University of Southern Queensland

Faculty of Health, Engineering & Sciences

EXPLORATION OF EVAPORATION MITIGATION MEASUREMENT TECHNIQUES

A dissertation submitted by

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Abstract

This dissertation documents signification research conducted into exportation mitigation techniques. In doing so the dissertation firstly explores current mitigation techniques floating, shade and chemical covers. The dissertation highlights suitable methods for monitoring evaporation loss in small water facilities. Using the NCEA Evaporation Compound Facility field trials were conducted. Understanding the behaviour at the air/water, will hopefully lead to improvements in the performance of monolayers through the identification of optimum application periods.

The field research conducted compares the evaporative performance of an artificially imposed warm and cold surface film. Using black plastic covers to impose a warm surface film and a bilge pump to mix water and impose a cold surface film. A series of thermocouple probes are used to analysis the air/water interface and monitoring the presents of warm and cold surface film within two tanks. Through field trials an understanding of the natural resistance to evaporation loss imposed by a thermally stable warm surface film is explored. It is predicted that the resistance of a thermally stable warm surface film may exceed the resistance imposed by an artificial monolayer.

The dissertation finds that a warm surface film consistently recorded higher rate of evaporative loss. However significant turnover events are experienced within the tank where the artificial warm surface film is imposed. The turnover event causes the resistance imposed by the warm surface film, to be outweighed by a dominate cold surface film. The turnover which occurs daily around 5:00pm implies that the application of a monolayer overnight would significantly reduce rates of evaporation.

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Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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With appreciation

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Chapter 1 Introduction

1.1 Background

There is in excess of 7000 GL of water being stored in over two million farms across Australia, with a further 80 000 GL detained in registered large dams (Craig 2008). In agricultural regions of Australia a growing issue is water loss through evaporation of storage water, with potential losses exceeding 40 percent (Dagley, 2012). This significant loss of stored water threatens the productivity of the Australian Agricultural Industry. Irrigation alone is consuming roughly 70 percent of Australia’s fresh water. However this natural resource is vastly diminishing. The atmospheric evaporative demand, management of water storages and the overall size of the water body are key factors influencing the amount of water lost to evaporation. Rising temperature, prolonged drought periods and a growing concern regarding global warming draws attention towards the need for improvements in water sustainability within Australia.

While there has been considerable research and applications of evaporation mitigation solutions throughout Australia the main products available are designed for small storage (less than 10 hectares) applications. Floating covers both continuous and modular and suspended shade structures have proven to be successful. However their application to large scale projects has not proved as effective and involve enormous financial outlay. In the case of large reservoirs chemical or polymer-based monolayers have been tested. This cover provides a chemical ultra-thin film which makes it ideal for application to both large and small storage water (Craig, 2008). Chemical covers do provide a solution to evaporation mitigation and are seen as the most suitable for storages larger than 10 hectares. However the extremely variability in performance has meant that chemical covers have not been widely adopted.

1.2 Research Significance

Research highlights numerous limitations and deficiencies that are seen as responsible for the variable field performance of original monolayer products. The performance of chemical covers in the form of artificial monolayers are recognised as being affected by sublimation, wind, solar radiation, water quality and microbial degradation. However the effects which occur at the air/water interface have seldom been considered. The significance of this research surrounds the exportation of temperature differentials and the thermal boundary layer. This dissertation looks to understand temperature differential and the associated gaseous exchange at the air/water interface. Understanding the behaviour at the air/water, will hopefully lead to improvements in the performance of monolayers through the identification of optimum application periods.

1.3 Project Scope and Overview

This project seeks to investigate novel evaporation mitigation performance measurement techniques for stored irrigation water using the existing USQ Ag-Plot Evaporation Compound Facilities. The major purpose and significance of this research is to examine the temperature profile at the surface of a stored water body. The overall aim is to conduct a series of field trials to understand the natural resistance to evaporation loss imposed by a thermally stable warm surface film. The hypothesis is that the resistance of a thermally stable warm surface film may exceed the resistance imposed by an artificial monolayer.

This project focuses on identifying whether evaporation losses will be greater under a cold, thermally unstable surface film or a thermally stable warm surface film. Exploration of the temperature profile will be undertaken using a series of floating thermocouples spaced at constant depth intervals close to the air/water interface. The available data logging equipment will allow a maximum of five thermocouples to be position in each tank at a minimum spacing of 0.01m. Tests will be conducted using two polyethylene troughs (water surface 2.4 m^2, diameter 1.75 m, height 0.7 m, volume 200 L), of similar diameter to a Class A evaporation pan (1.20 m). Analysing the temperature profile data gathered from field trials the research hopes to identify optimum time periods for monolayer application when the added resistance of a monolayer will most cost-effectively reduce evaporative loss.

This research project focused on firstly confirming that the temperature profiles within the two test tanks are identical when placed under the same conditions. Once satisfied, a warm and cold surface film were artificially imposed and a series of tests were conducted to confirm if a warm surface film naturally reduces evaporative losses relative to a cold surface film. Evaporative losses within the tanks will be monitored using a plastic ruler positioned in a common location within the tanks. Discussion and analysis of the effects of external parameters such as; wind speed, air temperature and rainfal on evaporation rates will also be examined using data available from the USQ weather station facilities.

Chapter 2 Literature Review

2.1 Introduction

The Literature Review chapter will investigates three key areas related to evaporation mitigation research. The chapter will begin by discussing the physics behind the evaporative process, temperature differentials and the thermal boundary layer. The chapter will then explore evaporation mitigation technologies currently available and from this identify the technology which has the best potential for application to both large and small storage facilities. The final section will examine evaporation measurement equipment previously implemented in similar research projects, while also acknowledging further methods of measurement which could potentially be implemented in this field of research.

2.2 The Evaporative Process

It is a common understanding that the evaporation process involves the transfer of a liquid such as water into a gas or vapour. Heat is the governing factor of the evaporative process and is responsible for breaking down the bonds that hold water molecules together. The evaporation process takes place when heat is applied to water. When the water temperature reaches boiling point at 100°C, water easily transfers into a gas and evaporates. However the temperature of water does not necessarily need to reach boiling point for evaporation to take place, this is only a special case during which the evaporation process is extremely obvious. Evaporation actually occurs at all temperatures below the boiling point. The molecules which make up liquid water hold a variety of kinetic energies and certain individual molecules can occupy sufficient energy to escape from the surface of the liquid (USGS, 2014).

There are three major requirements for evaporation to take place. The first requirement is an energy source, namely solar radiation for the sun. Wind also plays a major role in the evaporative process. While solar energy is obviously the largest contributing factor, bulk air flow across the air/water interface is a significant source of energy within the evaporation process. Furthermore the second requirement is a transport mechanism for water vapour. Together these first two requirements describe the 'environmental demand' or 'atmospheric demand'. The third and final requirement is a water source. Evaporation will vary considerable bases on the physical conditions of the water body. Each of these requirements of evaporation are independent, yet for significant evaporation to take place all three requirements need to be met.

Evaporation takes place at the air/water interface, molecules will experience an unbalance of forces and this will cause surface tensions to develop. Furthermore evaporation takes place when there is a mass transfer of molecules through the gas-liquid interface into the air (Pittaway, 2011). There is a series of transport resistances which a molecule has to overcome in order to evaporate from a liquid phase. This includes; liquid phase's resistance, interfacial resistance and gas phase resistance. The liquid phase refers to the movement of molecules to overcome the transport resistance of the liquid phase as they absorbing to the surface (Davies & Rideal, 1963). Once the molecules have absorbed to the surface they must overcome surface tensions and the interfacial resistance. At the surface molecules vaporising into the gaseous phases, thus evaporation from liquid phase is complete.

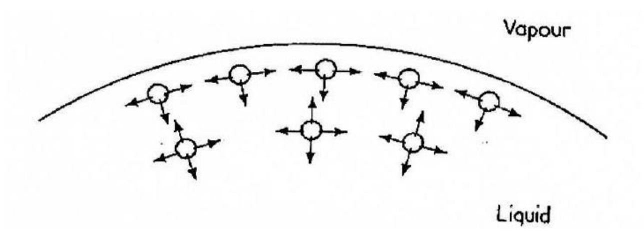


Figure 2.1: The evaporative process acting at the air/water interface (Davies & Rideal, 1963)

Figure 2.1 shown above (reproduced from, Davies and Rideal 1963) illustrates the behaviours of molecules and the direction of forces acting at the air/water interface within the evaporative phase. The molecules at the water's surface experience a greater level of 'free energy' which results in the contraction and development of the surface tension.

The temperature profile at the water surface is another factor that will also affect the rate of evaporation. The natural convective circulation that occurs beneath the surface is directly influenced by wind speed and the temperature difference between the air and water. When a cold surface film occurs it causes downward cellular convection to take place, whereas a warm surface film is gravitationally stable (Pittaway, 2011). Due to the decent of convective thermals the transfer of heat through a cold surface film is considerably higher than the transfer experienced with a warm surface film. The convective circulation results in the formation of capillary waves which intern reduce the thickness of the liquid thermal boundary layer (Pittaway, 2011). According to Gladyshev, 2002, the liquid boundary layer of a warn surface film is considerably thicker and more noticeable than a cold surface film. Ranging between depths of 40 to 80 mm beneath the water's surface.

2.3 Available Mitigation Techniques

There are four major classes of cover that have been developed to prevent evaporation of water from on farm storage facilities. These types of covers can be classified as floating covers either continuous or modular, suspended shade structures and chemical covers (monolayers).

2.3.1 Floating Covers

Floating covers are commonly classified under one of two categories; continuous floating or modular floating. The basic principle of floating covers is to reflect incoming solar radiation, through creating a physical barrier and preventing the movement of water vapour in both a horizontal and vertical movement. The application of floating covers is predominately more suitable for application on small scale water storage facilities and have not been widely implement on large dams and reservoirs (Yao, et al., 2010).

2.3.1.1 Continuous Floating Covers

This method of evaporation mitigation commonly comprises of a thin plastic sheet which is floated across the water body to cover the entirety of the storage water supply. In general continuous floating covers act on the water surface to directly lessen evaporation by creating an impermeable barrier. While plastic sheeting is the most commonly implemented continuous floating cover numerous other materials have been trialled and implemented (Yao, et al., 2010). In the past products such as foam, polystyrene and wax have all been tested. However it has been materials of polyethylene plastics which have proven most successful. Their ability to directly reduce evaporation rates and the long term durability of polyethylene plastics far exceeded all other materials implemented under this cover type. Continuous floating covers are widely implement as they are cost effective to purchase and easy to install. The ease with which continues floating covers can be implement is a major selling feature, as this cover can be floated and suspended easily over varying water bodies. Unlike suspended covers, which will be discussed in section 2.3.2 of the dissertation, this cover has a reduced reliance upon additional infrastructure as floating covers are self-supported on the water's surface. Continuous floating covers have performed well in numerous farm applications designed to withstand strong winds and harsh weather events. The major downfall or issue associated with continuous floating covers is during rain events the cover's impermeable surface catches water and this can cause the cover to sink, affecting the covers ability to reduce evaporation. Following significant rain events continuous floating covers need to be removed and reapplied to the water body. However this can present a difficult task with the increased weight of the water on the covers surface (Craig, 2008).

Figure 2.2: Continuous floating covers in use at St George, QLD *(Craig, 2008)*

Figure 2.3: Floating bubble-wrap type sheets (Yao, et al., 2010)

Figure 2.2 and Figure 2.3 shown above illustrate evaporation control using continuous floating covers. The design of the plastic material incorporates a multilayered polyethylene membrane. The material is comparable to 'bubble wrap' and swimming pool covers, in that the product contains a membrane of air voids referred to as buoyancy cells. Commonly the outer surface of continuous floating covers is white, as this colour best reflects sunlight and radiation. The underlay of the cover is black, this significantly removes the presence of natural light in the water beneath the cover (Craig, 2008). The polyethylene material used to create the flat sheets for continuous floating cover is biodegradable and widely used in food processing. This reinforcing that the use of this material possess minimal threats towards the environment in which it is being used.

2.3.1.2 Modular Floating Covers

Modular covers are relatively similar to continuous floating covers in the way they function. Both cover types are self-supported by the water body and required minimal additional infrastructure. Modular covers are distinguished by a series of individual units. These individual modular pieces are not restrained to one another in any form and are therefore free to manoeuvre over the water surface. Due to their design modular floating covers will take considerably longer to install. However compared to continuous floating covers they are in theory less expensive to implement. The ability of modular floating cover to reduce evaporation solely depends upon how tightly modular units are grouped (Craig, 2008). Therefore evaporation reduction of modular floating covers is generally somewhat lower than continuous floating covers. Modular floating covers perform exceptionally well in rain events, their unique structure allowing water to easily pass into the water storage facility. However having numerous individual units increases potential impacts from wind. During windy weather modular units can become overlayed, however modular units will generally redistributed as conditions change. The severity of impacts from wind ultimately depends upon the size, weight and design of the modular units. The free floating nature of this cover allows it to travel with the wind and quite often it is the downwind area of the storage tank or dam which occupies the warmest water and thus highest evaporation (Craig, 2008). The unique design of modular covers expose sections of the water’s surface and allows wind to cool the water surface and remove humid air. Once again the evaporation efficiency of modular covers is dependent upon the design, shape and grouping of units.

Existing prototypes of modular floating covers include; a circular, hexagonal and rectangular design. Some illustrations of available modular products are shown below;

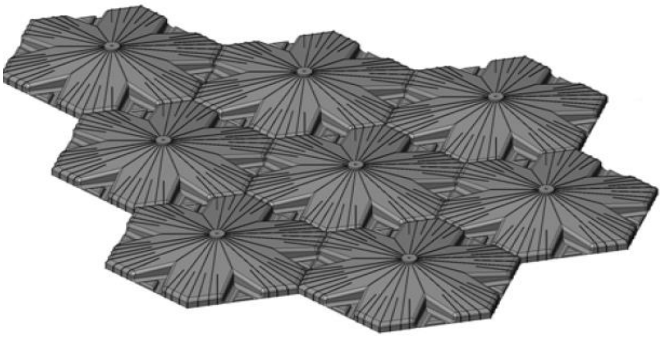


Figure 2.4: Hexagonal modular floating cover (Craig, 2008)

Figure 2.5: Circular modular floating cover (Craig, 2008)

Figure 2.5 shown above illustrates the movement of modular units to the windward end of the storage facility. The close-fitting formation is acting over the warmer water, where commonly highest evaporation levels take place.

Figure 2.6: Individual modular unit

Figure 2.6 shows an example of a large modular floating unit. Larger units weigh more and are less prone to disruption from wind. During high wind speeds modular units can become overlaid, however the unique domed design quite often allows units to redistribute themselves. Modular floating covers, if effectively managed and implemented have the potential to be the most environmentally friendly cover type. Modular covers also allow a considerable level or natural light and oxygen to enter the water. Natural light is a necessary ingredient to help the water supply remains clean, healthy and free of bacteria and water borne diseases.

2.3.2 Suspended Shade Covers

Suspended shade covers generally comprise of a “horizontal sail-like structures” which is suspended by a support structure of steel cables and posts (Yao, et al., 2010). The material used to construct a suspended cover widely vary influenced by commercial availability of shade products, however the material will generally be a porous material (Finn & Barnes, 2007) or alternatively an impermeable (impermeable to wind and light, but permeable to rain) polyethylene material (Martínez, et al., 2006). There are two factors that determine the ability of a suspended cover to reduce evaporation and this includes; how the cover is installed and the rate at which water vapour can transition through the cover (Yao, et al., 2010). The shade covers act as a physical barriers against solar radiation and this in turn reduces thermal energy, while trapping humid air beneath the cover. While air can still pass through, shade covers considerably reduce impacts of wind via reducing the vapour pressure gradient across the surface of the water (Yao, et al., 2010).

A major benefit of shade covers is that the water can be easily accessed by irrigators, while the cover is still in place. This is made possible as the suspended covers are not in direct contact with the water’s surface. When analysing performance, shade covers are not as effective in reducing evaporation compared to well-maintained continuous floating covers. However shade covers present fewer problem and once installed the cover can have a lifespan of 5 to 10 years. Once again the lifespan of the suspended cover is dependent upon the durability of material from which it is constructed and how the cover is maintained.

The pores design of the shade cover allows water to easily entry the storage facility while ensuring the cover will dry quickly. Shade covers also act as a barrier against debris and therefore allow storage water to remain relatively clean. When it comes to installation, shade covers are economically feasible with application best suited to water body less than 10 hectares. Water storage facilities larger than this require high levels of additional infrastructure development and this presents high upfront costs. Figure 2.7 and Figure 2.8 shown below illustrated examples of impermeable and permeable suspend shade covers in uses.

Figure 2.7: SuperSpan suspended impermeable covers (Finn & Barnes, 2007)

Figure 2.8: Suspended permeable (shade cloth) covers (Yao, et al., 2010)

2.3.3 Chemical Covers

Chemical covers involved the forming of a fatty, oily film on the water's surface and can be several microns thick. There are many different chemical covers which have been developed around the world. However the two more common chemical films which have been developed and tested in Australia, are Aquatain and WaterSavr (McJannet, et al., 2008). Aquatain is an oily film many microns thick, the product increases the albedo much like physical covers (refer sections 2.3.1 & 2.3.2) reflecting heat and light. WaterSavr is a monolayer and provides a much finer layer. The most widely implemented chemical monolayers products C16 is cetyl alcohol or hexadecanol, C18 is octadecanol (Craig, 2008).

A monolayer is simply an ultra-thin surface films which are characteristically one molecule thick (Dagley, 2012). The figure below illustrates the typical formation of a chemical monolayer on the water's surface.

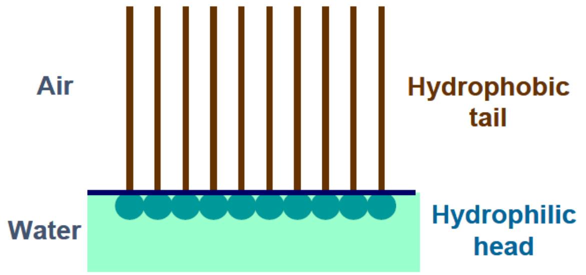


Figure 2.9: Typical formation of a monolayer on water (Dagley, 2012)

As can be seen in Figure 2.9, the formation of a monolayer commonly consists of a hydrophilic head which acts like an anchor holding the molecule of the water's surface. The lines which extend from the hydrophilic head are referred to as hydrophobic tail and these tails group tightly at the air/water interface (Prime, et al., 2012).

One of the most impressive characteristics of monolayer technology is the capacity to re-distribute itself over the water surface following common everyday disturbances such as those initiated by wind, livestock, birds and other animals. The unique chemical design of monolayers coupled with the products ability to reform following disturbances ensure that this technology poses minimal physical disturbances detrimental towards wildlife and humans using the treated water. Chemical covers are highly suited to small storage facilities, the properties of product allow for a reasonable self-spreading abilities meaning it can be easily applied from the perimeter of a tank or bank of a dam. When it comes to larger water bodies a mechanical application system is required to evenly disperse the monolayer across the entirety of the reservoir.

2.3.3.1 Product limitations

Chemical monolayers are greatly influenced by wind, ultraviolet radiation and water borne bacteria. These sustained actives are causing monolayers to degrade more quickly than initial lab testing predicted. Chemical covers have been effective in reducing evaporation when apply in cool clam weather conditions. However chemical monolayers degrade rapidly when exposed to high wind speeds and sustained disturbance.

2.3.3.2 Autonomous Application Systems

Figure 2.10 illustrates how wind speed plays a major role in monolayer performance. Wind speed and the thermal gradient between the surface and the liquid thermal boundary layer greatly influence the diffusion of oxygen. At wind speeds less than 3 m/s, the water is calm and minimal internal convection occurs. However when wind speeds increase greater than 6 m/s, bulk thermal convection increases the diffusion of molecules and evaporation levels (Gladyshev, 2002). Monolayer performance is greatly influenced by wind and performs best when wind speeds are less than 6 m/s.

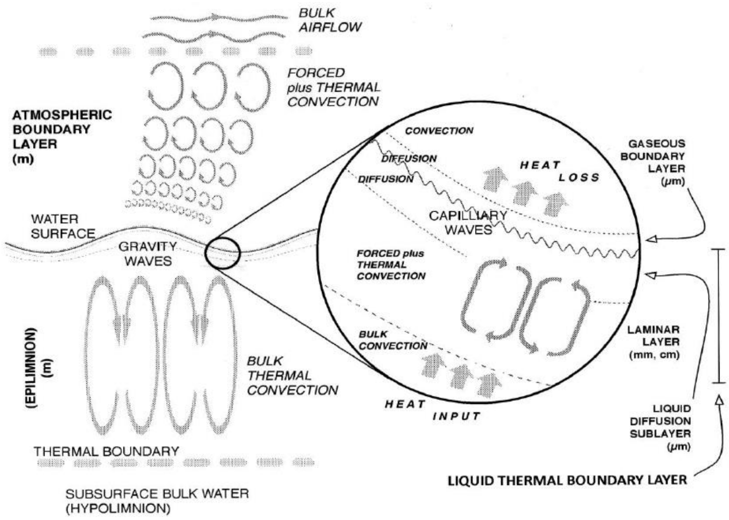


Figure 2.10: The air/water interface (Pittaway, 2011)

It is beneficial to regulate monolayer application relative to wind speeds and this is why autonomous application systems are needed to improve the cost-effectiveness of monolayer products. Autonomous application programmed to only apply monolayers when wind conditions (less than 6 m/s) are optiminal. These surface conditions guarantee the film will reduce evaporation loss. The performance of monolayers in reducing evaporation is fundamentally a function of wind speed.

2.3.3.3 Environmental Implications

There is minimal literature available which directly details the aquatic toxicity of chemicals monolayers. However research indicates that the most vulnerable period is during the breakdown of the monolayer (Prime, et al., 2012). Repeat application of the chemicals and forming a film may be potentially toxic.

The potential for environmental impacts and reduction of water quality are influence greatly by features of the storage facility; factors such as the size of the facility, whether or not lining materials are implement and the turbidity of the water all play a major role. Research conducted by Urban Water Security Research Alliance, suggest that the environmental impacts of monolayers is virtually unrecognisable. This is due to the fact that most reservoirs already have a certain level of naturally occurring microlayers on the water’s surface. These naturally occurring microlayers result from the decay of organic materials. The potential impacts to water quality from monolayers can be classified under three section and these include;

- breakdown of the chemical product
- changes in gas transfer across the air/water interface, and
- changes to the energy balance of the storage

(McJannet, et al., 2008)

Changes in the energy water balance can be influenced by natural changes in the temperature profile of the water. The natural convective circulation that occurs beneath the surface is directly influenced by wind speed and the temperature difference between the air and water. When a cold surface film occurs it causes downward cellular convection to take place, whereas a warm surface film is gravitationally stable (Pittaway, 2011).

2.4 Evaporation Measurement

This section of the dissertation looks at the types of equipment which have been used to measure evaporation in previous research. Two devices which will be explored are the pressure sensitive transducer and water level sensor probes. Pressure sensitive transduces and rulers have previously been used while conducting evaporation research at the University of Southern Queensland in 2005. Furthermore in 2011 a series of evaporative tests were undertaken on a site at Dookie, Victoria where evaporative losses were measured using a capacitance to frequency depth sensors (Prime, et al., 2012). Additional research was also conducted to identify further equipment which could potentially be used to measure evaporation. This included; external measurement gauges, hook gauge, ultrasonic level sensors and Magnetorestricitve transmitters.

2.4.1 Pressure Sensitive Transducers

A Pressure Sensitive Transducer instrument have been used to analyse water depths and evaporative losses in previous tests conducted at the University of Southern Queensland, (NCEA). The Pressure Sensitive Transducer used in this research was a vented Druck, type PDCR 4030 Series (350mBar). This PST type is suggested to record data with an accuracy of ±0.04% (±1.4mm) over a 3.5m range. (Craig, et al., 2005)

Figure 2.11: Pressure Sensitive Transduces - Duck PMP 4030 PST

The Pressure Sensitive Transduces measures depth pressure according to the electrical resistivity of a deforming micro-machined silicon crystal, isolated from the water with a corrosion resistant diaphragm (Craig, et al., 2008). The water pressure is calculated relative to atmospheric pressure and this is delivered by a crushproof air tube situated inside the transducer cable (Craig, et al., 2008).

The figure shown above illustrates the Pressure Sensitive Transducer component used in previous research undertake by the University of Southern Queensland. The Pressure Sensitive Transduce is a submersible device, design to be suspended beneath the water's surface. In order for the Pressure Sensitive Transduce to maintain it submersed position a float and weight is necessary (Figure 2.12). The weight ensures that the device holds its position in the water body.

Finally between the float and the weight the Pressure Sensitive Transducers is secured to the rope at an appropriate depth.

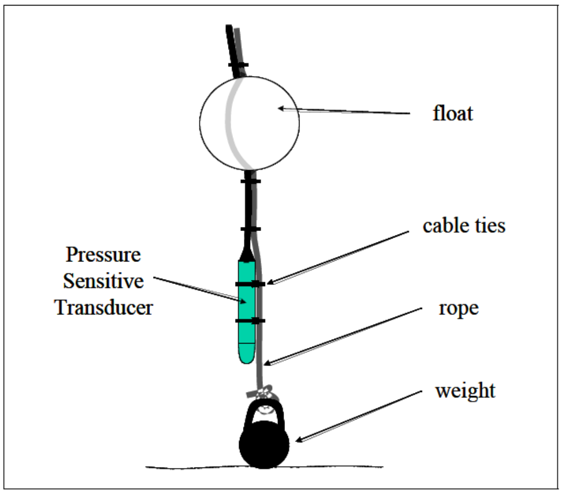


Figure 2.12: The PST water depth sensor suspension mechanism (schematic)

The Pressure Sensitive Transduces unit is simple to operate and well suited to ponds, tanks and dams for water level measurement. Different types of PST measure different parameters and thus not all PST are suitable for measuring evaporation within a submerged environment.

2.4.2 Ruler measurement

One of the simplest methods of measuring pan evaporation can be achieved using a basic ruler. A clear plastic ruler is generally the best option as it is transparent and easy to read. The position of the ruler is not restricted, as long as the ruler can be easily read positioning is optional.

The most common position of the ruler is in one of two locations; either against the tank wall or in the centre of the water storage facility. When attaching the ruler to the wall it is common to zero the ruler at the water surface and record evaporation as the water level in the tank drops. Measuring with a ruler provides an accurate, easy, and inexpensive means of monitoring evaporation rates in small storage test environments (Simonne, et al., 1995).

While research indicates that measurement with a ruler provides an accurate, easy, and inexpensive means of monitoring evaporation levels in small storage facilities, there is potential for considerable measurement inaccuracies with this process. The nature of water molecules causes the water to curve when in contact with another surface. In the case of this research a meniscus will from where the water meets the wall of the tank and thus the ruler. A magnifying glass may be used when reading measurements from the ruler to improve measurement accuracy.

2.4.3 Capacitance to frequency depth sensor

Figure 2.13: Odyssey's capacitance sensor probe

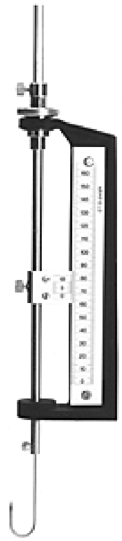
In 2011 a series of evaporative tests were undertaken on a site at Dookie, a small town in the Goulburn Valley region of Victoria, Australia. At the site six water troughs (water surface 3.7 m^2) were used to conduct the evaporative research. The evaporative losses in these troughs was measured using an automatic water depth measuring devices called the Odyssey's capacitance water level sensor probe. This device is suggested to have an interval accuracy ± 1 mm. To improve measurement and system accuracy the device was encased using a section of PVC tube. The PVC tube was installed to shield the device and the water around the probe from wind-induced wave action. The Odyssey's capacitance water level sensor probe is a versatile piece of equipment capable of measuring and recording data at a range of intervals. In the 2011 research the device was used to record data at 10 minute intervals. The Odyssey's capacitance water level sensor probe has also been used in irrigation channel at Yanco Agricultural Institute, New South Wales, recording and logging hourly data (Prime, et al., 2012).

2.4.4 External measurement gauge

A further expansion from measuring with rulers may involve the plumbing of a calibrated clear plastic tube, which runs from the base of the tank to the full water level of the tank. The figure below highlights an example of a measurement tube or gauge located on the outside of the tank wall. As water in the tank evaporates and the water level drops, so too does the level of the water in the clear plastic gauge. A major benefit of this technique is it allows for measurements to be recorded easily from the outside of the tank. The major issue associated with this method is preventing algae from growing inside the tube and obscuring measurements.

Figure 2.14: External measurement gauge

2.4.5 Hook Gauge



A Vernier Hook & Point Gauges instrument can also be used to measure the change of water levels in a tank resulting from evaporation. The Hook & Point Gauge are frequently used due to the highly accurate measurements the device can record. The Vernier Hook & Point Gauges are also regularly used during hydraulic investigations to measure the levels of a steady water surface. The figure shown above highlights a standard Vernier Hook & Point Gauges instrument, consisting of a hook suspended from a Vernier measurement scale. The device is manually operated to position the point of the hook at the water's surface. A measurement is taken related to the vertical movement of the hook. Most devices will have a turning knob to adjust the hook positon. The process associated with taking a measurement using a Hook & Point Gauges basically involves lowing the hook through the water surface until a small depression forms around the point of the hook due to capillary action on the water surface. From here the hook is then very gradually lowered unit the depression pops and disappears and once this has occurred a water level reading can be taken (Armfield Ltd, 2015).

The Hook & Point Gauges device significantly reduces errors as this device is not influenced by water meniscus. Furthermore the Vernier measurement scale allows greater measurement accuracy reducing observation errors such as those associated with the ruler measurement method (Armfield Ltd, 2015).

The added advantage of the Hook & Point Gauge is that the device can be zeroed anywhere in the operating range to ensure simple and accurate water level inspections. The Hook & Point Gauges display is easy to read, with an expected accuracy of ±0.01mm. The main application of the Hook & Point Gauge is in areas of meteorology and water engineering. (Armfield Ltd, 2015).

2.4.6 Magnetorestrictive Transmitters

Magnestostrictive level transmitters are another regularly implemented device which can be used to measure evaporative losses. Magnetostrictive Transmitters equipment are generally very precise, while offering a wide range of configuration settings. The Magnetostrictive transmitter is also extremely versatile and can be used as a direct insertion transmitter or externally mounted to a magnetic level indicator for non-invasive level control (Emerson Electric Co, 2015).

The basic operation of an in direct insertion service involves the sensor probe having a magnetic float which is inserted into a tank. As the water or liquid level changes the float rises or falls accordingly and the transmitter will output the substance level. Furthermore for an externally mounted service, as the name suggests the probe senses the float inside the magnetic level indicator (Emerson Electric Co, 2015).

2.4.7 Ultrasonic level sensor

The ultrasonic level sensors are used for non-contact level sensing, the sensors within the device emit high frequency waves. These waves are then reflected back to the emitter and detected by the emitting transducer which records a reading of the substance level (Siemens AG , 2015).

The SITRANS Probe LU, is one particular version in Siemens Ultrasonic Level Sensor range. This device would be extremely suited for evaporative research and application in water tanks. The device is capable of monitoring water levels, volume and flow monitoring of liquids in open channels and stored water (Siemens AG , 2015).

Figure 2.15: SITRANS Probe LU – Ultrasonic Level Sensor (Siemens)

Chapter 3 Methodology

3.1 Introduction

This chapter will discuss the field trails undertaken to meet the research objectives. The chapter will begin by outlining the instruments and materials used during the testing phase along with the final design of the test setup. The chapter will discuss the site preparation work at the NCEA, Ag-plot Evaporation Compound Facility where testing was conducted.

3.2 Objectives

The objects of the research project were to conduct a series of field trials to understand the natural resistance to evaporation loss imposed by a thermally stable warm surface film. It was hypothesised that the resistance of a thermally stable warm surface film may exceed the resistance imposed by an artificial monolayer. The objectives of the field research were to artificially impose a cold and warm surface film and analyse related evaporation loss.

3.3 Test Equipment

The following list highlights the equipment which was uterlised with the research project;

- Thermocouples
- Data logger
- Power source (12volt batteries & solar panels)
- Test rig (materials)
- Measuring ruler
- Black plastic

- Bilge Pump
- Tanks

The following sections provide details of where products were sources and relevant costings.

3.3.1 Thermocouples

The thermocouples which were used within the temperature profile testing were a standard general purpose, probe K Type thermocouple. This thermocouple probe is capable of measuring external temperature reading on DMMs, between temperature of -50ºC and +1200ºC (actual range depends on the DMM the thermocouple probe is used with). The thermocouple is extremely versatile, suitable for use in gas and liquid, both with exceptional accuracy (-40ºC to 750ºC accuracy 2.5ºC or 0.75% of temperature). Ten thermocouple probes were required for the field trails and the products were purchased through the University from Jaycar Electronics for $10.35 per device.

