was 10% deviation between theoretical and experimental data in their energy balance.

8 Materials Selection Assessment

8.1 Introduction

In this next section, the research will consider the most appropriate plate material for the collector plate. An assessment criterion has been developed to consider the different material options before making a recommendation.

8.2 Collector Plate Material Options

Mani et al (1994) found the critical design aspect to be corrosion resistance due to the corrosive nature of brine effluent and its exposure to elements. The assessment criterion for considering the different material options is as follows:-

Table 3 – Collector Plate Material Assessment Criterion

Criterion	Function
1. Thermal conductivity	Ability to transfer heat to the brine overflowing
2. Corrosion resistance	Resistant to brine effluent constitutents
3. Ease of handling	Able to handle manually or with lifting devices
4. Availability	Commercially available in Australia in standard sizes
5. Cost	Cost effective in Australia and around the world

The key criterion areas and their functions are thermal absorption, corrosion resistance, ease of handling, availability and cost effectiveness in Australia.

The most widely accepted material in marine and industrial environments is Stainless Steel 316 (SS316). The SS316 plate material satisfies the requirement for high thermal conductivity, and can provide the level of corrosion resistance required, through a chrome finish.

SS 316 is a commercially available material, and could be sourced in standard sizes of (length by width dimensions, 2440 mm by 1175 mm), with a nominal thickness of 2 mm (Personal communication, J Spain, February 2005).

8.3 Plate Material Selection

The study will adopt SS316 as the collector plate material. It can be readily sourced from within Australia and with a chrome finish the material can offer a relatively high level of corrosion resistance.

9 Design, Construction and Commissioning

A pilot collector plate unit will be designed, constructed and commissioned to satisfy the research aims.

9.1 Detailed Design

The unit detail design will consider the collector plate, pipe work and pumps to recycle effluent around the unit and arrangement of pilot tanks used to simulate evaporation ponds.

It was decided the collector plate unit should include a sample (STK) tank to simulate the principal evaporation pond. The sample tank (STK) along with the collector plate will form a closed loop, with all flows recycling through the STK via the brine pumps and down the inclined collector plate. The STK and collector plate (together referred to as collector plate unit) act as a pilot scale version of an evaporation pond.

The design will feature a control tank (CTK) adjoining the STK, to determine the contribution of the collector plate evaporation. This comparison between collector plate evaporation and pan evaporation from the tanks will hereon be described as 'evaporation enhancement'. The final pilot tank will include a reference tank (RTK) to measure the difference between brine and potable water evaporation.

The three pilot tanks are circular in geometry, and uPVC in material. The surface area of the selected pilot tanks will be approx. 1 m^2 in surface area with a volume capacity of 304 L. The SS316 collector plate will be sealed with a primer and top coat to offer improved corrosion resistance.

The first coat will protect the SS316 plate from the weather elements and act as a corrosion barrier to brine effluent. The second coat will be black chrome to resist the blistering that occurs with the increases in plate temperature on peak summer days (Personal communication, C. Broad, 2005).

9.2 Construction

The collector plate unit will be assembled on the roof of Building 7 at the RMIT City Campus, in the Melbourne CBD. The instrumentation consists of a weather station, water level probes (installed in STK, CTK and RTK), and water temperature sensors (installed in STK, CTK and RTK, and at three positions along the collector plate, top, middle and bottom). The weather station selected for the project is an Environdata MK4. The weather station will be installed next to the unit. The MK4 unit was able to collect rainfall (mm/hr), relative humidity (%), solar radiation (MJ/m^2), air temperature (°C) and wind speed (m/s).

Mobile instrumentation included a conductivity meter for taking daily EC readings to allow back calculation of the tank salinity value (g/L), and a water temperature sensor for taking daily results. To verify the water level data recorded by the electronic data loggers, manual readings will be taken using a graduated ruler. The instrumentation installed for the collector plate unit is detailed at Table 4. A detailed schematic of the experimental system is located at Appendix 17.

Table 4 – Collector Plate Unit Instrumentation

Instrumentation	Type	Make	Model	Error	Resolution
Environdata MK4 Weatherstation	Air Temperature	Environdata Australia	TA 10	-	-
	Relative Humidity	Environdata Australia	RH21	-	-
	Solar Radiation	Environdata Australia	SR 10	-	-
	Wind Speed	Environdata Australia	WS 30	± 5 %	-
	Rainfall	Environdata Australia	RG20	-	0.2 mm
Onset - Water Temperature Sensors	Water Temperature - Tank (s)	Onset	H8	-	-
	Water Temperature - Plate	Onset	H08-001-02	-	-
Hach - Conductivity	Conductivity	Hach	HQ 30d	-	0.01 µS/cm
Electrosense - Water Level Sensors	Water Level - Tank (s)	Electrosense	Aquagauge	-	1 mm

9.3 Commissioning

The commissioning of the collector plate unit will occur over a 4 week period. The commissioning phase will consider the unit control parameters to remain constant and those to vary during the experimental period. The key operational parameters are plate orientation, plate area, pump operational time, plate inclination angle, tank water height, testing period duration, rainfall and plate rainfall runoff and surface tension.

Plate Orientation

In the southern hemisphere to maximise solar exposure, the collector plate will be centered due north to face the equator (Dingham 1994). For operational reasons, the collector plate will be orientated to face due north.

Plate Area

The SS316 collector plate had a wetted surface area of 2.65m^2. The selected surface area reflects the standard sizes of SS316 sheets, with wetted plate dimensions of 1,115mm wide by 2,380mm long.

Pump Operational Time

At the start of the commissioning phase, it had been planned to operate the two recycle pumps (one duty/one standby) during daylight hours over the winter and summer periods. However, in the course of commissioning it become apparent at the start of each day that once the unit had stopped operating the previous day the NaCl in the overflowing brine solution would crystallize and settle on top of the collector plate. The effect being de-watered NaCl crystals requiring manual removal each day before testing could commence.

The other notable observation the level of evaporation occurring overnight as evident by the changes in pan evaporation from 6pm the previous evening to 9am the next day. The research found 35 to 45% of the pan evaporation was occurring over night due to free convection, which supported the findings of Hipsey (2006) regarding levels of evaporation that occur during night time hours. Therefore, it was decided to operate

24 hours a day to ensure the integrity of the enhanced evaporation data and to prevent the settling of de-watered NaCl crystals on the collector plate surface overnight.

Plate Inclination Angle

The effect of inclination angle was reviewed by Duffe and Beckman (2006), who found for maximum solar absorption, the plate inclination angle should be 10° to 15° less than the latitude (in the case of Melburne CBD, the latitude is – 37.5°), and during the winter months the opposite.

Therefore, the suggested inclination angle for the collector plate should be 25° to the horizontal during summer months and 40° during the winter months. However, Duffe and Beckman (2006) admitted deviations of 15° resulted in solar availability reductions in the order of 5%.

The unit design allowed for the collector plate to be inclined at three different inclination angles. The angles (from lowest to highest) were 14.1°, 19.3° and 24.7°. In the course of the commissioning phase, the plate was trialed in all three positions. It was decided to set the inclination angle at 14.1° on the grounds that it would not significantly affect the available level of solar absorption, and encouraged the greatest level of surface wetting across the collector plate.

Tank Water Height

During the commissioning phase, an evaluation was undertaken of the freeboard needed for the STK having regard to collector plate runoff and the need to prevent spillage of brine waste. It was concluded based on the collector plate having a surface area two and half times that of STK, that it was appropriate to provide a freeboard of no less than 120 mm. The selected tank height will be 280 mm (i.e. 400 mm total height minus 120 mm freeboard).

On a daily basis at 9 am (and during the summer period at 5 pm), the water level was manually recorded in all three pilot unit tanks. Where there was a reduction in water level from the set point of 280 mm (i.e. due to either collector plate and/or brine pan evaporation), an aqueous solution with a conductivity (mS/cm) equivalent to that particular testing period was used as make up solution to return the water level to a set point of 280mm .

Conversely, if the recorded water level was above the set point of 280mm (i.e. due to rainfall), a liquid volume equivalent to that amount above 280mm was removed. Once the water level was returned to 280mm, the tank conductivity (mS/cm) was recorded. If the conductivity was less or greater than the required conductivity level for the particular test, make up solutions were made up and mixed into the STK and CTK.

Rainfall and Collector Plate Runoff

It was observed during the commissioning phase that collector plate runoff had a dilution effect on the EC values in the STK, and thus altered the brine water characteristics between the STK and the CTK. To ensure the integrity of the experimental program, all days where rainfall fell was excluded from the experimental program.

Surface Tension

It was observed during the commissioning phase that the level of collector plate wetting was critical for achieving optimal evaporation enhancement and collector plate evaporation. While, the collector plate material, SS316 had a lower surface tension (approx. 44 dynes/cm^2 at 25 °C) than water (approx. 72.8 dynes/cm^2 at 25 °C), the black paint coatings applied had a surface tension of 65 dynes/cm^2 at 25 °C, only 8 dynes/cm^2 less than water (Bulenov et al, 2003).

It was observed pump flow rate could overcome the surface tension to the extent that 70% of the collector plate could be wetted by the overflowing brine waste. However, the beading over the collector plate amounted to approx. 30% of the wetted area on a constant basis. The beading was occurring due to the hydrogen bonding in water acting as an inward force (Dingman, 1994).

10 Research Methodology

10.1 Research Approach

The research approach consists of operating the collector plate unit under different synthetic brine concentrations to simulate the potential to enhance the evaporation rate of brine stored in evaporation ponds under different weather conditions.

The experimental program will cover a fourteen month period, covering summer, spring and winter weather conditions. Over this time, the unit will vary operational parameters flow rate, brine (NaCl) concentration and water film thickness while keeping the collector plate inclination angle, overflowing water velocity, and plate orientation constant to evaluate the evaporation enhancement capabilities of the unit.

For the pilot trial period from June to October, 2005 the brine solution will be 3.5% NaCl with a wetted film height of 0.30mm. The thickness will provide an acceptable level of surface wetting under the winter weather conditions. The water velocity across the collector plate will be 12.1cm/sec. The exposure time of the brine to the atmosphere, that is time allowable for the liquid to evaporate at the collector plate surface can be found by the equation below.

$$Exposure \quad (\sec) = \frac{Plate - Length}{Water - Velocity}\frac{mm}{mm \; / \sec} \qquad \text{Equation 1}$$

Where the length of collector plate is 2380 mm, the exposure time will be 19.6 seconds. For the periods over the summer months the pump flow rate will be reduced from 136 L/hr to 95 L/hr.

The reduction in pump flow rate across the plate is driven by two objectives, the desire to reduce energy required to power the pump with its associated environmental and cost advantages, and secondly, Mani et al (1994) found a linear relationship between increasing collector plate evaporation and decreasing water film thickness under all weather conditions.

It was observed using a graduated ruler that a flow rate of 95 L/hr could deliver an approx. film thickness across the collector plate of 0.2 mm. The water flow velocity reduced 12.1 to 11.8cm/sec, and the exposure time will be 20.1 seconds.

For the period between June and August, 2006 where the brine solution will be 3.5%, the plate area will be reduced by half to enable the pump flow rate to be dropped to 28L/hr without affecting the level of surface wetting. The water film thickness will be 0.15mm high for an exposure time of 21.3 seconds.

The changes in hydraulic flow conditions meant the hydraulic retention time (HRT) will be allowed to increase from 1.95 hours for brine 3.5% NaCl - Film Ht 0.3 mm, to 2.8 hours for Brine 7.0 and 12.5% NaCl and to 9.5 hours for brine 3.5% NaCl – Film ht 0.15 mm.

The approach adopted to find HRT is expressed below.

$$HRT\ (hrs) = \frac{Volume}{Flowrate}\frac{L}{L\ /\ day}\frac{24\ hrs}{1\,day} \qquad \text{Equation 2}$$

The HRT will be allowed to vary based on the advice of Barranco et al (2001), that HRT can range from 50 to 500 days for evaporation ponds depending on the volume of flow, land available, water quality requirements (if any), and rates of daily evaporation.

The selection of the three collector plate film thicknesses 0.30, 0.20 and 0.15 mm allowed the exposure time (i.e. time allowable for evaporation of the brine from the collector plate surface to the atmosphere to occur) to remain approximately the same. The advantage being that each test condition is subject to weather conditions for approximately the same period of time.

The water level changes in the STK will be recorded electronically every hour to enable comparison with hourly changes in key weather parameters, solar radiation, wind speed, relative humidity and air temperature.

10.2 Enhanced Evaporation Ratio

The rate of evaporation achieved by collector plate units connected to evaporation ponds is referred to as 'enhanced evaporation'. The term enhanced evaporation refers to the additional level of evaporation achieved by an equivalent area of collector plate area as compared with an evaporation tank.

The external research location (e.g. on the roof of building 7 at RMIT City Campus – 47 m AHD), means the unit will be subject to varying weather conditions and as such, non standard laboratory conditions apply to the research.

A research simplification will be applied to separate the level of brine pan evaporation from the level of collector plate evaporation. It will be assumed with the CTK and STK having the same brine volume, tank geometry, synthetic brine concentration and located next to one another, that each tank achieved similar levels of brine pan evaporation.

The research simplification means the measured difference between the STK and CTK brine pan evaporation is the level of collector plate evaporation. The evaporation enhancement ratio (EER) is the ratio of STK evaporation versus CTK evaporation.

$$EER = \left(\frac{STK - Evap}{CTK - Evap} \right) \qquad \text{Equation 3}$$

The accuracy of the pan evaporation measurements as recorded during the experimental period shall be +/- 1.0 mm, the lowest level possible using both the water level sensor and water level datum readings.

10.3 Brine Wastewater

Brine wastewater typically contains heavy metals, so a synthetic brine solution is required for two key reasons, the difficulty in sourcing actual brine effluent, and further the safety and disposal issues associated with using actual brine effluent.

The three synthetic brine concentrations selected are 3.5%, 7.5% and 12.5% NaCl. The 3.5% NaCl level has been selected because it's consistent with seawater, the level 7.5% because it's twice the saline NaCl and finally, 12.5% because it's hyper saline.

The research source water for the synthetic brine is Melbourne CBD potable water. For illustration purposes only, the respective water quality levels for each of the three synthetic brine concentrations are detailed at Table 5 below.

Table 5 – Brine Characteristics Vs Research Source Water

Parameters	Units	STK/ CTK @ 3.5% NaCl	STK/CTK @ 7.0% NaCl	STK/ CTK @ 12.5% NaCl	RTK - Research Source Water
NaCl	%	3.5%	7.0%	12.5%	0.2%
NaCl	g/L	35.08	70.00	125.00	0.02
NaCl	mg/L	35,084	70,000	125,000	20
Density	kg/m3	1,023	1,046	1,082	1,000
EC	uS/cm	53,158	102,187	-	111
EC	mS/cm	53	102	-	0
Arsenic	mg/L	<0.001	<0.001	<0.001	<0.001
Cadmium	mg/L	<0.001	<0.001	<0.001	<0.001
Hardness (as CaCO3)	mg/L	26	26	26	26
Lead	mg/L	<0.001	<0.001	<0.001	<0.001
Mercury	mg/L	<0.0001	<0.0001	<0.0001	<0.0001
Bromate	mg/L	<0.01	<0.01	<0.01	<0.01

* The EC of 12.5 % NaCL could not be determined using Perkins et al (1980)

It is not possible to measure salinity (% or mg/L) for a particular mass of salt in solution following the Practical Salinity scale of 1978. A back-calculation approach can be used to find salinity (% or mg/L) using an EC meter (Perkins et al, 1980).

The methodology involves the application of co-efficients to find the level of practical salinity (μS/cm at 25° C). Using the approach, the salinity, S value (g/L) could be calculated for a particular brine waste.

$$EC\ (\mu S/cm) = \begin{pmatrix} 20 + 0.69608 \times (S - 32.188) + 0.0013094 \times (S - 32.188)^2 - \\ 0.000011918 \times (S - 32.188)^3 + 0.0000001739\ 2(S - 32.188)^4 - \\ 0.0000000031\ 12 \times (S - 32.188)^5 \end{pmatrix} \quad \text{Equation 4}$$

The methodology for finding TDS (mg/L) involves applying a ratio of 0.6 to a given EC value (Anderson and Cummings, 1999).

$$TDS\ (mg/L) = EC\ (\mu S/cm) \times 0.6 \quad \text{Equation 5}$$

10.4 Key Weather Parameters

The MK4 weather station set up adjoining the collector plate unit will collect data on the four key meteorological parameters. A brief description of the four parameters follows:-

- Solar radiation ($MJ/m^2/d$) a measure of the total amount of solar energy that falls on a horizontal surface for a particular day.
- Relative humidity (%) the ratio of the amount of moisture actually in the air to the maximum amount of moisture which the air could hold at the same temperature.
- Wind speed (m/s) a measure of the wind speed.
- Air temperature (°C) actual temperature of the humid air (BOM, 2008).

The research could also draw on data from the Australian Bureau of Meteorology (BOM) base station approx. 400 m due east of the research location. However, the difference in AHD (i.e. approx. 19 m) and the surrounding of the BOM station with high rise buildings lead to significant differences in daily and hourly wind and pan evaporation data. A review concluded the BOM base station data could not be used because of the variability and spread of the data.

11 Results and Discussion

11.1 Introduction

The experimental program between June 2005, and August 2006 will consider the evaporation enhancement capabilities of the collector plate unit under different operating and weather conditions.

The methodology employed to find the level of evaporation enhancement begins by measuring the level of brine pan evaporation on a daily basis. The tanks used in the trial (CTK, STK, and RTK) have a diameter of 1100 mm, which equates to a surface area of 0.95 m^2.

The reference water level in each of the tanks will be 280 mm. The total volume in units of L for each of the tanks to be determined, with the abbreviation 'TKvol' referring to the tank volume as :-

$$TKvol = (0.95\ m^2) \times (0.28\ m) = 0.266\ m^3 = 266\ L$$

The evaporation data will be collected in units of mm/d. The evaporation results from the tank will needed to be multiplied by a factor of 1/0.95 m^2 to standardise the data to an equivalent surface area (1m^2).