Figure 3.1: Probe K Type Thermocouple

Figure 3.1 illustrates the thermocouple type used within this investigation. The thermocouple consist of a stainless steel rode of 3mm diameter and 60mm length (similar to a thermometer in appearance) with a 500 mm connection cord attached. This type of thermocouple is plastic sealed during manufacturing. However the product specification state the device is not suitable to be submerged in water. A holding apparatus was designed to float the thermocouple at a constant depth intervals. This will be discussed in detail within section 3.5.1.1, Thermocouple Vessel.

3.3.2 Data Logger

The data logger used to conduct the temperature profile testing was a, GRAPHTEC midi LOGGER GL220. This device was loaned from the electronics workshop, University of Southern Queensland. The machine is capable of recoding data at an extensive series of intervals, with ten channels. The product has a wide range of feature which makes it ideal for application within this evaporative research. The device can operate stand-alone or PC-connected operation, 10 analog channels, input-to-output and channel-to-channel isolation. USB PC interface allowing for easy download and collection of data. This product is highly durable and robust making it extremely suited to field research. The figure below shows the data logger (GRAPHTEC midi LOGGER GL220) used for the temperature profile testing.

Figure 3.2: GRAPHTEC midi LOGGER GL220

3.3.3 Power Source

The data logger and the bilge pump were the two pieces of equipment which needed to be supplied power during the field tests. A series of three 12volt batteries was used as the main power source.

Figure 3.3: 12 volt battery supply

Two 250 watt solar panels were also installed to ensure sufficient levels of power was maintained in the batteries. By installing the solar panels it meant that batteries did not have to be disconnected and taken off site for recharging.

Figure 3.4 Solar panels (250watts)

A major concern associated with the power supply was the bilge pump. This device demanded considerable power (Amp draw: 2.1 @ 12v) and concerns were raised as to whether the device had the potential to damage the batteries. If poor weather conditions were experienced there was a possibility that the solar panels would not supply necessary levels of power and this may cause the batteries to be drained below recommended thresholds. To overcome this concern a 'battery controller' was include within the power supply system. This device monitor the power levels with the batteries and power produced by each solar panel. The device was programed to automatically shut down the bilge pump if the bulk battery power fell below 11.5 volts and switch back at 12.5 volts.

Figure 3.5: Battery Controller

3.3.4 Test rig materials

The materials which were associated with the development of the test rig are illustrated within Table 3.1 shown below.

Table 3.1: Material requirement

Test Rig - Material Requirement

Component	Size (mm)	Quantity required
Circular aluminium tube	12 x 2.0 mm x 400mm	4 lengths
Square aluminium tube	25 x 25 x 2.0mm x 550mm	1 length
weights	-	1170 gram
Grub screws	3dia x 10	20
Self-tapping screws	2mm	2

Various components of the test rig were produced using 3D Printer facilities available at the University of Southern Queensland Electronics Workshop. The printer model used was the UP BOX 3D printer by Tiertime. Each component was sketched using TINKER CAD and then exported to the 3D printer. The components were produced from ABS (acrylonitrile butadiene styrene) plastic.

Figure 3.6: UP BOX 3D Printer by Tiertime

3.3.5 Measuring Ruler

Two white 15cm plastic rulers were used to measure the evaporation within the tanks. The rulers were supplied by the Toowoomba Council free of charge.

3.3.6 Black plastic

Black plastic was used to cover the water troughs to artificially impose a warm surface fill. Two milk crates were place in the centre of the tanks to support the plastic covers and rope was used to hold the covers in place. The black plastic and four milk crates used were kindly donated by co-supervisor Pam Pittaway.

3.3.7 Bilge Pump

Rule Bilge Pump, Model 24, 12 volt. The Bulge Pump was purchased from BCF for $29.95 and the necessary wiring for 12 volt battery connection was completed by the Electronic Workshop.

- non-automatic submersible
- 360 GPH/1360 LPH
- Ignition protection
- High efficiency low amp motor
- No burn-out when dry
- Stainless steel shaft

Figure 3.7: Rule Bilge Pump

3.3.8 Tanks

The NCEA Evaporation Compound Facility housed six small water troughs (diameter - 1.75m, depth – 70cm) suitable for evaporative testing. Two troughs were required to undertake the temperature profile and evaporative loss analysis.

3.4 Site Preparation

The evaporation research facility based at the NCEA site was a major component of this research project. Initial plans for the project where to conduct field research using three plastic lined water storage tanks at the site (10 metres in diameter and 0.8 meters in depth). Significant progress was made towards restoring the facility and the three tanks, which had not been used since 2005. However a major change was made to the research Project Specification, due to availability of test equipment. The change of focus meant that the restoral of the three large tanks had to be abandoned and the small water troughs were adopted. A major benefit of this change was that considerable less water was required to undertake testing and potential for leakage and testing delays was greatly reduced. An outline of the restoration work completed and the challenges encountered while restoring the three large tanks has been including within Appendix D, Restoral of NECA Facility.

As previously outlined within section 3.3.8 there was also a number of water troughs housed within the compound which had been used in past research. It was decided that using two of the available water troughs would allow for easier manipulation and measurement of the air/water interface. Before the field testing could commence there were a number of tasks that firstly needed to be completed. This included; site selection, tank preparation and ruler attachment.

3.4.1 Site selection

The first process involved selecting a suitable location for the water troughs within the evaporation compound. Figure 3.8 shows an aerial view of the NCEA facility, the three large ponds are situated within an enclosures area of approximately 400 square meters. It was decided that the best location for the water troughs was between the first two tanks from entry side of the compound. This site was also within a suitable distance of a water source, ensuring that a garden hose could be easily used to fill the troughs with water.

Figure 3.8: Areal view of NCEA and selected site

The next process was to clear and level the site. All weeds and clumps of grass were removed and basic gardening equipment (shovel, mattock and rake) were then used to level to surface. The water troughs were placed on the levelled surface and a spirit level was used to ensure that site had be properly levelled. Figure 3.9 illustrates how the spirit level was used to check the ground level of the site.

Figure 3.9: Tanks were levelled using a split-level and a section on steel tube placed across the top edge of the two tanks

3.4.2 Tank Preparation

Two green polyethylene livestock water troughs were used as water storage facilities during testing. Detergent and scrubbing brush were used to remove algae and grim which had developed from the stagnant water pooled in the troughs. Furthermore once the tanks had been properly cleaned and thoroughly rinsed, the trough bung had to be replaced.

Figure 3.10 Original trough conditions

As a result two new bungs were purchased for Bunning Warehouse at a cost of $2.45 each. The bungs were installed and thread tape and silicon was applied around the connection to ensure that the water troughs did not leak during testing. Figure 3.11 shows the pipe plug's which were purchased.

Figure 3.11: Pipe Plug (2 in)

3.4.3 Ruler Attachment

A variety of plastic glues were tried as numerous difficulties were experienced when bonded the two plastic surfaces. Some minor research was conducted regarding bonding of different plastics. Selleys all plastic fix (Glue and Primer) was selected as the most suitable product for outdoor conditions. The surface of the two materials being bonded were first primed used the ‘primer pen’ supplied. The resin based glue was then smeared onto one surface, the back of the ruler. The rule was then positioned in the correct location and pressure was applied for roughly 30 seconds to achieve an instant bond, no clamps were required to supply continued pressure. The glue was allowed to cure for 48 hour prior to the tanks being filled. Figure 3.12 illustrates the glue which was used to attach the ruler to the polyethylene water trough.

Figure 3.12: Selley's All Plastic Fix (Glue + Primer)

Figure 3.13: Positioning of Ruler

The rulers used to measure the evaporative losses within the tanks were fixed in a common location within the tanks. Figure 3.13 highlights the location where the ruler were positioned in the tanks. This location is where the float component of the water trough would otherwise be installed (if used for livestock purposes). The selected location was flat, and readings could be taken after a black cover was placed over the tank to reduce wind turbulence.

3.5 Test Set-up

Figure 3.14: Test Set-up

Figure 3.14 highlights the test set-up implemented to analysis the air/water interface and evaporation loss in the water troughs. The following text discusses the major components of the set-up and the process undertaken to reach the final design.

3.5.1 Test rig/apparatus

The apparatus supporting the data logger and the thermocouple vessels has been referred to as the test rig. By ‘sandwiching’ data logger between the two tanks it was possible to place five thermocouples in each tank. The leads were run from the floating containers up through the aluminium tube connecting to the data logger.

Figure 3.15: Test Rig support the data logger & thermocouple vessels

3.5.1.1 Thermocouple vessel

The major component of the test rig was the thermocouple vessel. The vessel was produced using the 3D printer at the University of Southern Queensland. The USQ Electronics Workshop was able to produce this product from a basic TINKER CAD drawing of the holding apparatus. A trial print was first produced to ensure that the cylinder was of appropriate size to allow the thermocouples to be installed. Figure 3.16 illustrates the test print of the thermocouple vessel.

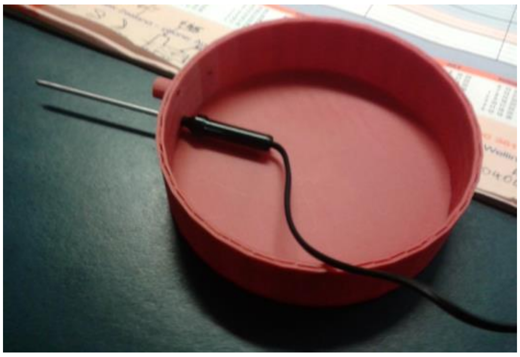


Figure 3.16: Test print of thermocouple vessel

Ten holes were printed in the containers two columns of five holes spaced at 20mm increments. The holes had to be offset to achieve the desired spacing of 10mm.

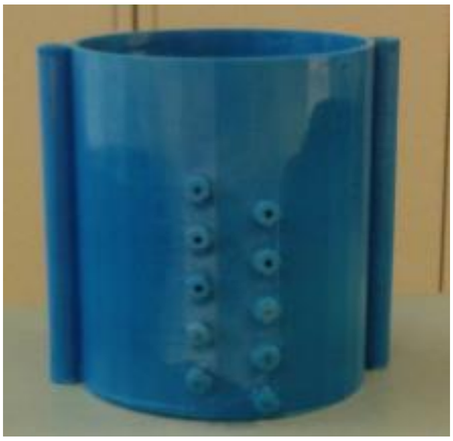


Figure 3.17: Thermocouple vessel

3.5.1.2 Positioning of Thermocouples

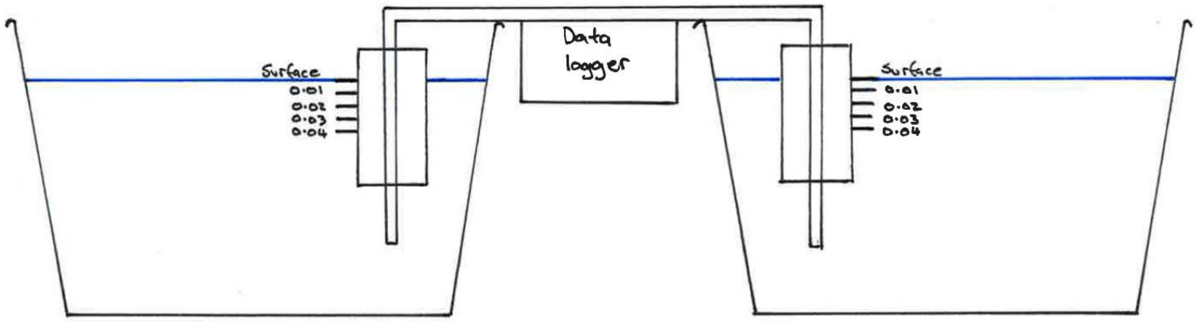


Figure 3.18: Experimental design

Previous research surrounding surface film temperature and their relationship to evaporation rates have been limited by the use of fixed arrays of thermocouples. Thus a major requirement of this research was to design a test rig capable of supporting a series of thermocouples at constant depth intervals. The aim was to position the top thermocouple as close to the water's surface as physically possible. Five thermocouples were positioned in each tank, as shown via Figure 3.18. The first thermocouple was located at the surface with the remaining thermocouples located below at intervals of 0.01m.

The five thermocouples were positioned in the top five holes of the thermocouple vessel and the remaining five holes were plugged using silicon. By utilising the top five holes it allowed a greater surface area of the vessel to be submerged and this ensured greater stability of the thermocouple probes. Silicon was also smeared around the thermocouple probe to prevent potential leaks. The vessels were rinsed with solvent acetone to seal any imperfections in the plastic mould.

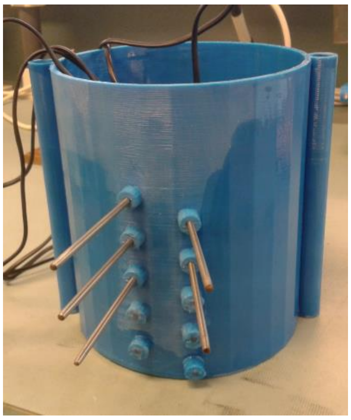


Figure 3.19: Positioning of the thermocouples

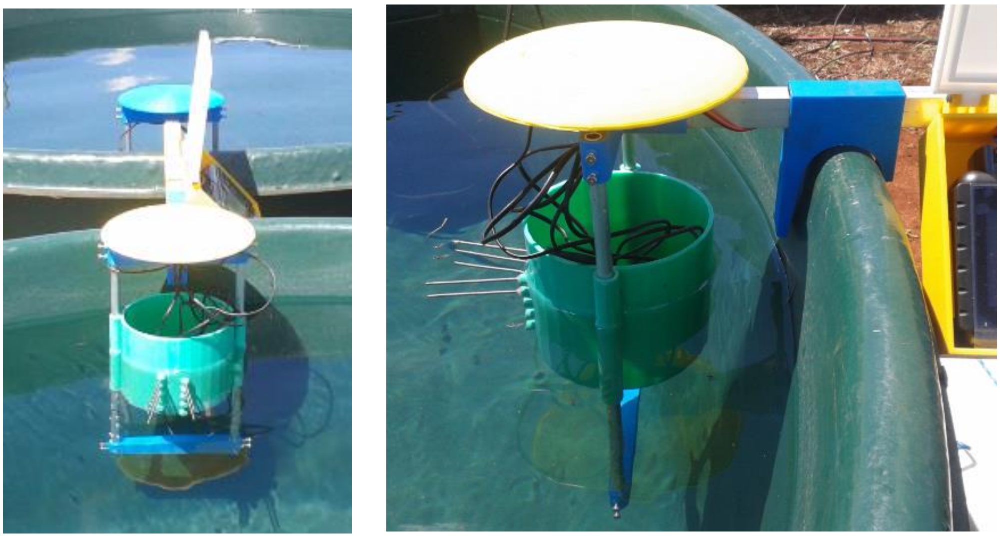


Figure 3.20: Floating the thermocouple vessel

Circular aluminium tube was used to hold the vessel in position. The vessel was deigned to slide up and down with the changing water level; the guides on the outside of the vessel allowed this to be achieved. Brackets were created using the 3D printer and were responsible for holding the aluminium tube in the correct position. The thermocouple vessels were supported by a section of square aluminium tube spanning between the two tanks.

In order to make the thermocouples float at the correct depth, an assortment of weights were placed inside each vessel. A process of trial-and-error was undertaken to reach the correct weighting, the approximate weight was 1170 grams. A circular lid was also included in the design to prevent water collecting in the vessels during rain events. Grub screws were used to hold each component of the test rig in position as highlighted in the below figure.

Figure 3.21: Grub screws

Figure 3.22 highlights the brackets (tank bracket) which were used to support and hold the test rig in the correct alignment. A number of prototypes of the bracket were produced before the final design was reached. In the below figure it can be seen how the alignment of the bracket was refined using a spirit level. The square tube needed to be level as this tube supported the thermocouple vessel. The tank bracket was fixed in position using a single self-tapping screw.

Figure 3.22: Test Rig - tank bracket

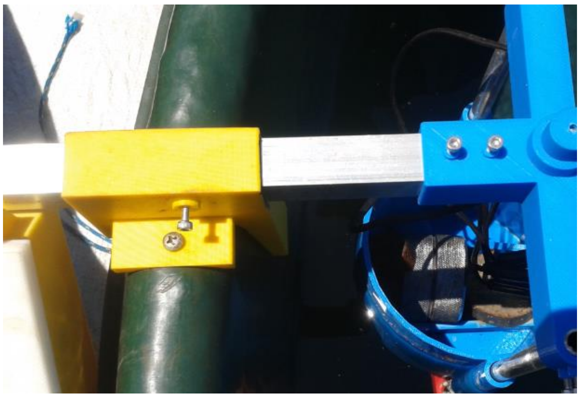


Figure 3.23: A single self-tapping screw held the test rig in position

3.6 Field Trials

The objectives of the field tests were to measure the evaporative loss and surface film temperature under a series of test conditions. The tanks were first placed under the same conditions and monitored to ensure that thermocouples recorded similar readings. The next challenge was to manipulate the air/water interface. This involved artificially impose a warm and cold surface film and analysing how these treatments influenced evaporation loss.

3.6.1 Temperature Profile

The tanks were initially placed under the same condition and monitored to ensure that similar readings for the five thermocouples placed in each tank were recorded. The data logger was programmed to record temperature profile data at 10 minute intervals.

3.6.1.1 Artificially imposing a warm surface film

A major challenge in this research was to work out the best method of artificially imposing a warm and cold surface film.

Initial plans were to disperse boiling water over the surface of one tank to create a warm surface film. However there were a number of issues surrounding this idea. The main concerns were;

- sourcing and delivering boiling water to the compound
- safely and evenly apply the warm water, and
- what volume of water would be required to create a noticeable warm surface film?

The weather was another major concern. If conditions were windy how long would the warm surface film actually last. Furthermore what if the weather was hot and there was no wind, would a warm surface film then also naturally occur in the other tank and ruin the test. It was decided that a black plastic cover should be used. The cover excluded wind, while the black cover absorbed heat resulting in thermal stratification (warm surface film).

The black cover provided a method for warming the surface water, however the impermeable material preventing water vapour from moving and evaporation occurring. To allow water vapour to escape from the tanks a circular holes were cut in the centre on the cover. A flap was also included in the cover at the perimeter of the tank to ensure that evaporative losses could be measured (twice daily) using the ruler. The cover was supported by two milk crates staked in the centre of the tanks.

Some difficulties were experienced when applying the covers, especially around the test rig. Rope was used to hold the cover in position. Existing screws located around the outer lip of the water troughs provide usefully when securing the cover with the rope. Figure 3.24 illustrates the black covers used to artificially impose the water surface film.

Figure 3.24: Artificially imposing a warm surface film

3.6.1.2 Artificially imposing a cold surface film

Applying the black cover created a warm surface film in both tanks. Therefore a process needed to be developed to remove the warm surface film, while the black cover was still in place. Naturally a cold surface film presents when bulk air flow causes thermal convection to develop beneath the water's surface. Therefore a device was require to manually created convection and cool the water. A Bulge Pump provided a simple solution for providing the necessary turbulence within the water to eliminate the warm surface film. Figure 3.25 highlights what would be seen beneath the black cover when imposing a cold surface film. The bilge pump was positioned in the centre of the tanks, within the bottom milk crate. A ¾ inch tube directed the water toward the outer perimeter, circulating and cooling the water within the tank.

Figure 3.25: Imposing a cold surface film was achieved by including a bilge pump in one tank

3.6.2 Evaporative Loss

A numbers of factors such as; cost, available time, and ease of installation ultimately distinguished that a ruler provides the most suitable method for measuring evaporative losses due to the give circumstances. A magnifying glass and Vernier callipers were used when measuring the water level and these tool significantly improve that accuracy of data collected.

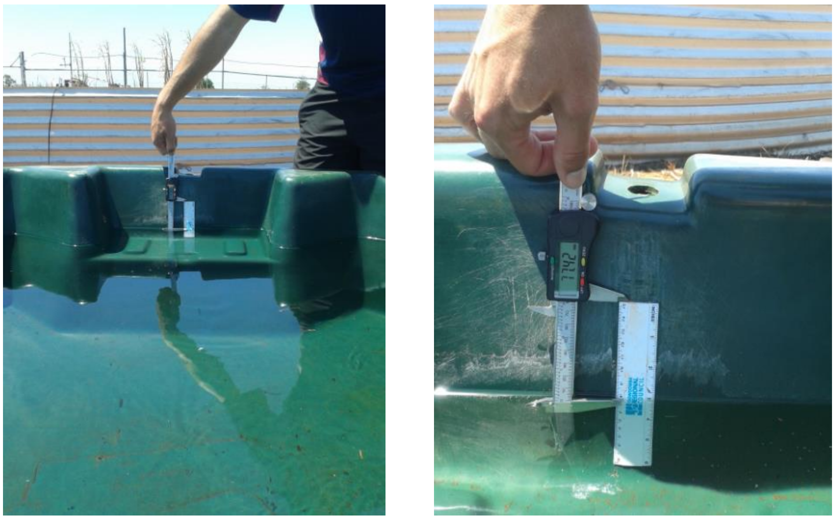


Figure 3.26: Digital Vernier Callipers were used to accurately monitor the water level in the tanks

Some difficulties were experienced when taking manual reading of the water level, prior to the covers. Based on the small surface area exposed in these tanks it was assumed that wind would have little noticeable impact on water level measurement. However this was not the case, with even a light breeze making it hard to accurately measure the water level within tanks. Before covers were implemented, on windy days the water level had to monitored for a period of two to three minutes and an average water level was assumed based on the maximum and minimum fluctuation observed.

Data collection involved reading and recording tank water levels morning (9:00am) and afternoon (5:00pm) for the period of one week. At the end of the week the tanks were refilled (topped up) and the testing could then continue for another week. Data recorded in the field was compiled within an excel spreadsheet for the purposes of modelling and graphical analysis.

Figure 3.27: Monitoring evaporation loss in the tanks

Chapter 4 Results

4.1 Introduction

This chapter analysis the results that were gathered from tests conducted at the NCEA Evaporation Compound Facility. The first section of the chapter highlights the open air evaporation capacity of the test tank (water troughs) and initial thermocouple measurement checks. The chapter will then look at the four tests which explored evaporation loss under a cold surface film and thermally stable warm surface film. All test were conducted over seven days, one week duration. A major component in the analysis of the warm and cold surface films was the use of the University of Southern Queensland weather station data. The data which has be used within this dissertation has been obtained from the weather station facility located within the USQ Ag-Plot Evaporation Compound Facilities.

4.2 Thermocouple Measurement Check

The first section of this chapter will identify the results gathered from the thermocouple calibration test. The significance of this test was to identify that thermocouples were measuring similar temperature profiles across the two tanks. The thermocouple accuracy was extremely important when later analysing an artificially imposed warm and cold surface film. The data logger recorded the temperature profile (surface, 0.01, 0.02, 0.03 and 0.04m) data at intervals of 10 minutes. The temperature profile data was downloaded from the logger and compiled within an excel spread sheet. A scatter plot was created from the temperature profile data. Figure 4.1 and Figure 4.2 highlight the temperature profile for two identical tanks (Tank 1 and Tank 2).

The thermocouples over the seven days recorded similar temperature profiles between the two tanks. Minor variations (less than 1 ^{0}C) were recorded for the thermocouple positioned at the surface. Inconsistency may relate to the east-west alignment of the two tanks (water troughs).

4.2.1 Temperature Profile Results

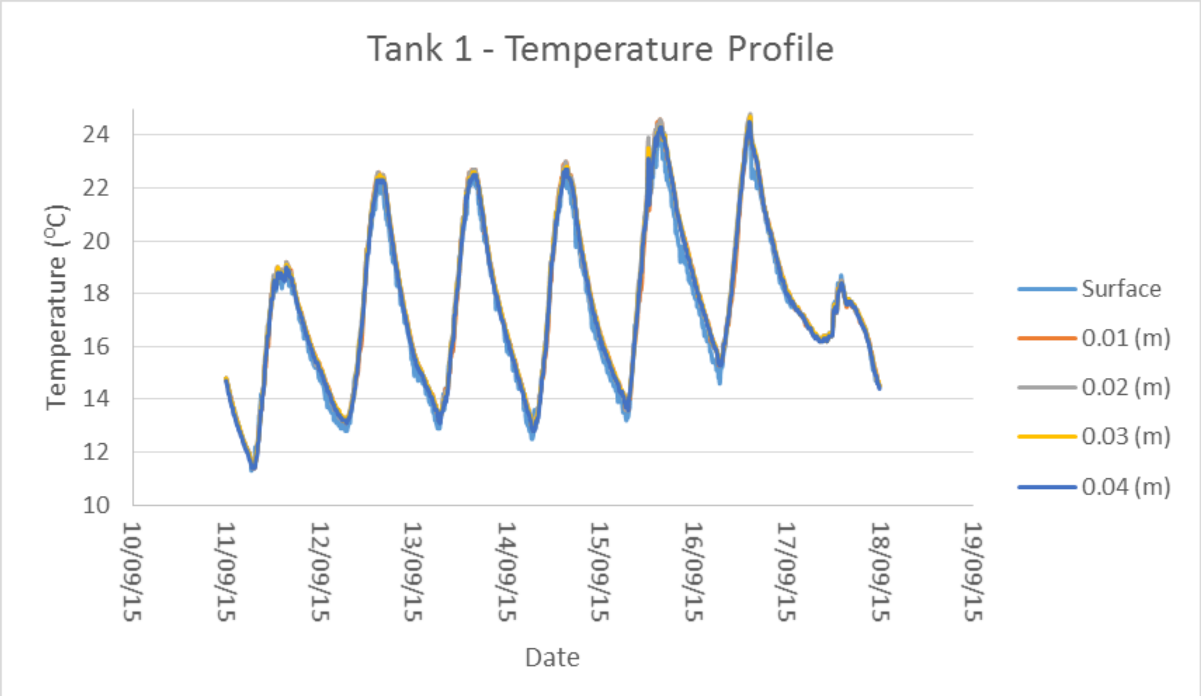


Figure 4.1: Temperature Profile for Tank 1

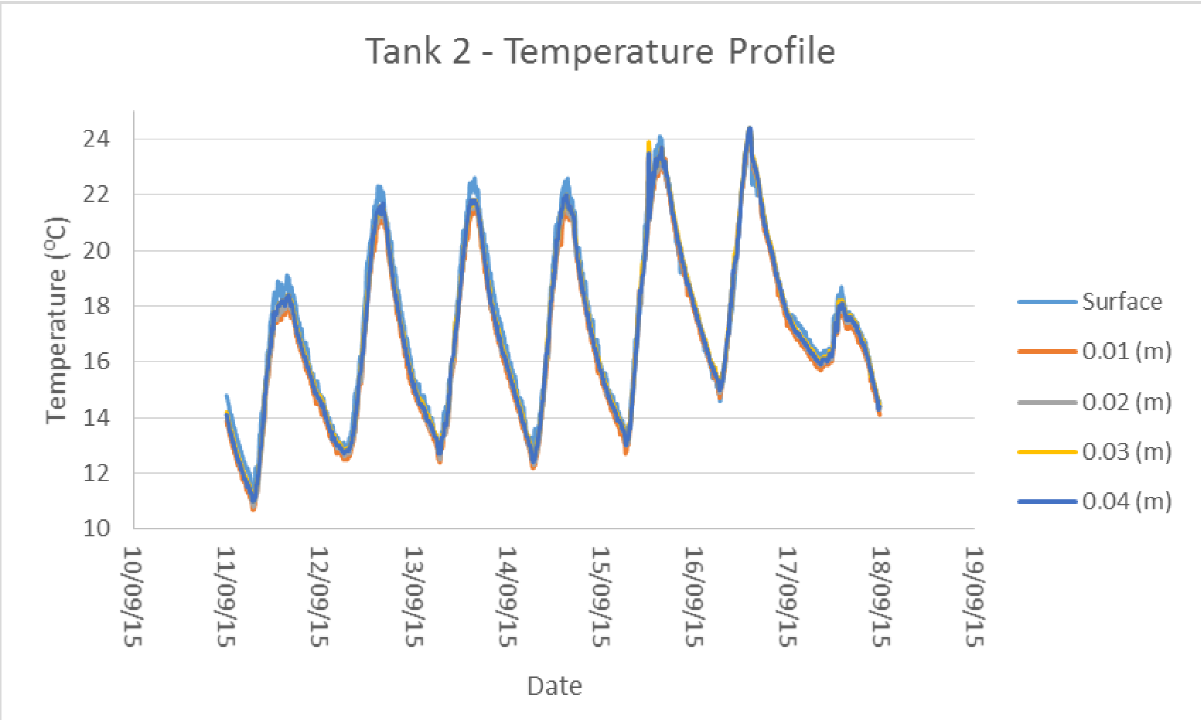


Figure 4.2: Temperature Profile for Tank 2

4.2.2 Evaporation Loss

The results indicate an accuracy of ±1mm between the total evaporative losses in the two tanks. Based on the accuracy associated with the ruler measurements technique. A difference of ±1mm can be ignored and e evaporative loss assumed as equal.

Table 4.1: Water level measurement for the two tanks were recorded twice daily. Both tanks were fill to full capacity, the full capacity of tank 1 was 10.5cm and the full capacity of tank 2 was 9.5cm. Note the difference between the full water level measurement resulted from minor variations in the positioning of the ruler, the total volume of water within the tanks was equal.

		Water level	
Date	**Data Recording**	**Tank 1**	**Tank 2**
11/09/15	Morning Reading (9:00am)	10.5	9.5
	Afternoon Reading (5:00pm)	10.1	9.16
12/09/15	Morning Reading (9:00am)	9.8	8.9
	Afternoon Reading (5:00pm)	9.55	8.65
13/09/15	Morning Reading (9:00am)	9.5	8.6
	Afternoon Reading (5:00pm)	9.4	8.25
14/09/15	Morning Reading (9:00am)	9.2	8.2
	Afternoon Reading (5:00pm)	8.85	7.65
15/09/15	Morning Reading (9:00am)	8.5	7.4
	Afternoon Reading (5:00pm)	8.15	7.3
16/09/15	Morning Reading (9:00am)	8	7.1
	Afternoon Reading (5:00pm)	7.4	6.7
17/09/15	Morning Reading (9:00am)	7.35	6.55
	Afternoon Reading (5:00pm)	7	6.1
Total Evaporative loss in each tank		**3.5cm or 35mm**	**3.4 cm or 34mm**

Figure 4.3 illustrates the cumulative evaporation loss from tank 1 and tank 2. A linear trend can be identified for the cumulative evaporation. Minor fluctuations in the cumulative evaporation may be explained by human error associated with the ruler measurement technique.

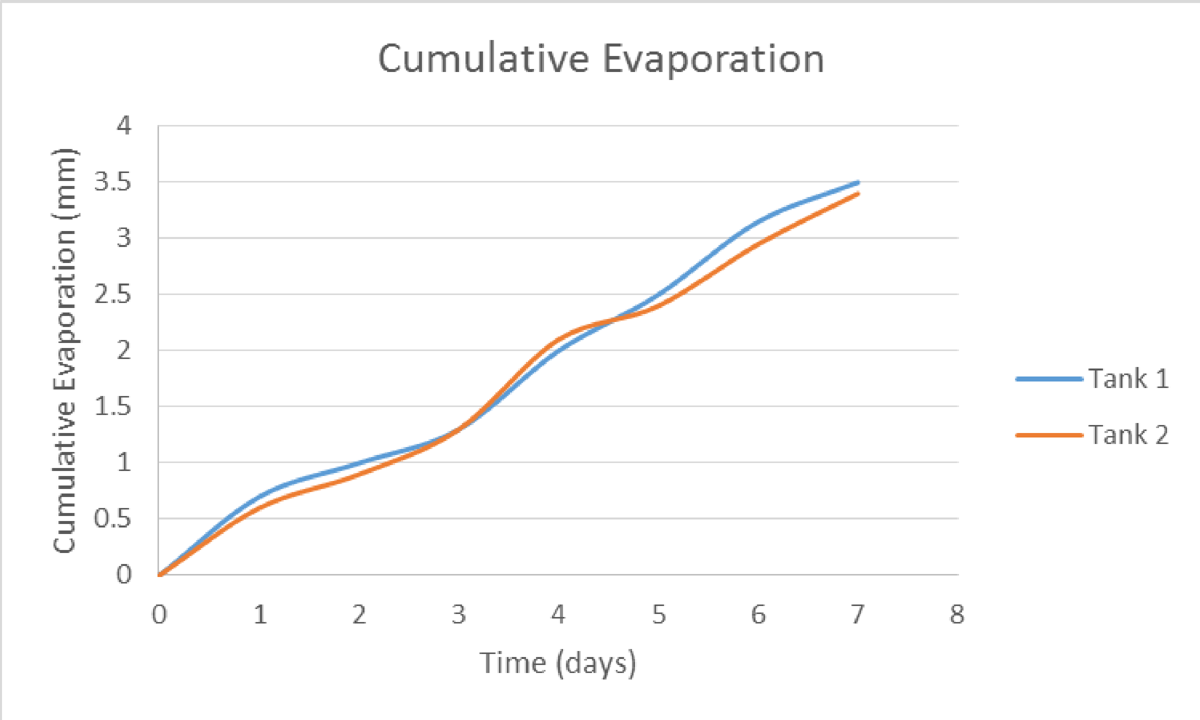


Figure 4.3: Cumulative evaporation over 7 day test period

4.3 Test 1 (21/9/2015 – 27/9/2015)

4.3.1 Weather Station Data

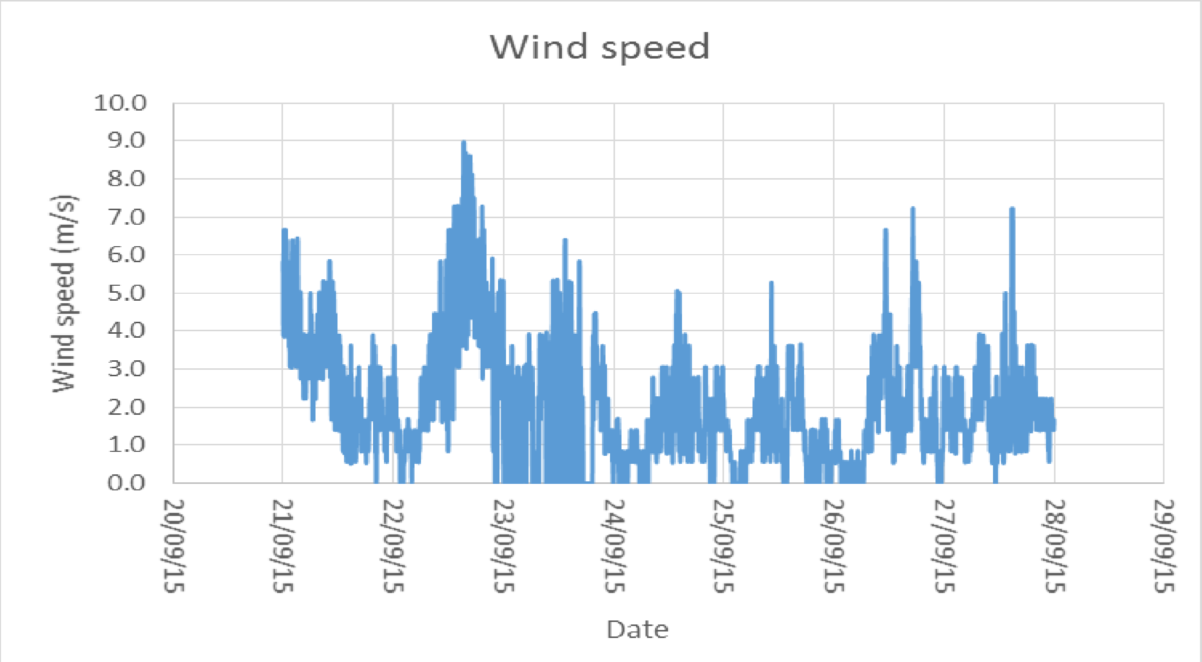


Figure 4.4: Test 1 - wind speed data for the period of 21/09/15 to 27/09/15

The average wind speed for the week was 2.1 m/s and the maximum wind speed 8.9 m/s.