The methodology involves subtracting the water loss, WL mm from the initial water level of 280 mm and multiplying the water loss by a factor (1/0.95 m^2) to find the water loss in L/m^2/ d. The abbreviation 'tank evap' will be used to express the level of brine pan evaporation from the CTK.

$$TankEvap = \frac{\left(0.95\ m^2 \times (WL - mm)/10^3\right)}{\left(0.95\ m^2\right)} = L/m^2/d$$

The methodology adopted to find collector plate evaporation, L/m²/d involves finding the level of brine pan evaporation from the STK, consisting of both brine pan and collector plate evaporation. The results separated by applying the research assumption that STK and CTK brine pan evaporation is similar. To ensure the level of collector plate evaporation and the ratio of evaporation enhancement is representative of 1m², the evaporation result will be multiplied by a factor of 1 /2.65 m² (i.e. the collector plate surface area).

$$Col - plate - evap\ (L/m^2/d) = \frac{(STKevap - CTKevap)L/m^2/d}{\left(2.65\ m^2\right)}$$ Equation 6

The fresh pan evaporation results from the RTK will be similarly collected using the same method. The availability of both fresh and brine pan evaporation data provides the means for evaluating the effect of brine concentration on evaporation.

The results for the collector plate unit will be expressed in terms of collector plate evaporation and ratio of evaporation enhancement, referred to as EER. The results for the four key meteorological parameters will be presented on a daily average basis for air temperature (°C), relative humidity (%) and wind speed (m/s). The results for solar radiation (MJ/m²/d) will be presented as a cumulative total for the daily period.

The discussion will focus on both peak and average results for evaporation enhancement and collector plate evaporation, and consider whether results reflect individual meteorological parameters or ranges of results for the individual parameters.

The means of discussing the results will be through polynomial regression. Results from the collector plate unit were tested using a suite of different statistical tools, and they include and not limited to ANOVA, and Multiple Regression to find the statistical tool most appropriate for analysing the meteorological and evaporation data. The data assessment showed the polynomial approach, consisting of either second, third, fourth or fifth order polynomials was best suited to expressing the relationship between meteorological parameters and evaporation data – collector plate evaporation and evaporation enhancement. Polynomial regression has been used many times in the field to analysis evaporation data (see Akridge, 2007).

The mechanism for measuring the relationship otherwise known as the degree of fit to the subject data will be the co-efficient of determination (otherwise referred to as the R^2 value). Typically, the closer the R^2 value to 1.0, the better the level of fit (Smith, 1999).

11.2 Performance of CPU for Brine at 3.5% NaCl

The experimental period for 3.5% NaCl involves testing the performance of the collector plate, both in terms of evaporation enhancement and collector plate evaporation for three film heights 0.3 mm, 0.2 mm and 0.155 m.

<u>Brine Film Height – 0.3 mm</u>

The first trial period commenced on Friday, 24th June and finished on Wednesday, 19th October, 2005. The unit results are presented in Tables 6 and 7, for the research period Friday, 24th June to Thursday, 1st September, 2005 and the period Friday, 2nd September to Wednesday, 19th October, 2005.

Table 6 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.3 mm

June, July & August	Collector Plate Evaporation	EER	BOM Solar Radiation	BOM Relative Humidity	Wind Speed	BOM Air Temp
Time	mm/m^2.d	#	MJ/m^2.d	%	m/s	°C
Friday, 24 June 2005	**0.39**	**0.46**	**8.6**	**78.8**	**1.7**	**9.8**
Saturday, 25 June 2005	0.13	0.15	9.6	71.6	1.4	9.0
Sunday, 26 June 2005	0.13	0.15	-	72.0	1.3	9.4
Monday, 27 June 2005	0.13	0.15	-	80.8	1.2	8.5
Tuesday, 28 June 2005	0.13	0.15	-	84.6	1.4	9.4
Wednesday, 29 June 2005	0.36	0.38	7.9	81.9	1.6	8.9
Sunday, 3 July 2005	**0.82**	**0.78**	**4.8**	**72.9**	**0.7**	**12.3**
Monday, 4 July 2005	0.36	0.38	4.3	67.3	1.1	12.4
Tuesday, 5 July 2005	0.36	0.19	-	65.5	2.1	12.2
Monday, 11 July 2005	0.36	0.19	4.2	79.1	0.9	10.9
Friday, 15 July 2005	0.36	0.38	-	84.0	1.6	10.4
Sunday, 17 July 2005	0.36	0.38	8.3	64.0	2.3	9.3
Monday, 18 July 2005	0.36	0.38	-	66.0	1.2	9.6
Tuesday, 19 July 2005	0.36	0.38	-	74.0	0.8	10.1
Wednesday, 20 July 2005	0.36	0.38	-	75.1	1.4	12.0
Thursday, 21 July 2005	0.36	0.38	9.2	62.1	1.7	10.3
Friday, 22 July 2005	**0.90**	**0.47**	**9.3**	**56.6**	**2.6**	**13.3**
Saturday, 23 July 2005	0.18	0.19	4.7	58.3	2.9	12.9
Wednesday, 27 July 2005	0.36	0.19	4.1	71.0	1.4	13.0
Thursday, 28 July 2005	0.36	0.38	5.9	66.5	1.9	14.2
Friday, 29 July 2005	**0.72**	**0.75**	**7.9**	**55.3**	**2.5**	**14.3**
Saturday, 30 July 2005	0.18	0.09	4.0	68.8	1.3	12.1
Sunday, 31 July 2005	0.18	0.09	8.6	69.9	1.0	12.8
Monday, 1 August 2005	0.36	0.09	6.8	73.3	1.2	11.3
Tuesday, 2 August 2005	**3.58**	**1.88**	**9.5**	**62.4**	**1.9**	**13.5**
Tuesday, 9 August 2005	0.36	0.19	2.5	68.1	2.3	11.7
Thursday, 11 August 2005	0.90	0.63	4.8	74.5	2.3	7.0
Wednesday, 17 August 2005	1.07	0.57	11.0	58.4	1.9	11.8
Thursday, 18 August 2005	0.33	0.11	3.3	44.5	2.3	15.6
Friday, 19 August 2005	1.07	1.13	0.3	63.3	2.2	14.9
Thursday, 25 August 2005	**1.79**	**0.63**	**11.3**	**69.4**	**1.3**	**11.8**
Friday, 26 August 2005	**1.79**	**0.63**	**9.7**	**70.1**	**1.4**	**11.7**
Monday, 29 August 2005	**5.84**	**1.54**	**12.1**	**48.3**	**3.3**	**18.0**
Wednesday, 31 August 2005	1.43	0.75	8.4	59.8	3.5	11.5
Thursday, 1 September 2005	0.90	0.94	12.1	55.3	2.2	9.3
Friday, 2 September 2005	1.07	0.38	11.9	61.9	1.7	11.0

The collector plate unit achieved an evaporation enhancement of 0.46 on 24th June. The collector plate evaporation level, 0.39 mm/m^2/d represented 0.46 or 46% of the brine pan evaporation result, 0.86 mm/m^2/d. Reflecting the winter weather conditions, both the total solar radiation and average air temperature were less than 10 MJ/m^2/d and less than 10 °C respectively.

In this context where the evaporation enhancement result was less than 1.0, no evaporation enhancement occurred as the level of brine pan evaporation from the CTK exceeded the level of evaporation achieved by an equivalent area of collector plate.

The peak EER result for the month of July occurred on 3rd July with a result of 0.78. Despite lower daily levels of solar radiation and wind speed available, the collector plate was able to draw on the surrounding air with a temperature of 12.3°C to achieve a collector plate evaporation result of 0.82 mm/m^2/d.

The next highest evaporation enhancement result, 0.75 was achieved on 29th July. The level of collector plate evaporation and evaporation enhancement was in the same order, with former achieving a result of 0.72 mm/m^2/d. The wind speed results were approx. the same on a daily basis, but perhaps a combination of the relative humidity at 55.3%, and the air temperature at 14.3 °C provided stable weather conditions for the collector plate to retain heat for evaporation of overflowing brine.

The evaporation enhancement results for the month of July were all lower than 1.0, indicating under these winter weather conditions, the collector plate could not achieve a higher level of evaporation than an equivalent tank area. It was a research hypotheses the night time ambient air temperatures were cooling the recycling flows across the collector plate to the extent the water temperature in the STK was dropping a number of degrees below that of the CTK.

The highest collector plate evaporation result occurred on Friday, 22nd July with 0.90 mm/m^2/d. The evaporation enhancement result was less than 0.5 at 0.47. The results for the meteorological parameters air temperature at 13.3°C, solar radiation at 9.3 MJ/m^2/d, wind speed at 2.6 m/s and relative humidity at 56.6% were at or near the optimum for the month suggesting a relationship between collector plate evaporation near 1.0 mm/m^2/d and the range of meteorological data collated for this date.

The collector plate generated almost twice the rate of pan evaporation on 2nd August with evaporation enhancement result of 1.88. The data for solar radiation, relative humidity and air temperature were all at the upper end of the ranges possible during winter conditions. The peak result suggests under winter conditions, an average wind speed in the order of 1.9 m/s was preferable for achieving optimum evaporation enhancement because of the susceptibility for heat to be lost from the plate when subject to high wind gusts of cooler air.

The peak level of evaporation enhancement, 1.13 was recorded on 19th August. The results for relative humidity, wind speed and air temperature were at the higher end of the range recorded for the test week, but significantly not solar radiation the daily total was 0.3 $MJ/m^2/d$. The peak result indicates in absence of incident solar radiation, evaporation enhancement is still possible with the collector plate able to absorb and retain heat where the ambient air temperature remains warm.

The collector plate evaporation result on 29th August was 5.84 $MJ/m^2/d$. The rate of evaporation enhancement was 1.54 times that of brine pan evaporation from the evaporation tank (CTK). The data for two key weather parameters was at the upper range possible for August, with relative humidity at 48.3%, and air temperature at 18 °C. It was suspected the results for the two parameters contributed to the high level of collector plate and evaporation tank evaporation. But, the total daily solar radiation at 12.3 $MJ/m^2/d$ was lower than expected, and the wind speed at 3.3 m/s may have both combined to reduce the heat absorbed by the collector plate, and thus, reduce the level of evaporation enhancement recorded.

The key weather parameter data on 25th and 26th August were similar and reflected in the data for collector plate evaporation and rate of evaporation enhancement. The data suggests a degree of reliability about evaporation data (i.e. collector plate evaporation approx. 1.8 $mm/m^2/d$, and evaporation enhancement approx. 0.6) for brine 3.5 % NaCl, film ht 0.3 mm when the solar radiation ranged between 9.5 and 11.5 $MJ/m^2/d$, relative humidity approx. 70%, wind speed approx. 1.35 m/s, and finally, when the air temperature was approx. 11.75 °C.

The weather conditions between 1st and 6th September were relatively constant, with solar radiation, relative humidity and wind speed in the range 10.3 to 13.9 $MJ/m^2/d$, 55.3 to 68 %, and 1.2 to 2.2 m/s respectively. The peak evaporation enhancement result within the period occurred on September 1, 0.94 where the average air temperature was only 9.3 °C. It was suspected the heat absorbed by the plate (solar radiation 12.1 $MJ/m^2/d$), combined with the relative humidity (55.3%) and wind speed (2.2 m/s) to provide the meteorological conditions for the evaporation result.

Table 7 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.3 mm

Brine 3.5 % NaCl - Film Ht 0.3 mm						
September / October	Collector Plate Evaporation	EER	BOM Solar Radiation	BOM Relative Humidity	Wind Speed	BOM Air Temp
Time	$mm/m^2.d$	#	$MJ/m^2.d$	%	m/s	℃
Thursday, 1 September 2005	**0.90**	**0.94**	**12.1**	**55.3**	**2.2**	**9.3**
Friday, 2 September 2005	1.07	0.38	11.9	61.9	1.7	11.0
Sunday, 4 September 2005	0.54	0.38	10.3	68.0	1.2	12.0
Monday, 5 September 2005	0.72	0.19	11.8	63.5	1.4	12.5
Tuesday, 6 September 2005	0.72	0.38	13.9	57.3	1.8	12.8
Wednesday, 7 September 2005	1.97	0.46	7.8	51.5	2.9	16.1
Thursday, 8 September 2005	**6.09**	**1.28**	**5.7**	**45.1**	**3.2**	**19.9**
Wednesday, 21 September 2005	1.61	0.68	14.9	66.5	2.1	14.0
Thursday, 22 September 2005	1.07	0.38	6.0	64.5	2.4	16.8
Sunday, 25 September 2005	1.23	0.52	-	67.6	1.9	13.5
Wednesday, 28 September 2005	**0.72**	**0.75**	**0.4**	**75.5**	**2.8**	**14.9**
Friday, 30 September 2005	1.43	0.50	7.5	53.3	1.7	14.9
Monday, 3 October 2005	**5.01**	**1.76**	**16.2**	**44.3**	**3.0**	**17.3**
Tuesday, 4 October 2005	3.58	0.63	16.1	55.3	1.8	14.5
Wednesday, 5 October 2005	**1.43**	**1.51**	**1.0**	**51.3**	**2.6**	**16.2**
Thursday, 6 October 2005	**3.58**	**1.88**	**12.3**	**53.1**	**2.7**	**13.6**
Friday, 7 October 2005	3.22	1.70	4.2	64.5	1.1	12.3
Monday, 10 October 2005	1.07	0.38	20.0	52.1	2.3	15.3
Thursday, 13 October 2005	0.72	0.38	18.8	46.6	2.8	16.6
Monday, 17 October 2005	0.36	0.19	17.9	70.3	1.3	16.0
Tuesday, 18 October 2005	0.72	0.75	20.0	65.5	1.7	17.9
Wednesday, 19 October 2005	1.07	0.57	11.8	50.5	2.0	18.9

The peak EER of 1.28 was recorded on 8th September. The air temperature and relative humidity 19.9 °C and 45.1% were at the upper end of the data range for August, but the total solar radiation at 5.7 $MJ/m^2/d$ was at the lower end of the data range.

An evaporation enhancement result of 0.75 was recorded on 28th September. The result was achieved despite minimal solar radiation (0.4 $MJ/m^2/d$) and the average air temperature being 14.9 °C. The result adds weight to the observation that the unit performance can approach brine pan evaporation without significant incident solar radiation providing the air temperature and relative humidity are at the upper and lower ends of their range, and the wind speed results are approx. average for the particular conditions.

For the month of October, the highest level of evaporation enhancement, 1.88 was recorded on 6th October. The collector plate evaporation was 3.58 mm/m^2/d. The next best result was 1.76 achieved earlier in the week (3rd October) while the collector plate evaporation was 40% more at 5.01 mm/m^2/d. The weather data reflected the variation in collector plate evaporation, with the solar radiation, 3.9 MJ/m^2/d higher, relative humidity 8.8% lower and the air temperature 3.7°C higher. However, significantly the levels of evaporation enhancement were relatively similar.

The level of evaporation enhancement recorded on 5th October should be noted. Despite a total solar radiation of 1.00 MJ/m^2/d the EER for the test day was 1.51 and the collector plate evaporation was 1.43 mm/m^2/d. As observed previously, where the relative humidity (51.3 %) and air temperature (16.2 °C) results are relatively high for the weather period, the unit can produce reasonable levels of evaporation enhancement in the absence of incident solar radiation.

The collector plate evaporation results over the month of October were lower than expected having regard to the key weather data. But, the results for evaporation enhancement appear to show the plate performance were not inconsistent with the brine pan evaporation from the evaporation tank (CTK). It is suspected the results for the test days were affected by the high number of rainfall days, and as such, not representative of the expected unit performance under typical Melbourne weather conditions.

Brine Film Height – 0.2 mm

The first part of the film height trial for 0.2 mm commenced 12th December and finished 23rd December, 2005 and the second part of the trial ran between 4th and 12th February,

2006. In contrast to the 0.3 mm test above, the unit was tested under more evaporation favourable meteorological conditions over the summer period. The results from the research period are outlined in Table 8 below.

Table 8 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.2 mm

December, 2005 and February, 2006	Collector Plate Evaporation	EER	WS Solar Radiation	WS Relative Humidity	WS Wind Speed	WS Air Temp
Time	mm/m^2.d	#	MJ/m^2.d	%	m/s	℃
Monday, 12 December 2005	1.97	0.59	30.4	48.9	1.1	21.7
Wednesday, 14 December 2005	2.86	1.51	24.8	56.8	0.9	19.7
Thursday, 15 December 2005	4.30	0.75	21.5	62.3	1.3	19.4
Saturday, 17 December 2005	**11.10**	**2.92**	**13.8**	**68.2**	**1.2**	**21.8**
Sunday, 18 December 2005	7.88	2.07	28.8	55.8	1.4	23.0
Tuesday, 20 December 2005	6.80	1.02	29.9	55.6	1.2	22.4
Wednesday, 21 December 2005	4.66	0.98	26.3	53.0	1.9	25.9
Friday, 23 December 2005	**11.46**	**1.34**	**22.6**	**68.0**	**1.2**	**21.8**
Saturday, 4 February 2006	5.55	1.17	19.0	53.3	1.3	17.2
Sunday, 5 February 2006	5.91	1.24	23.8	55.9	1.3	20.9
Monday, 6 February 2006	6.45	1.13	17.1	61.8	1.0	19.7
Tuesday, 7 February 2006	4.30	0.90	23.2	49.5	1.4	18.1
Wednesday, 8 February 2006	5.37	1.88	28.1	35.3	1.7	26.3
Saturday, 11 February 2006	**9.67**	**2.54**	**21.1**	**55.9**	**1.3**	**20.9**
Sunday, 12 February 2006	8.87	1.87	23.0	54.9	1.3	21.1

The peak evaporation enhancement result for the period occurred on 17th December, with a result of 2.92. The collector plate evaporation result was 11.10 mm/m^2.d. The thermal inputs to the collector plate weren't to the level expected, the total solar radiation was 13.8 MJ/m^2/d and the relative humidity was 68.2%. However, critically the average daily air temperature was 21.8 °C suggesting rather than heat convection from surrounding air systems made a strong individual contribution to the result.