The above plot has been generated from 5 minute interval wind speed data. Analysing the data it was identified that there were 43 (5 minute intervals) recordings were wind speeds are greater than 6 m/s. This equates to approximately 2% of the week being unsuitable for monolayer application.

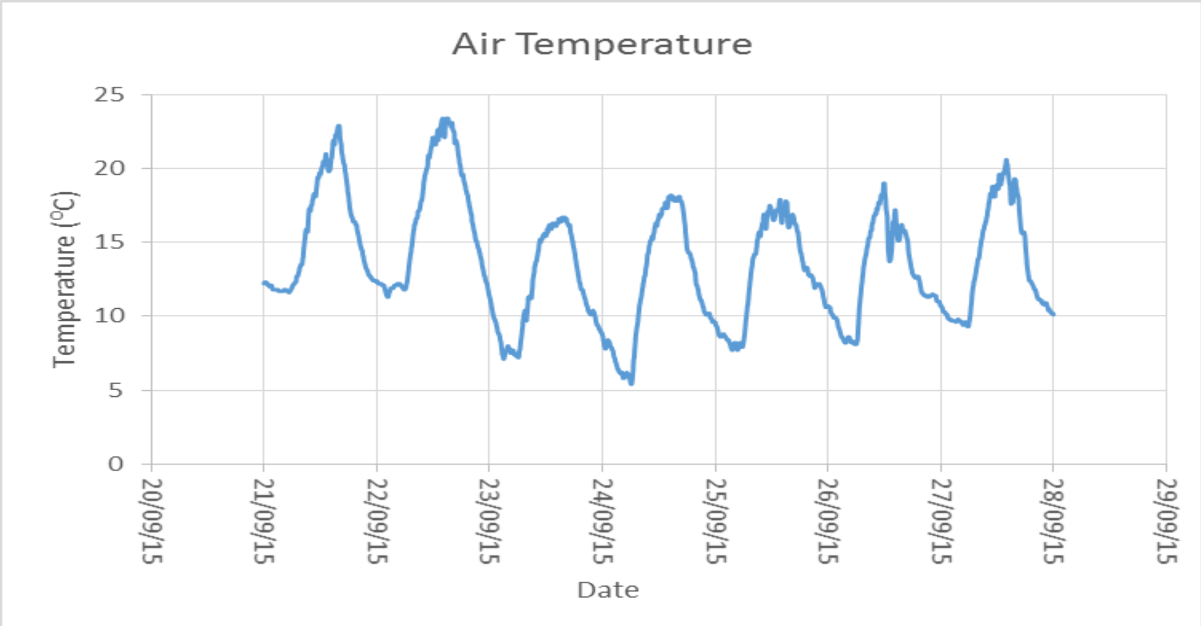


Figure 4.5: Test 1 - air temperature data for the period of 21/09/15 to 27/09/15

The average air temperature for the week was 13.7^{0}C and the maximum air temperature was 23.4^{0}C.

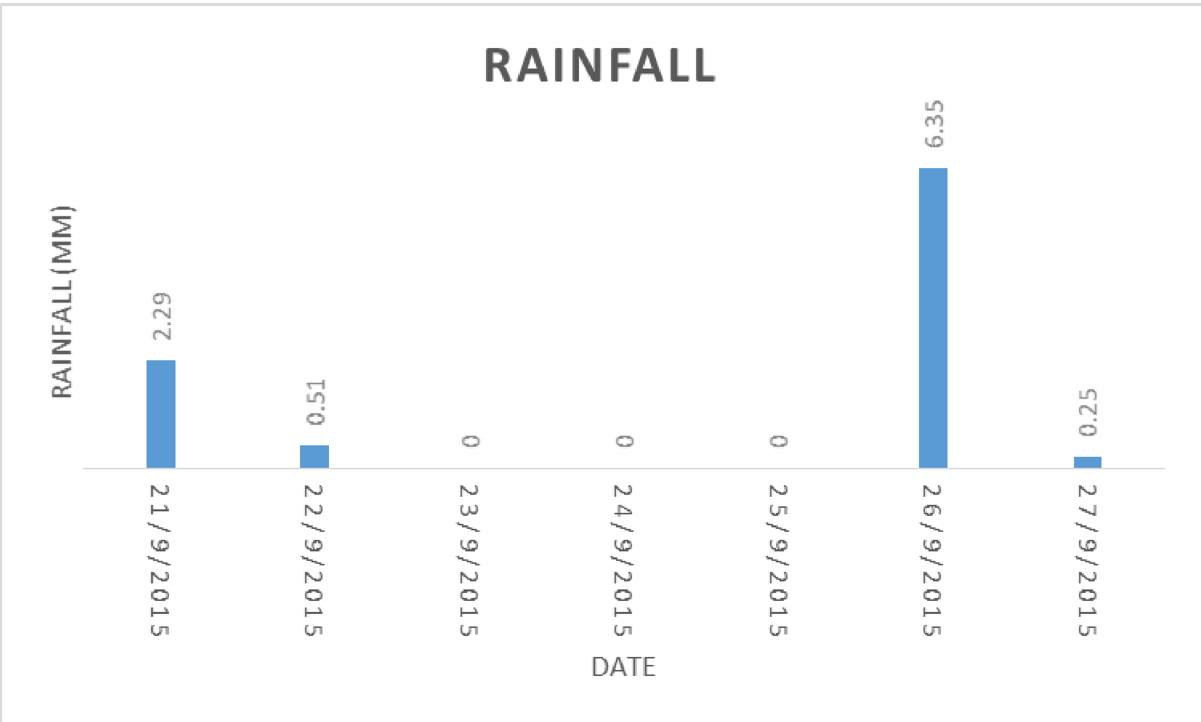


Figure 4.6: Test 1 – Rainfall data for the period of 21/09/15 to 27/09/15

4.3.2 Tank 1 – Cold Surface Film

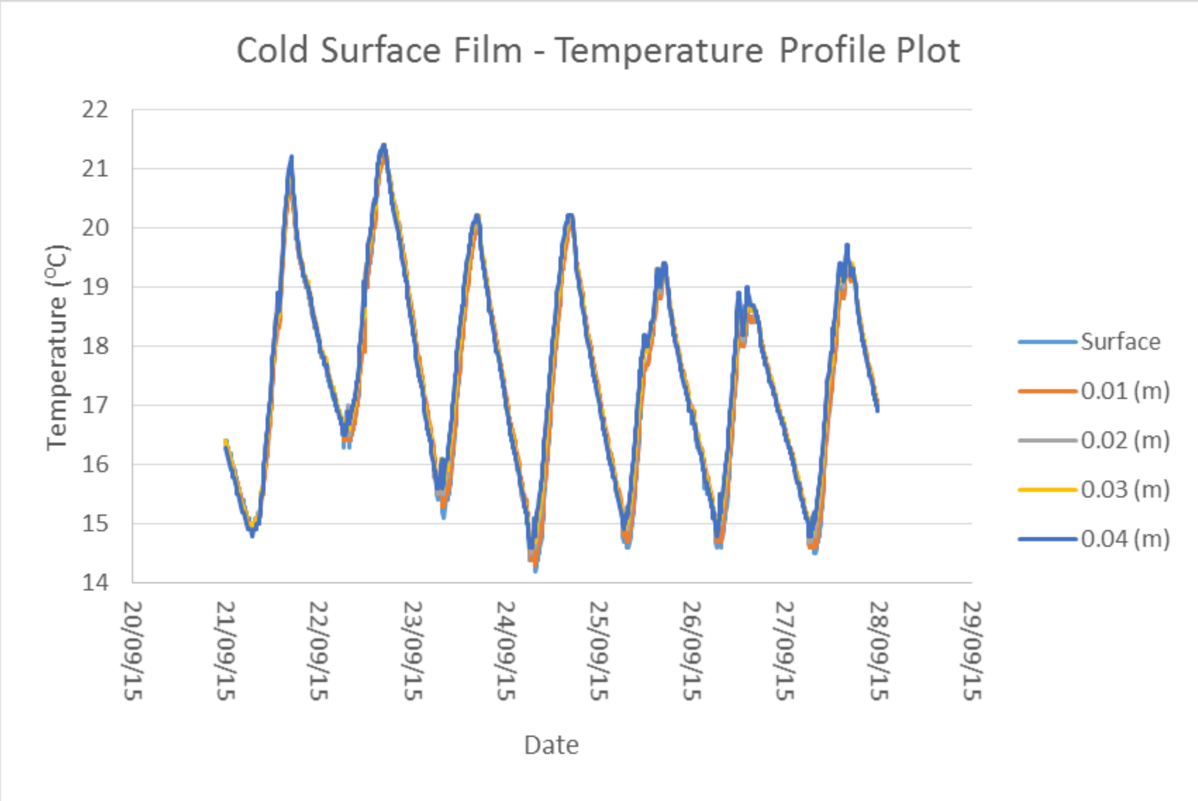


Figure 4.7: Test 1 cold surface film temperature profile plot (Tank 1)

Figure 4.7 illustrates the temperature profile of the cold surface film which was imposed on tank 1 during Test 1. It is very difficult to analysis the temperature profile over an extended period. It is necessary to analysis shorter time periods to better understand the presents of the cold surface film. The temperature profile has be analysed over a twenty-four hour period. The following results highlight how the weather directly influence temperature profile data. Appendix B an example of 1 day temperature profile data. Appendix C provides the full set of temperature profile plots for Test 1.

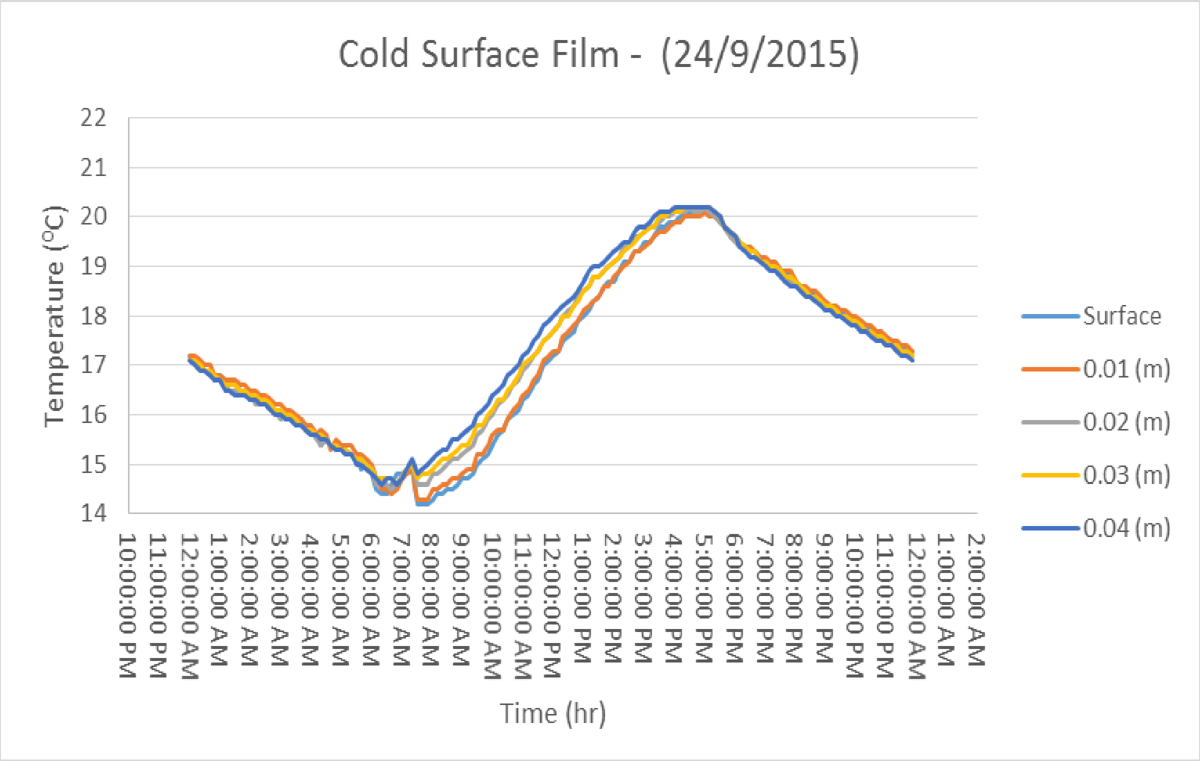


Figure 4.8: Test 1 - Temperature profile plot for consistent cold surface film in Tank 1 on 24/9/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

On the 24th of September thermocouples recorded a consistent cold surface film. Cool calm conditions with wind speed averaging 2.8m/s throughout the day promoted a consistent cooling and mixing of the water within tank 1. A distinct cold surface film is evident between 8:00am and 11:00am. Between 11:00am and 6:00pm, while the cold surface film is still active. It can be identified that the temperature profiles of thermocouple position at 0.01m and 0.02m are very similar. The thermocouple positioned at 0.03m and 0.04m are also seen to have a similar temperature profile during the period of 11:00am to 6:00pm. The thin layered cold surface film identified between 11:00am and 6:00pm has most like resulted from the increase in air temperature towards the midday period.

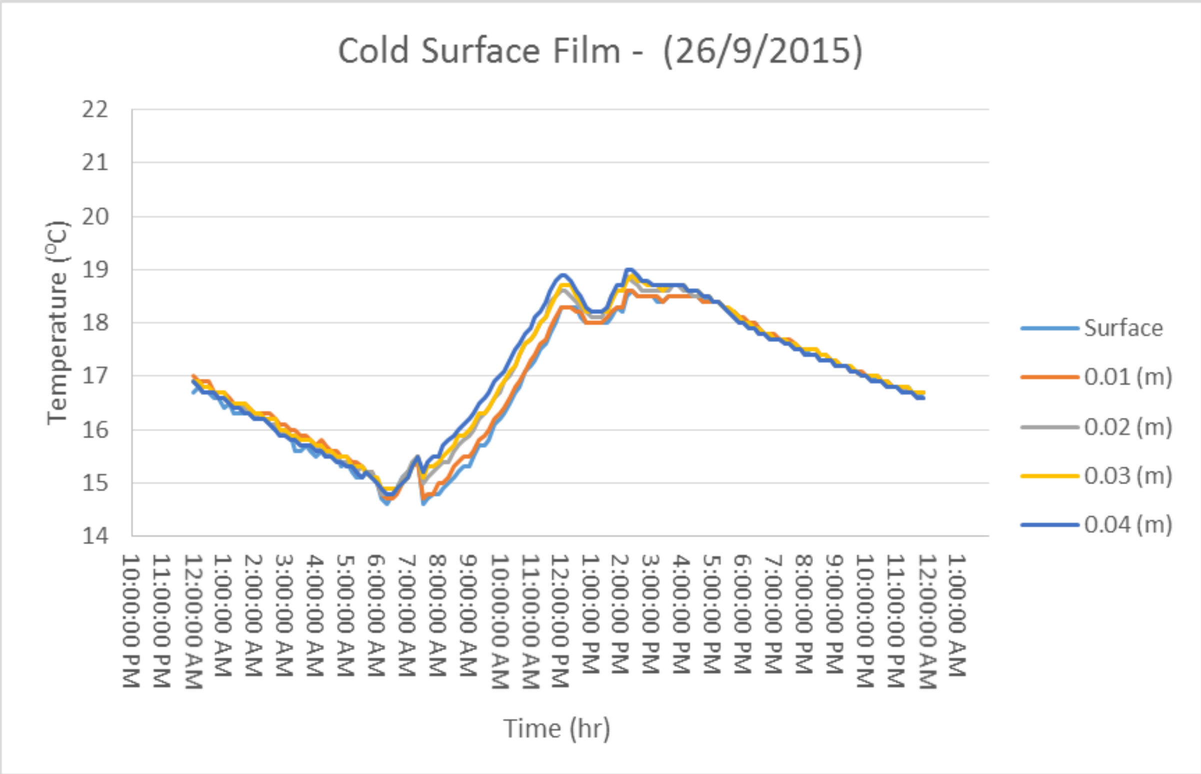


Figure 4.9: Test 1 - Temperature profile plot for disrupted cold surface film in Tank 1 on 26/9/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period. The disrupted cold surface film shows instances of rapid evaporative cooling.

Temperature profiles data collected for the 26th of September provides evidence of a disrupted cold surface film. A distinct cold surface film is evident for 8:00am to 12:00pm, after which rapid evaporative cooling has occurred. The disturbance of the cold surface film is the result of a short burst rainfall event. Over a twenty minute periods (12:35pm to 12:55pm) 5.59 mm rainfall was recorded. The rain event has resulted in almost instant evaporative cooling of the surface film within the disturbed tank. The temperature profile highlights that this was a short burst rain event as the water temperature increases again before gradually cooling in the late afternoon.

4.3.3 Tank 2 – Warm Surface Film

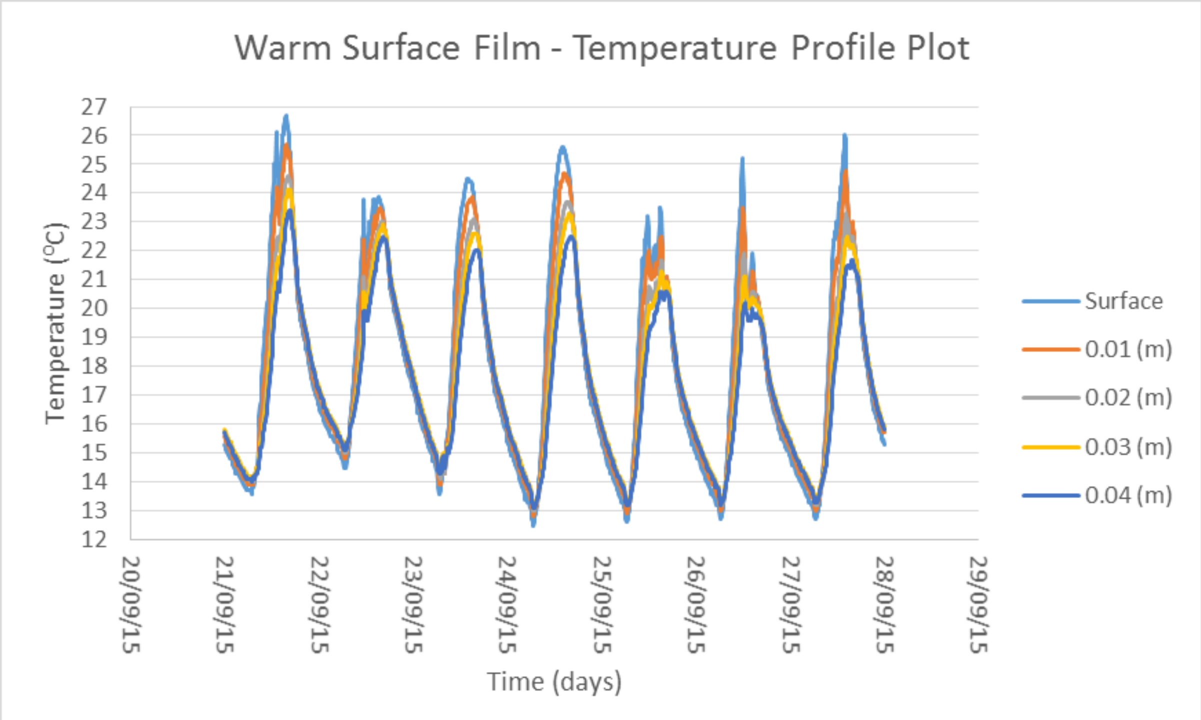


Figure 4.10: Test 1 - warm surface film temperature profile plot (Tank 2)

A noticeable warm surface film is evident on all seven days within Test 1. On the 23rd and 24th of September a consistent warm surface film has been imposed. A moderately consistent warm surface film is evident on 21st and 22nd of September. However an inconsistent warm surface film is identifiable over the 25th, 26th and 27th of September.

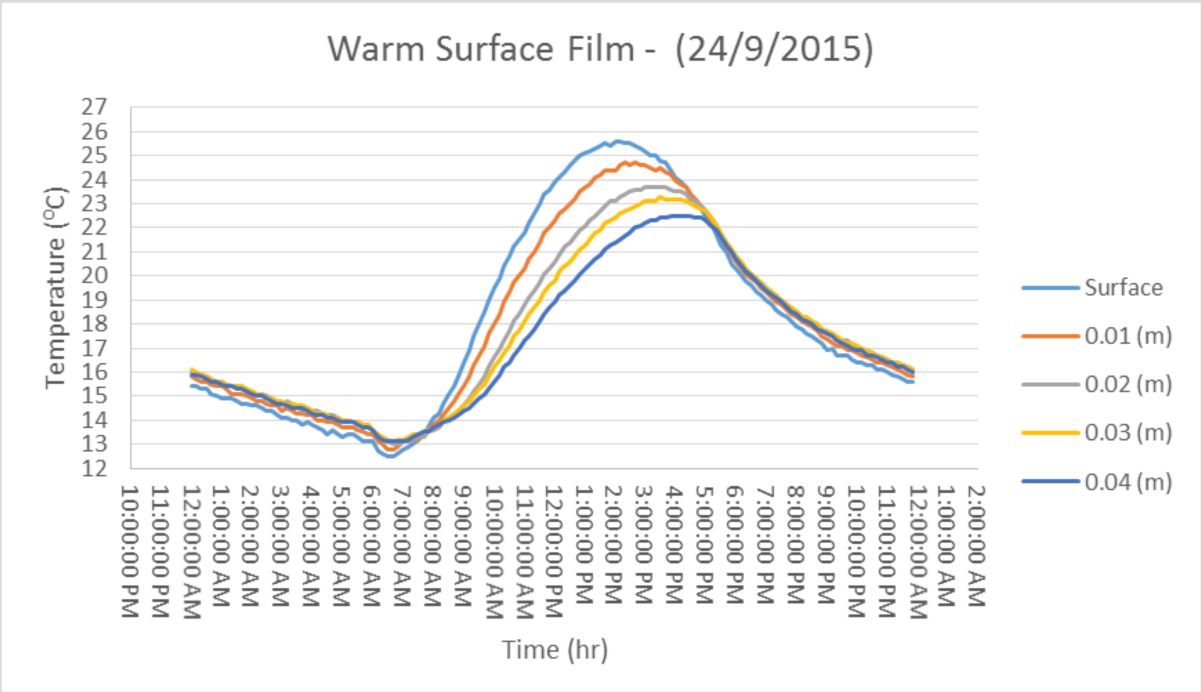


Figure 4.11: Test 1 - Temperature profile plot for consistent warm surface film in Tank 2 on 24/9/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

A consistent warm surface film has been imposed on the 24th of September. The temperature profile has determined roughly a 4^0C temperature difference between the five thermocouple when the warm surface film is most prominent (1:00pm). The warm surface film is imposed from approximately 9:00am till 5:00pm. Evidence of a turnover event can be identified (Figure 4.11).

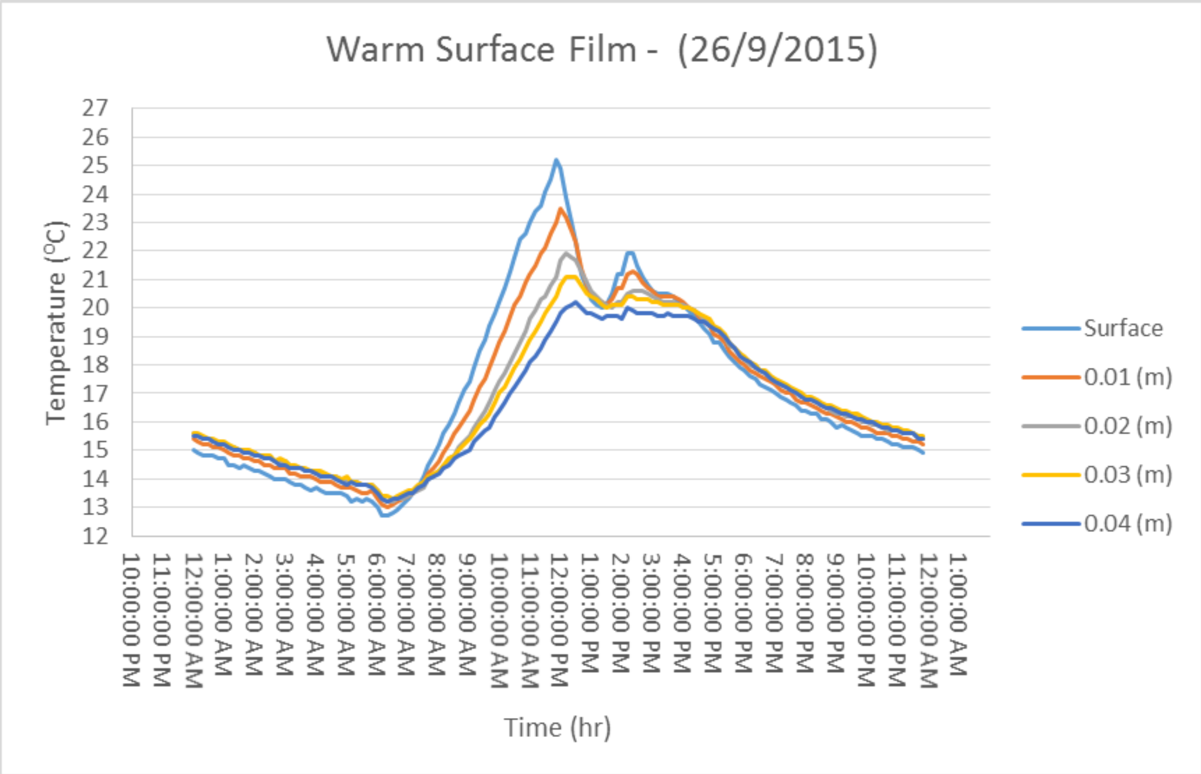


Figure 4.12: Test 1 - Temperature profile plot for disrupted warm surface film in Tank 2 on 26/9/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period. The disrupted warm highlights the warm surface film stratifying during the day.

The black covers have caused a distinct warm surface film to form in the undisturbed tank. However at a short burst rain event has resulted in rapid disturbance of the warm surface film. Rapid cooling and of the warm surface film has occurred, stratifying quickly during the day. The air temperature increased following the short burst rain event and the warm surface begins to reform before a turnover occurs at 5:00pm.

4.3.4 Tank Evaporation

Table 4.2: Water level measurement for two tanks were recorded twice daily using Venire Callipers. Measurements have been taken between the top edge of the ruler and the water surface.

		Water level	
Date	**Data Recording**	**Tank 1**	**Tank 2**
21/09/15	Morning Reading (9:00am)	49.00	54.00
	Afternoon Reading (5:00pm)	49.00	54.00
22/09/15	Morning Reading (9:00am)	49.00	54.00
	Afternoon Reading (5:00pm)	49.00	54.00
23/09/15	Morning Reading (9:00am)	49.00	54.02
	Afternoon Reading (5:00pm)	49.02	54.07
24/09/15	Morning Reading (9:00am)	49.08	54.10
	Afternoon Reading (5:00pm)	49.11	54.17
25/09/15	Morning Reading (9:00am)	49.17	54.19
	Afternoon Reading (5:00pm)	49.23	54.31
26/09/15	Morning Reading (9:00am)	49.31	54.37
rain*	Afternoon Reading (5:00pm)	49.38	54.47
27/09/15	Morning Reading (9:00am)	49.28	54.37
	Afternoon Reading (5:00pm)	49.29	54.40
Total Evaporative loss in each tank		**0.29cm or 2.9mm**	**0.40cm or 4.0m**

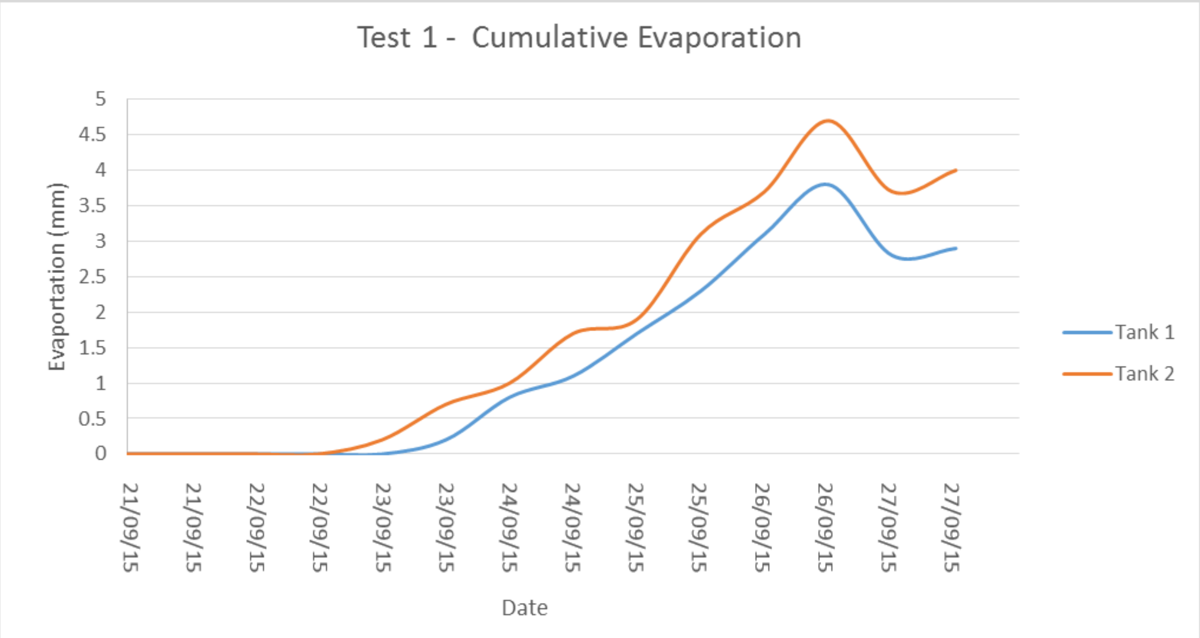


Figure 4.13: Cumulative evaporative loss recorded during Test 1. Tank 1 refers to the disturbed cold surface film. Tank 2 refers to the undisturbed warm surface film. The two increments for each day refer to the 9am and 5pm (twice daily) data collection.