The next day, 18th December the data for solar radiation was significantly higher, with a total solar radiation level of 28.8 MJ/m^2/d, a lower relative humidity (55.8%), and higher daily air temperature (23°C). However, the evaporation enhancement result was lower than the previous day (December 17), at 2.07, with the collector plate evaporation being 7.88 MJ/m^2/d. The weather data for 20th December, shows an even higher total solar radiation of 29.9 MJ/m^2.d, similar relative humidity (55.6%), and air temperature (22.4°C), yet the evaporation enhancement is lower again at 1.02 with a collector plate evaporation level of 6.80 mm/m^2.d.

The data appears to suggest collector plate performance in terms of EER decreases with increasing incident solar radiation beyond 30 MJ/m^2/d. The most notable examples being 12th December where the evaporation enhancement was 0.59 despite the total solar radiation being 30.4 MJ/m^2/d, and 23rd December where the evaporation enhancement (1.23) was less than half the level achieved on 17th December. The weather data for wind speed, air temperature and relative humidity was very similar on both days, but the solar radiation result was 8.8 MJ/m^2/d higher on 17th December. It's suspected the EER results decrease with increasing solar radiation beyond 30 MJ/m^2/d because the evaporation tanks have a greater thermal mass than the collector plate. Further research would be suggested during peak summer conditions to investigate this issue further.

The peak collector plate performance during the second part of the 0.2 mm trial occurred on 11th February with a result of 2.54, where the collector plate evaporation was 9.67 mm/m^2/d. The brine pan evaporation was 3.8 mm/m^2/d but the fresh pan evaporation for the same day was 5 mm/m^2/d representing a brine/fresh pan evaporation ratio of 0.76. A result which is generally consistent with both Fahey (1999) and Ahmed et al (2000), who suggested a ratio 0.70 was appropriate for relating brine waters (3.5% NaCl) to fresh water evaporation. The weather conditions for February 11 included a total solar radiation level of 21.1 MJ/m^2/d, a relative humidity result of 56%, and average air temperature of 20.9 °C.

The weather conditions were more favourable on 8th February, and this was reflected in the level of fresh pan evaporation (11.5 mm/m^2/d). However, the level of evaporation enhancement was lower than February 11, at 1.88 with a collector plate evaporation level of 5.37 mm/m^2/d. Similar to previous test days (see 12th and 18th December, and 18th January), the test day was subject to a high level of incident solar radiation (28.1

MJ/m²/d), high average air temperature (26.3°C), and very low relative humidity (35%), but the unit performance wasn't to the level expected.

As suggested previously, the 3.5 % NaCl waste may be sensitive to high ambient air temperatures, to the extent the brine waste temperature increase to a higher level than fresh water. It's believed this lack of a temperature differential between the ambient air temperature and the water temperature of the brine in the evaporation tank and overflowing the collector plate may be responsible for the reduced levels of evaporation enhancement during favourable weather conditions.

Brine 3.5% NaCl - Film Height – 0.15 mm

The trial involving a film height of 0.15 mm ran between 1st and 21st June and from 26th to 31st August, 2006. The trial occurred under winter weather conditions, similar to the 3.5 % NaCl trial the previous winter period. The film ht was set at 0.15 mm, approx. half the previous winter test ht to assess the effect of film height on evaporation performance. The results for the period at detailed at Table 9 below.

Table 9 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.15 mm – Pt A

June & August 06	Collector Plate Evaporation	EER	Brine Pan Evap	Fresh Pan Evap	Brine / Fresh Pan Ratio	WS Solar Radiation	WS Relative Humidity	WS Wind Speed
Time	$mm/m^2/d$	#	$mm/m^2/d$	$mm/m^2/d$	#	$MJ/m^2/d$	%	m/s
Thursday, 1 June 2006	0.36	0.38	0.95	0.00	-	6.30	70.63	0.90
Friday, 2 June 2006	0.36	0.38	0.95	1.00	0.95	6.60	73.13	1.00
Sunday, 4 June 2006	0.18	0.19	0.95	1.00	0.95	8.76	75.67	1.00
Monday, 5 June 2006	0.18	0.38	0.48	1.00	0.48	3.18	76.63	0.96
Tuesday, 6 June 2006	0.18	0.19	0.95	1.50	0.63	9.63	70.04	0.89
Wednesday, 7 June 2006	0.18	0.38	0.48	0.50	0.95	8.60	75.79	0.62
Thursday, 8 June 2006	0.36	0.38	0.95	1.00	0.95	6.60	77.75	0.59
Friday, 9 June 2006	0.36	0.38	0.95	1.00	0.95	6.50	82.58	0.47
Saturday, 10 June 2006	0.18	0.19	0.95	1.00	0.95	3.91	90.38	0.45
Sunday, 11 June 2006	0.36	0.38	0.95	1.00	0.95	6.75	63.88	2.12
Tuesday, 13 June 2006	0.36	0.38	0.95	1.00	0.95	4.29	68.92	0.52
Wednesday, 14 June 2006	0.36	0.38	0.95	1.00	0.95	6.94	67.58	0.51
Thursday, 15 June 2006	0.18	0.38	0.48	2.00	0.24	4.27	64.50	0.63
Saturday, 17 June 2006	0.54	0.38	1.43	2.00	0.71	3.28	70.46	0.52
Sunday, 18 June 2006	0.36	0.19	1.90	3.00	0.63	2.76	76.33	0.39
Monday, 19 June 2006	0.36	0.38	0.95	0.00	-	8.44	74.42	0.58
Tuesday, 20 June 2006	0.18	0.19	0.95	1.00	0.95	8.47	80.13	0.50
Wednesday, 21 June 2006	0.36	0.38	0.95	1.00	0.95	5.58	79.06	0.62
Saturday, 26 August 2006	**0.72**	**0.75**	**0.95**	**3.00**	**0.32**	**11.10**	**70.25**	**0.75**
Sunday, 27 August 2006	0.72	0.68	1.90	3.00	0.63	8.48	62.83	0.58
Monday, 28 August 2006	0.72	0.38	1.90	2.00	0.95	9.17	61.79	0.57
Tuesday, 29 August 2006	**1.43**	**0.75**	**1.90**	**3.00**	**0.63**	**11.11**	**64.88**	**0.57**
Wednesday, 30 August 2006	1.79	0.63	2.85	2.00	1.43	14.89	64.71	0.64
Thursday, 31 August 2006	1.61	0.68	2.38	4.00	0.59	15.17	57.17	0.89

The peak evaporation enhancement achieved over the period was 0.75, recorded on two test days 26th and 29th August. The collector plate evaporation results were 0.72 and 1.43 $mm/m^2/d$ respectively. The weather conditions were more favourable to evaporation on 29th August and this is reflected in the brine and fresh pan evaporation results of 1.9 and 3.0 $mm/m^2/d$ respectively.

The solar radiation and air temperature results were 11.1 MJ/m²/d and 13.9 °C respectively. Most notably, the STK water temperature at 13.7 °C was 0.2 °C less than the air temperature, but the plate inlet temperature was 15.7 °C suggesting an immediate increase of 2 °C (on average) in water temperature as the brine falls down the plate. By contrast, the water temperatures in the CTK and RTK were 15.9 and 15.3 °C respectively.

Table 10 – CPU Trial of Brine at 3.5% NaCl Film Ht 0.15 mm – Pt B

June & August 06	Plate Inlet Temperature	Water Temp - STK	Water Temp - CTK	Water Temp - RTK	WS Air Temp
Time	°C	°C	°C	°C	°C
Thursday, 1 June 2006	12.8	13.8	11.5	10.1	11.8
Friday, 2 June 2006	12.5	13.9	11.4	10.1	10.8
Sunday, 4 June 2006	12.8	14.8	12.4	10.9	11.1
Monday, 5 June 2006	10.1	14.2	9.0	9.0	9.1
Tuesday, 6 June 2006	12.4	13.3	11.4	9.6	12.4
Wednesday, 7 June 2006	12.7	13.5	12.3	10.2	10.9
Thursday, 8 June 2006	10.5	13.5	9.8	9.0	9.3
Friday, 9 June 2006	10.7	12.4	10.4	9.0	9.0
Saturday, 10 June 2006	9.9	8.9	12.3	8.5	8.8
Sunday, 11 June 2006	12.1	10.0	12.3	8.6	11.1
Tuesday, 13 June 2006	11.4	9.6	12.2	9.0	10.7
Wednesday, 14 June 2006	12.3	10.5	12.4	9.0	11.4
Thursday, 15 June 2006	13.5	11.8	13.5	10.4	13.1
Saturday, 17 June 2006	13.5	11.4	13.3	11.4	12.5
Sunday, 18 June 2006	12.7	11.0	13.5	10.6	11.9
Monday, 19 June 2006	11.2	9.3	12.3	8.8	10.0
Tuesday, 20 June 2006	12.8	9.7	10.0	8.4	9.2
Wednesday, 21 June 2006	14.8	10.3	10.8	8.9	10.6
Saturday, 26 August 2006	**13.17**	**11.3**	**13.3**	**12.7**	**11.6**
Sunday, 27 August 2006	14.07	12.1	14.6	13.47	13.5
Monday, 28 August 2006	15.94	13.4	15.2	14.9	15.0
Tuesday, 29 August 2006	**15.73**	**13.7**	**15.9**	**15.3**	**13.9**
Wednesday, 30 August 2006	15.53	13.3	16.3	15.4	14.6
Thursday, 31 August 2006	17.73	14.8	17.8	17.2	17.1

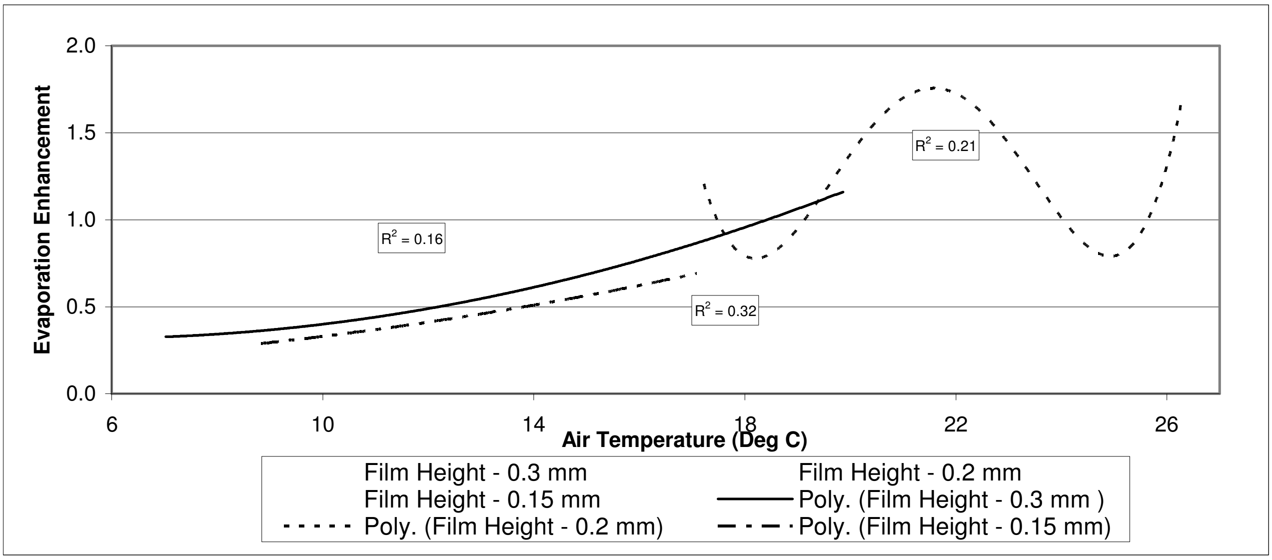
Given the similarity in water temperature results, its suspected incident solar radiation plays a strong part in warming the collector plate and evaporation tanks (CTK and

RTK). The results for brine and fresh pan evaporation equate to a ratio of 0.63 which is generally consistent with both Fahey (1999) and Ahmed et al (2000), who suggested a ratio 0.70 was appropriate for relating brine waters (3.5% NaCl) to fresh water evaporation.

<u>Brine 3.5% NaCl, Film Hts 0.3 mm, 0.2 mm and 0.15 mm</u>

Analysis of the data for the 0.3 mm, 0.2 mm and 0.15 mm test trials was presented in Figure 1 using second and fourth order polynomial trend lines. Figure 1 presents the evaporation enhancement results based on the daily average air temperature (displayed on the x axis).

Figure 1 – EER vs. Air temperature – Brine 3.5% NaCl



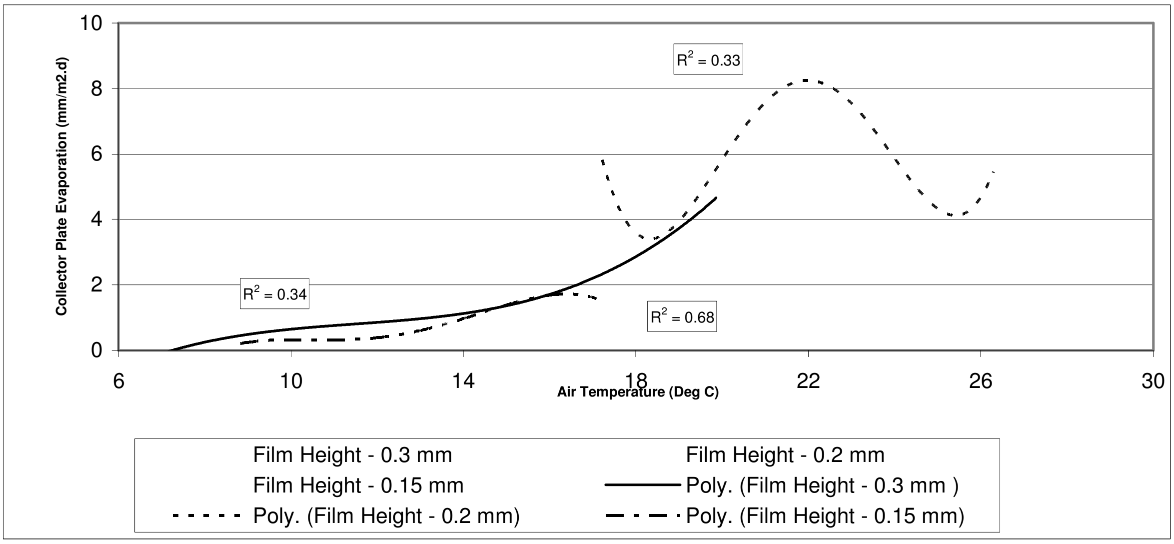
Analysis shows for the 0.3 mm and 0.15 mm film heights over the respective winter periods, similar trend lines with the 0.3 mm film height for evaporation enhancement rising up to 1.25 with air temperature approaching 20 °C. The trend line for the 0.15 film height test, albeit with a smaller data set than the 0.3 mm film ht approaches an EER result of 0.75 with air temperature extending past 20 °C.

The trend line for 0.2 mm film height differed from the other two film heights, being a fourth order polynomial rather than a second order polynomial. The trend line shows EER results greater than 1.5 occurred when air temperature was between 20 and 24 °C.

However, the fit of the trend line to 15 data points is low suggesting there isn't a direct relationship.

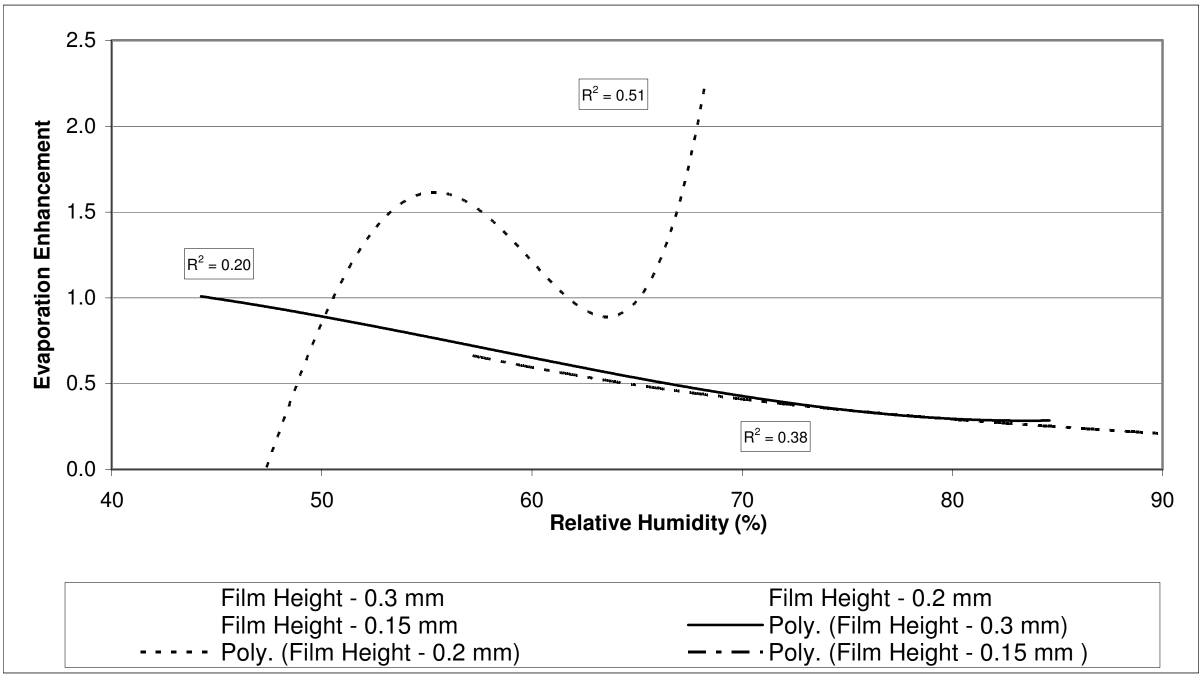
The collector plate trend lines at Figure 2 for the three film heights were relatively similar to those for brine evaporation. However, the trend lines for collector plate evaporation area were a better fit to the air temperature data, especially for the 0.3 mm and 0.15 mm film heights. The R^2 value for the 0.3 mm and 0.15 mm film heights were 0.34 and 0.68 twice the respective values presented in Figure 1. The trend line equation for the 0.15 mm film ht (see R^2 value, 0.68) shows a relationship between air temperature between 15 and 17 °C, and collector plate evaporation between 1.5 and 2.0 mm/m²/d.