4.4 Test 2 (28/9/15 – 4/10/15)

4.4.1 Weather Station Data

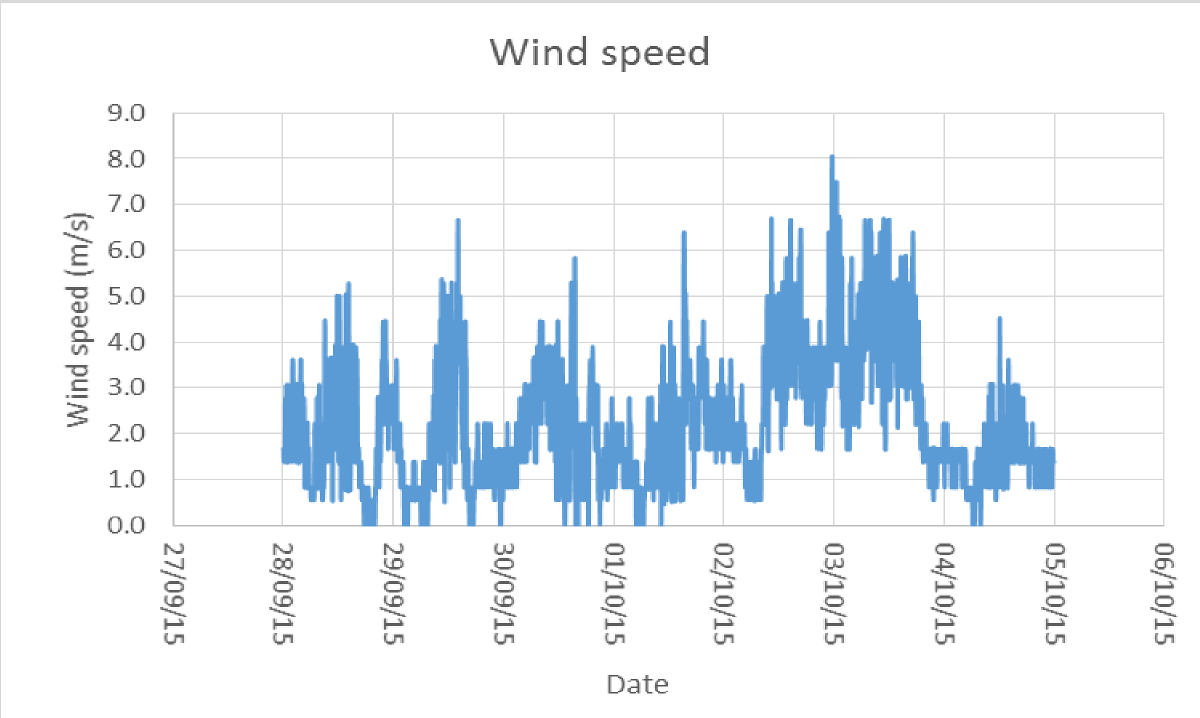


Figure 4.15: Test 2 - wind speed data for the period of 27/09/15 to 4/10/15

The average wind speed for the week was 2.2 m/s and the maximum wind speed 8.1 m/s.

The above plot has been generated from 5 minute interval wind speed data. Analysing the data it was identified that there were 24 (5 minute intervals) recordings were wind speeds are greater than 6 m/s. This equates to approximately 1% of the week being unsuitable for monolayer application.

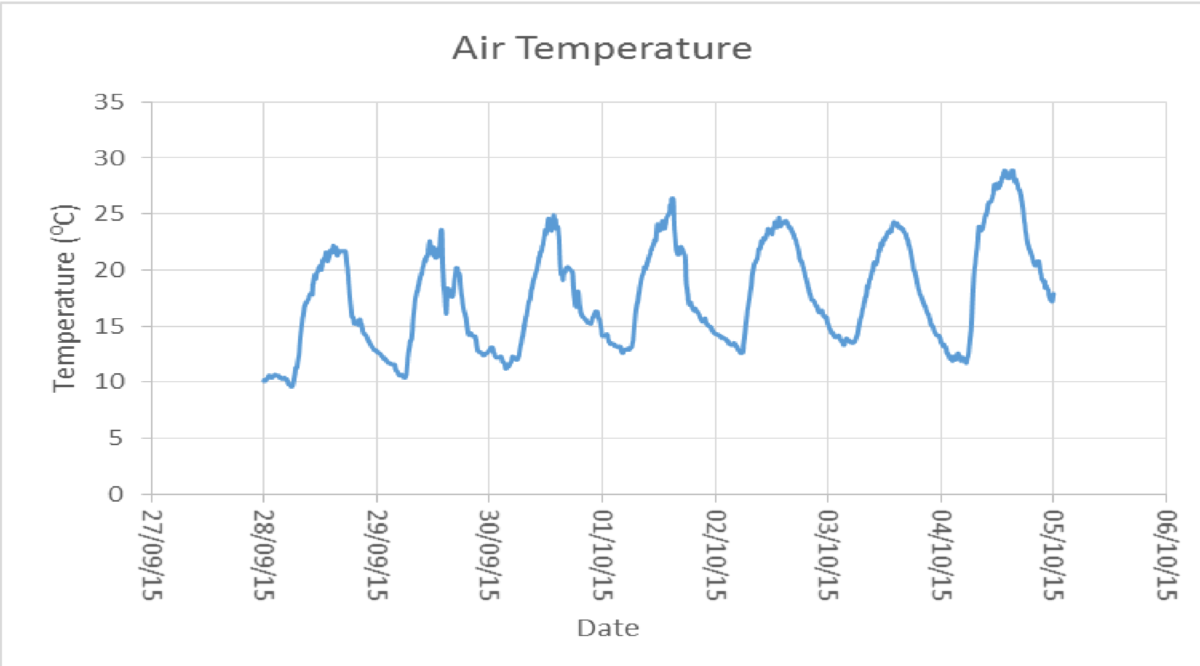


Figure 4.16: Test 2 – air temperature data for the period of 27/09/15 to 4/10/15

The average air temperature for the week was 17.7^{0}C and the maximum air temperature was 28.9^{0}C.

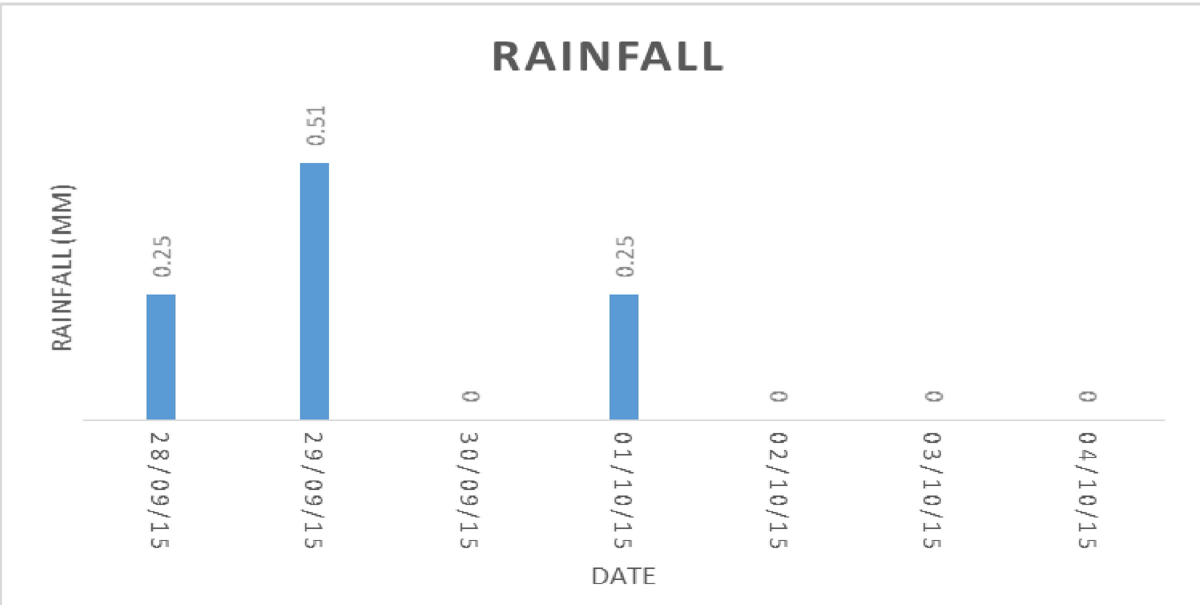


Figure 4.17: Test 2 – rainfall data for the period of 27/09/15 to 4/10/15

4.4.2 Cold Surface Film

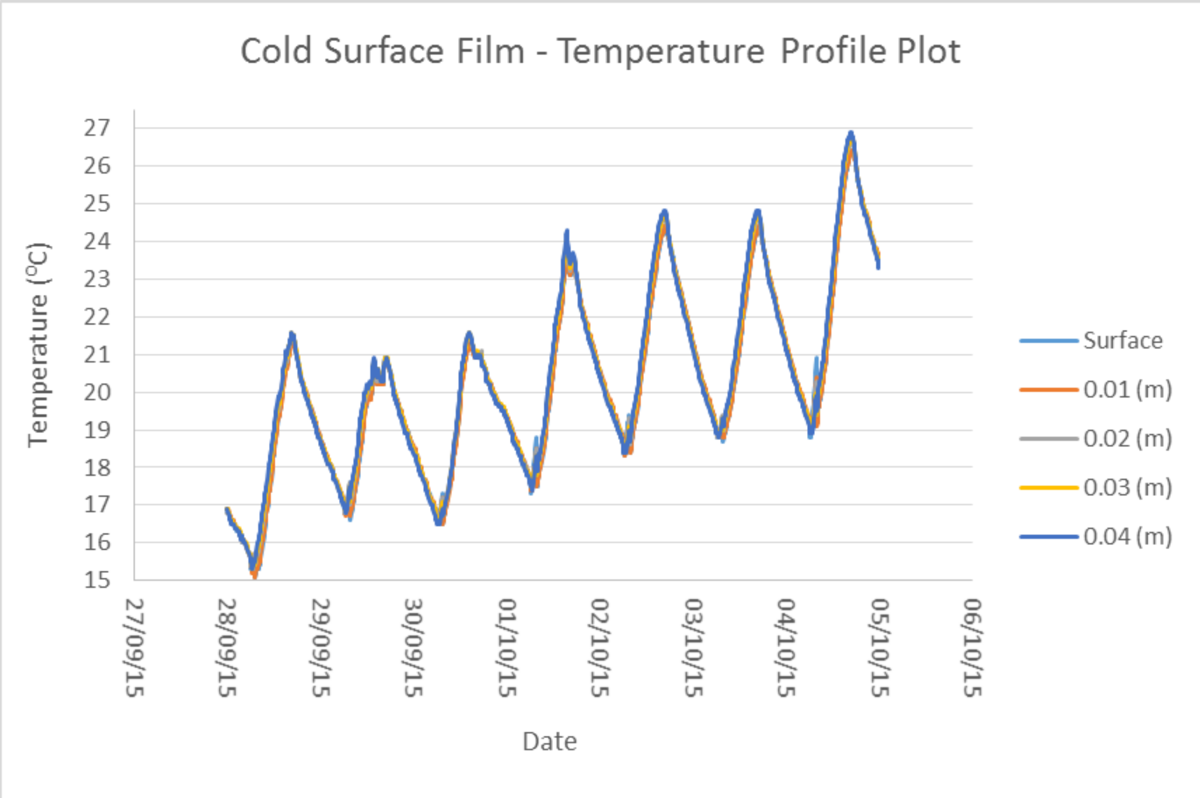


Figure 4.18: Test 2 - cold surface film temperature profile plot (Tank 1)

A cold surface film is evident on all seven days within Test 2. On the 28rd of September, 2nd, 3rd and 4th of October a consistent cold surface film has been imposed. An inconsistent cold surface film is evident over the 29th, 30th of September and 1st of October.

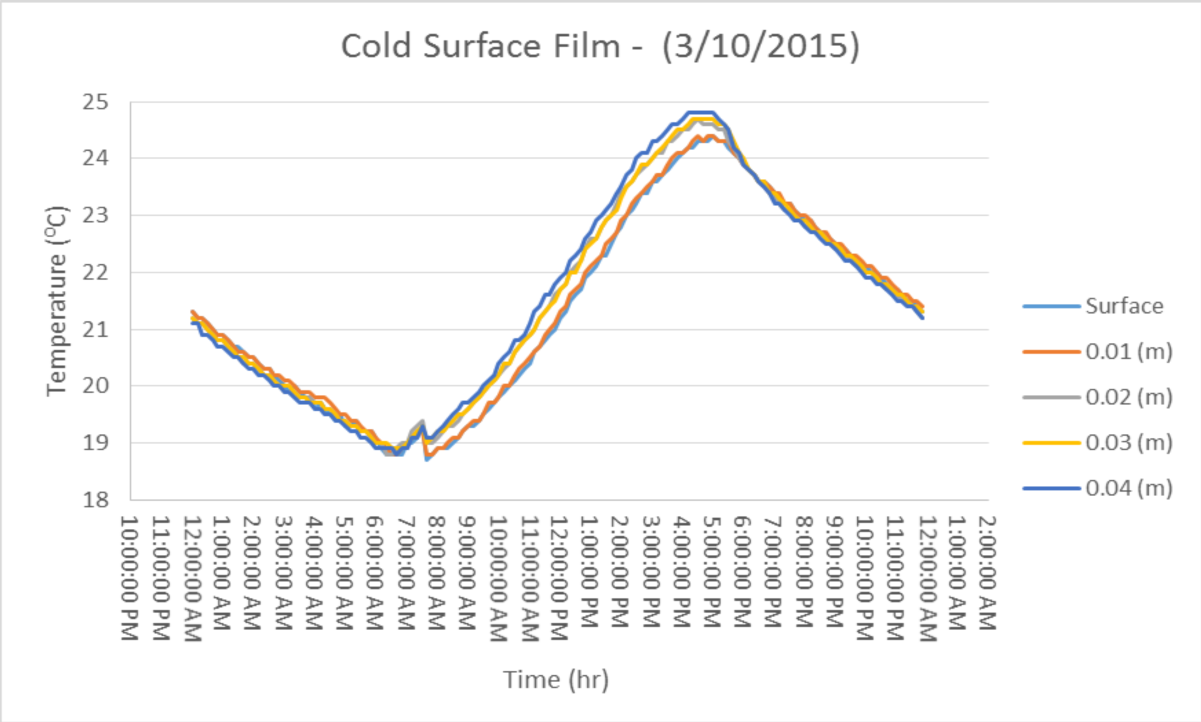


Figure 4.19: Test 2 - Temperature profile plot for consistent cold surface film in Tank 1 on 3/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

On the 3rd of October thermocouples recorded a consistent cold surface film. Air temperatures below 25^{0}C and an average wind speed throughout the day of 3.1 m/s resulted in optimum conditions for a cold surface film to be imposed.

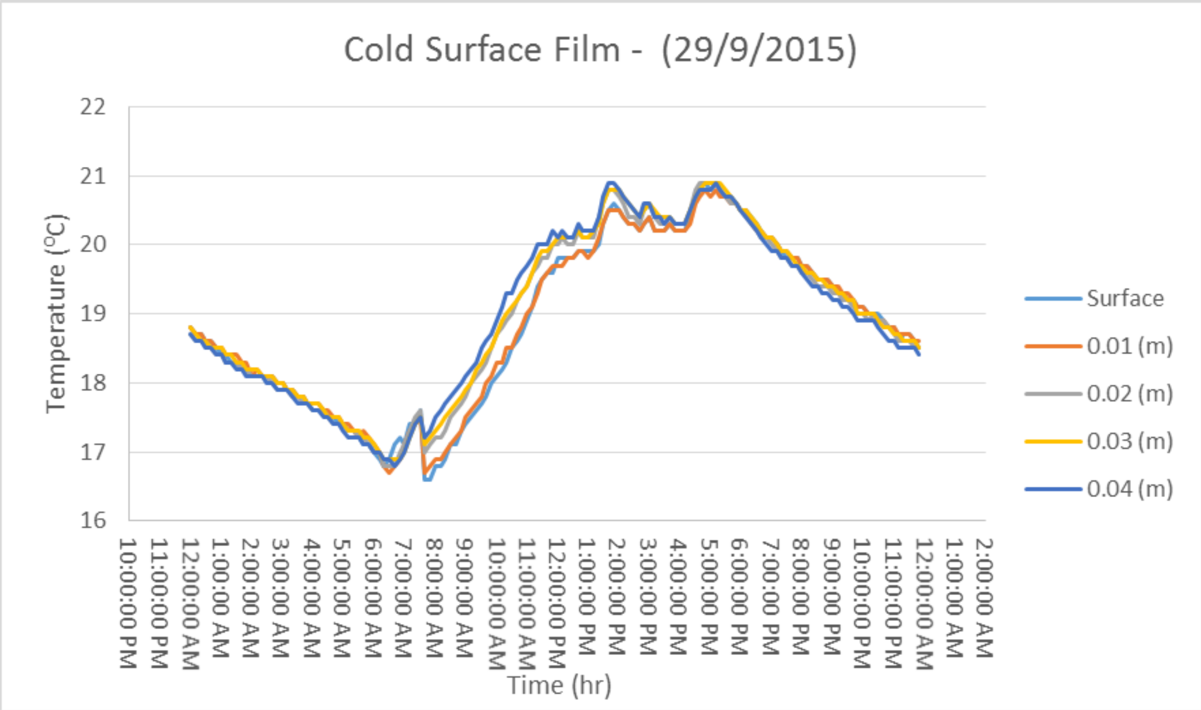


Figure 4.20: Test 2 - Temperature profile plot for disrupted cold surface film in Tank 1 on 29/9/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

Evident of minor bilge pump failure is indicated prior to the forming of a cold surface film on the 29th of September. A consistent cold surface film is apparent between 8:00am and 12:00pm. Overcast conditions developed around lunchtime and light rain (0.51mm) resulted in rapid cool of the surface film. A spike in air temperature late in the day further disrupted the cold surface film.

4.4.3 Warm Surface Film

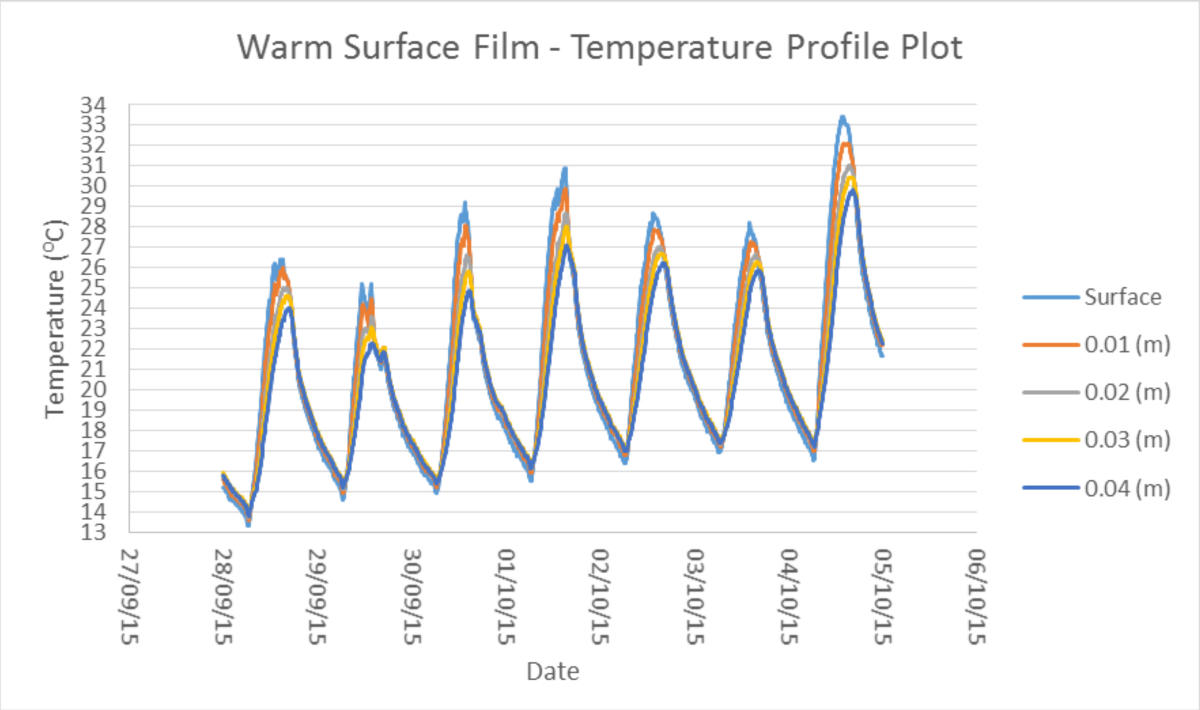


Figure 4.21: Test 2 - warm surface film temperature profile plot (Tank 2)

A noticeable warm surface film is evident on all seven days within Test 2. Tuesday the 29th of September the warm surface film noticeable impacted. All other days recorded a consistent warm surface film.

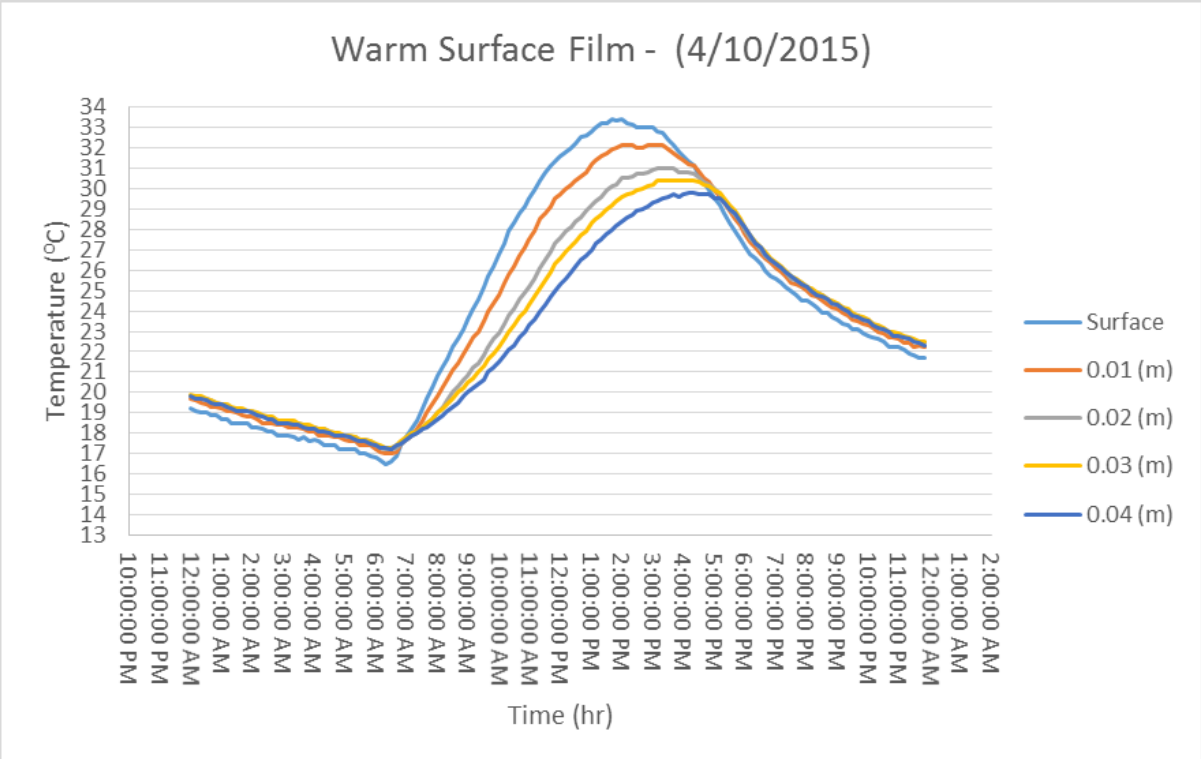


Figure 4.22: Test 2 - Temperature profile plot for consistent warm surface film in Tank 2 on 4/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

Sunday the 4th of October recorded an extremely consistent warm surface film. Air temperatures increased late in the week, in the vicinity of 28°C. Wind speed averaged of 1.5m/s throughout the day allowed the black cover to impose quite a thick warm surface film. The warm surface film occurred within the undisturbed tank between, 8:00am and 6:00pm. A turnover event is evident at 5:00pm in tank 2. The result is a cold surface film imposed overnight until sunlight heats the cover and imposing the warm surface film again the following day.

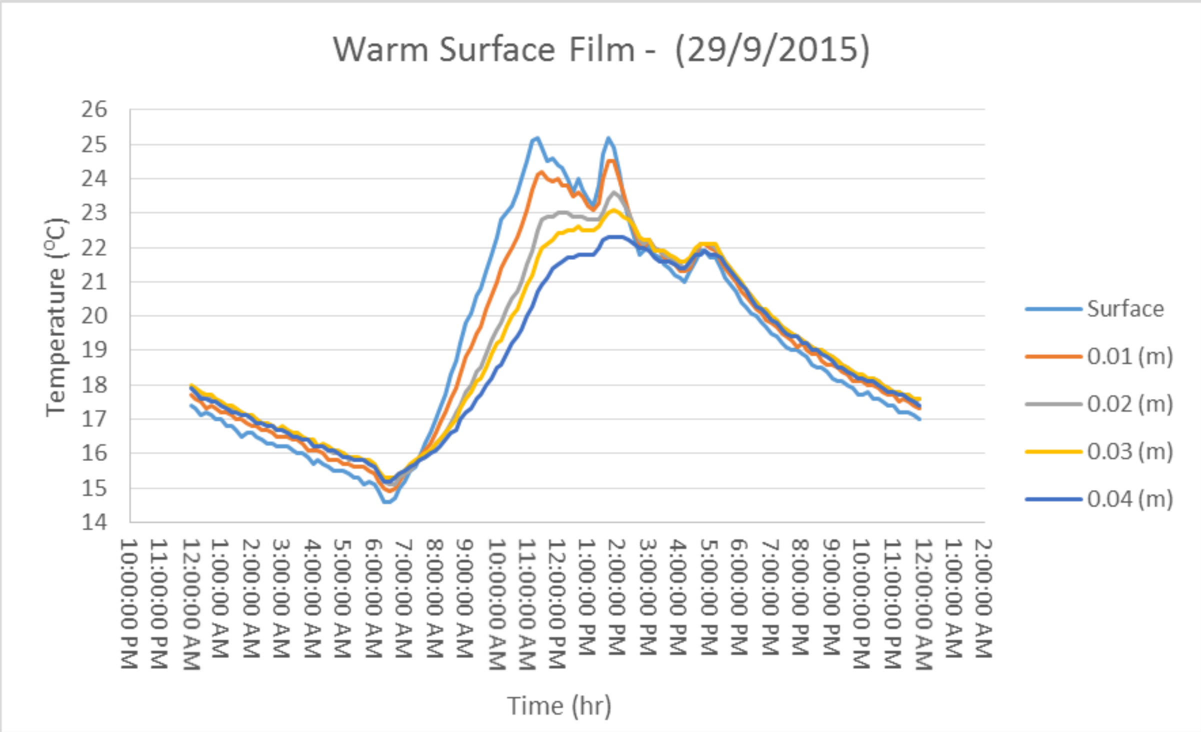


Figure 4.23: Test 2 - Temperature profile plot for disrupted warm surface film in Tank 2 on 29/9/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

Overcast conditions developed around lunchtime and light rain (0.51mm) resulted in rapid cool of the surface film. A spike in air temperature late in the day further disrupted the warm surface film at approximately 5:00pm. Considerable stratification is evident between 12:00pm and 2:00pm. The warm surface film is imposed from seven hours between 8:00am and 3:00pm.

4.4.4 Tank Evaporation

Table 4.3: Test 2 - Water level measurement for two tanks were recorded twice daily using Venire Callipers. Measurements have been taken between the top edge of the ruler and the water surface.

		Water level	
Date	**Data Recording**	**Tank 1**	**Tank 2**
28/9/2015	Morning Reading (9:00am)	49.00	54.00
	Afternoon Reading (5:00pm)	49.00	54.00
29/9/2015	Morning Reading (9:00am)	49.02	54.06
	Afternoon Reading (5:00pm)	49.05	54.07
30/9/2015	Morning Reading (9:00am)	49.06	54.14
	Afternoon Reading (5:00pm)	49.08	54.14
1/10/2015	Morning Reading (9:00am)	49.09	54.22
	Afternoon Reading (5:00pm)	49.12	54.25
2/10/2015	Morning Reading (9:00am)	49.16	54.30
	Afternoon Reading (5:00pm)	49.18	54.30
3/10/2015	Morning Reading (9:00am)	49.23	54.34
	Afternoon Reading (5:00pm)	49.25	54.34
4/10/2015	Morning Reading (9:00am)	49.27	54.39
	Afternoon Reading (5:00pm)	49.30	54.44
Total Evaporative loss in each tank		**0.30cm or 3.0mm**	**0.44cm or 4.4mm**

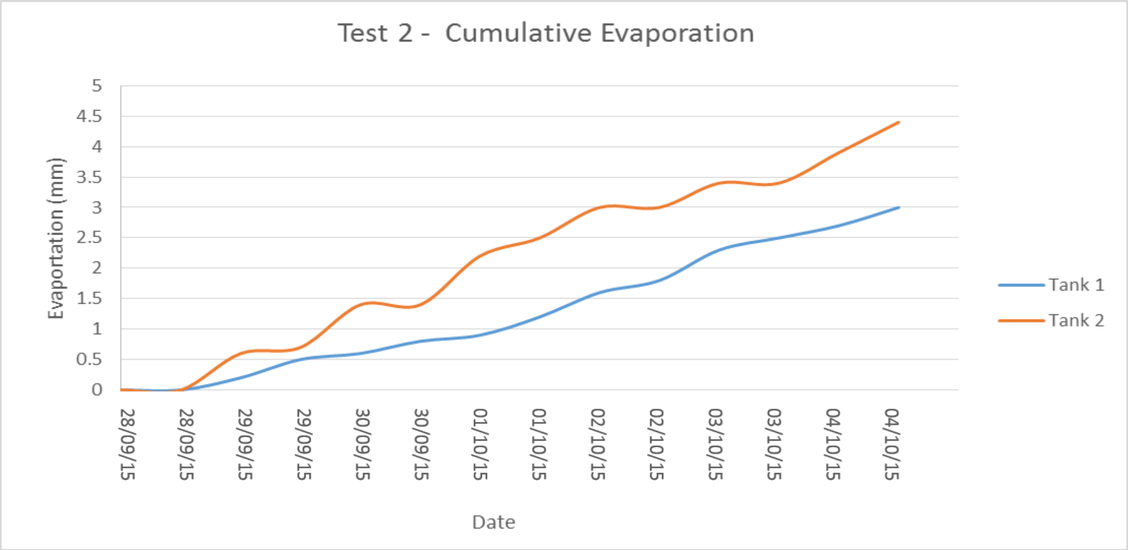


Figure 4.24: Cumulative evaporative loss recorded during Test 2. Tank 1 refers to the disturbed cold surface film. Tank 2 refers to the undisturbed warm surface film. The two increments for each day refer to the 9am and 5pm (twice daily) data collection.

4.5 Test 3 (5/10/15 – 11/10/15)

4.5.1 Weather Station Data

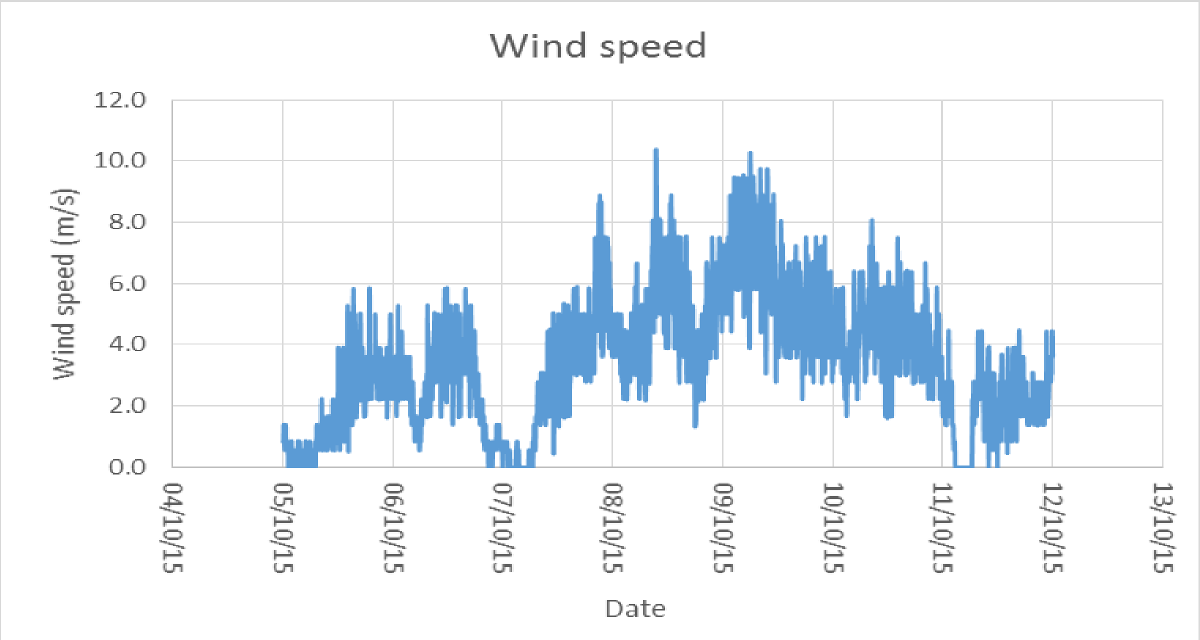


Figure 4.25: Test 3 - wind speed data for the period of 5/10/15 to 11/10/15

Average and maximum wind speed during the Test 3 were; 3.4 m/s and 10.3 m/s respectively.