Figure 2 – Collector Plate Evaporation vs. Air temperature – Brine 3.5% NaCl



The trend line at Figure 3 shows the relationship between EER and relative humidity for the 0.2 mm film ht (see R^2 value, 0.51). The trend line shows EER greater than 1.5 could be expected on days where the average daily relative humidity was between 52 and 57 %. The trend line for 0.3 mm and 0.15 mm film heights were relatively similar, with the trend line for the 0.3 mm suggesting the daily relative humidity needed to be approx. 45% to achieve an evaporation enhancement result of 1.0. While, the trend line for 0.15 mm (see R^2 value, 0.38) suggested an evaporation enhancement of 0.65 could be achieved on days where the relative humidity was less than 60%.

Figure 3 – EER vs. Relative Humidity – Brine 3.5% NaCl



The trend line profiles at Figure 4 for collector plate evaporation and relative humidity were relatively similar to enhanced evaporation, except the data shows the polynomial equations are a better fit. The fifth order polynomial equation for the 0.2 mm film test ht shows a high correlation between collector plate evaporation results greater than 6 mm/m²/d where the daily level of relative humidity was between 52 and 57%.

Figure 4 – Collector Plate Evaporation vs. Relative Humidity – Brine 3.5% NaCl

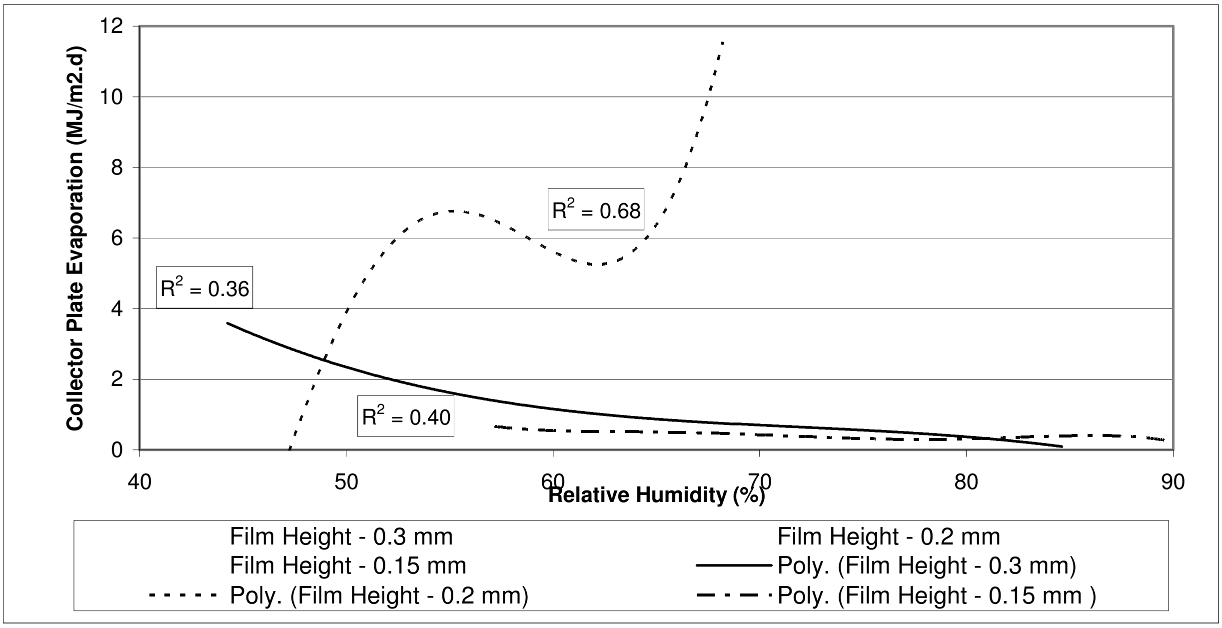


Figure 5 shows the difference in solar radiation available during winter and summer periods. For the 0.2 mm film ht test, undertaken in the summer period EER results greater than 1.5 could be achieved where the total level of solar radiation reached approx. 20 MJ/m²/d. During the winter period where the levels of solar radiation available were much lower, an evaporation enhancement result of 1.0 was possible where the total solar radiation approx. 14 MJ/m².

Figure 5 – EER vs. Solar Radiation – Brine 3.5% NaCl

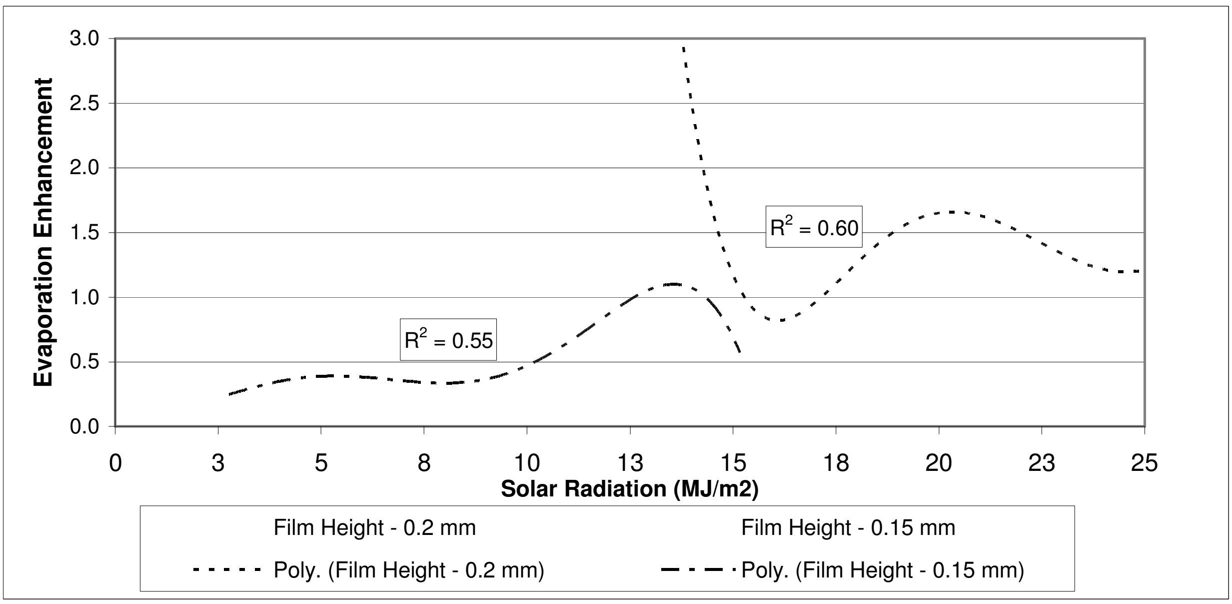


Figure 6 shows the trend lines fitted to 0.2 mm and 0.15 mm film ht data sets. The data for the 0.15 film ht shows collector plate evaporation of 2 mm/m²/d can be achieved where the total solar radiation approaches 15 MJ/m²/d. The equation fitted to the 0.15 mm film ht data, shows the strong relationship between collector plate evaporation and solar radiation (see R^2 value, 0.81).

Figure 6 – Collector Plate Evaporation vs. Solar Radiation – Brine 3.5% NaCl

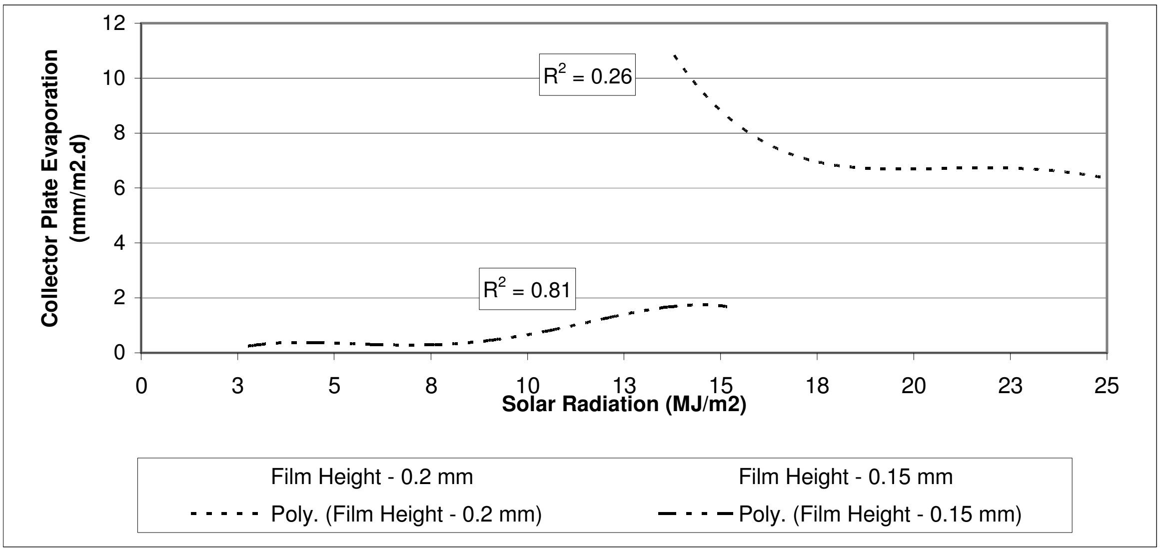


Figure 7 shows the trend lines fitted to the 0.2 mm and 0.15 mm data sets for EER relative to the average daily wind speeds. The position of the trend lines shows the seasonal variation in wind speeds, with the range for 0.2 mm film ht being between 0.9 m/s and 1.8 m/s, as opposed to between 0.4 and 1.1 m/s for the wetted film height 0.15mm trial undertaken during the winter period. The data shows a peak EER result of 1.9 can be reached for a film ht of 0.2 mm where the wind speed result approaches 1.75 m/s.

Figure 7 – EER vs. Wind Speed – Brine 3.5% NaCl

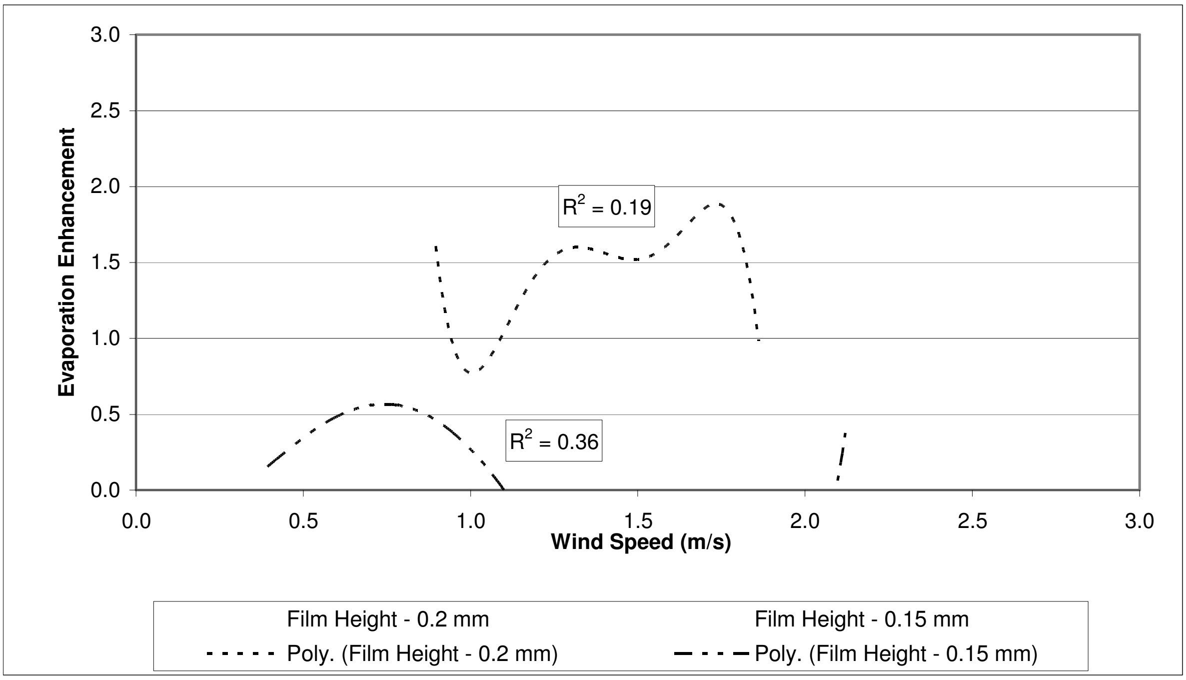
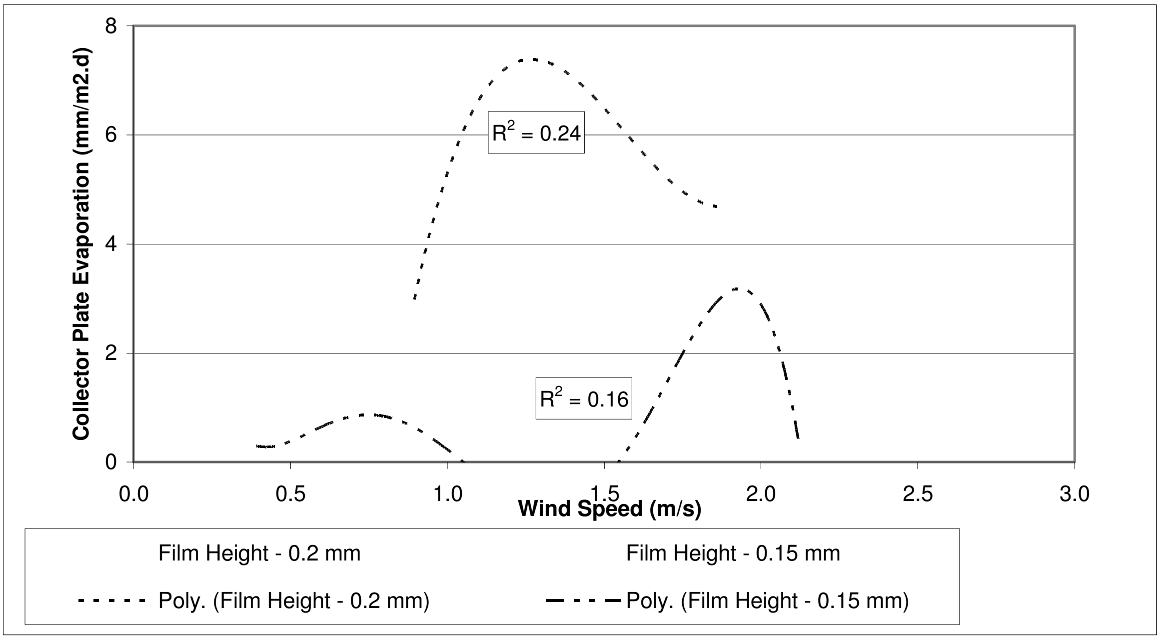


Figure 8 shows the trend lines fitted to the 0.2 and 0.15 mm film ht data sets of collector plate evaporation relative to wind speed. Similar to the EER trend lines, the ranges of wind speed vary from summer to winter, for the 0.2 mm film ht the range of wind speed results was from 0.9 to 1.8 m/s, while during the winter period the wind speed range was much larger from 0.4 to 2.2 m/s.

Figure 8 – Collector Plate Evaporation vs. Wind Speed – Brine 3.5% NaCl



Analysis of the 0.2 mm film data set shows with wind speeds between the range of 1.1 to 1.5 m/s, the level of collector plate evaporation can exceed 6 mm/m²/d. However, the trend line for the 0.15 mm has a much lower degree of fit to the data set, as evident by the result (see R^2 value, 0.16).

11.3 Performance of CPU for Brine at 7.0% NaCl

The trial involving testing of Brine 7.0% NaCl - film height 0.2 mm ran between 28th December and 5th January, and 14 to 16th January, 2006. The results for the period are detailed at Table 11 below.

Table 11 – CPU Trial of Brine at 7.0% NaCl Film Ht 0.2 mm

December, January and February - 05/06	Collector Plate Evaporation	EER	WS Solar Radiation	WS Relative Humidity	WS Wind Speed	WS Air Temperature
Time	$mm/m^2.d$	#	$MJ/m^2.d$	%	m/s	°C
Wednesday, 28 December 2005	**2.86**	**1.00**	**32.3**	**26.0**	**1.3**	**32.2**
Thursday, 29 December 2005	3.22	1.70	26.6	35.5	1.3	28.5
Friday, 30 December 2005	4.66	2.45	30.5	40.3	1.2	28.3
Saturday, 31 December 2005	2.51	1.32	28.3	45.4	1.0	29.9
Monday, 2 January 2006	6.09	1.28	28.7	55.8	1.1	19.8
Tuesday, 3 January 2006	**10.03**	**2.64**	**18.5**	**58.3**	**1.2**	**18.7**
Wednesday, 4 January 2006	**12.53**	**2.64**	**18.9**	**51.4**	**1.4**	**18.0**
Thursday, 5 January 2006	6.45	1.70	27.7	54.8	1.4	19.4
Tuesday, 14 February 2006	1.43	0.38	16.8	62	0.9	19
Wednesday, 15 February 2006	7.88	1.04	19.5	68	1.1	21.0
Thursday, 16 February 2006	2.51	0.53	20.2	68	1.0	23.9

The peak EER result's of 2.64 occurred on both 3rd and 4th January, 2006. The collector plate evaporation results were 10 and 12.5 $mm/m^2/d$ respectively, indicating variability in pan evaporation results despite similar levels of solar radiation, and air temperature being recorded.

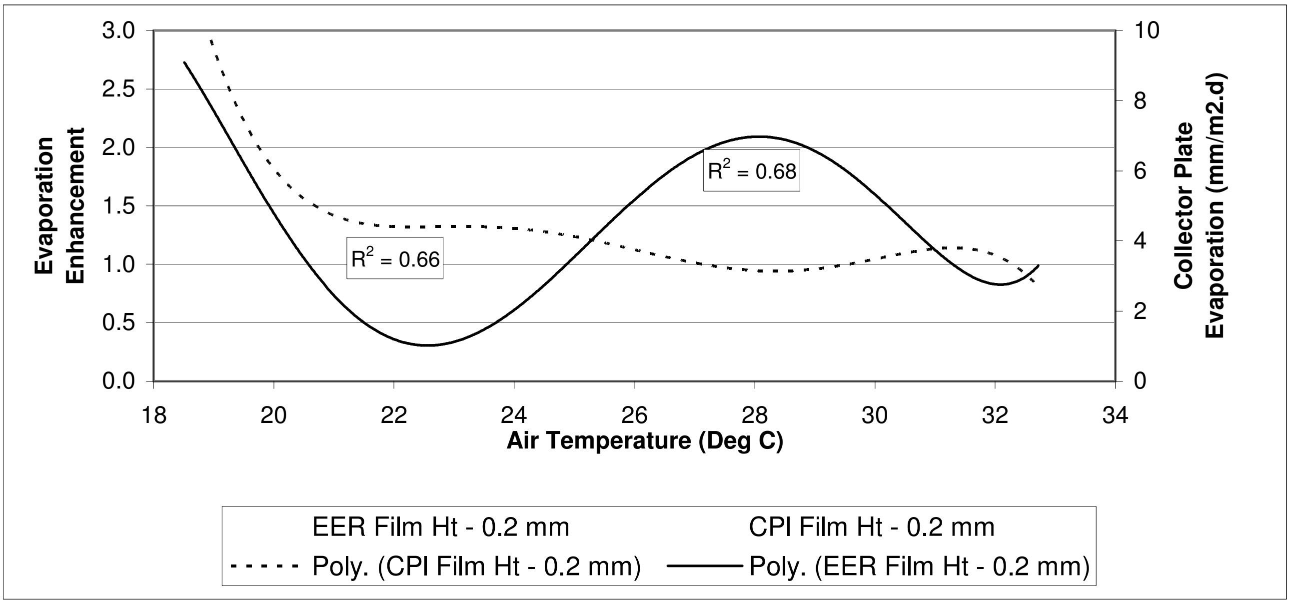
The peak weather conditions occurred on 28th December, where the solar radiation was 32.3 $MJ/m^2/d$, the relative humidity was 26%, and the air temperature was 32.2 °C. However, the collector plate evaporation was only 2.86 $mm/m^2/d$ and the evaporation enhancement result was only 1.0. The data supports previous results from the 3.5 %

NaCl test days (12th December and 18th January), where neither the level of EER or collector plate evaporation were as high as previously predicted.

Given the brine 7.0% NaCl featured only film height, 0.2 mm, the data for both evaporation enhancement and collector plate evaporation will be considered together for each meteorological parameter.

Figure 9 shows EER results greater than 2.5 and collector plate evaporation levels greater than 10 mm/m^2/d are possible with air temperature results around 19 °C. Figure 9 shows a fall in the trend lines as the air temperature rises into the early twenties, and the collector plate evaporation approaches 4.5 mm/m^2/d.

Figure 9 – CPU Evaporation vs. Air temperature – Brine 7.0% NaCl

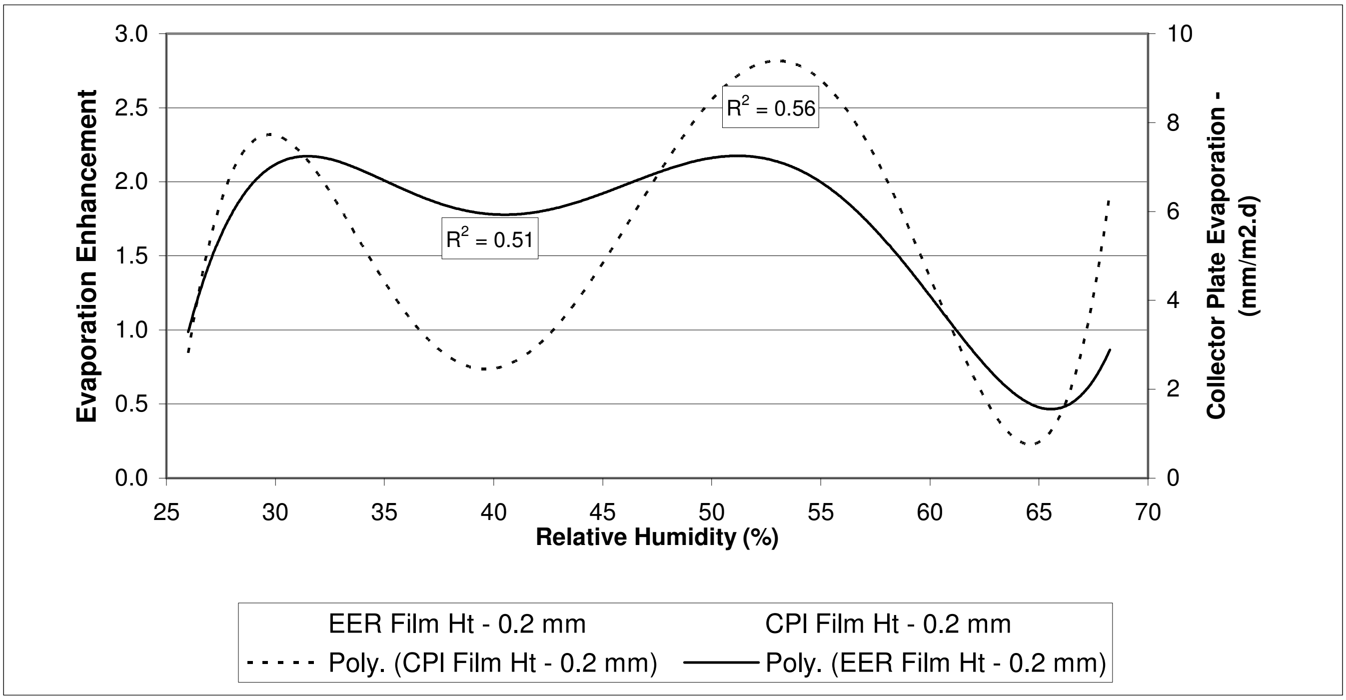


As the air temperature rises into the mid twenties, the EER (solid line) trend line rises up over 2.0 when the air temperature reaches 28 °C before falling again to less than 1.0 as the air temperature passes over 30 °C. Notably, the collector plate evaporation (dashed line) rises near 4 mm/m^2/d as the air temperature approaches 32°C. The trend lines indicate the variability in brine pan evaporation from the collector plate and from the evaporation tank with increasing air temperature.

The data indicates that brine pan evaporation does not increase linearly with air temperature rather peak results are possible from 19°C subject to other meteorological parameters, in particular solar radiation being above a certain threshold.

Figure 10 presents the data for collector plate evaporation and evaporation enhancement versus relative humidity. The collector plate evaporation (dashed line) trend line shows results higher than 7 mm/m²/d can be achieved when relative humidity results are within the range of 27 to 32%, and greater than 9 mm/m²/d when the relative humidity results are within the range of 47 to 57%. In between, the data shows that collector plate evaporation falls below 4 mm/m²/d when the relative humidity ranges between 36 and 44%. The fit of the fifth order polynomial trend line to the data, represented by the R^2 value of 0.56 suggests the legitimacy of the fluctuation in the data.

Figure 10 – CPU Evaporation vs. Relative Humidity – Brine 7.0% NaCl

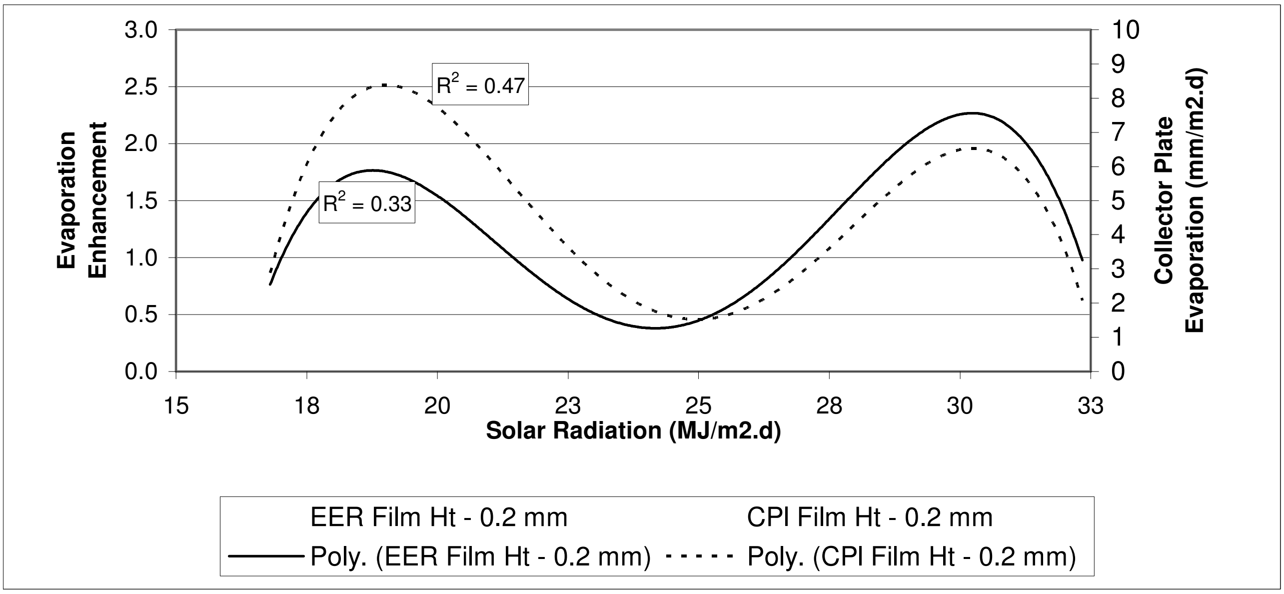


In contrast, the trend line for the evaporation enhancement (solid line) data shows peaks within the same ranges of relative humidity, but critically does not fall to the same extent as the trend line representing the data for collector plate evaporation.

Thus, it can be concluded peak evaporation enhancement can occur within the range of 30 to 52% for Brine 7.0% NaCl.

Figure 11 results provide an insight into the evaporation performance of the collector plate unit with Brine 7.0 % NaCl. The data shows levels of collector plate evaporation (dashed line) higher than 8 mm/m²/d and evaporation enhancement greater than 1.5 are possible when the total solar radiation reaches approx. 20 MJ/m²/d. Further, the evaporation enhancement (solid line) results were greater than 2.0 and collector plate evaporation levels greater than 7 mm/m²/d were possible when the solar radiation level exceeds 30 MJ/m²/d.

Figure 11 – CPU Evaporation vs. Solar Radiation – Brine 7.0% NaCl



While, the correlation of the fourth order polynomial trend lines to the data was not high, the data nevertheless shows that brine evaporation does not increase linearly with increasing solar radiation, rather peak evaporation results can occur depending on other meteorological parameters, air temperature in particular once the total solar radiation level reaches 19 MJ/m²/d.

Figure 12 presents the trend lines for both collector plate evaporation and evaporation enhancement relative to wind speed. The data shows evaporation enhancement (solid line) increases from 1.0 with wind speed near 1.1 m/s up to in excess of 2.5 when the wind speed approaches and exceeds 1.2 m/s. But, critically EER falls below 1.5 when the wind speed approaches 1.35 m/s before rising up to near 3.0 as the wind speed approaches 1.4 m/s. The fit of the fifth order polynomial equation, as evident by the R^2 value at 0.83 suggests a wind speed in the order of 1.2 m/s would generate a near optimum evaporation enhancement result.

Figure 12 – CPU Evaporation vs. Wind Speed – Brine 7.0% NaCl

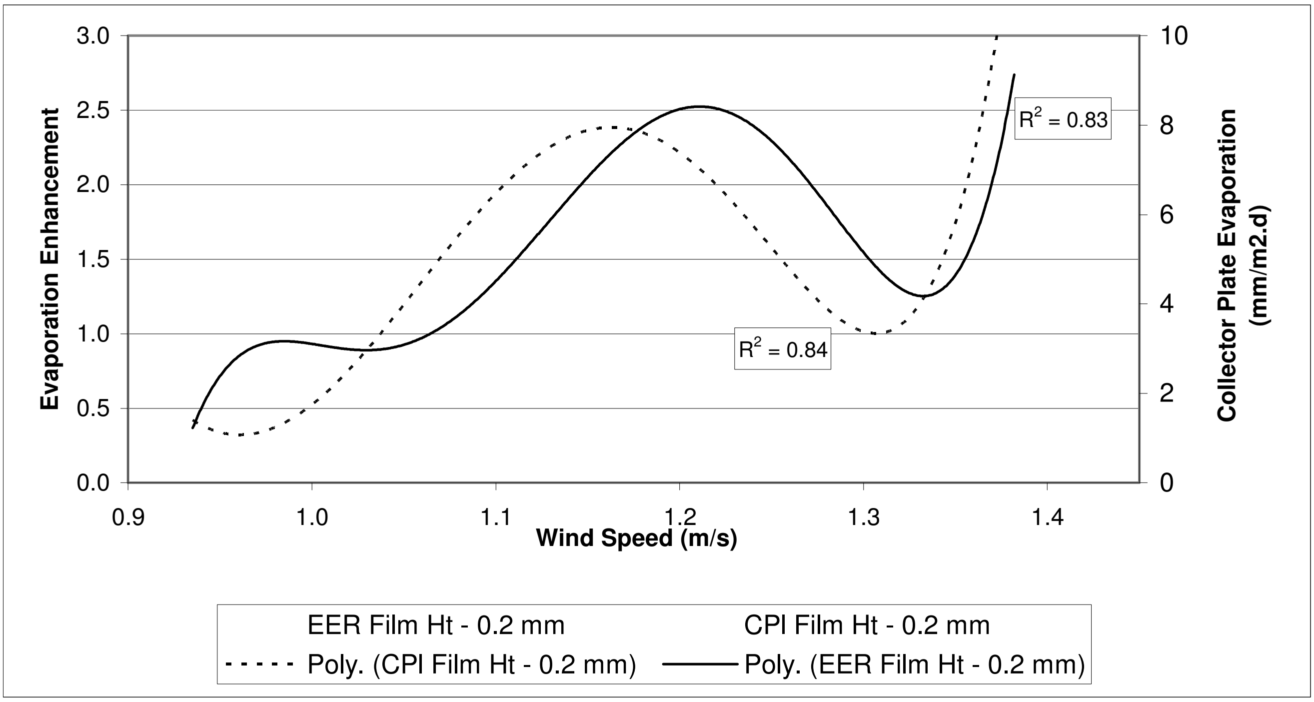


Figure 12 shows the trend line for collector plate evaporation (dashed line) follows a similar profile to evaporation enhancement, increasing from 3.5 mm/m^2.d up to near 8 mm/m^2.d as the wind speed increased from 1.05 m/s up to 1.15 m/s. Similarly, the level of collector plate evaporation reached up to 10 mm/m^2/d as the wind speed approached 1.35 m/s. Further, the fifth order polynomial equation (with an R^2 value at 0.83) for collector plate evaporation suggests the trend line discussed was in good agreement with the data.

11.4 Performance of CPU for Brine at 12.5% NaCl

The trial involving Brine 12.5% NaCl began on 6th January, and finished on 26th January, 2006. The results for the period are detailed at Table 12 below.