The above plot has been generated from 5 minute interval wind speed data. Analysing the data it was identified that there were 235 (5 minute intervals) recordings were wind speeds are greater than 6 m/s. This equates to approximately 12% of the week being unsuitable for monolayer application. Between Wednesday and Friday 92% of the high wind gusts have taken place.

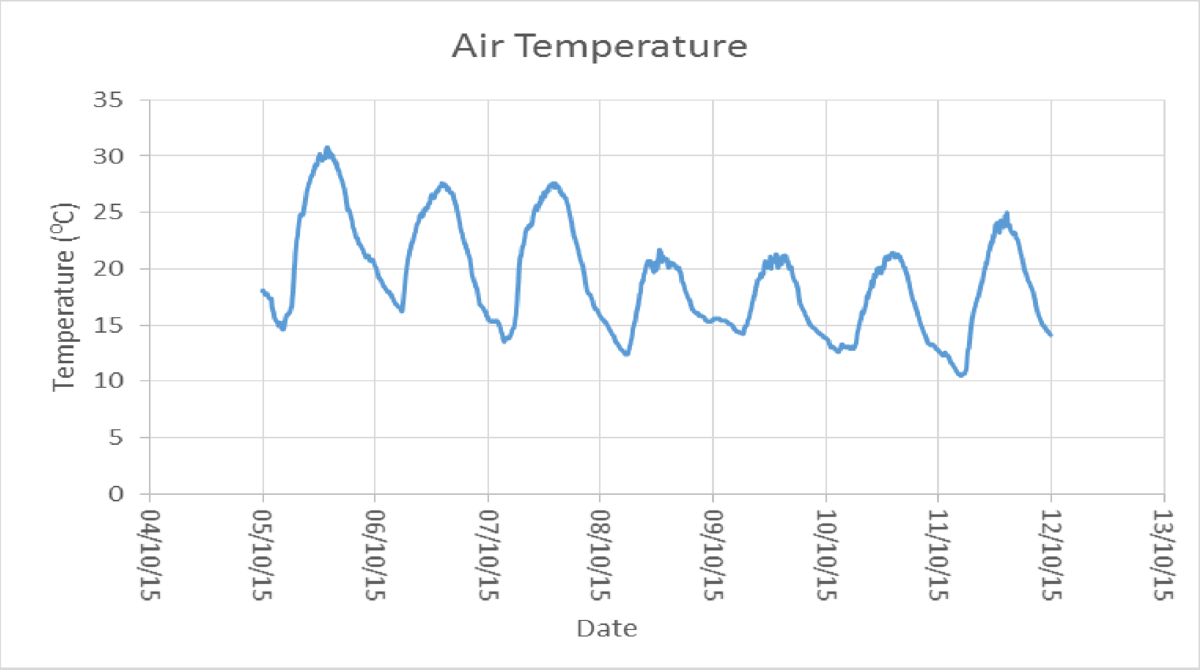


Figure 4.26: Test 3 – air temperature data for the period of 5/10/15 to 11/10/15

Average and maximum air temperature during Test 3 were; 19.1 ^{0}C and 30.8 ^{0}C respectively. No rainfall was recorded for this week.

4.5.2 Cold surface film

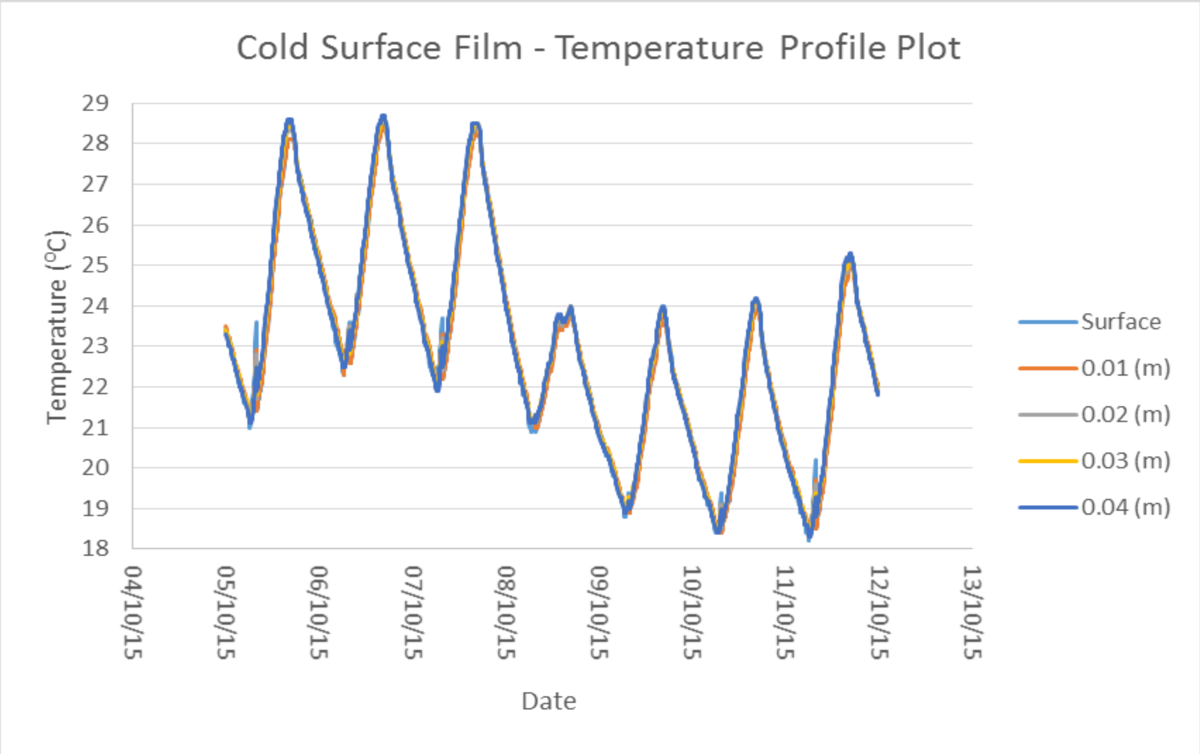


Figure 4.27: Test 3 - cold surface film temperature profile plot (Tank 1)

Two consistent trends can be identify from the temperature profile data recorded for Test 3. It is evident that there is a consistent cold surface film from Monday to Wednesday. An inconsistent cold surface film occurs on Thursday (due to a significant drop in air temperature) before levelling out late in the week. Monday Wednesday and Sunday show signs of possible bilge pump shutdown.

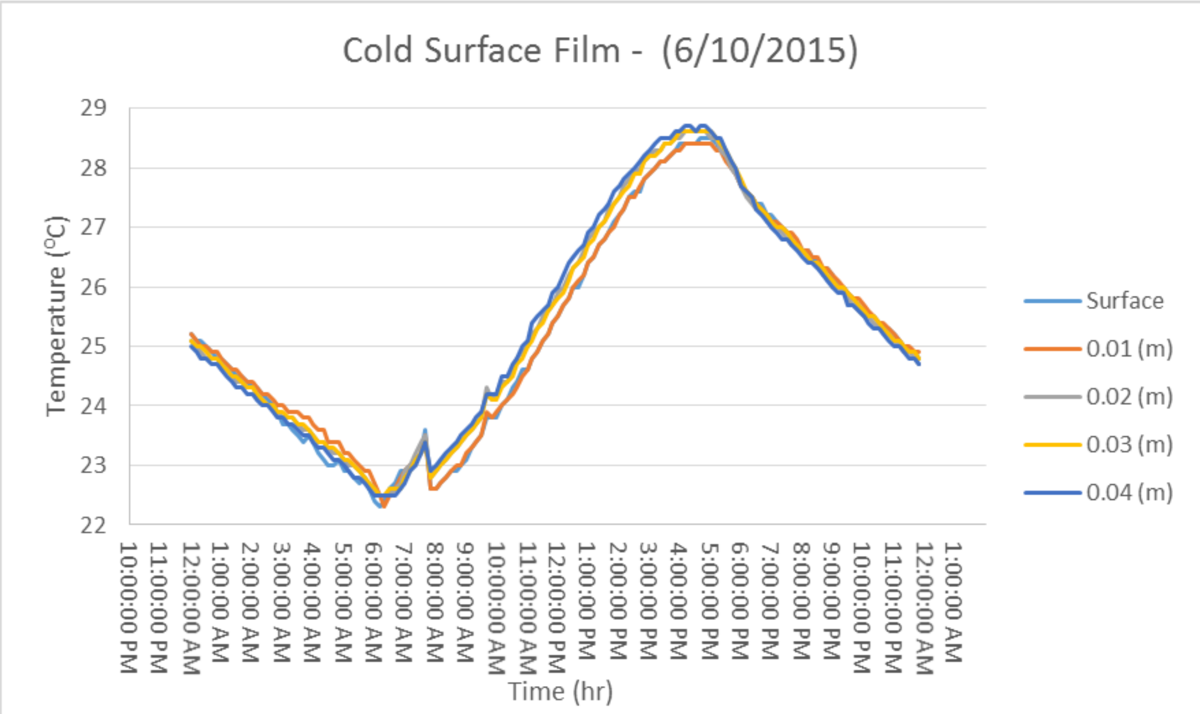


Figure 4.28: Test 3 - Temperature profile plot for consistent cold surface film in Tank 1 on 6/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

Air temperatures below 21.8^{0}C and an average wind speed throughout the day of 2.6 m/s resulted in optimum conditions for a cold surface film. Evidence of minor bilge pump shutdown can be identified by the warm surface film spike between 6:00am and 8:00am. A cold surface film has occurred between 8:00am and 5:00pm.

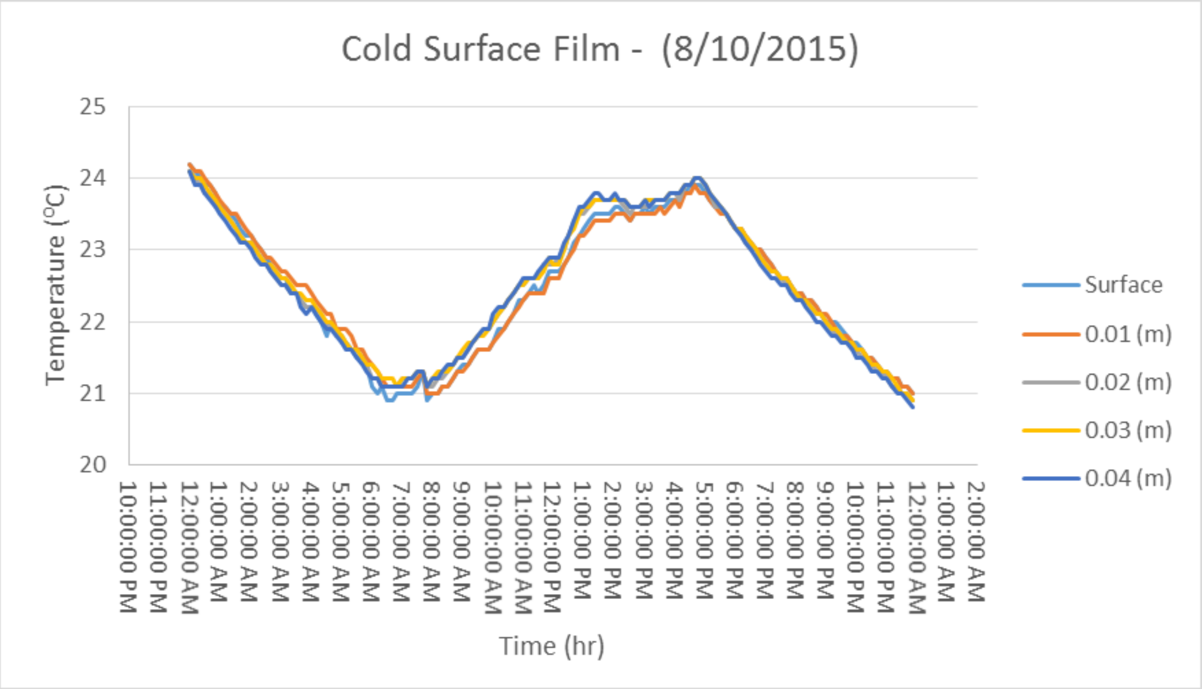


Figure 4.29: Test 3 - Temperature profile plot for disrupted cold surface film in Tank 1 on 8/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

An average daily air temperature of 17.1^{0}C and inconsistent wind speeds throughout the day has greatly influenced the cold surface film. A cold surface film is evident between 8:00am and 12:00pm. High winds speeds were recorded between 3:00pm and 5:00pm and this resulted in destabilisation of the surface film. Evidence possible overturning can be identified at approximately 5:00pm.

4.5.3 Warm surface film

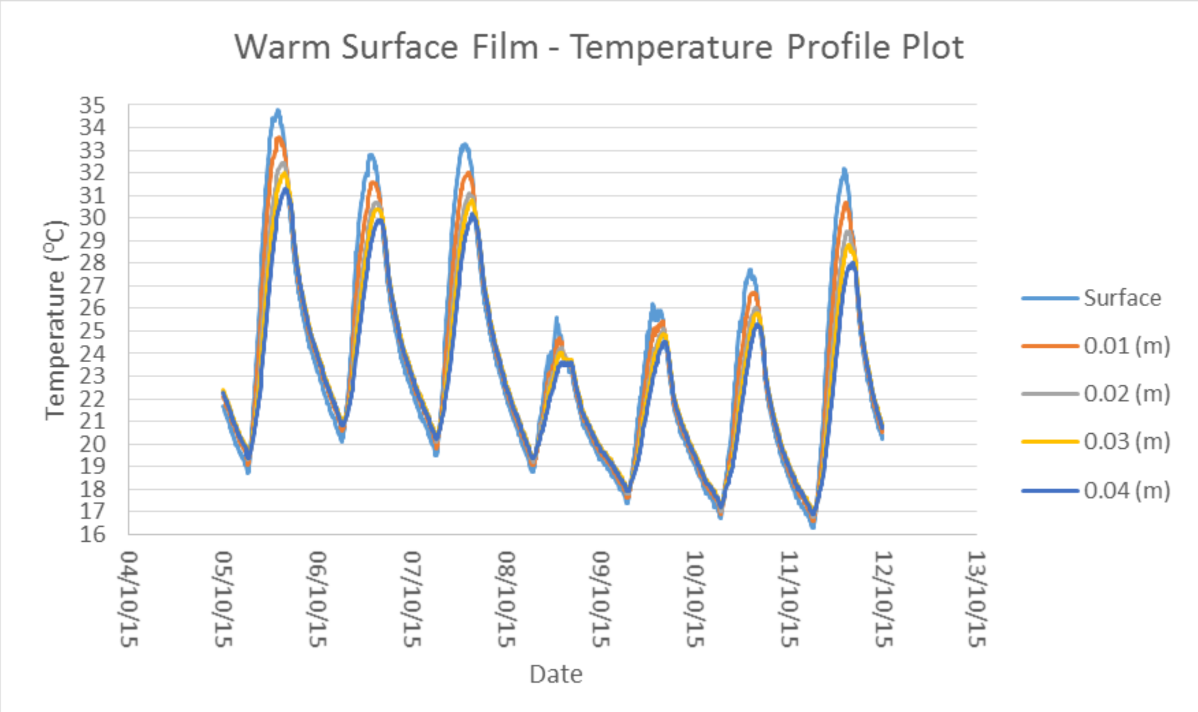


Figure 4.30: Test 3 - warm surface film temperature profile plot (Tank 2)

A consistent warm surface film was imposed early in the week. A major plummet in air temperature resulted in a disrupted warm surface film on 8th and 9th of October. Temperatures increased over the weekend and consistent warm surface films were seen again. As there was a consistent warm surface film for the majority of the week it could be assumed that the water body in tank 2 was thermally stable and thus should had promoted lower levels of evaporation than the disturbed tank. However cumulative evaporative losses from tank 2 were greater due to consistent turnover events.

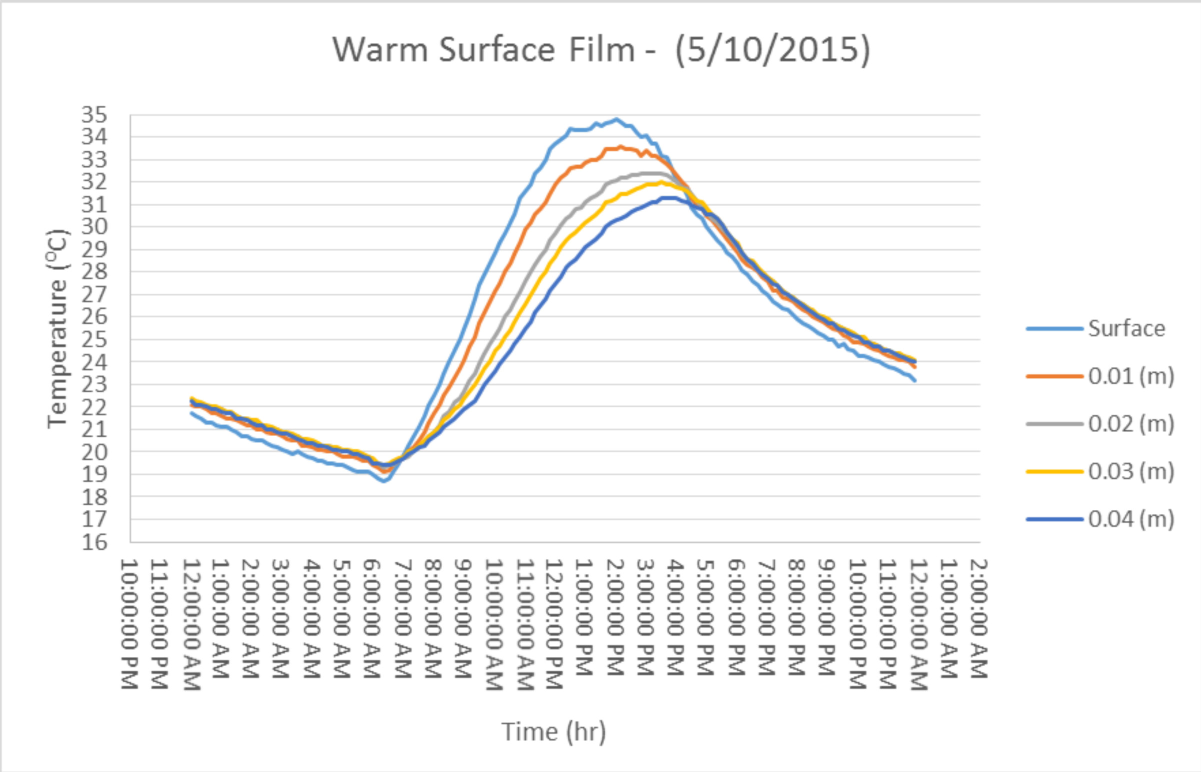


Figure 4.31: Test 3 - Temperature profile plot for consistent warm surface film in Tank 2 on 5/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

Air temperature peak around 30^{0}C on the 5th of October. The warm conditions allowed the black cover to rapidly absorbed heat and a very distinctive warm surface film was imposed. A consistent warm surface film occurred between 8:00am and 5:00pm, before another turnover event took place.

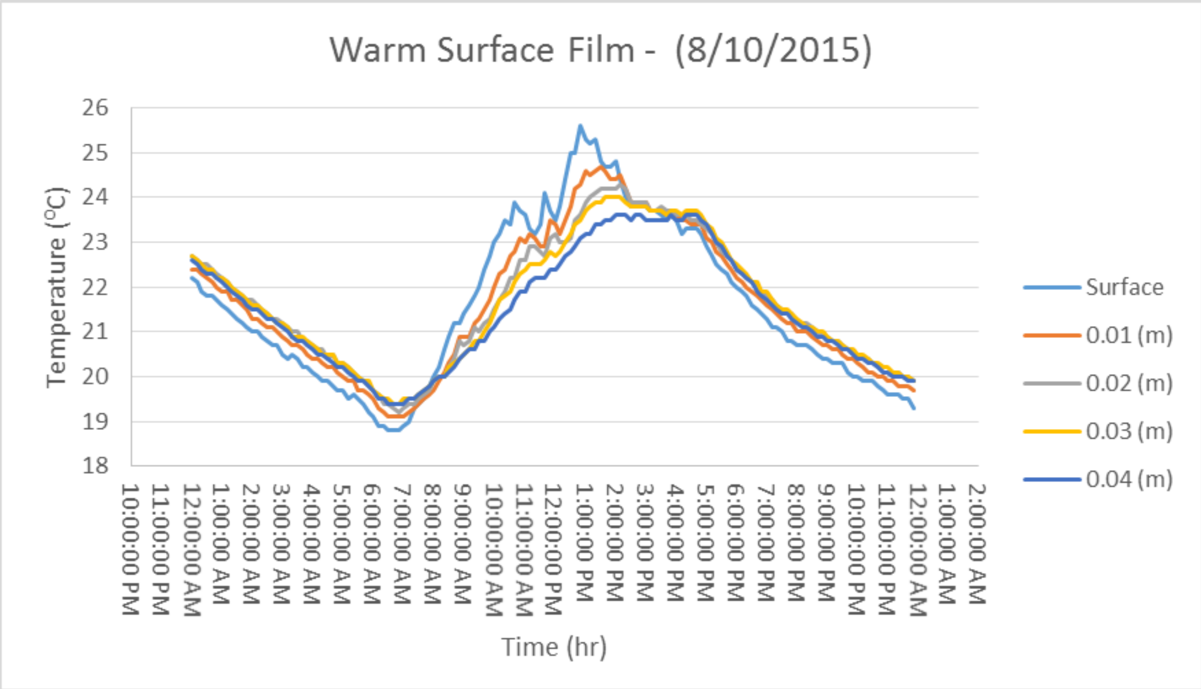


Figure 4.32: Test 3 - Temperature profile plot for disrupted warm surface film in Tank 2 on 8/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period

Thursday the 8^{th} of October was the only day during Test 3 where the warm surface film showed obvious signs of disturbance. Similarly to the cold surface film, inconsistencies developed due to a low average daily air temperature of 17.1^{0}C and inconsistent wind speeds throughout the day.

4.5.4 Tank Evaporation

Table 4.4: Test 3 - Water level measurement for two tanks were recorded twice daily using Venire Callipers. Measurements have been taken between the top edge of the ruler and the water surface.

		Water level	
Date	**Data Recording**	**Tank 1**	**Tank 2**
05/10/15	Morning Reading (9:00am)	49.00	54.00
	Afternoon Reading (5:00pm)	49.05	54.10
06/10/15	Morning Reading (9:00am)	49.06	54.25
	Afternoon Reading (5:00pm)	49.13	54.35
07/10/15	Morning Reading (9:00am)	49.18	54.49
	Afternoon Reading (5:00pm)	49.26	54.51
08/10/15	Morning Reading (9:00am)	49.29	54.63
	Afternoon Reading (5:00pm)	49.36	54.68
09/10/15	Morning Reading (9:00am)	49.41	54.76
	Afternoon Reading (5:00pm)	49.43	54.78
10/10/15	Morning Reading (9:00am)	49.46	54.86
	Afternoon Reading (5:00pm)	49.49	54.90
11/10/15	Morning Reading (9:00am)	49.53	54.91
	Afternoon Reading (5:00pm)	49.59	54.91
Total Evaporative loss in each tank		**0.59cm or 5.9mm**	**0.91cm or 9.1m**

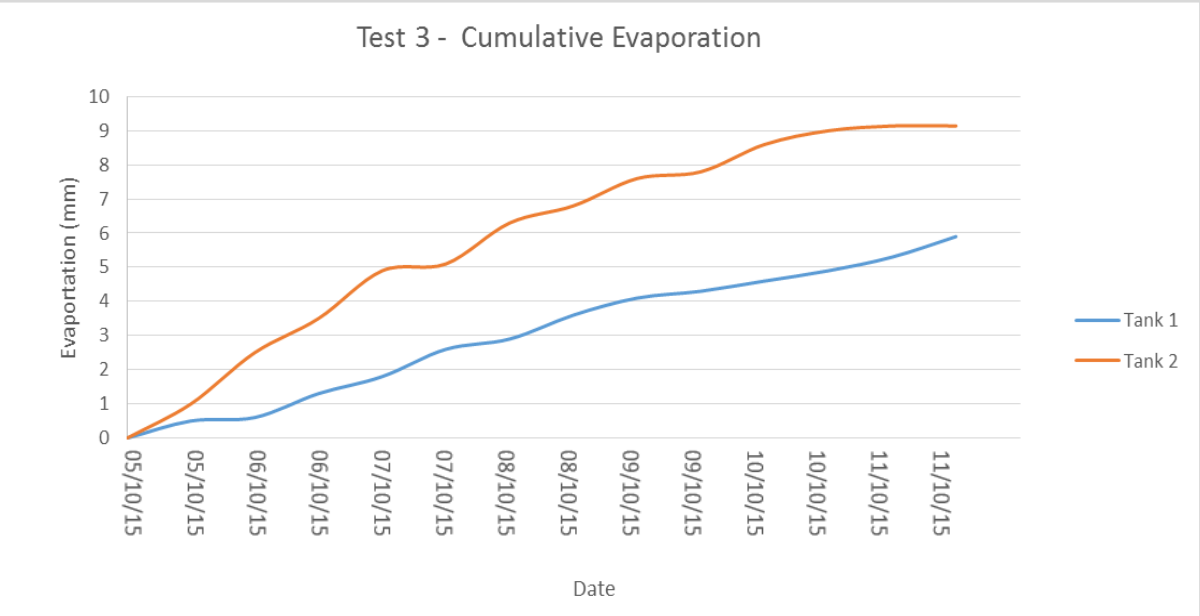


Figure 4.33: Cumulative evaporative loss recorded during Test 3. Tank 1 refers to the disturbed cold surface film. Tank 2 refers to the undisturbed warm surface film. The two increments for each day refer to the 9am and 5pm (twice daily) data collection.

4.6 Test 4 (12/10/15 - 18/10/15)

4.6.1 Weather Station Data

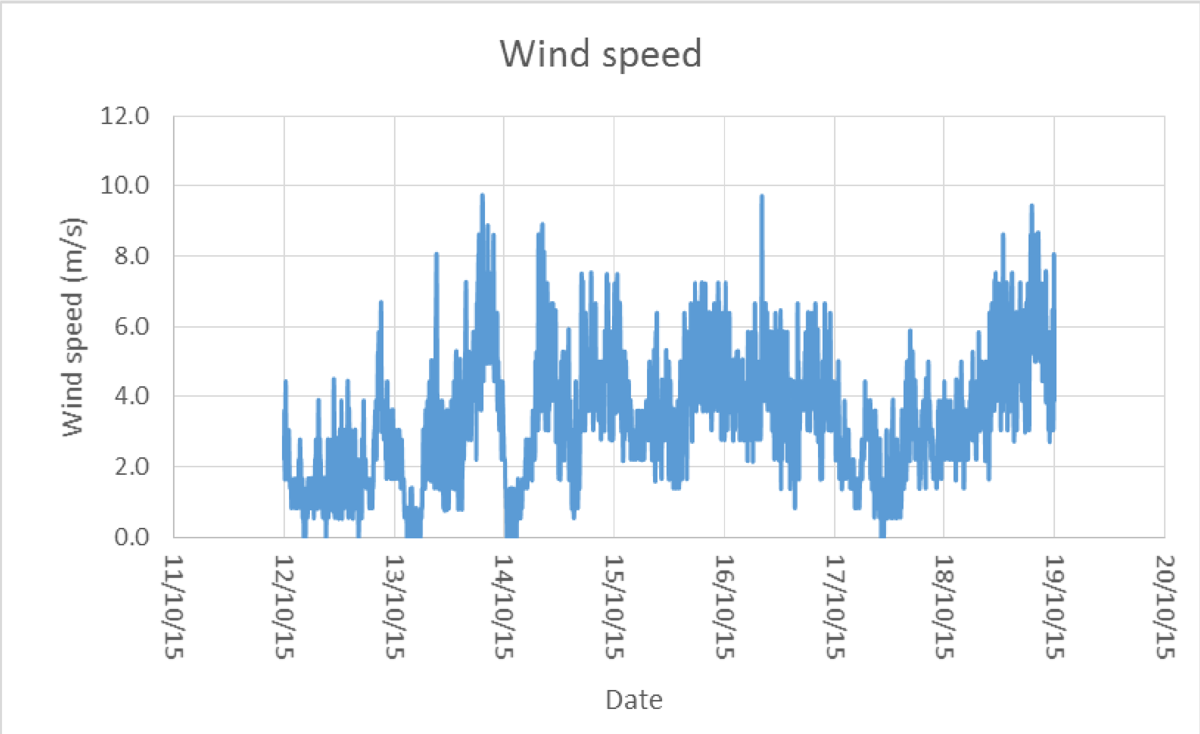


Figure 4.34: Test 4 - wind speed data for the period of 12/10/15 to 18/10/15

Average and maximum wind speed during Test 4 were; 3.4 m/s and 9.7 m/s respectively.

The above plot has been generated from 5 minute interval wind speed data. Analysing the data it was identified that there were 159 (5 minute intervals) recordings were wind speeds are greater than 6 m/s. This equates to approximately 8%% of the week being unsuitable for monolayer application.

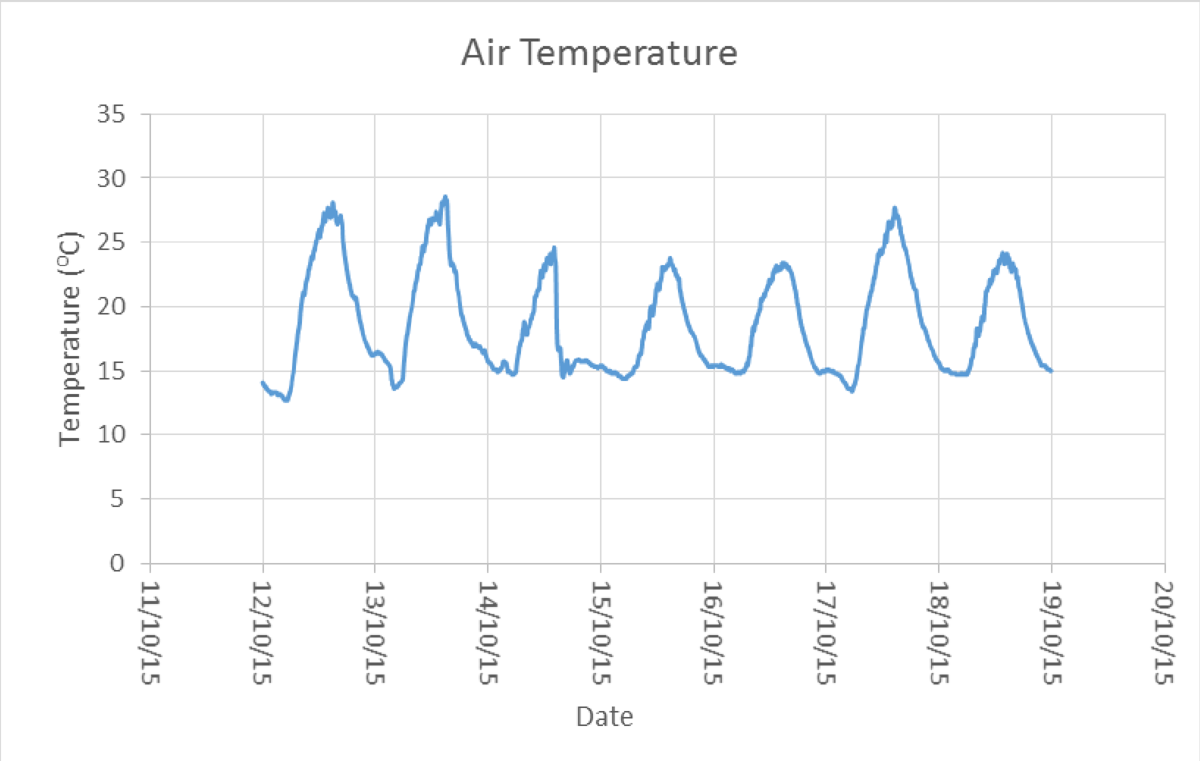


Figure 4.35: Test 4 – air temperature data for the period of 12/10/15 to 18/10/15

Average and maximum air temperature during Test 4 were; 18.7 ºC and 28.6 ºC respectively.

No rainfall was recorded during Test 4.