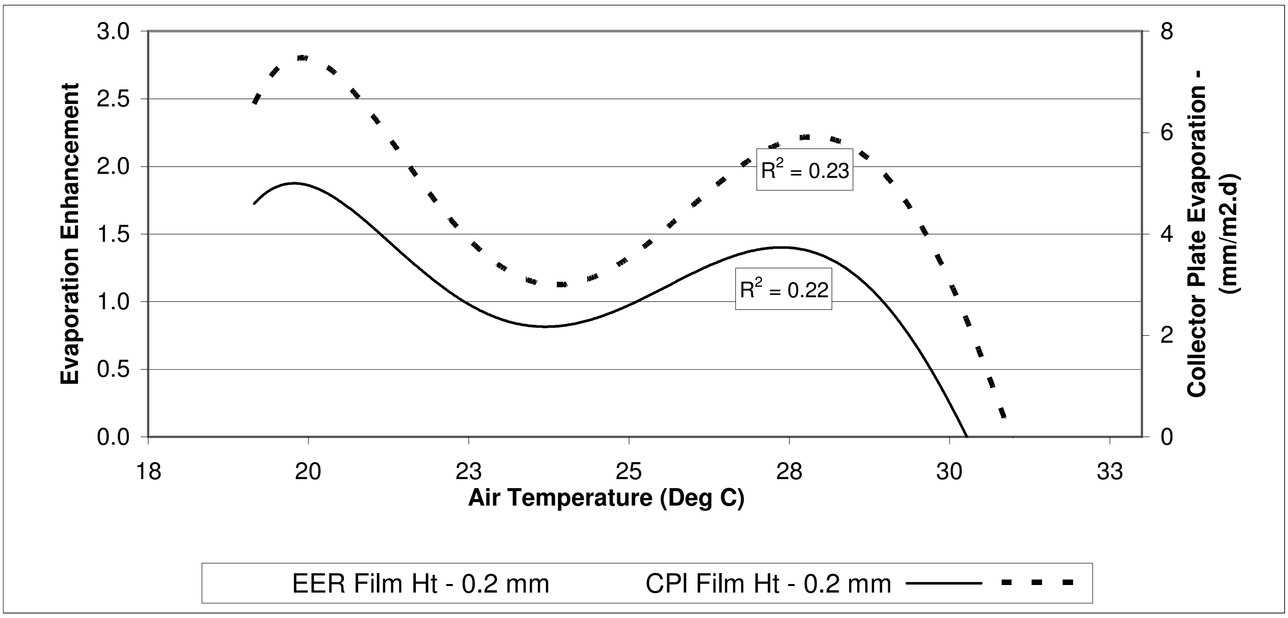
Table 12 – CPU Trial of Brine at 12.5% NaCl Film Ht 0.2 mm

Jan-06	Collector Plate Evaporation	EER	WS Solar Radiation	WS Relative Humidity	WS Wind Speed	WS Air Temp
Time	$mm/m^2/d$	#	$MJ/m^2/d$	%	m/s	℃
Friday, 6 January 2006	2.51	0.66	29.2	52.5	2.0	22.1
Saturday, 7 January 2006	3.22	1.13	23.6	61.5	1.4	22.6
Sunday, 8 January 2006	**8.24**	**2.89**	**32.7**	**53.9**	**1.1**	**25.7**
Monday, 9 January 2006	**6.09**	**1.07**	**8.7**	**53.8**	**0.8**	**26.8**
Tuesday, 10 January 2006	5.01	1.06	20.4	66.1	0.6	23.5
Saturday, 14 January 2006	**9.31**	**2.45**	**27.2**	**59.1**	**1.1**	**19.2**
Sunday, 15 January 2006	2.15	0.57	25.6	62.3	1.3	19.4
Monday, 16 January 2006	2.51	0.44	15.8	58.9	0.8	22.3
Tuesday, 17 January 2006	2.86	1.00	21.5	68.2	1.2	21.8
Wednesday, 18 January 2006	2.15	0.45	27.7	55.8	1.4	23.0
Thursday, 19 January 2006	3.58	0.54	29.0	46.8	1.1	27.0
Friday, 20 January 2006	3.22	1.13	27.6	46.1	2.1	27.1
Sunday, 22 January 2006	3.22	0.42	27.3	35.4	1.5	35.1
Monday, 23 January 2006	3.22	0.57	19.3	60.2	1.2	23.7
Tuesday, 24 January 2006	8.59	1.81	26.2	50.9	1.7	20.6
Wednesday, 25 January 2006	**11.46**	**3.01**	**28.6**	**54.5**	**0.9**	**20.8**
Thursday, 26 January 2006	**5.01**	**0.88**	**28.5**	**40.9**	**1.2**	**29.5**

The peak EER occurred on 25th January with a result of 3.01. The collector plate evaporation was 11.46 $mm/m^2/d$, equal highest to date (see 23rd December). The solar radiation result was relatively high at 28.6 $MJ/m^2/d$, but the air temperature was lower than expected at 20.8 °C. The next best EER result occurred on 8th January, with a result of 2.89. The solar radiation result higher again at 32.7 $MJ/m^2/d$, and similarly, the air temperature higher than 26th January, with a result of 25.7°C. The test day 9th January, the highest average daily temperature was recorded 26.8 °C. However the EER result was less than expected at 1.07. It's believed the solar radiation result of 8.7 $MJ/m^2/d$ may have contributed to the lower EER result.

Figure 13 presents the evaporation data for both the collector plate evaporation (dashed line) and enhanced evaporation (solid line) as a function of air temperature. The trend lines fitted to the data for the evaporation enhancement peaked at 1.75 with the air temperature at 20°C, and fell to less than 1.5 as the air temperature increases to 23.5°C. Notably, the level of evaporation enhancement returned to near 1.5 as the air temperature increased up to 28°C but then fell sharply as the air temperature increased beyond 30°C.

Figure 13 – CPU Evaporation vs. Air temperature – Brine 12.5% NaCl



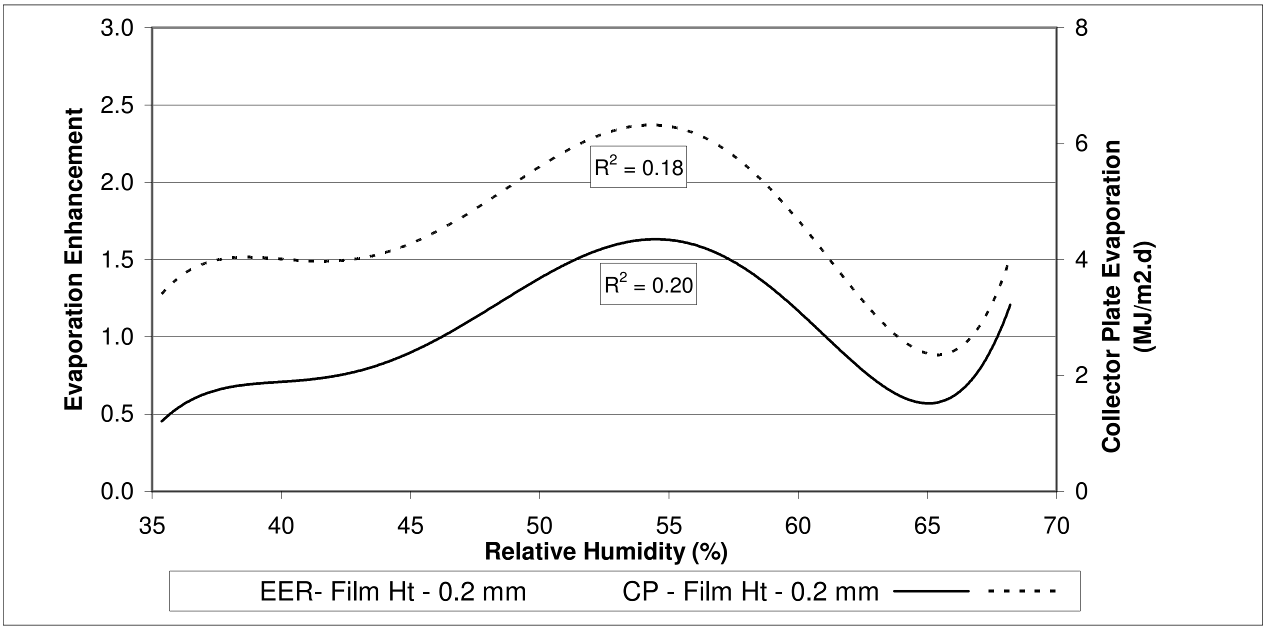
The collector plate evaporation trend line followed a similar profile to EER with peak results of 7.5 $mm/m^2/d$ with the air temperature at 20°C, and 6 $mm/m^2/d$ with the air temperature at 28.5°C. However, the trend lines were not in good agreement as reflected by the R^2 values (e.g. 0.22 and 0.23), which suggests a high degree of scatter.

In the course of the data analysis, a sixth order was fitted to improve the fit but it did not improve the agreement for either data set. It's suspected in contrast to the high R^2

values for the 7.0% NaCl, that the higher brine concentration at 12.5% NaCl makes the data more variable and as such, lacking the stability to allow a suitable correlation to be found.

Figure 14 presents the trend line for collector plate evaporation (dashed line) as a function of relative humidity. The data shows collector plate evaporation results greater than 6 mm/m²/d can be achieved where the relative humidity ranges between 52 and 56%. The trend line for the evaporation enhancement results follows a similar profile to collector plate evaporation, achieving a level greater than 1.5 when the level of relative humidity ranges between 52 and 57%.

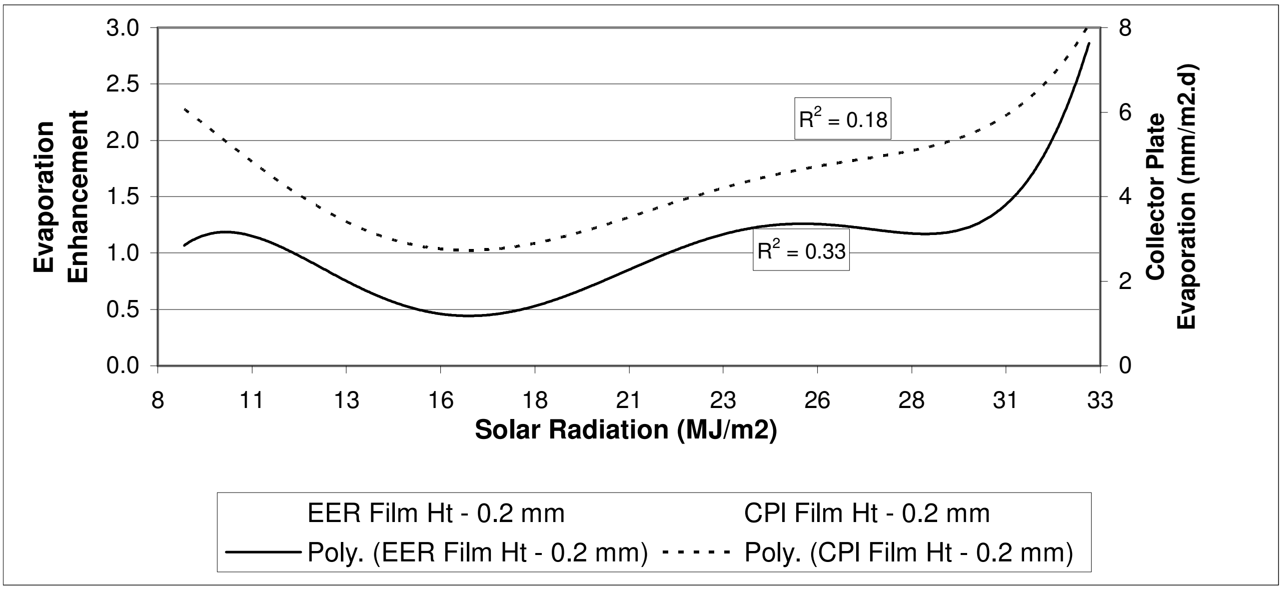
Figure 14 – CPU Evaporation vs. Relative Humidity – Brine 12.5% NaCl



The trend lines representing the collector plate evaporation and evaporation enhancement data were not a good fit with the data (see R^2 values, 0.18 and 0.2). The data similar to the air temperature data contains a lot of scatter and despite attempts to improve the level of agreement by applying higher orders the level of fit could not be improved.

Figure 15 presents the trend lines for the evaporation enhancement (solid line), and collector plate evaporation (dashed line) relative to solar radiation for Brine 12.5% NaCl. The data shows evaporation enhancement peaking at near 2.9 with the solar radiation level at near 33 MJ/m²/d. The next highest evaporation enhancement results are approx. 1.2 where solar radiation approaches 11 MJ/m².d and in-between a drop in evaporation enhancement to less than 0.5 where the solar radiation level approaches 17 MJ/m²/d, there was peak at 1.35 when the solar radiation level hit 25 MJ/m²/d.

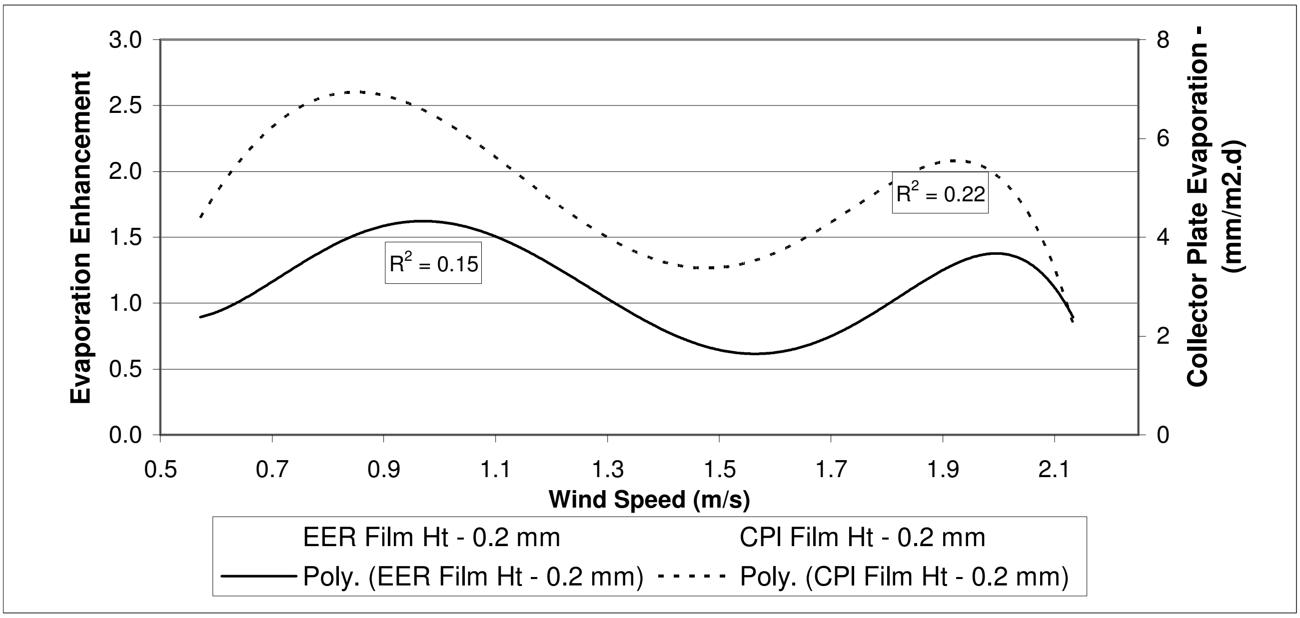
Figure 15 – CPU Evaporation vs. Solar Radiation – Brine 12.5% NaCl



The trend line for the collector plate evaporation shows evaporation levels increasing from 2.75 to near 8 mm/m²/d as solar radiation increased from 17 to 33 MJ/m²/d However, this arrangement does not have a degree of fit (as represented by the R^2 value of 0.18) suggesting like for other meteorological parameters relative humidity, and air temperature that high levels of evaporation are possible with higher brine concentrations (i.e. in excess of 8 mm/m²/d) but are less predictable than brine 3.5% and 7.0% solutions under similar meteorological conditions.

The trend line at Figure 16 for collector plate evaporation (heavy line) shows a peak of approx. 7 mm/m^2/d when the wind speed approaches 0.8 m/s, before falling to less than 4 mm/m^2/d with the wind speed at 1.5 m/s and then rising up to more than 5 mm/m^2.d with the wind speed at approx. 1.95 m/s.

Figure 16 – CPU Evaporation vs. Wind Speed – Brine 12.5% NaCl



The evaporation enhancement trend line (dashed line) follows a similar pattern to the evaporation enhancement trend line with two peaks of 1.6 and 1.4 and a low of 0.6 with wind speeds of 0.95 m/s, 1.6 m/s, and 2.0 m/s respectively. The similarity in the profiles suggests despite the relatively low R^2 values a degree of correlation for the 12.5% NaCl brine solution between wind speed and evaporation enhancement, and collector plate evaporation data.

11.5 Discussion

This section will analyse in more depth the data presented for the 3.5%, 7.0% and 12.5% NaCl brine solutions for the evaporation data, evaporation enhancement and collector plate evaporation relative to the key meteorological parameters, solar radiation, air temperature, relative humidity and wind speed on an hourly basis.

The discussion will consider the fit of results having regard to the four meteorological parameters. The EER polynomial equations for the four parameters fitted to the 3.5% NaCl data are outlined below:

Table 13 – Polynomial Line of Best Fit – 3.5% NaCl – Film Ht 0.2 mm

Meteorological Parameter, x	EER	x^5	x^4	x^3	x^2	x	C	R^2
Wind Speed	y	-164.2	1138.2	-3117.5	4213.3	-2806.5	737.39	0.19
Solar Radiation	y	0	0.02	-0.99	21.4	228.55	961.8	0.60
Air Temperature	y		0.01	-0.65	20.95	-296.33	1559.8	0.21
Relative Humidity	y		0	-0.02	1.8	-61.87	782.83	0.51

The level of fit achieved by the solar radiation data was higher than the other three parameters. The R^2 value for the equation at 0.6 indicates a degree of correlation between solar radiation and evaporation enhancement.

The data analysis found EER results near 3.0 can be achieved where solar radiation exceeds 15 MJ/m^2/d subject to the other three key meteorological parameters (i.e. wind speed results greater than 1.5 m/s, air temperatures greater than 20 °C, and relative humidity results less than 55 %) achieving results in the upper quartile of their range. Where the results for the other parameters don't reach those levels, the data shows solar radiation levels higher than 30 MJ/m^2/d rather can't individually induce higher levels of brine pan evaporation.

A link between relative humidity and evaporation enhancement was present despite a high degree of scatter under different weather conditions (as illustrated by the R^2 value of 0.51).

The relationship between wind speed and air temperature was detectable but not close due to a high degree of scatter in the evaporation enhancement data. A comparison of the brine evaporation with the fresh pan evaporation results found evaporation ratio's in the order of 0.66 for brine 3.5% NaCl under summer weather conditions, and 0.80 for brine 3.5% NaCl under winter weather conditions. See Table 14.

Table 14 – Pan Evaporation – Brine vs. Fresh Water

Pan Evaporation - Brine Vs Fresh Water	Air Temperature	Water Temp (CTK)	Water Temp (RTK)	Brine Pan Evaporation (CTK)	Fresh Pan Evaporation (RTK)	Ratio
Daily Average	°C	°C	°C	$mm/m^2.d$	$mm/m^2.d$	
Brine 3.5% NaCl - 0.2 mm	20.88	-	-	4.73	7.18	0.66
Brine 3.5% NaCl - 0.15 mm	11.82	12.66	10.83	1.26	1.57	0.80

The EER polynomial equations for the four parameters fitted to the 7.0% NaCl data are outlined below:

Table 15 – Polynomial Line of Best Fit – 7.0% NaCl – Film Ht 0.2 mm

Meteorological Parameter, x	EER	x^5	x^4	x^3	x^2	x	C	R^2
Wind Speed	y	12,141	-69,167	156,825	-176,905	99,298	-22,190	0.83
Solar Radiation	y		0	0.15	-5.28	82.7	-475.18	0.33
Air Temperature	y	0	-0.03	1.42	-33.55	388	-1754.7	0.68
Relative Humidity	y	0	0	0.03	-1.37	30.13	-255.72	0.51

The lines of best fit represented by the R^2 values indicate wind speed and air temperature at 0.83 and 0.68 were closest in agreement with the evaporation enhancement data. The wind speed equation provides a high degree of correlation with the evaporation enhancement data. The data for brine 7.0 % shows evaporation enhancement results greater than 2.0 concentrated in the range of 1.1 to 1.25 m/s. By comparison with brine 3.5 % which recorded a R^2 value of 0.19, the wind speed results were concentrated in the 1.1 to 1.9 m/s range, and the trend line showed evaporation enhancement results all below 2.0. The air temperature trend line show a large concentration of evaporation enhancement results greater than 1.5 in the range between 26 and 30 °C.

Given changes in wind speed are largely functions of changes in air temperature at other surrounding locations. The high degree of fit to both data sets indicates a relationship between evaporation enhancement results greater than 2.0 and wind speed results between 1.1 to 1.3 m/s and air temperature results between 26 and 30 °C. The fit of the results for the 7.0% trial, with the R^2 value at 0.51 was also in good agreement with the results of the brine 3.5% NaCl trial.

The EER polynomial equations for the four parameters fitted to the 12.5 % NaCl data are outlined below:

Table 16 – Polynomial Line of Best Fit – 12.5% NaCl – Film Ht 0.2 mm

Meteorological Parameter, x	EER	x^5	x^4	x^3	x^2	x	C	R^2
Wind Speed	y	-11.25	71.35	-169.35	185.43	-92.34	17.79	0.15
Solar Radiation	y	0	0	0.07	-1.2	10.04	-30.39	0.33
Air Temperature	y	0	-0.04	2.14	-54.43	683.22	-3388.1	0.22
Relative Humidity	y	0	0	0.06	-3.12	74.27	-698.43	0.20

All four meteorological parameters show a wide range of scatter in their evaporation enhancement results, and this was reflected in the R^2 values with solar radiation the highest at 0.33.

The wide variability and scatter about the data tends to suggest the higher 12.5% NaCl concentration has an adverse effect on the evaporation rate, both in terms of collector plate evaporation and brine pan evaporation.

Figure 17 shows evaporation results relative to water temperature data for the period 1st to 11th June within the Brine 3.5% NaCl – 0.15 mm wetted film height.

Figure 17 shows the changes in average daily water temperatures at the plate inlet, STK, CTK, RTK, and ambient air temperatures in comparison with EER over the same period. The data shows the water temperature in the STK remains the warmest of all the evaporation tanks with the returning flows from the collector plate warming the water in the STK.

Further, the water temperatures at the plate inlet and CTK follow a similar pattern. While, the water temperature in the RTK tracked at a lower level over the same time. The brine solutions contained within the CTK and STK comprising ionic constitutuents contributing to the higher mean water temps as compared with the RTK. Over this study period, the evaporation enhancement trend did not follow the pattern of the water temperature in either of the water tanks or ambient air temperature.

To further the analysis in this area, a second period will be presented for the same brine concentration (3.5% NaCl – Film height 0.15 mm) involving warmer weather in August, 2006.

Figure 17 – EER Vs CPU Temperature – Brine 3.5% NaCl – Film Ht 0.15 mm – Pt A

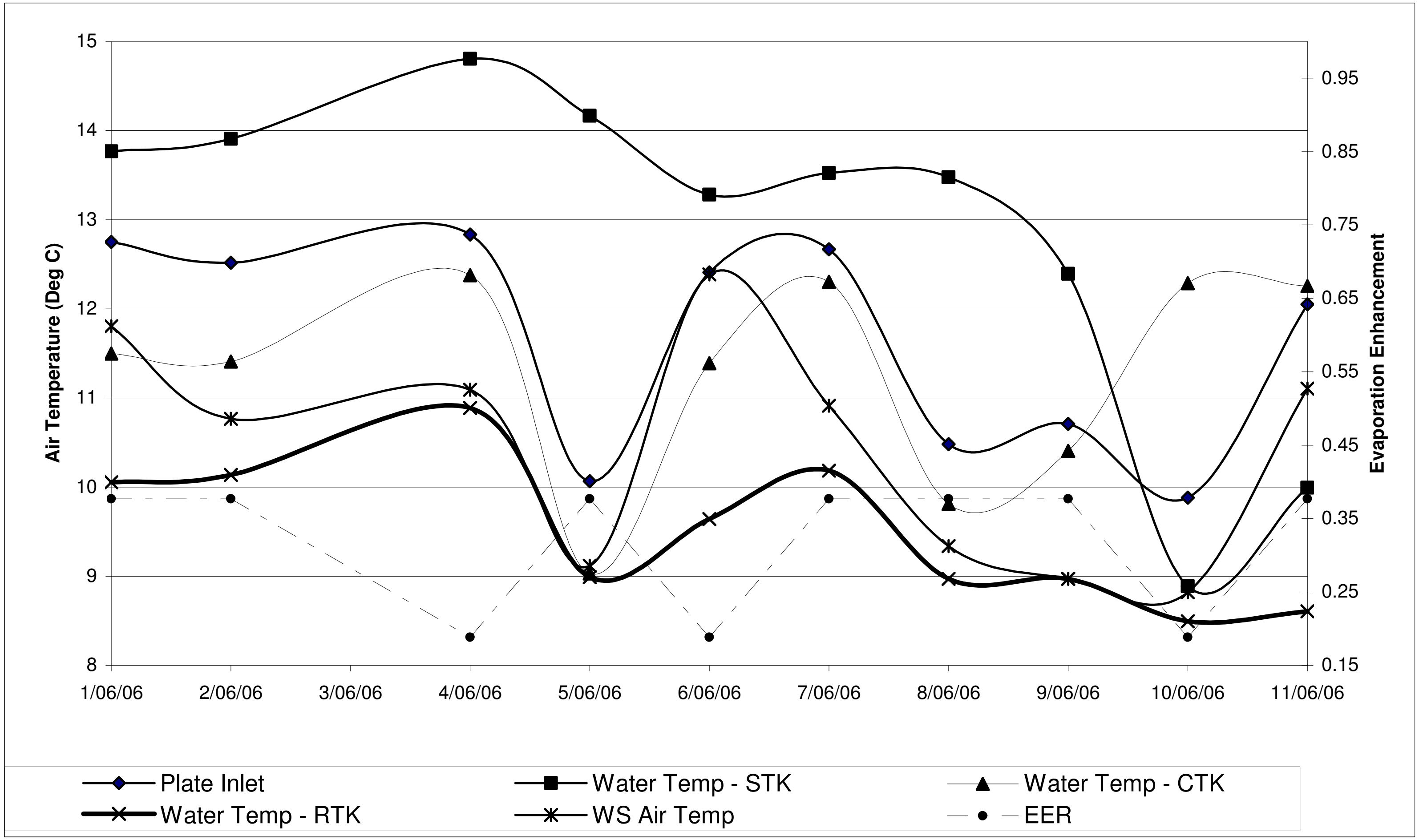
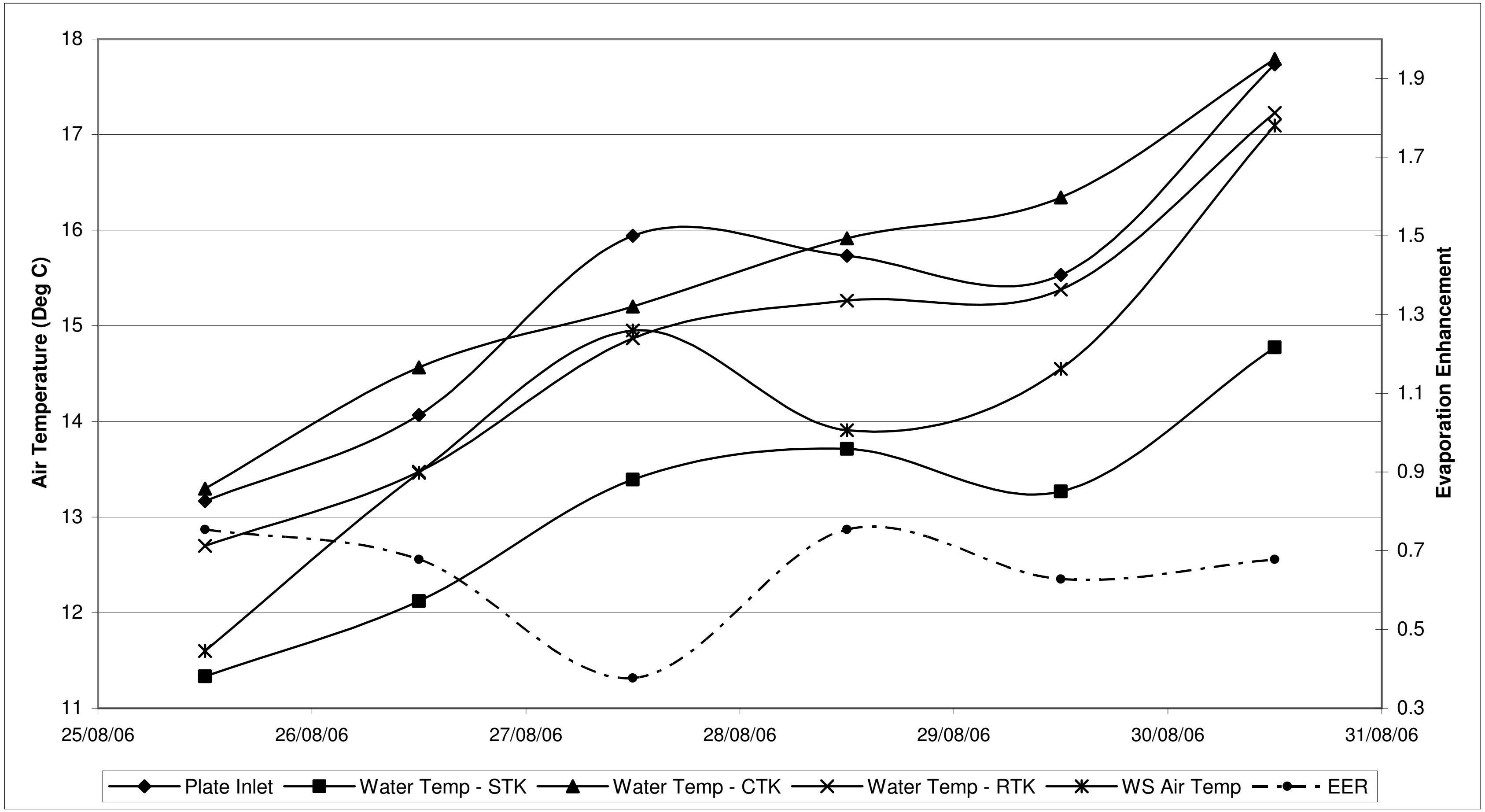


Figure 18 presents evaporation enhancement relative to water temperature data for the period 26th to 31st August, within the Brine 3.5 % NaCl – 0.15 mm trial period.

In this period, the water temperatures tracked the highest in the CTK over the study period. The water temperatures in the STK tracked 1.5 to 2.0 Deg (°C) lower than the plate inlet temperatures and the ambient air temperatures.

The ambient air temperatures followed a similar pattern to the RTK results. Despite the warmer air temperatures there does not appear to be a direct relationship between the water temperatures in the tanks, and ambient air temperature with evaporation enhancement over this study period.

Figure 18 – EER vs. CPU Temperature – Brine 3.5% NaCl – Film Ht 0.15 mm – Pt B



The research found the maximum enhanced evaporation ratio from the collector plate was 3.0 times the level of brine pan evaporation from an equivalent area of standing brine water. The ratio was achieved during the month of January, with the synthetic waste comprising a NaCl concentration of 12.5%. The level of EER achieved was dependent on the key thermal inputs from the weather, in particular solar radiation, relative humidity and air temperature.

The average EER over the same period was 1.52, ensuring the average volume reduction due to collector plate units was 50% for every metre square of collector plate to evaporation pond area. The peak EER over the same period was 3.01, however EER results in the range above 2.5 were limited and as such, indicate collector plate technology is best utilised in locations which boast similar weather locations to Melbourne at the height of summer for most of the year.

The research findings under average conditions were less than Srithar and Mani (2006), who reported results for experiments which tested soak liquors, where the NaCl concentration (%) ranged from 5 to 20%, and the mass flow rate varied between 200 L/hr and 500 L/hr. Srithar and Mani (2006) found for every square metre, their collector plate unit could achieve an average volume reduction in the order of 40 % for every square metre of collector plate to evaporation pond area. However, it's submitted the difference in results could be largely attributed to the more favourable meteorological conditions in India for evaporation, and the lower flow rates tested in this research, ranging from 28 L/hr to 136 L/hr.

In the scenario where the evaporation pond covers 2 ha, and 1 metre depth (total volume of 20,000 m^3), the area subject to nominal average weather conditions for Melbourne CBD, there are 100 units and the testing period is 100 days. Note, the nominal weather conditions include solar radiation of 20.0 $MJ/m^2/d$, air temperature of 20.0 °C, relative humidity of 55%, and a wind speed of 1.2 m/s. The expected reduction in volume with an average EER of 1.52% is a reduction of 0.44% or 88 L loss from the evaporation pond.

The risk of groundwater contamination where unlined evaporation ponds are used can never be eliminated but the risk can be mitigated by incorporating collector plate units into evaporation pond systems. The volume of water removed by enhanced evaporation will always be influenced by the weather conditions in the sample locality, and the number of collector plate units installed.

The reduction in evaporation pond volume by collector plate units helps to mitigate the risk associated with suspended constituents in brine waste seeping through the soil strata and contaminating the groundwater.

The data analysis found that despite the scattering in the evaporation enhancement data that weather conditions low in relative humidity (less than 40%), high in total incident solar radiation (greater than 20 $MJ/m^2/d$), steady, constant wind speeds (between 1.1 and 1.3 m/s), and high daily average air temperatures (greater than 25 °C) would generally produce average EER results of 1.52 with concentrations up to 7.0 % NaCl under those prescribed weather conditions.

The data analysis identified high levels of evaporation enhancement were not possible with a 12.5% NaCl brine solution. The evaporation enhancement results for the 12.5 % trial were in the range of 1.5 to 2.0 despite occurring during the peak of summer. The data appeared to show evaporation enhancement under weather conditions in Melbourne CBD was limited to brine solutions of 3.5 and 7.0% NaCl.

12 Theoretical Evaporation

12.1 Brine Pan Evaporation

The literature review found there were two widely accepted brine pan evaporation equations, Dalton and Modified Penman. The paper will next consider the equation with the best fit to the evaporation results and the associated weather conditions in Melbourne CBD. The means for assessing the equation with the best fit is a review of the variance in BOM pan evaporation results against the average meteorological results recorded by the BOM for the four key parameters.

The variance of pan evaporation results was checked for both equations across a range of weather conditions over the 2005 year, and it was concluded, for the Melbourne CBD the modified Penman model had a closer fit to the actual BOM data recorded by the BOM base station. The wind speed parameter had the greatest direct effect on the variance in results, with the Dalton equation more suited to coastal or inland locations which are characteristically subject to high wind speeds. The BOM base station as previously mentioned is located in the Melbourne CBD and is surrounded by high rise buildings. Hence, it was decided to adopt the modified Penman model as the selected theoretical equation for determining pan evaporation.

The advantage of having a theoretical equation with a high level of fit is the energy balance has a higher degree of accuracy in predicting energy flows in and out from the collector plate unit, and thus, can be used to understand the means of optimizing the evaporation performance of the unit.

The modified Penman Equation can be expressed as follows:

$$E = \frac{\beta \Delta H}{\beta \Delta + \psi} + \psi f(u) \frac{\beta_e * a - e_a}{\beta \Delta + \psi} \qquad \text{Equation 7}$$

The equations behind the nomenclature expressed in the Modified Penman approach are outlined below.

Nomenclature

E = Evaporation rate (W/m^2)

$$Evaporation(W/m^2) = \frac{Evap(kg/hr) \times Latent-heat(kJ/hr)}{3.6}$$ Equation 8

β = Activity co-efficient (ratio)

$$= \frac{saturation-vapor-pressure-industrial\ (kPa/m^2)}{saturation-vapor-pressure-fresh\ (kPa/m^2)}$$

Δ = slope of saturation vapor pressure ($kP_a\ K^{-1}$)

$$= \frac{(4097.76 \times kP_a)}{(237.269 + Tw - max)}^2$$ Equation 9

Ψ = psychometric constant ($kP_a\ K^{-1}$) =

$$= 0.0016286\ x(\Delta H_v / P_{atm})$$

Where ΔHv = MJ/kg vapor = $(2.50025 - 0.002365\ x(T_a))$

P_{atm} = $(1013 - (0.1055\ xAHD)x(10^2)$

AHD = altitude above sea level (m)

f (u) = wind function ($W\ m^2\ kP_a^{-1}$)

$$f(u) = \left[\left(2.7(T_w - T_a)^{(1/3)}\right)^2 + (3.1u)^2 \right]^{0.5}$$ Equation 10

e_a = ambient vapor pressure at air temperature =

$$= 0.61078\ \exp^{[17.269\ T_a/(237.3 + T_a)]}$$

e^*_a = saturation vapor pressure at air temperature =

$$= 0.61078 \exp^{[17.269 T_a /(237.3 + T_a) x RH / 100]}$$

RH = relative humidity (%)

H = available solar energy (W/m^2)

$$= S(1-\alpha) + \varepsilon Ld - \varepsilon\sigma T^4 - Cwh \frac{\delta Ti}{\delta t}$$

α = albedo of the water body

L_D = long wave radiation, coming from the atmosphere (Dingham, 1994)

$$= 0.97(1.19 \times 10^{-7} calcm^{-2} d)\left[(Air - temp(°C) + 273.2)K\right]^4 - 663 calcm^{-2} d$$

ε = surface emissivity

σ = Stefan-Boltzman constant = 5.667×10^{-8} W m^2 K^{-4}

C_w = volumetric heat capacity of the water body (J m^{-3} K^{-1})

h = depth of the water column (m) ≈ 0.28m

δT / δt = integrated average temperature change within column with respect to time

T_a = air temperature (°C)

12.2 Collector Plate

The Mani and Murthy (1994) research on effluent from tannery operations in India has been adapted for application to this paper. Mani and Murthy (1994) documented the key mass and energy equations and they have been followed for the purposes for this research. The key equations relate to atmospheric and thermodynamic equations atmospheric pressure, enthalpy, dynamic viscosity, thermal conductivity and specific humidity.