4.6.2 Cold surface film

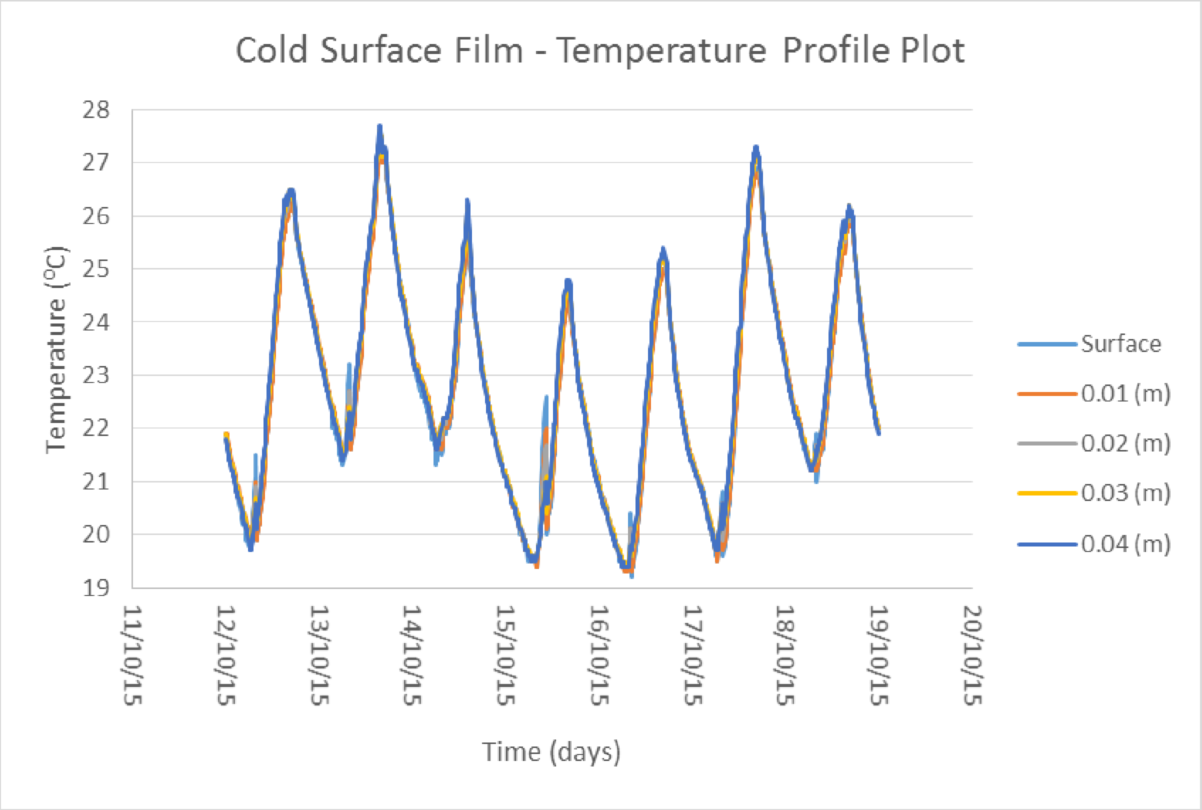


Figure 4.37: Test 4 - cold surface film temperature profile plot (Tank 1)

Significant variation in air temperature and wind speed throughout the week resulted in varying water temperature profiles. A consistent cold surface film is evident on 12th, 16th, 17th and 18th of October. A major bilge pump failure occurred on the 15th of October. Numerous minor bilge pump failures have occurred during Test 4 and therefore potential impact the accuracy of data gathered.

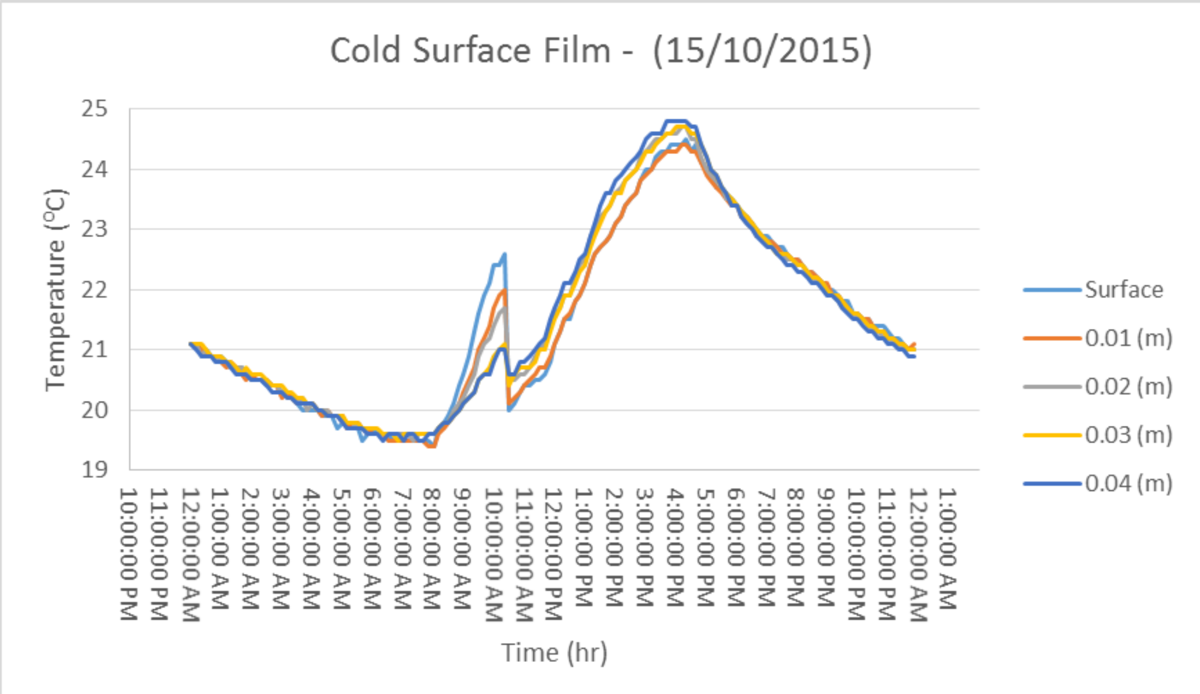


Figure 4.38: Test 4 - Temperature profile plot for disrupted cold surface film in Tank 1 on 15/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

A major bilge pump failure has resulted in quite a significant warm surface film forming. A warm surface film is evident between 8:00am and 11:00am, while the pump has been shut down. It is believed that gradual battery decline has occurred over the consecutive weeks and a moderately overcast weather conditions on the 16th of October have resulted in the failure.

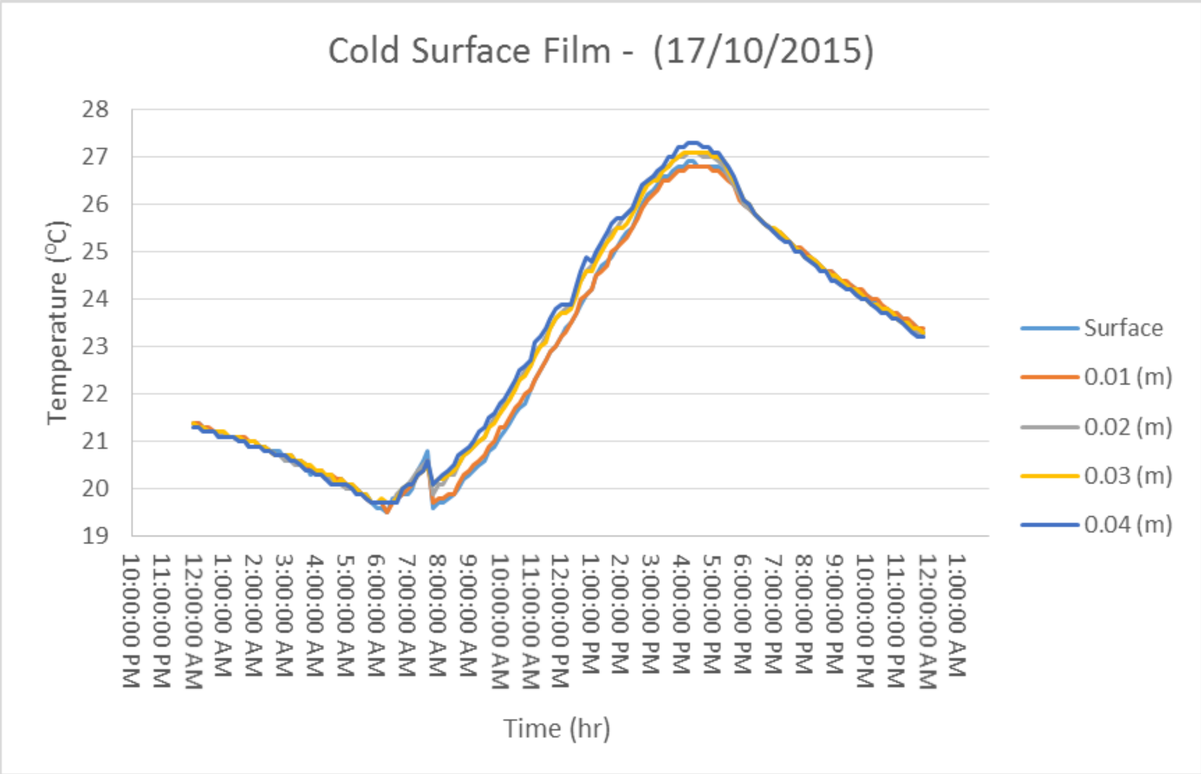


Figure 4.39: Test 4 - Temperature profile plot for consistent cold surface film in Tank 1 on 17/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

An average daily air temperature and wind speed of 19.6^{0}C and 2.4 m/s resulted in optimum cool calm conditions for a cold surface on the 17th of October. Evidence of minor bilge pump failure between 6:00am and 8:00am (Figure 4.39).

4.6.3 Warm surface film

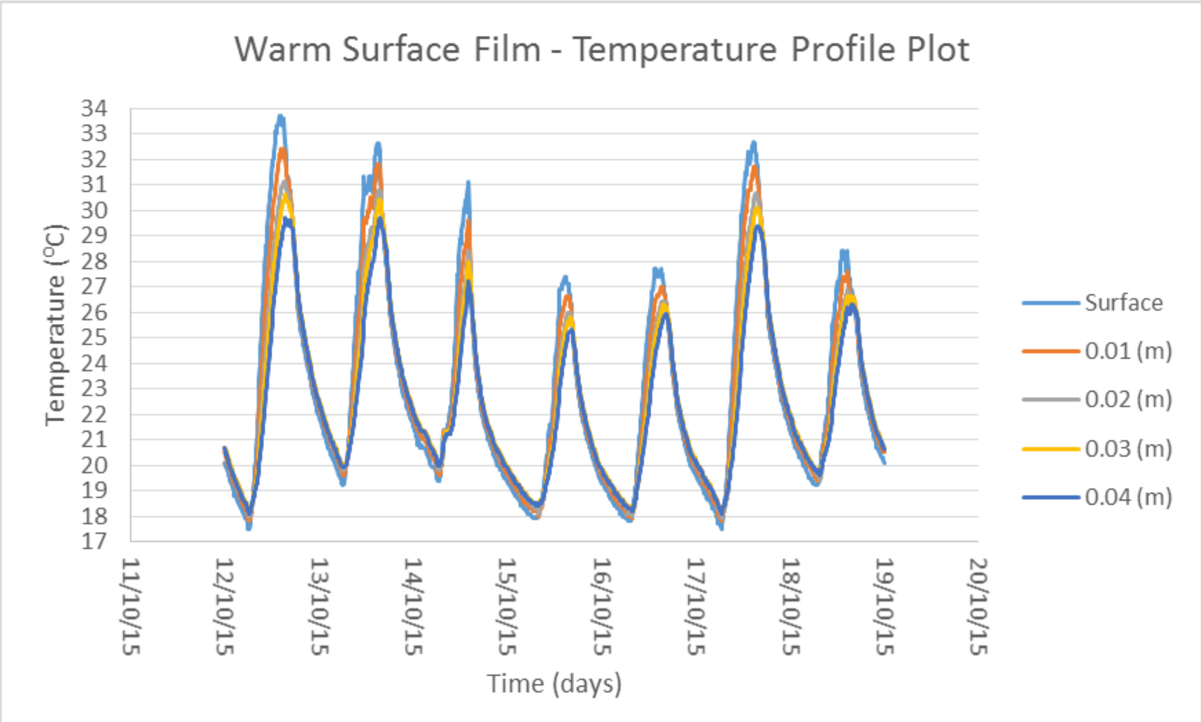


Figure 4.40: Test 4 - warm surface film temperature profile plot (Tank 2)

A noticeable warm surface film is evident on all seven days within Test 4. On the 12^{rd}, 17^{th} and 18^{th} of October a consistent warm surface film has been imposed. A moderately consistent warm surface film is evident on 14^{st} and 15^{th} of October. However an inconsistent warm surface film has occurred on 13^{th} 16^{th} of October.

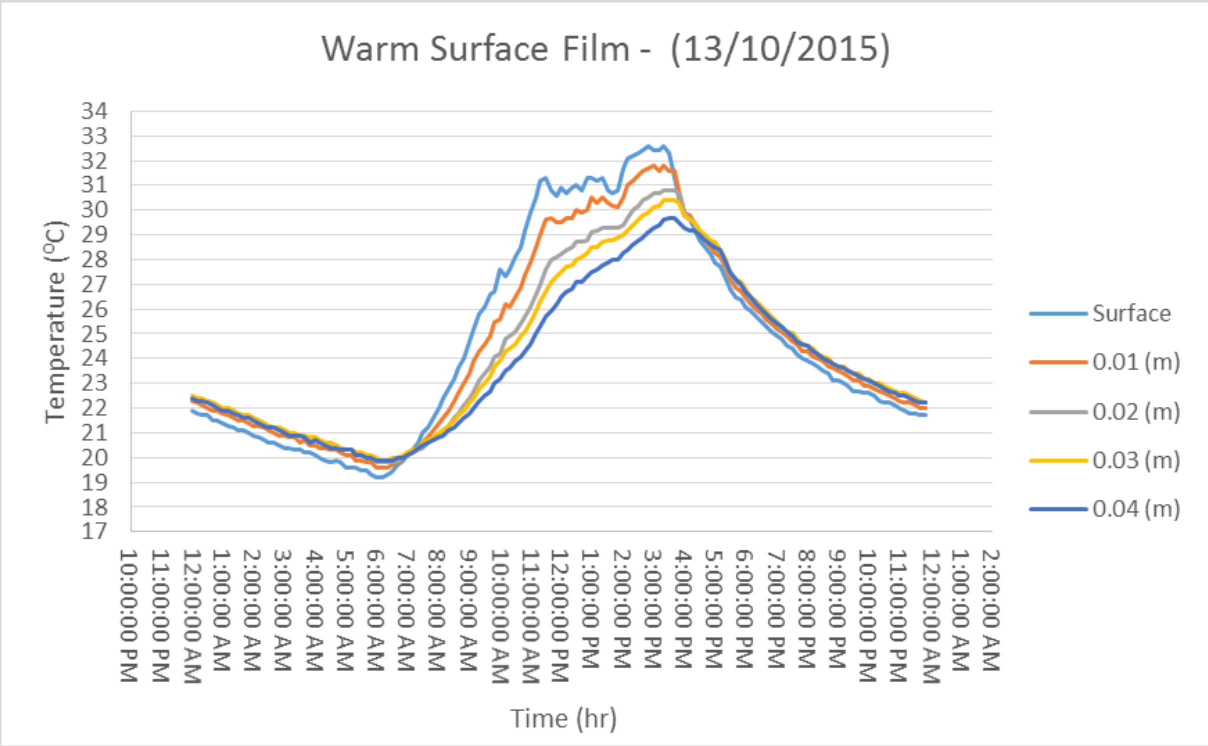


Figure 4.41: Test 4 - Temperature profile plot for disrupted warm surface film in Tank 2 on 13/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period

On the 13th of October wind speeds were light before rapidly increasing around midday. The wind speed fluctuated considerable between 11:00am and 4:00pm and the caused rapid variations in air temperature. As a result obvious cooling evident between midday and 3:00pm

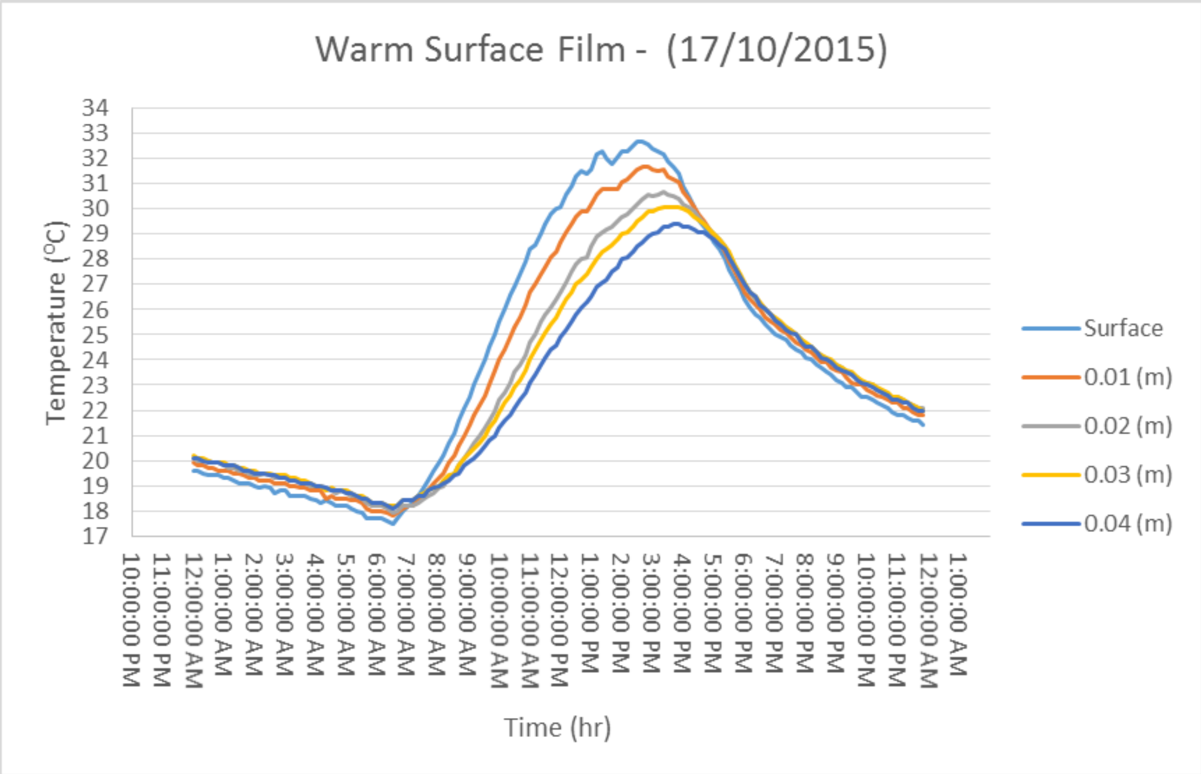


Figure 4.42: Test 4 - Temperature profile plot for consistent warm surface film in Tank 2 on 17/10/2015. Ten minute temperature profile data has been analysed over one hour increments for a twenty-four hour period.

An average daily air temperature and wind speed of 19.6^0C and 2.4 m/s resulted in the black cover impose a strong warn surface film on the 17^{th} of October. The warm surface film has been imposed from 9:00am to 5:00pm. Turnover event is evident at 5:00pm.

4.6.4 Tank Evaporation

Table 4.5: Test 3 - Water level measurement for two tanks were recorded twice daily using Venire Callipers. Measurements have been taken between the top edge of the ruler and the water surface.

		Water level	
Date	**Data Recording**	**Tank 1 (cm)**	**Tank 2 (cm)**
12/10/15	Morning Reading (9:00am)	49.00	54.00
	Afternoon Reading (5:00pm)	49.01	54.00
13/10/15	Morning Reading (9:00am)	49.01	54.01
	Afternoon Reading (5:00pm)	49.04	54.05
14/10/15	Morning Reading (9:00am)	49.09	54.17
	Afternoon Reading (5:00pm)	49.11	54.19
15/10/15	Morning Reading (9:00am)	49.19	54.34
	Afternoon Reading (5:00pm)	49.22	54.39
16/10/15	Morning Reading (9:00am)	49.28	54.60
	Afternoon Reading (5:00pm)	49.34	54.62
17/10/15	Morning Reading (9:00am)	49.42	54.76
	Afternoon Reading (5:00pm)	49.49	54.86
18/10/15	Morning Reading (9:00am)	49.56	55.01
	Afternoon Reading (5:00pm)	49.61	55.04
Total Evaporative loss in each tank		**0.61 cm or 6.1 mm**	**1.04 cm or 10.4 mm**

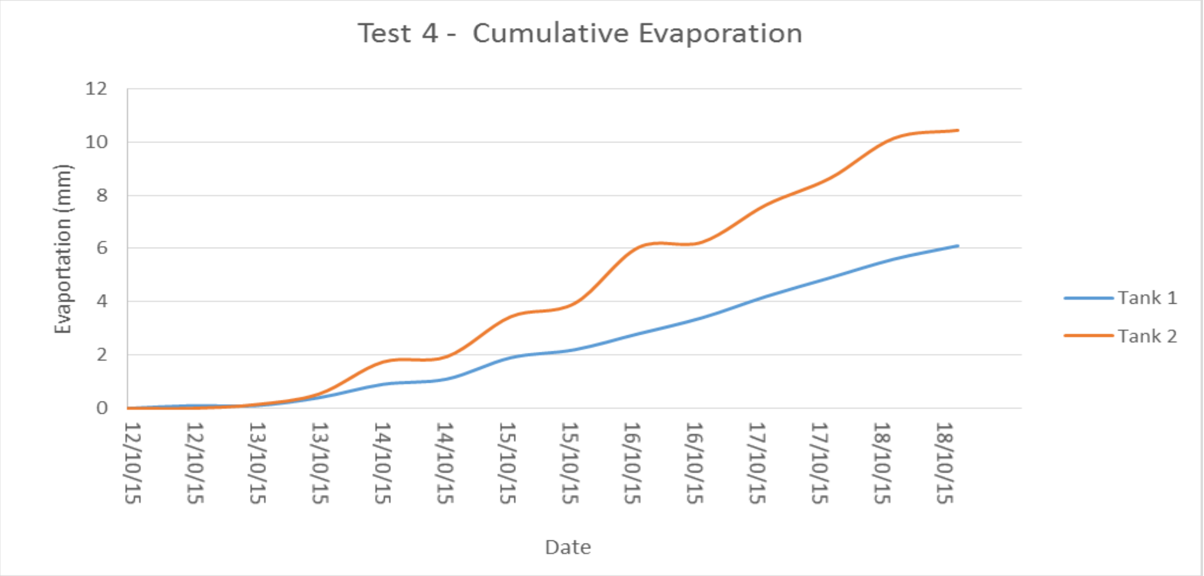


Figure 4.43: Cumulative evaporative loss recorded during Test 4. Tank 1 refers to the disturbed cold surface film. Tank 2 refers to the undisturbed warm surface film. The two increments for each day refer to the 9am and 5pm (twice daily) data collection

Chapter 5 Discussion

5.1 Testing the Accuracy of Thermocouple Probes

Minor inconsistencies were recorded between the surface thermocouple probes. It is believed that the east-west alignment may have influenced the surface thermocouple probe. Variations of 1 ^{0}C were recorded mid to late afternoon, with the tank to the west (Tank 1) recording the highest temperature. The thermocouple vessel lid did not shade the thermocouples in tank 1 from the afternoon sun. While thermocouple probes positioned in the tank 1 (green thermocouple vessel) experienced direct afternoon sun, thermocouple probes positioned in the tank 2 (blue thermocouple vessel) were shaded by the tank wall and vessel lid. To overcome temperature inconsistences experienced at the surface thermocouple probe and north-west tank alignment is recommended.

Figure 5.1: East-west tank alignment

5.2 Evaporative loss without covers

It was important to understand the evaporative capacity of the tanks prior to implementing the black plastic covers. Difficulties were experienced when measuring the water level, due to the disturbance caused by wind and water meniscus. A magnifying glass was used to improve the accuracy of measurements. This test highlighted that not only was the cover important for artificially imposing a warm surface film. It would also greatly reduce the impact of when and therefore allowing more accurate data to be recorded. This test also highlighted that a more accurate method for measuring water levels was necessary and this is why Vernier Callipers (digital) were used in later tests.

5.3 Artificially imposing a surface film

The use of black covers to artificially impose a warm surface film was extremely effective. The addition of a bilge pump within tank 1 caused the necessary convection of the water needed to impose a consistent cold surface film. On average across the four test conducted the results indicated that a consistent warm and cold surface film was imposed between 8:00am to 5:00pm daily. Due to the high levels of heat the black covers were able to absorbed, the warm surface film produced was extremely more pronounced compared to the cold surface film. The cold surface film was most consistent and recognisable between 9:00am and 11:00am prior to when the warm surface film was most obvious around 12:00pm to 2:00pm (typically the warmest period of the day). On numerous occasions tests showed how rainfall, changes in air temperature and wind speed can significantly distorted the surface film. Even though the covers prevented rainfall from entering the tanks temperature profiles experienced rapidly cooling. The warm surface film imposed was largely affected by the occurrence of 'turnover' event. Inconsistences were also evident in the cold surface film and it is believed that they were the direct results insufficient power supply.

5.4 Turnover Events

A turnover event was noticed daily within tank 2 (warm surface film). The red circle marked on the below figure highlights a turnover event occurring at roughly 5:30pm on the 4th of October. Turnover events are commonly associated with water bodies of large depths, such as dams and lakes. Shallowed lakes experience very little lake turnover and it was understandably not expected to occur within a small water trough.

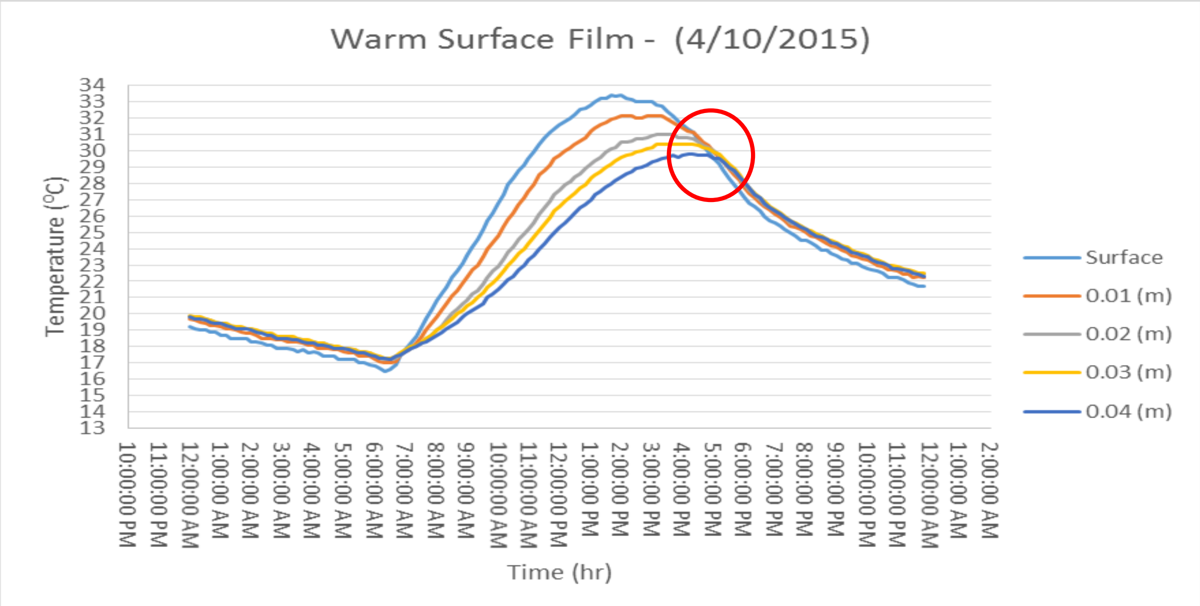


Figure 5.2: Turnover event removed the warm surface film imposed on tank 2

A turnover event in a lake or dam occurs when the top layer, epilimnion, turns over to the bottom, hypolimnion (Figure 5.3). The warm surface film imposed in tank 2 meant that less dense water was at the surface and more dense water was nearer to the bottom. It is believed that an imbalance of pressures beneath the cover has occurred late in the afternoon. As the air temperature declined the density of the surface water has begun to increase. The sinking action and mixing of the water promoted by wind entering beneath the cover had resulted in the exchange of surface and bottom waters which is called "turnover." A limitation of this research was not being able to measure the air temperature beneath the cover. Under ideal conditions a sixth thermocouple would have been installed in each tank to monitor the air temperature. The data logger used support ten channels, therefore it was not possible to record air temperature. A possible solution may involve scarifying one thermocouple (in each tank). Using four thermocouples to monitor the surface film would reduce accuracy of temperature profile data.

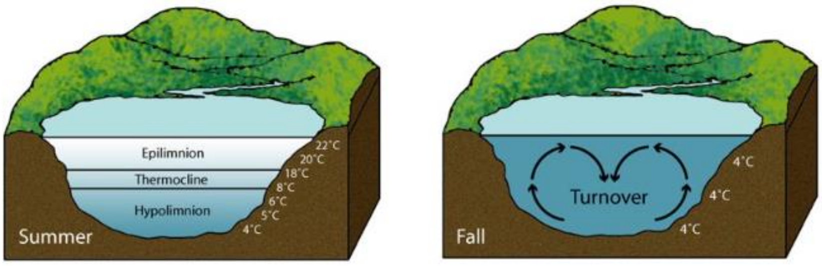


Figure 5.3: The process of a turnover events (Geographic, National, 2015)

5.5 Bilge Pump Failure

Common spikes or errors in temperature profile date have been identified within numerous plots. The spikes involve a warm surface film forming in the disturbed tank. The warm surface film has been linked to failure of the bilge pump. The battery controller monitoring the power supply system was automated to switch off the bilge pump to prevent possible damage (over draining) of the batteries. The controller was programmed to automatically shut down the bilge pump if the bulk battery power fell below 11.5 volts and switch back when power supply reaches 12.5 volts. Thorough analysis of weather station data revealed that overcast conditions caused the solar panels to inadequately charge the batteries during the day.

Figure 5.4 illustrates evidence of a minor pump failure. This plot taken from test 1 highlights that the pump has shut down for a short time period, most like one or two hours. Therefore it can be assumed that the shutdown has not impacted the cold surface film and shouldn't influence changes to evaporative loss in the disturbed tank.

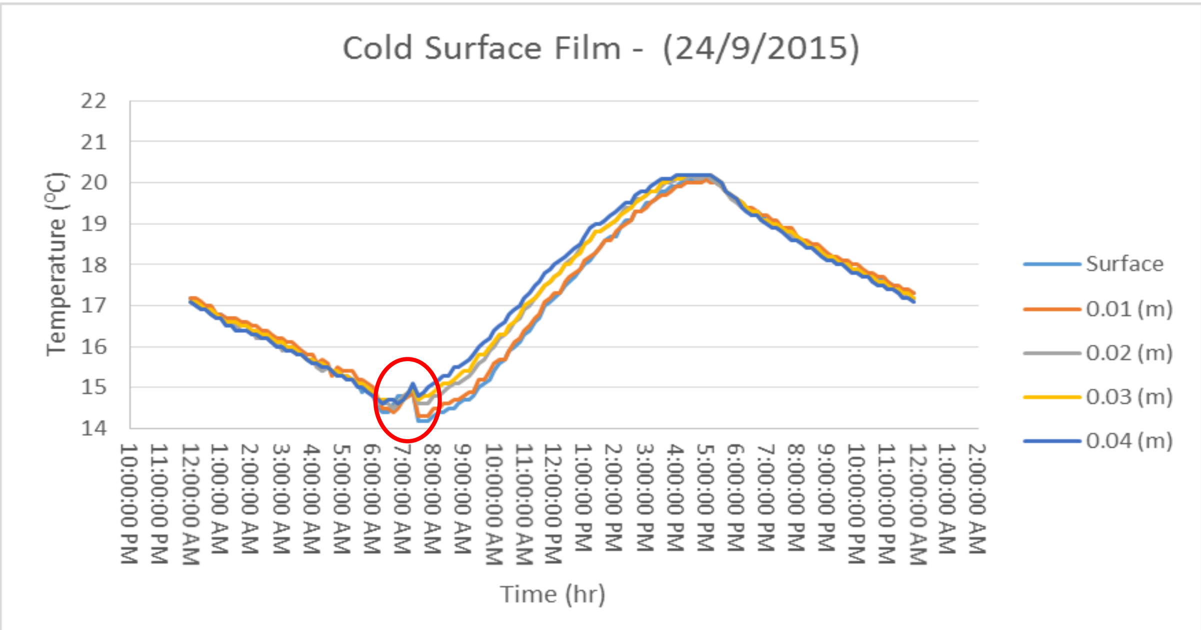


Figure 5.4: Minor bilge pump failure

A combination of several day’s overcast weather conditions and gradual power loss (system operated continuously over 4 weeks) resulted in significant bilge pump failure. This occurred on the 15th of October during Test 4. The shutdown of the bilge pump caused a prominent warm surface film to form in the disturbed tank. Many spikes in temperature profile data were identified during Test 4 and therefore the results gathered from this test have been assumed inaccurate.

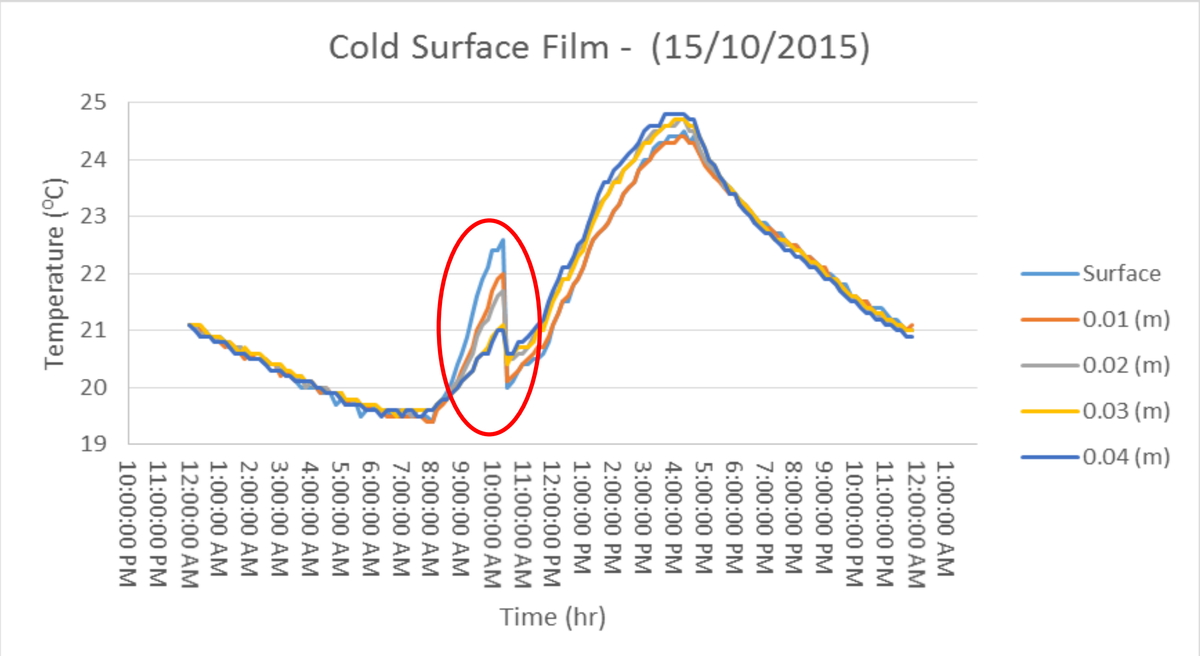


Figure 5.5: Significant failure of the bilge pump

5.6 Analysing Evaporative Losses

Analysing the evaporative loss in the tanks indicates that results do not support the research hypotheses. It was predicted that the resistance imposed by a thermally stable warm surface film would encourage lower rates of evaporative loss. The covers were effective at artificially imposing the warm surface film. However the covers greatly restricted evaporation and therefore it is difficult to compare rates of evaporation respective to a warm and cold surface film. While rates of evaporative loss were very similar between the two tanks, it was the undisturbed tank (Tank 2) which recorded consistently higher rates of evaporation (Table 5.1). The turnover event is believed to be the main reason why high levels of evaporation were recorded in tank 2 (warn surface film). Rainfall fall was recorded during Test 1 and Test 2 and therefore cumulative evaporation was lower during these weeks. However similar weather conditions were experienced during Test 3 and Test 4 and similar measurements were recorded between the two tanks. The similarity of results highlights that using Vernier callipers (digital) increased the accuracy of water levels measurements.

Table 5.1: Summary of cumulative evaporation loss in Tank 1 and Tank 2.

Test	Tank 1	Tank 2
No covers	35mm	34mm
1	2.9mm	4.0mm
2	3.0mm	4.4mm
3	5.9mm	9.1mm
4	6.1mm	10.4mm

5.7 Research Outcomes

This project aims to outline optimum period for monolayer application. Monolayers are most effective when wind speed are less than 6 m/s. The wind speed data has been critically analysed and optimum time periods for monolayer application have been identified. The wind speed data for Test 1 indicted that there were 43 (5 minute interval) recordings were wind speeds were greater than 6 m/s. This equates to roughly 2% of the week being unsuitable for monolayer application. Based on this week alone monolayer product would have been most effective if applied on Wednesday (23/9/15). Overall the low wind speeds recorded during Test 1 promoted suitable condition for monolayer application. Test 2 recorded the most favourable weather conditions, only 24 (5 minute interval) recording identified were wind speed may have affect the performance of a monolayer. Test 3 recorded the most unfavourable conditions for monolayer. During this week there were 235 (5 minute interval) recordings were wind speeds were greater than 6 m/s. Of the 235 wind speeds, 92% were recorded between Wednesday (7/10/15) and Friday (9/10/15). In practice to maximise the performance of a monolayer, application should have been avoided over these three days. Test 4 also recorded unfavourable condition for monolayer application. There were 159 (5 minute interval) recordings, thus for 8% of this week conditions were unfavourable. This analysis of wind speed data illustrates that in order for a monolayer to have the greatest resistance against evaporation, autonomous application systems need to be automated to disperse monolayer under ideal weather conditions.

Thorough analysis of the water level measurements indicates that slightly higher evaporation took place during the night when the cold surface film was imposed (following turnover event). On average the warm surface film occurred between 9:00am and 5:00pm, with a turnover occurring at roughly 5:00pm daily. Therefore the cold surface film imposed by the turnover event was active on the water surface for ten hours longer than the warm surface film. The artificially imposed warn surface film was outweighed by the cold surface film imposed by the turnover event and this lead to greater levels of evaporation from the undisturbed tank (tank 2). Based on these results in order to improve the performance of chemical covers autonomous application system should to be programed to apply monolayer overnight. This is aimed at reducing the evaporation which occurs due to the cold surface film produced by turnover events. This research highlight that turnover events are not restricted to deep lakes and dams and therefore may have a greater influence upon rates of evaporation form on farm storage facilities than original expected.

Chapter 6 Conclusion

The overall aim was to conduct a series of field trials to understand the natural resistance to evaporation loss imposed by a thermally stable warm surface film. The hypothesis was that the resistance of a thermally stable warm surface film may exceed the resistance imposed by an artificial monolayer. It was therefore hypothesised that a cold surface film would cause higher rates of evaporation, compared to a thermally stable warm surface film. Field trails revealed that while similar rates of evaporation occurred between the two test tanks. Slightly higher rates of evaporative loss took place within the tank with a warm surface film, disagreeing with the predicted hypothesis.

The use of black plastic covers to artificially impose a warm surface film were extremely effective. The cover significantly increased the temperature of the surface film within the undisturbed tank (tank 2). Under optimum clam dry conditions the cover was able to develop a consistent warm surface film within tank 2. On average across the four tests conducted a warm surface film occurred between 9:00am and 5:00pm. During mid to early afternoon up to a 6^0C temperature difference was notice between that surface thermocouple and the thermocouple 40 millimetres below. The resistance of a thermally stable warm surface film encouraged high level of stratification during the day.

The bilge pump work practically well and produced the disturbance needed to mix the water within tank 1 and create a consistent cold surface film. Due to the intensity of the warm surface film during the middle of the day it was surprising how effect the addition of the bilge pump was at overcoming the warm surface film created by the black cover. The cold surface film imposed was not as obvious as the warm surface film, however this trend has been supported by research conducted within the Chapter 2 – Literature Review. The cold surface film occurred between a similar time-period as the warm surface film, with common trends identifiable. However the temperature profile of the cold surface film was considerable finer.

The results and discussion chapters highlight that an unexpected ‘turnover’ event occurred within the undisturbed tank. It is believed that the hole cut in the centre of the covers (to allow evaporation to take place) allowed a small amount of wind to enter the tank causing the destabilisation and the subsequent turnover event. The turnover event resulted in the warm surface film inverting to a cold surface film. The cold surface film caused by the turnover event displayed a temperature profile cooler than the cold surface film imposed by the disturbed tank. The turnover event actually resulted in a cold surface film being imposed for a longer duration than the artificially imposed warm surface film. Therefore the resistance imposed by the warm surface film was outweighed by the turnover event and the cold surface film which followed encouraged the evaporative process. It is believed that this is why higher rates of evaporation were being recorded in the undisturbed tank where the warm surface film had originally been imposed. Cumulative evaporation plots suggest that the overturning caused minor increases in evaporation rates overnight. This evaporation was recorded between the 5:00pm and 9:00am water level measurements.

The design and accuracy of the test system was evident in its ability to accurately monitor temperature profiles and identify the presents of a turnover event. The 10 millimetre spacing of the thermocouple probes critically analysed the air/water interface exposing the presents of both a warm and cold surface film in the tanks. Consistent trends in temperature profile data collected demonstrates that the thermocouple vessel developed was successful in maintaining a constant position on the surface as evaporation and precipitation caused the water level to change. Despite have a suitable test setup, a turnover event caused a cold surface film to outweigh the impacts of the artificially imposed warm surface film.

It has previously be identified that an autonomous application system is necessary for the systematic application of a chemical monolayer. A chemical monolayer is most effective during dry clam (not absolutely calm) conditions when wind speeds range between 3m/s and 6m/s. This research suggests that a chemical monolayer should also be applied when a cold surface film is evident. Based on the results gathered in order to improve the performance of chemical covers autonomous application system should to be programed to apply monolayer overnight. This is aimed at reducing the evaporation which occurs due to the cold surface film produced by turnover events.

6.1 Recommendation for Future Work

6.1.1 Power supply limitations

A limitation of the current test setup was the power supply system. A combination of overcast weather conditions and reduced sunlight led to inconsistences in power supply and resulted in equipment failure. On three consecutive days within the forth tested conducted, anomalies were identified in the temperature profile data. After analysing the USQ weather station data it was recognized that overcast conditions caused the bilge pump to stop operating due to insufficient power supply. If this field trials were to be undertaken again a recommendation would be to incorporate a third 250 watt solar panel or alternatively a forth 12 volt battery in series. This would ensure that the power supply system would be capable of supporting both the data logger and the bilge pump, if consecutive days of overcast weather were encountered.

Weather forecasting is a further recommendation for resolving issues surrounding the power supply system. Identification of time periods with optimum weather conditions would ensure that the current system performs effectively. The weather conditions experienced during the during first three temperature profile tests proved that the current system is capable of supply necessary rates of power when ideal weather conditions are experienced.

6.1.2 Tank Alignment

The test undertaken to confirm that the thermocouples in the two tanks were measuring similar temperature profiles highlighted minor inconsistence with the thermocouple positioned at the surface. The minor inconsistences have been connected with the east-west alignment of the water troughs. If tests were to be conducted again a north-south tank alignment would be applied. A north-west alignment may result in both thermocouple vessel receiving more even sunlight exposure, potential addressing the minor inconsistencies identify in the temperature profile of the surface thermocouple.

6.1.3 Dealing with Turnover Events

Due to research limitation field trials were not able to record the air temperature beneath the black covers. Because the air temperature was not recorded it cannot accurately identified what caused the turnover event. The pressure difference under the cover has potential resulted in an unbalance of forces acting on the surface water and a small gust of wind has most likely caused the overturn event to occur. In order to overcome the turnover event the black covers would need to be removed. If the black cover are removed new methods for artificially imposing a warm and cold surface film will need to be explored. A recommendation for future work may involve implementing the same field trailing undertaken within this research project in a glass house environment. At the Experimental Station of the University of Cartagena in south-eastern Spain similar tests have been conducted using two standard class-A evaporation pans. The investigation saw trials conducted in a “glass-covered, double continuous roof-vented greenhouse” (Gallego-Elvira, et al., 2013). Interestingly this trail was also carried out adopting a north-south tank orientation, supporting future recommendation stated.

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Appendices

Appendix A – Project Specifications

University of Southern Queensland
FACULTY OF ENGINEERING AND SURVEYING
ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: JONATHON MASKALL
TOPIC: EXPLORATION OF EVAPORATION MITIGATION MEASUREMENT TECHNIQUES
SUPERVISOR: Joseph Foley and Pam Pittaway
PROJECT AIM: The overall aim is to conduct a series of field trials to understand the natural resistance to evaporation loss imposed by a thermally stable warm surface film. The hypothesis is that the resistance of a thermally stable warm surface film may exceed the resistance imposed by an artificial monolayer.

PROGRAMME: Issue D, 20th October 2015

1. Research background information relating to current methods of evaporation mitigation for on farm water storage facilities.
2. Restore and modify water troughs at the Evaporation Research Facility based at NCEA, USQ to operational standard for water temperature profile analysis and measurement of evaporative loss.
3. Developing a floating vessel to protect thermocouples, with the upper thermocouple consistently floating at the water surface.
4. Confirm that the sensors in the two tanks were are measuring similar temperature profiles.
5. Analyse field data collected for temperature profiles at 10 minute intervals and evaporative loss at twice daily intervals.
6. Develop methods for artificially imposing a warm and cold surface film on two tanks.
7. Utilise on-site weather station data to identify periods where monolayer application will be most effective.
8. Monitor the difference in rates of evaporation from tanks with a warm and cold surface film.
9. Report findings via an appropriate academic dissertation.

AGREED:

____________ (Student) ____________ (Supervisor)
Date: __ / __ / __ Date: __ / __ / __

Appendix B – Sample of Temperature Profile Data

		Tank 1					Tank 2				
		NCEA Side (eventual cold surface film)					wagners side(eventual warm surface film)				
		CH6	CH7	CH8	CH9	CH10	CH1	CH2	CH3	CH4	CH5
		degC	degC	degC	degC	degC	degC	degC	degC	degC	degC
Sample Number	Date&Time	**Surface**	**0.01**	**0.02**	**0.03**	**0.04**	**Surface**	**0.01**	**0.02**	**0.03**	**0.04**
1	21/9/2015 0:00	**16.4**	16.4	16.4	16.4	16.3	**15.3**	15.6	15.7	15.8	15.7
2	21/9/2015 0:10	**16.4**	16.3	16.3	16.3	16.2	**15.2**	15.5	15.7	15.7	15.6
3	21/9/2015 0:20	**16.3**	16.3	16.3	16.3	16.2	**15.1**	15.4	15.6	15.7	15.6
4	21/9/2015 0:30	**16.3**	16.3	16.2	16.2	16.1	**15.1**	15.4	15.5	15.6	15.5
5	21/9/2015 0:40	**16.2**	16.2	16.2	16.2	16.1	**15**	15.3	15.5	15.6	15.5
6	21/9/2015 0:50	**16.2**	16.2	16.1	16.2	16	**15**	15.3	15.5	15.5	15.4
7	21/9/2015 1:00	**16.1**	16.1	16.1	16.1	16	**14.9**	15.2	15.4	15.4	15.3
8	21/9/2015 1:10	**16.2**	16.1	16	16.1	15.9	**14.9**	15.2	15.4	15.4	15.3
9	21/9/2015 1:20	**16.1**	16	16	16	15.9	**14.8**	15.1	15.3	15.4	15.3
10	21/9/2015 1:30	**16.1**	16	16	16	15.9	**14.8**	15	15.3	15.4	15.2
11	21/9/2015 1:40	**16**	16	15.9	16	15.9	**14.8**	15	15.2	15.3	15.2
12	21/9/2015 1:50	**16**	16	15.9	15.9	15.8	**14.7**	15	15.1	15.2	15.1
13	21/9/2015 2:00	**15.9**	15.9	15.9	15.9	15.8	**14.7**	14.9	15.1	15.2	15.1
14	21/9/2015 2:10	**15.9**	15.9	15.8	15.8	15.8	**14.6**	14.8	15.1	15.1	15
15	21/9/2015 2:20	**15.9**	15.8	15.8	15.8	15.7	**14.6**	14.8	15	15.1	14.9
16	21/9/2015 2:30	**15.8**	15.8	15.7	15.7	15.7	**14.5**	14.8	15	15	14.9
17	21/9/2015 2:40	**15.8**	15.7	15.7	15.7	15.6	**14.5**	14.8	14.9	15	14.9
18	21/9/2015 2:50	**15.7**	15.7	15.6	15.7	15.5	**14.3**	14.6	14.9	14.9	14.8
19	21/9/2015 3:00	**15.7**	15.7	15.6	15.6	15.5	**14.4**	14.6	14.8	14.9	14.8
20	21/9/2015 3:10	**15.6**	15.6	15.6	15.6	15.5	**14.3**	14.6	14.8	14.9	14.7
21	21/9/2015 3:20	**15.6**	15.6	15.5	15.5	15.4	**14.3**	14.5	14.8	14.8	14.7
22	21/9/2015 3:30	**15.5**	15.5	15.5	15.5	15.4	**14.3**	14.5	14.7	14.7	14.6
23	21/9/2015 3:40	**15.5**	15.5	15.4	15.4	15.4	**14.2**	14.5	14.7	14.7	14.6
24	21/9/2015 3:50	**15.5**	15.5	15.4	15.4	15.3	**14.2**	14.4	14.6	14.7	14.6
25	21/9/2015 4:00	**15.4**	15.4	15.4	15.4	15.3	**14.1**	14.4	14.6	14.6	14.5
26	21/9/2015 4:10	**15.4**	15.4	15.3	15.3	15.2	**14.1**	14.3	14.5	14.6	14.5
27	21/9/2015 4:20	**15.4**	15.3	15.3	15.3	15.2	**14.1**	14.3	14.4	14.5	14.4
28	21/9/2015 4:30	**15.4**	15.3	15.2	15.3	15.2	**14**	14.2	14.4	14.4	14.4
29	21/9/2015 4:40	**15.3**	15.3	15.2	15.2	15.2	**13.9**	14.2	14.4	14.5	14.4
30	21/9/2015 4:50	**15.3**	15.2	15.2	15.2	15.1	**13.9**	14.1	14.3	14.4	14.3
31	21/9/2015 5:00	**15.2**	15.2	15.1	15.2	15.1	**13.8**	14.1	14.3	14.4	14.2
32	21/9/2015 5:10	**15.2**	15.2	15.1	15.1	15	**13.8**	14.1	14.3	14.4	14.2
33	21/9/2015 5:20	**15.1**	15.1	15.1	15.1	15	**13.8**	14.1	14.2	14.3	14.1
34	21/9/2015 5:30	**15.1**	15.1	15	15	15	**13.8**	14.1	14.2	14.3	14.2
35	21/9/2015 5:40	**15.1**	15.1	15	15	14.9	**13.7**	14	14.1	14.3	14.1
36	21/9/2015 5:50	**15.1**	15	15	15	14.9	**13.7**	14	14.1	14.2	14.1
37	21/9/2015 6:00	**15.1**	15	15	15	14.9	**13.7**	13.9	14.1	14.2	14.1
38	21/9/2015 6:10	**15**	15	15	15	14.9	**13.7**	13.9	14.1	14.2	14.1
39	21/9/2015 6:20	**15**	15	15	15	14.9	**13.7**	13.9	14.1	14.1	14.1
40	21/9/2015 6:30	**15**	15	14.9	15	14.9	**13.7**	13.9	14	14.2	14.1
41	21/9/2015 6:40	**15**	14.9	14.9	15	14.8	**13.7**	13.9	14	14.1	14.1
42	21/9/2015 6:50	**14.9**	14.9	14.9	14.9	14.8	**13.6**	13.9	14	14.1	14
43	21/9/2015 7:00	**15**	14.9	15	15	14.9	**13.8**	14	14.1	14.2	14.1
44	21/9/2015 7:10	**15**	15	15	15	14.9	**13.8**	13.9	14.1	14.2	14.2
45	21/9/2015 7:20	**15**	14.9	15	15	14.9	**13.8**	14	14	14.2	14.1
46	21/9/2015 7:30	**15**	14.9	15	15	14.9	**14**	14.1	14.1	14.2	14.1
47	21/9/2015 7:40	**15**	15	15.1	15	14.9	**14.2**	14.2	14.1	14.3	14.2
48	21/9/2015 7:50	**15.1**	15	15.1	15.1	14.9	**14.4**	14.3	14.3	14.3	14.3
49	21/9/2015 8:00	**15.1**	15.1	15.1	15.1	15	**14.3**	14.5	14.5	14.5	14.3
50	21/9/2015 8:10	**15.1**	15	15.1	15.1	15	**14.5**	14.4	14.4	14.5	14.3

Sample data taken from Test 1 illustrating the first 50 temperature profile data entries recorded on the 21/9/15.

Appendix C – Test 1 (21/9/15 – 27/9/15) Temperature Profile Pots (Full-set)

Test 1 – Cold Surface Film Temperature Profile Plots

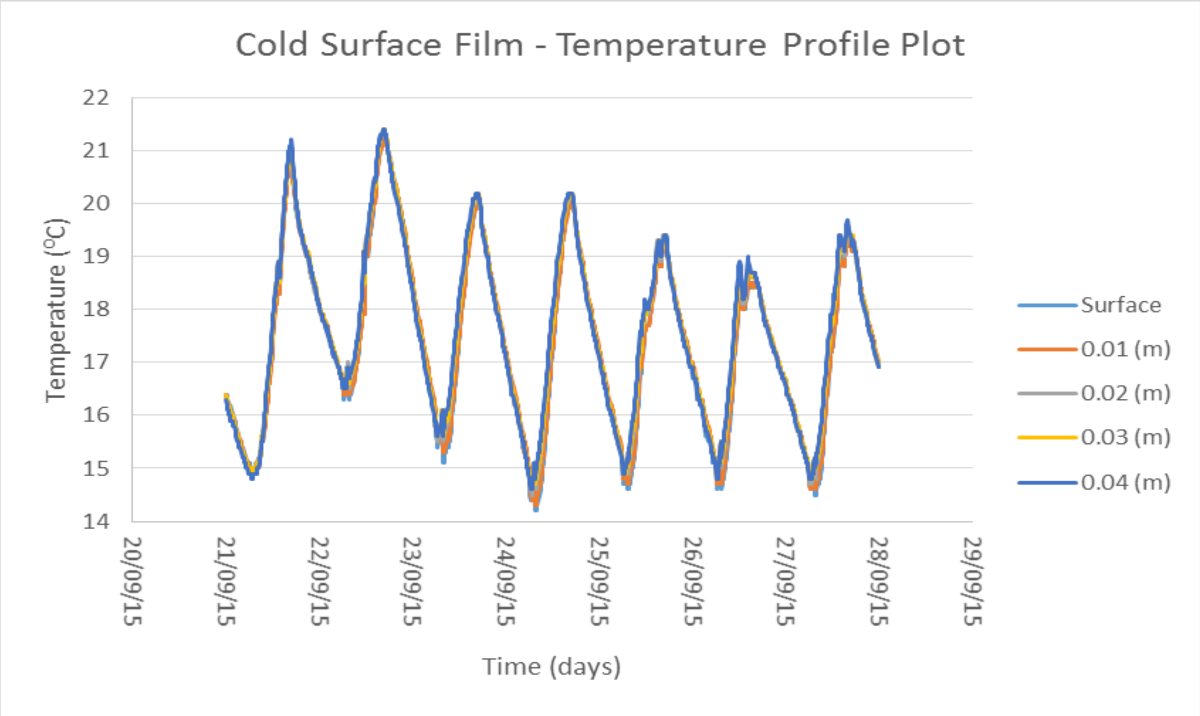

Figure 6.1: Test 1 cold surface film temperature profile plot (Tank 1)

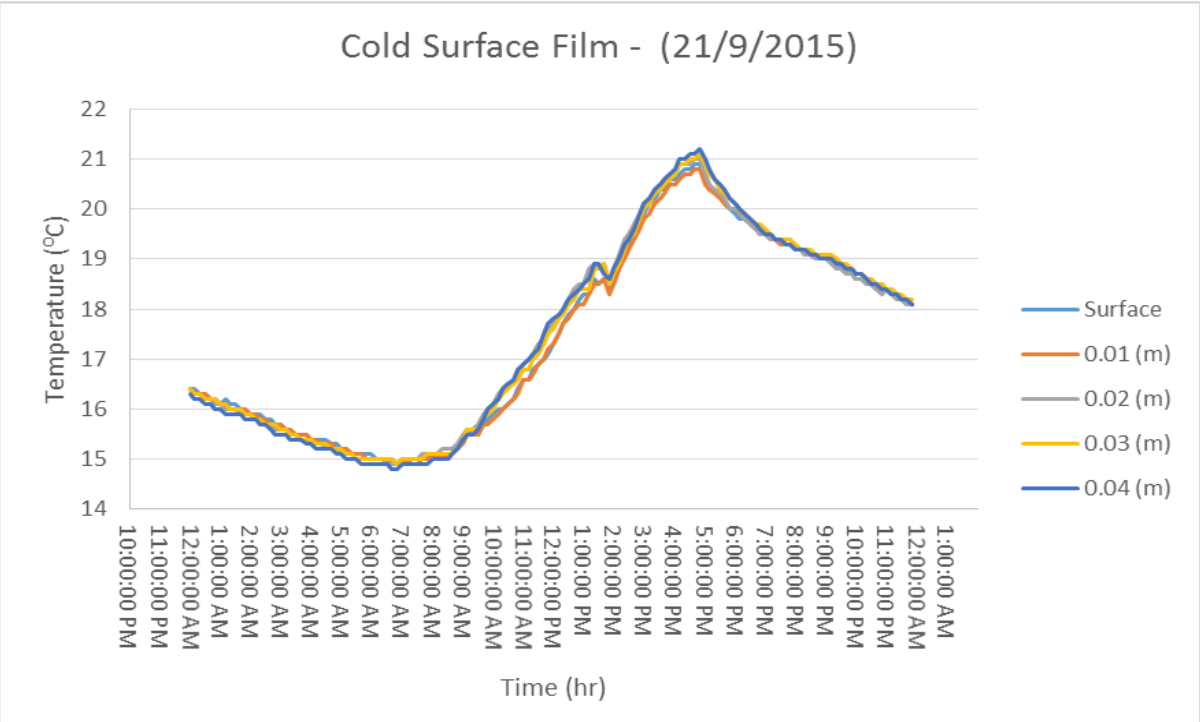

Figure 6.2: Test 1 - Temperature profile plot for cold surface film in Tank 1 on 21/9/2015

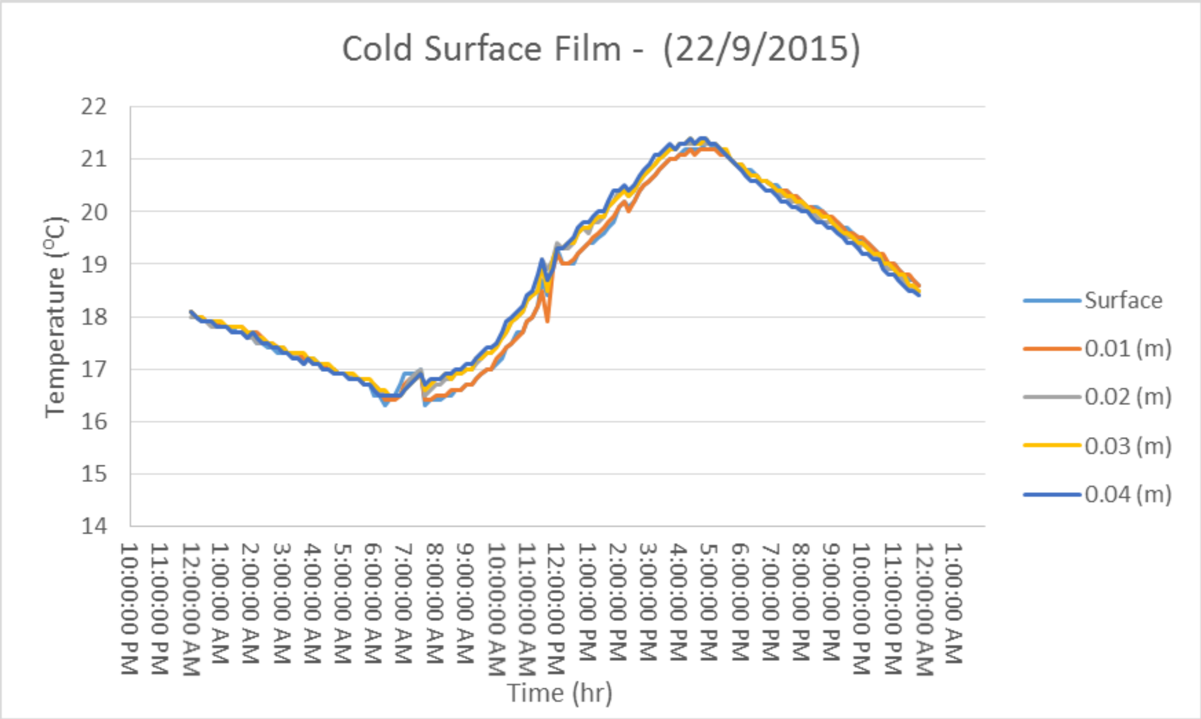

Figure 6.3: Test 1 - Temperature profile plot for cold surface film in Tank 1 on 22/9/2015

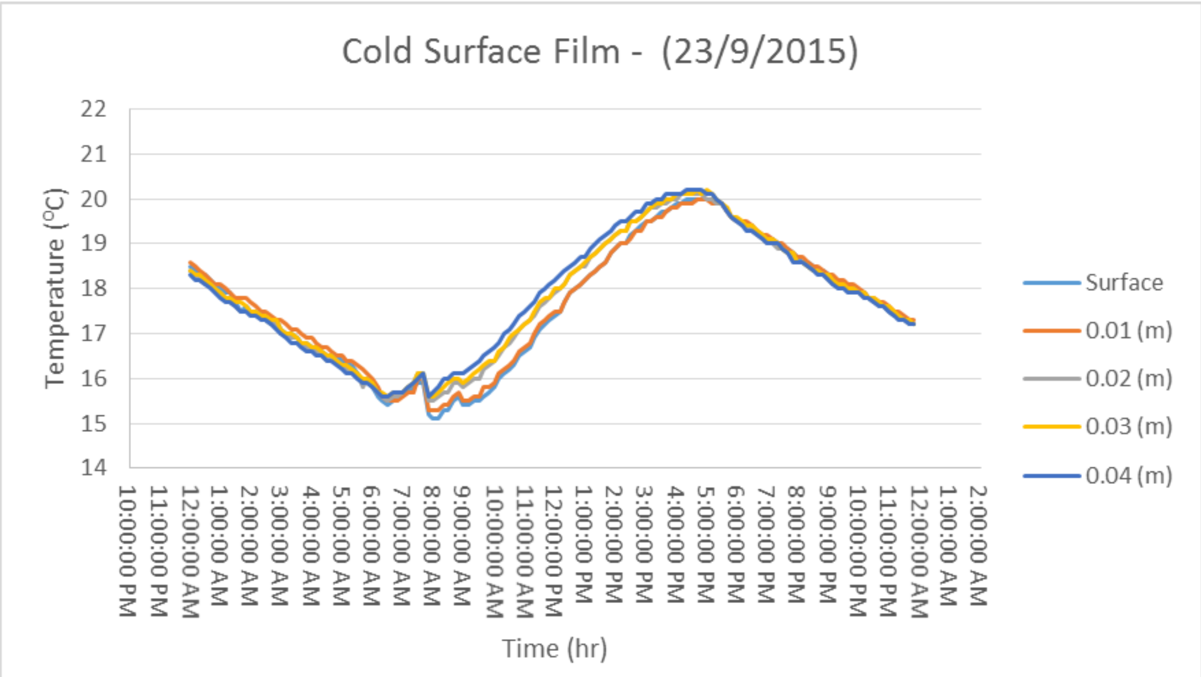

Figure 6.4: Test 1 - Temperature profile plot for cold surface film in Tank 1 on 23/9/2015

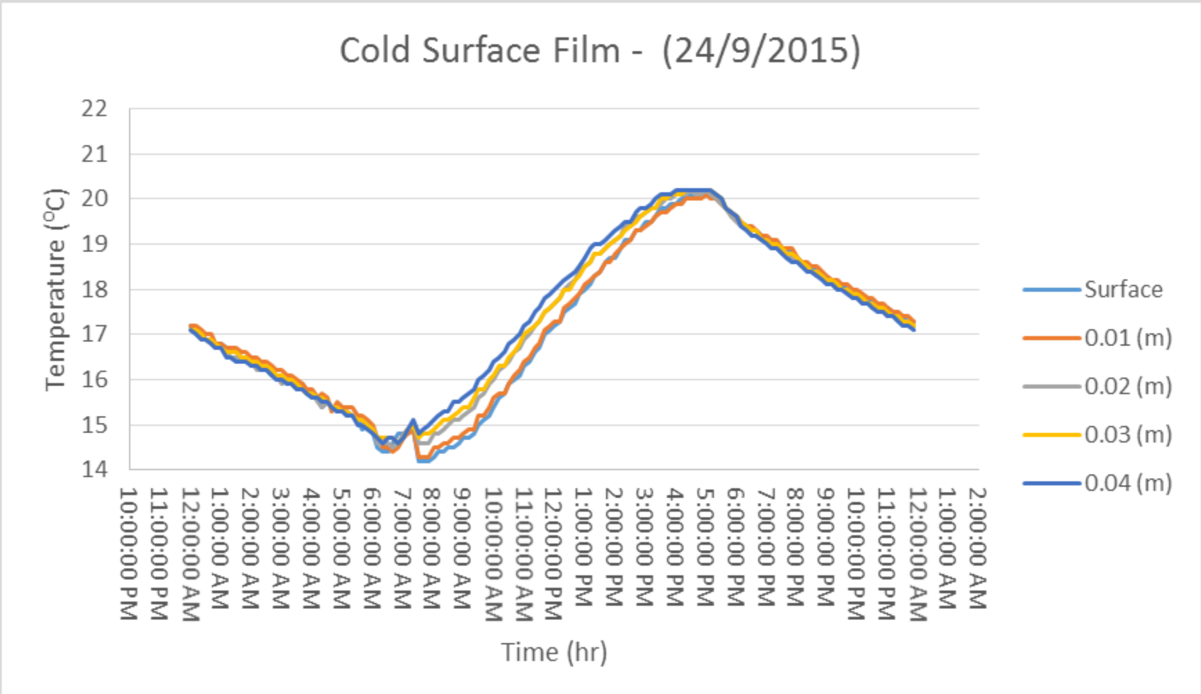

Figure 6.5: Test 1 - Temperature profile plot for cold surface film in Tank 1 on 24/9/2015