The other main adaptation was in the area of plate heat capacity where the Mani and Murthy (1994) work utilized a concrete collector plate. The plate material used for this research was Stainless Steel 316.

The equation used by Mani and Murthy (1994) to express the rate of evaporation of brine effluent overflowing a collector plate is expressed below.

$$Mass - evap = h_d (W_s - W_d)$$ Equation 11

The equations behind the nomenclature developed by Mani and Murthy are expressed below.

<u>Nomenclature</u>

$$Nu = 0.664(\mathrm{Re})^{0.5}(\mathrm{Pr})^{0.333}$$ Equation 12

$$\mu = viscW(T_W + 273.15, bar)$$ Equation 13

$$\mathrm{Re} = \frac{pxWvxD}{\mu}$$ Equation 14

$$\Pr = \frac{mCx \quad \mu}{k}$$ Equation 15

$$Patm\ (bar) = (1013 - \frac{(0.1055\ xHASL)}{10^3}$$ Equation 16

$$h_c = \frac{NuxK}{D}$$ Equation 17

$$h_D = \frac{h_w}{C_{pm}}$$ Equation 18

$$h_w = 5.7 + 3.8V_\infty$$ Equation 19

$$e_a = EXP(77.345 + 0.0057 * (273.15 + T_a) - 7235\frac{(273.15 + T_a)}{(273.15 + T_a)^{8.2}}$$ Equation 20

$$W_{air} = \frac{(0.622\ xP_{ws})}{(Patm - P_{ws})}$$ Equation 21

$$dm = h_D A_c (W_s - W_a) dt$$ Equation 22

<u>Nomenclature</u>

A = Area (m^2)

C = Specific heat (J/kg K)

D = Characteristic Length (m)

h = Enthalpy (J/kg)

h = Hour angle (deg)

h_c = Heat transfer coefficient (W/m^2 k)

h_D = Mass transfer coefficient (kg/m^2 s)

L = Length of the day (h)

l = latitude (deg)

(mC) = Heat Capacity (J/°C)

Nu = Nusselt number

N = Day of the year

Pr = Prandtl number

Re = Reynolds number

T = Temperature (°C)

t = time (s)

Vx = Velocity (m/s)

W = Specific humidity (g/kg of dry air)

X = Thickness (m)

<u>Greek letters</u>

α = Absorptivity

β = Angle between the horizontal and inclined collector surface (deg)

δ = Declination (deg)

τ = Time of day – sun rise (h)

<u>Subscripts</u>

a = Absorption, ambient

c = Convective heat transfer

D = Mass transfer

d = diffuse

fg = vaporization

h = Horizontal

i = inclined

max = maximum

p = plate

r = reflection and refraction

s = solution

wt = Water = 4186 (J /Kg °C)

HorPltLgh = Horizontal plate length = 2366 (mm)

TotPltLgh = Total plate length = 2440 (mm)

Pltht = Plate Height above horizontal = 596.5 (mm)

NaCl = Salinity concentration = 35 (g/L)

HASL = Height above sea level = 50 m

P_{ws} = saturation pressure of water vapor (Pa s)

W_{air} = Specific Humidity (g/kg)

13 Energy Balance

13.1 Introduction

An energy balance was developed following the Mani and Murthy (1994) approach. The development of an energy balance allows the performance of a collector plate unit to be optimised by understanding the sensitivity of the unit to changing variables, air temperature, solar radiation, relative humidity and wind speed.

The energy balance consists of major energy inputs, solar radiation, and convection, and major heat outputs, radiation and evaporation. The energy inputs and outputs due to conduction to CTK and collector plate were considered negligible and not included in the energy balance. The heat losses from the side and underside of the collector plate were not considered in the energy balance like Mani and Murthy (1994) because the losses were considered negligible.

The energy balance around the collector plate and for brine pan evaporation can be expressed as follows:

$$Q_{stored} = (Q_{radiation} + Q_{convection})_{in} - (Q_{radiation} + Q_{evaporation})_{out}$$

The solar radiation input and output derives from the solar radiation available and emissivity values of the evaporation pond surface, open water, and the collector plate surface, SS316 except with a black paint surface.

The convection energy input derives from the heat transfer coefficient with wind speed (m/s) the dependent parameter relative to the temperature of the evaporation pond and the collector plate. The approach for finding $Q_{convection}$ involves applying a widely accepted approach can be expressed as:

$$Q_{convection} = h_{conv}(T_p - T_{amb})\Lambda_p$$

Note, the parameter, Λ_p, relates the area of collector plate and evaporation tank. In both cases, the unit area is 1 m^2. The Australian Standard on Solar Heating for Swimming pools (Australian Standard 3634-1989) recommended the following wind coefficient values be used:-

$$h_{conv} = 3.1 + 4.1v$$

It is considered the Australian Standard values of 3.1 and 4.1 are consistent with a higher wind speed location than the research location (surrounded by high rise office buildings). Therefore, it is submitted the research will apply a and b values of 2.7 and 3.1 respectively as outlined by Asmar & Ergenzinger (1999) based on work by Salhorta et al (1985, 1987), and Oroud (1994). A review of the data found the a and b values suggested by Asmar & Ergenzinger (1999) had a better fit to the evaporation conditions at the research location.

13.2 Brine Pan Evaporation

An energy balance was formulated for brine pan evaporation using standard weather conditions for the research location (Melbourne), 20 MJ/m^2/d total for solar radiation, daily average air temperature of 20°C, average wind speed of 1.2 m/s and daily average relative humidity of 55%.

The energy balance (see Table 17) found that energy lost through evaporation from CTK was approx. 76% of the total heat lost, while solar energy re-radiated from water surface was 24%.

Table 17 – Energy Balance – Brine Pan Evaporation

Energy Balance - Brine Pan Evaporation				
Data Sources	Symbol	Units	Control Tank CTK	Percentage
Net Energy IN				
Radiation	$Q_{radiation}$	W/m^2	196.78	105.3%
Convection	$Q_{convection}$	W/m^2	-9.92	-5.3%
Sub-total		W/m^2	186.85	-
Net energy OUT				
Radiation	$Q_{radiation}$	W/m^2	34.73	24.3%
Evaporation	$Q_{evaporation}$	W/m^2	107.90	75.7%
Sub-total		W/m^2	142.63	100%
Net energy STORED				
Rate of Thermal Energy		W/m^2	44.23	

The energy balance shows a net level of energy stored by the CTK, under these meteorological conditions involves the transfer of 44.2 W/m^2 to the aqueous solution in the CTK. The transfer of thermal energy would raise the water temperature in CTK with the possibility pan evaporation may occur depending on the temperature differential with the ambient air temperature.

To increase the level of energy available for evaporation, Hahne & Kubler (1994) suggested the most effective means involves installing covers over the evaporation ponds at night. The possible cover materials include tarpaulin, uPVC or alike, with the size of the evaporation ponds and budget available the key considerations for undertaking a cost benefit analysis.

As noted above, heat losses due to conduction were not included in the energy balance. It was considered thermal conductivity of the CTK, uPVC at 0.16 W/(m K) @ 300 K was very low, so regardless of the temperature gradient across the inside and outside faces of the CTK the rate of heat transfer due to conduction across the side walls and bottom wall of the CTK would be very low. Its submitted for these reasons that any net input or output would be $\leq 1\%$ and as such, not worthy of inclusion in the energy balance.

13.3 Collector Plate Evaporation

An energy balance was formulated for collector plate evaporation using the balance given in Section 13.1 and the standard weather conditions, 20 $MJ/m^2/d$ total for solar radiation, daily average air temperature of 20°C, average wind speed of 1.2 m/s and daily average relative humidity of 55%.

The energy balance at Table 18 shows that the percentage of energy lost to evaporation where the wetted film height across the collector plate was 0.2 mm, amounted to 49%. The result was 2% less than the energy lost to radiation reflecting off the SS316 collector plate back to the atmosphere.

Table 18 – Energy Balance – Collector Plate Evaporation

Energy Balance - Collector Plate Evaporation					
		Plate Film Height (mm)			
	Units	0.3	0.2	0.15	Percentage
Net Energy IN					
Radiation	W/m^2	181.44	189.43	193.68	97%
Convection	W/m^2	4.96	4.96	24.81	3%
Sub-total		186.40	194.39	218.48	100%
Net energy OUT					
Radiation	W/m^2	50.06	42.07	37.82	51%
Evaporation	W/m^2	48.50	48.50	48.50	49%
Sub-total	W/m^2	98.57	90.57	86.33	100%
Net energy STORED					
Rate of Thermal Energy	W/m^2	87.83	103.82	132.15	

Table 18 shows the SS316 collector plate with a film height of 0.2 mm loses more than half its energy to re-radiation as compared with less than 25% for CTK showing the energy absorption differences between the CTK approx. 280 mm in depth, and 2 mm thick SS 316 collector plate.

The Mani and Murthy equation (1994) behind the energy balance expresses the thermal differences in the different film heights , with an inverse relationship between energy lost due to radiation and rate of thermal energy transferred to the SS 316 collector plate as the energy lost to evaporation remains constant across the three film heights .

As noted above, heat losses due to conduction were not included in the energy balance. It was considered while the thermal conductivity of the collector plate, was 16 W/(m K) @ 300 K having regard the SS 316 material. The plate materials, and in particular, the 20 mm thick layer of high density polyurethane foam under the collector plate would provide a barrier to heat conducting through the plate to the underside of the collector unit. Therefore, it's submitted any energy input or output would be ≤ 1%, and not worthy of inclusion in the energy balance (Cooper & Read, 1974).

14 Conclusion

This thesis investigated an innovative approach to augmenting the design of evaporation ponds for disposal of brine wastewaters.

The innovative approach involves the adoption of solar plate collector technology. The solar technology referred to as unglazed transpired collectors (UTCs). It may be considered a hybrid concept as it's a UTC except inclined like a typical solar collector plate.

This research investigated the ability to enhance evaporation using three different brine concentrations (3.5% NaCl, 7.0% NaCl and 12.5% NaCl), and three film heights (0.15 mm, 0.2mm and 0.3 mm) over a 14 month experimental period between June 2005 and August 2006. The research investigated the relationship between key weather parameters, solar irradiation ($MJ/m^2/d$), wind speed (m/s), ambient air temperature (°C), and relative humidity (%), and enhanced evaporation and collector plate evaporation from the collector plate unit.

The average rate of evaporation enhancement over the 14 month experimental period was 1.52, with the highest rate of evaporation enhancement of 3.01 occurring on 26th January, 2006. The rate was achieved by the collector plate unit with brine concentration at 12.5 % and a wetted film height of 0.2 mm. The meteorological conditions on that particular peak day were total solar radiation, 28.6 $MJ/m^2/d$, average relative humidity 54.5%, average wind speed 0.9 m/s, and average air temperature 20.8°C. The result demonstrated the unit could achieve a rate of evaporation 3.01 times the rate from an equivalent surface area of evaporation pond.

The research found there was a relationship between collector plate performance, and the key meteorological parameters. The evaporation enhancement observed indicated weather conditions low in relative humidity (less than 40%), high in total incident solar radiation (greater than 20 MJ/m^2/d), steady, constant wind speeds (between 1.1 and 1.3 m/s), and high daily average air temperatures (greater than 25 °C) would generally produce rates of evaporation enhancement between 2.0 and 3.0 for brine solutions with concentrations up to 7.0% NaCl.

It was observed during the 12.5% NaCl brine pilot trial that despite achieving the peak EER result of 3.01, that the EER results were less than expected based on the peak summer meteorological conditions. The data supported the observation with the EER results concentrated in the range between 1.5 and 2.0. The data suggests the collector plate unit was not able to generate peak evaporation enhancement with brine wastewater at 12.5% NaCl.

In the scenario where 100 nr collector plate units were connected to an evaporation pond covering 2 ha and 1 m in depth (total volume of 20,000 m^3), the area subject to typical weather conditions for the Melbourne CBD, and the evaporation time at 100 days. The collector plate unit has the potential to reduce the volume of the 20,000 m^3 evaporation pond by 1.73% under peak EER conditions.

The collector plate unit under average EER conditions in Melbourne CBD has the potential to reduce the surface area by 0.44% representing an 88 m^2 reduction in surface area for the 1 m deep evaporation pond.

An energy balance around the collector plate unit considering heat transfer by solar radiation, and evaporation was carried out. It was found the collector plate lost over 49% of its energy to evaporation as compared to 76% lost by the CTK due to brine pan evaporation.

The research results indicate the hybrid collector plate technology has the potential to augment existing evaporation ponds, especially unlined evaporation ponds where the weather conditions are consistent with those recorded in Melbourne during peak summer conditions.

The collector plate unit performance over the winter periods reflect the moderate weather experienced in Melbourne CBD, and contrasts with the good performance over the summer period. The annual average result of 1.51 over the 14 month experimental period reflects the moderate weather experienced in Melbourne CBD.

The research results suggest collector plate technology can be advanced by their installation at inland locations, where the weather conditions are more favourable to evaporation. As an example of an inland location with a high number of evaporation ponds, is the Murray Darling basin in Australia. In the basin there are approx. 190 evaporation ponds or lagoons used to evaporate brine waters, with a total area of over 15, 900 ha, a total storage capacity of 113 000 ML, and an annual disposal volume of over 210 000 ML/yr (Mickley et al, 1993 and Hostetler & Radke, 1995).

It's believed most of the approx. 190 evaporation ponds or lagoons in this region are unlined. This approach can enhance the evaporation rate of the existing ponds leading to a mitigation of risk associated with ground water contamination. If adopted, the technology would help the sustainability of industries in countries like Australia that rely on the evaporation pond approach for the disposal of their brine effluent.

15 Recommendations

Collector Plate Unit

- Investigate the increase in theoretical evaporation enhancement by modifying the collector unit to track the sun's azimuth
- To optimise the performance of the unit during the winter months, when the sun is lower in the sky, install a collector plate on a variable pitch frame that can support the weight of the collector plate, mounting board and alike while allowing inclination angles greater than 25°. The recommended inclination angles for the collector plate unit would be 30°, 35°, 40°, 45° and 50°.
- Determine the emissivity and absorption of a SS316 plate, coated with black paint such as black chrome which is widely used for solar hot water systems.

Brine Water

- Further investigate the evaporation enhancement performance of the collector plate of synthetic brine wastewater mixes within the research range of 3.5% NaCl and 12.5% NaCl
- Determine the effect of water temperature on the density of brine wastewater, and advise if activity coefficients in the literature could be modified
- Consider other contaminants or additives that could be incorporated into the synthetic mix to better reflect actual waste while operating in a laboratory environment

Collector Plate – Evaporation

- Find wind heat co-efficient values to fit the level of evaporation from the collector plate
- Find wind heat co-efficient values to fit the level of brine wastewater evaporation from the evaporation tanks

Brine Tank – Synthetic Evaporation

- Find wind heat co efficient values to fit the level of evaporation from the evaporation tank containing brine wastewater, and the reference tank containing fresh water
- Measure the tank material temperature to determine the conduction heat losses

Collector Plate and Tank Energy Balance

- Undertake pilot trials to determine if the expected heat loss from the underside and side of the collector plate and evaporation tank is negligible
- Review the thermal conductivity of the building materials selected for the unit, and advise if other suitable building materials are available to minimise heat loss from the collector plate
- Use dimensional analysis to formulate a heat transfer co efficient for the collector plate under different weather conditions

Application in the Field

- Set up and run a series of pilot trials at inland locations in central Australia or other remote locations at or near mining sites to better simulate the expected evaporation enhancement capability of the collector plate
- Operate the pilot unit with actual mining wastewater to determine the evaporation enhancement capabilities of the unit subject to actual brine wastewater
- Set up a pilot unit with actual brine wastewater to determine the effect of heavy metals and other contaminants on the durability of the collector plate.

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17 Appendix

17.1 Abbreviations

AHD – Australian Height Datum

BOM - Australian Bureau of Meteorology

CPA – Collector Plate Evaporation

CPU – Collector Plate Unit

CTK – Control Water Tank

Evap. – Evaporation

HRT – Hydraulic Retention Time

RH - Relative Humidity

RMIT – Royal Melbourne Institute of Technology

TDS – Total Dissolved Solids

NaCl – Chemical symbol for Sodium Chloride

RTK – Reference Water Tank

SA – Surface Area

STK – Sample Water Tank

UTC – Unglazed Transpired Collectors

EER – Evaporation Enhancement Ratio

17.2 Schematic Arrangement of Experimental System

Schematic Arrangement of Experimental System

A: Control Collection Tank
B: Sample Collection Tank
C: Reference Collection Tank
D: Solar Collector Plate
E: Inlet Header
F: Collection Tray
L1: Pipework to inlet header
L2: Return pipework to Tank B
P: Pump with valve
T1: Plate Top Water Temp
T2: Plate Mid Water Temp
T3: Plate Bot Water Temp
T4: Plate Tray Water Temp
TA: Water temp Tank A
TB: Water temp Tank B
TC: Water temp Tank C
WA: Level Indicator Tank A
WB: Level Indicator Ta
WC: Level Indictor Tank C
X: Plate Flow Length
Y: Plate Flow Width