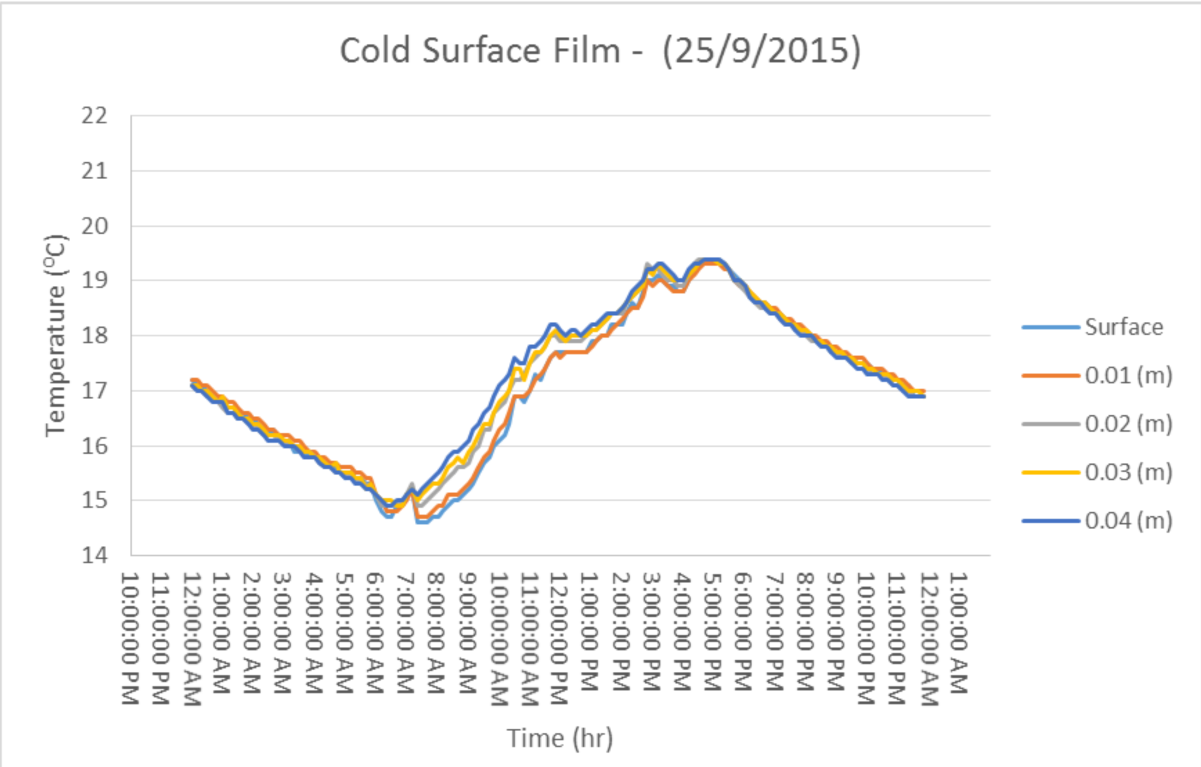

Figure 6.6: Test 1 - Temperature profile plot for cold surface film in Tank 1 on 25/9/2015

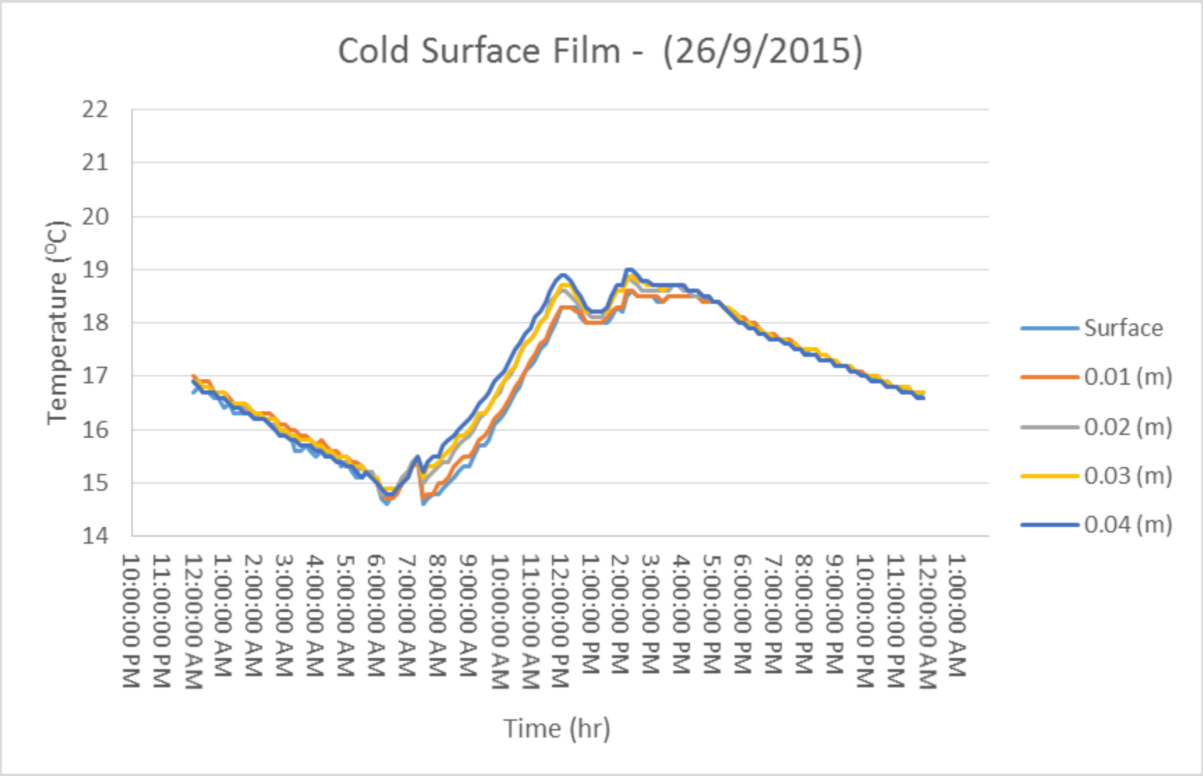

Figure 6.8: Test 1 - Temperature profile plot for cold surface film in Tank 1 on 26/9/2015

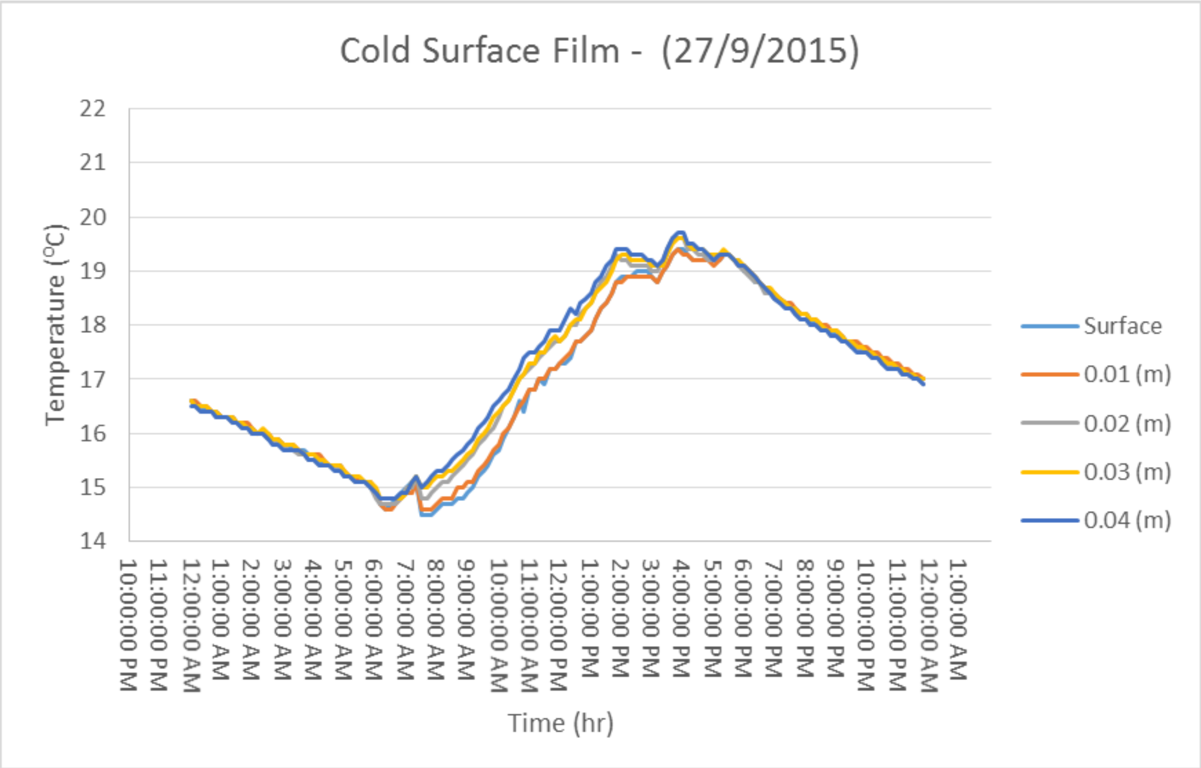

Figure 6.7: Test 1 - Temperature profile plot for cold surface film in Tank 1 on 27/9/2015

Test 1 – Warm Surface Film Temperature Profile Plots

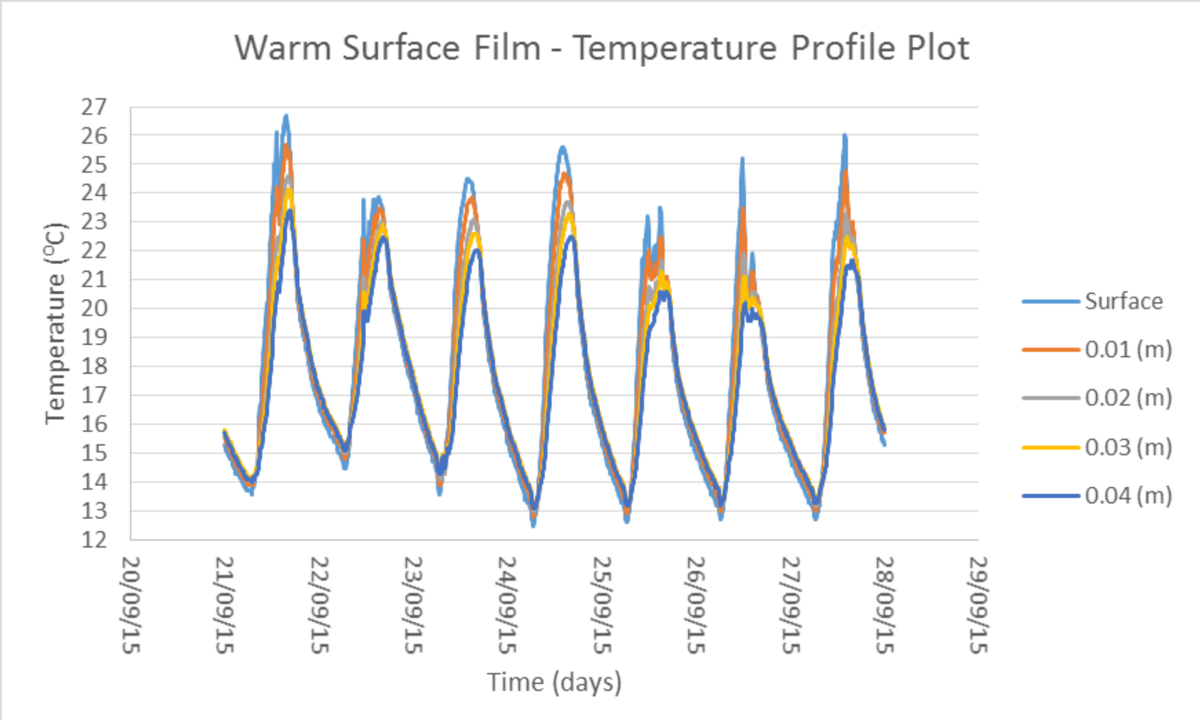

Figure 6.10: Test 1 warm surface film temperature profile plot (Tank 2)

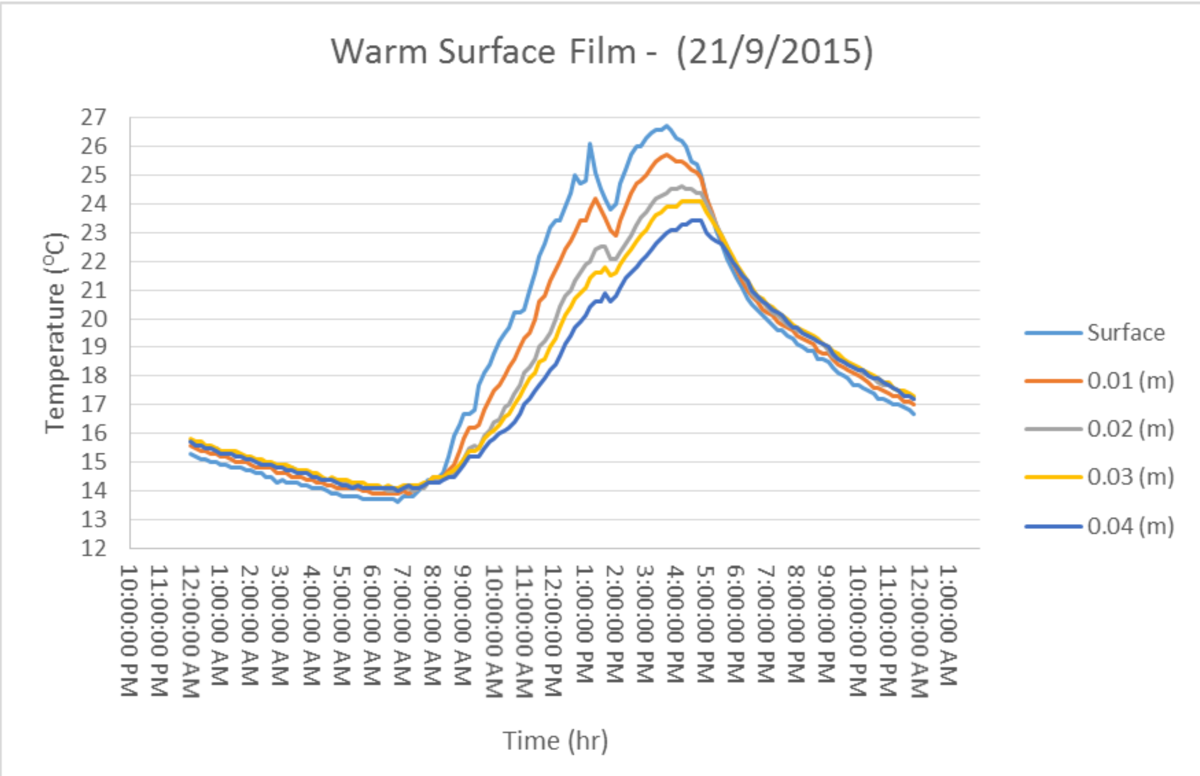

Figure 6.9: Test 1 - Temperature profile plot for warm surface film in Tank 2 on 21/9/2015

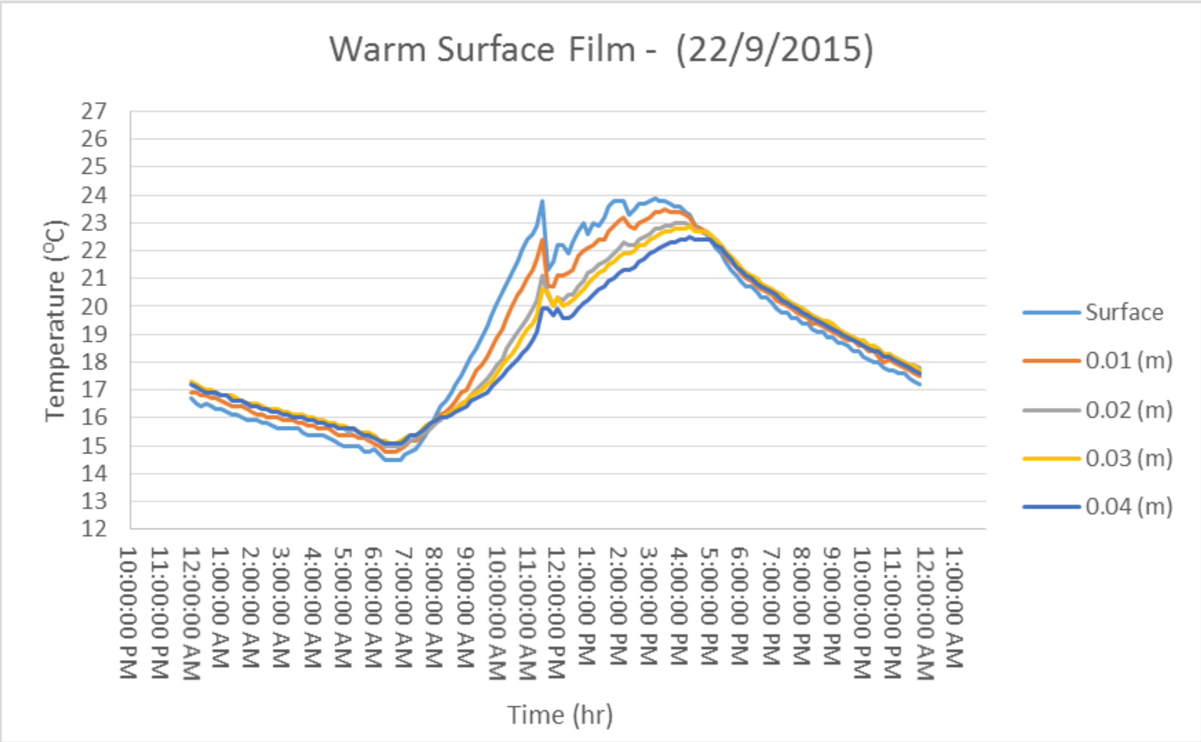

Figure 6.11: Test 1 - Temperature profile plot for warm surface film in Tank 2 on 22/9/2015

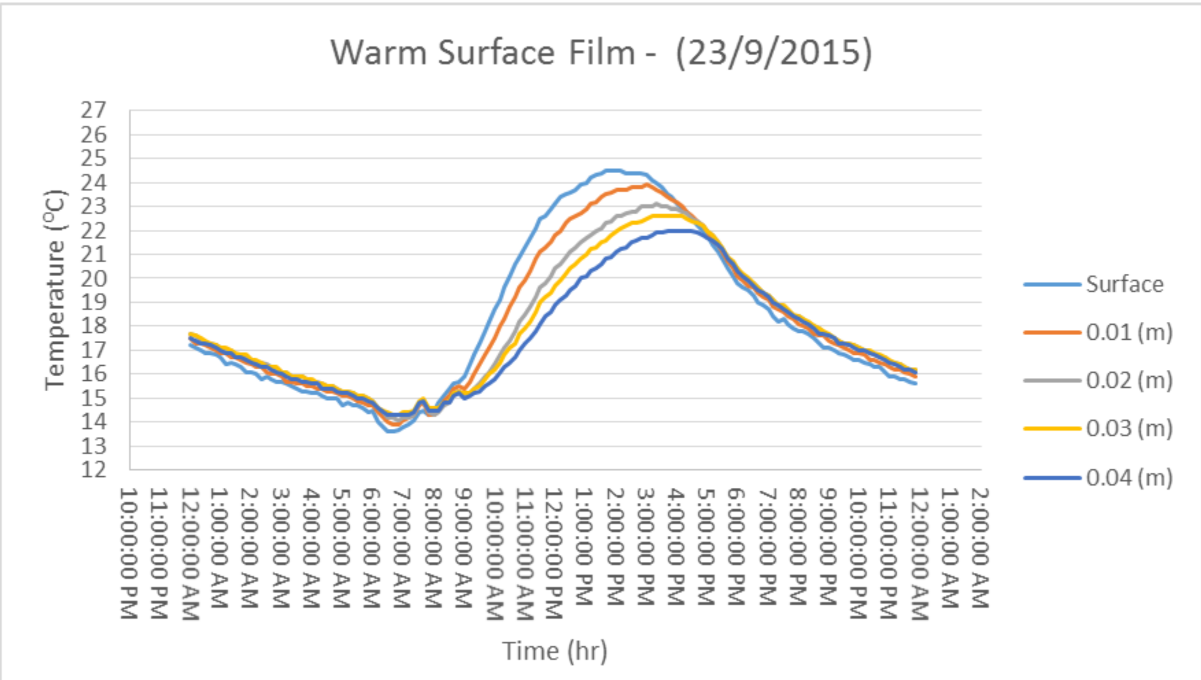

Figure 6.12: Test 1 - Temperature profile plot for warm surface film in Tank 2 on 23/9/2015

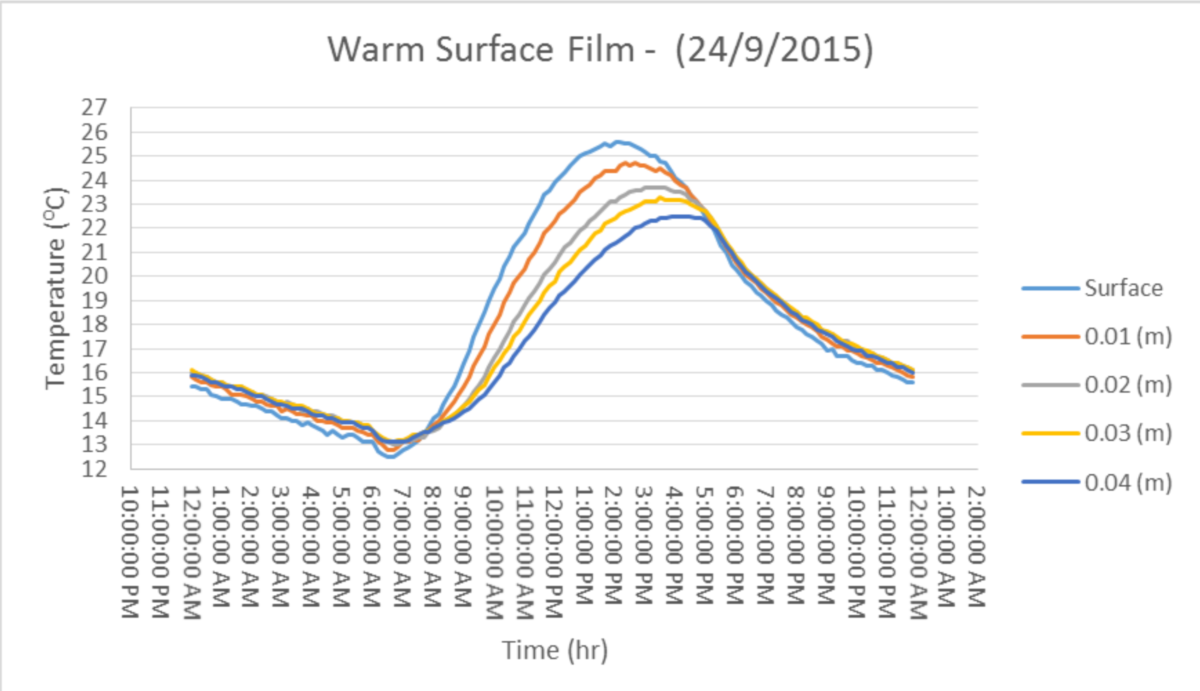

Figure 6.13: Test 1 - Temperature profile plot for warm surface film in Tank 2 on 24/9/2015

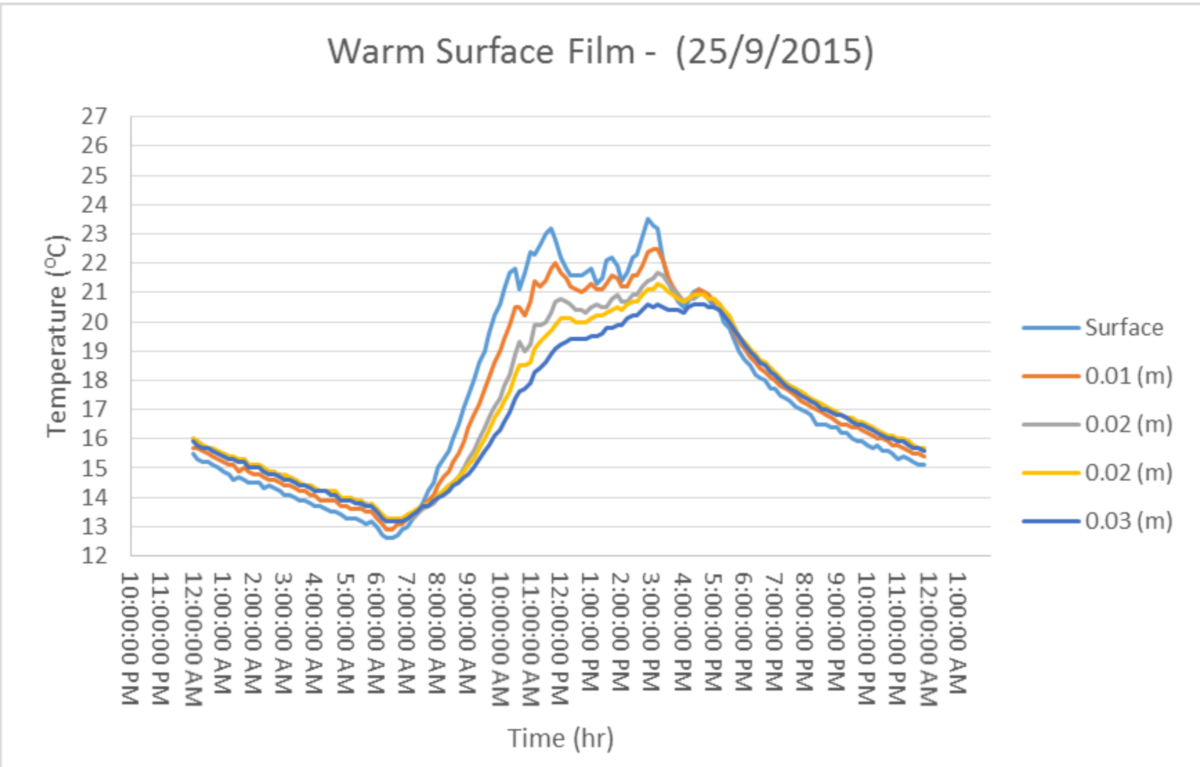

Figure 6.14: Test 1 - Temperature profile plot for warm surface film in Tank 2 on 21/9/2015

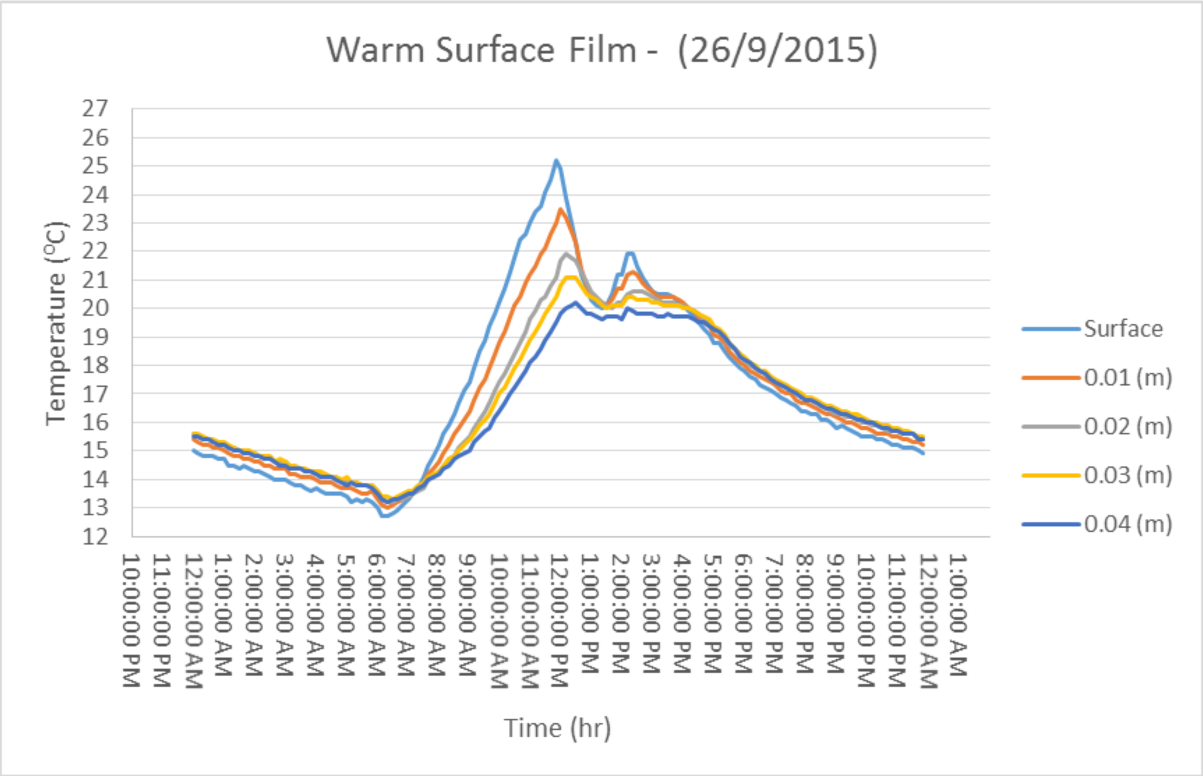

Figure 6.16: Test 1 - Temperature profile plot for warm surface film in Tank 2 on 26/9/2015

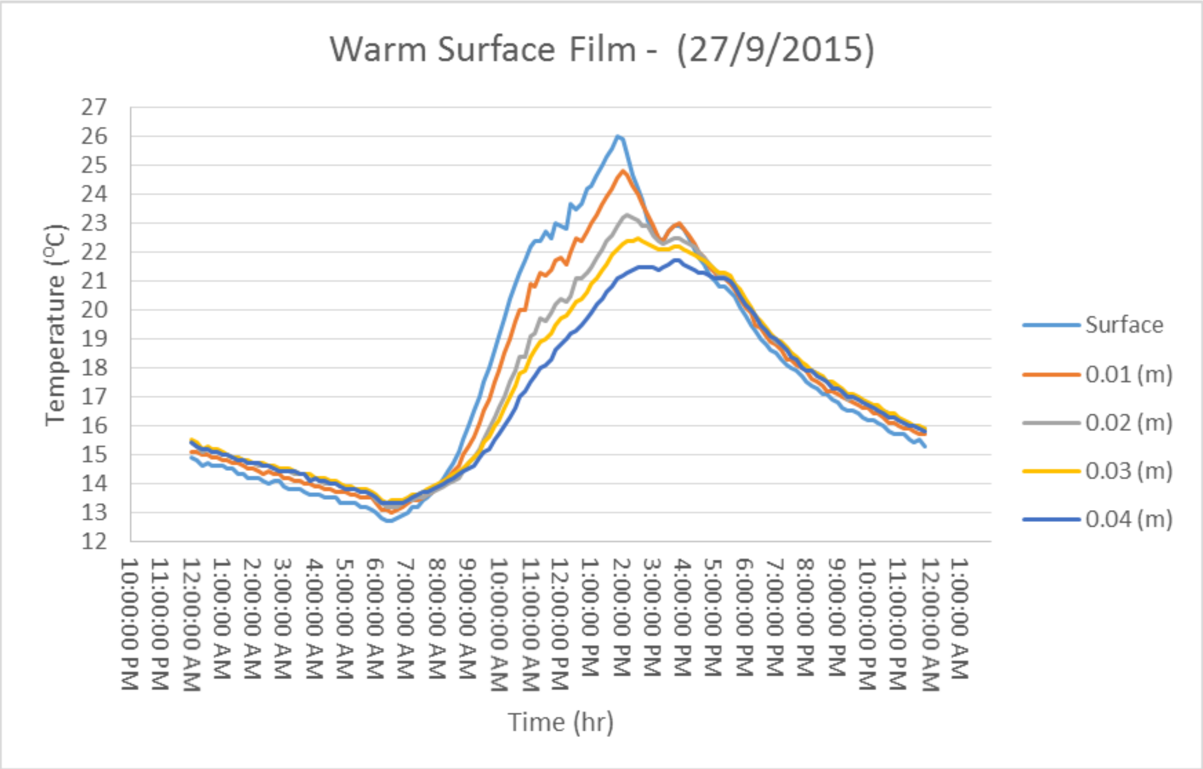

Figure 6.15: Test 1 - Temperature profile plot for warm surface film in Tank 2 on 27/9/2015

Test 1 - Warm and cold surface film comparison plots

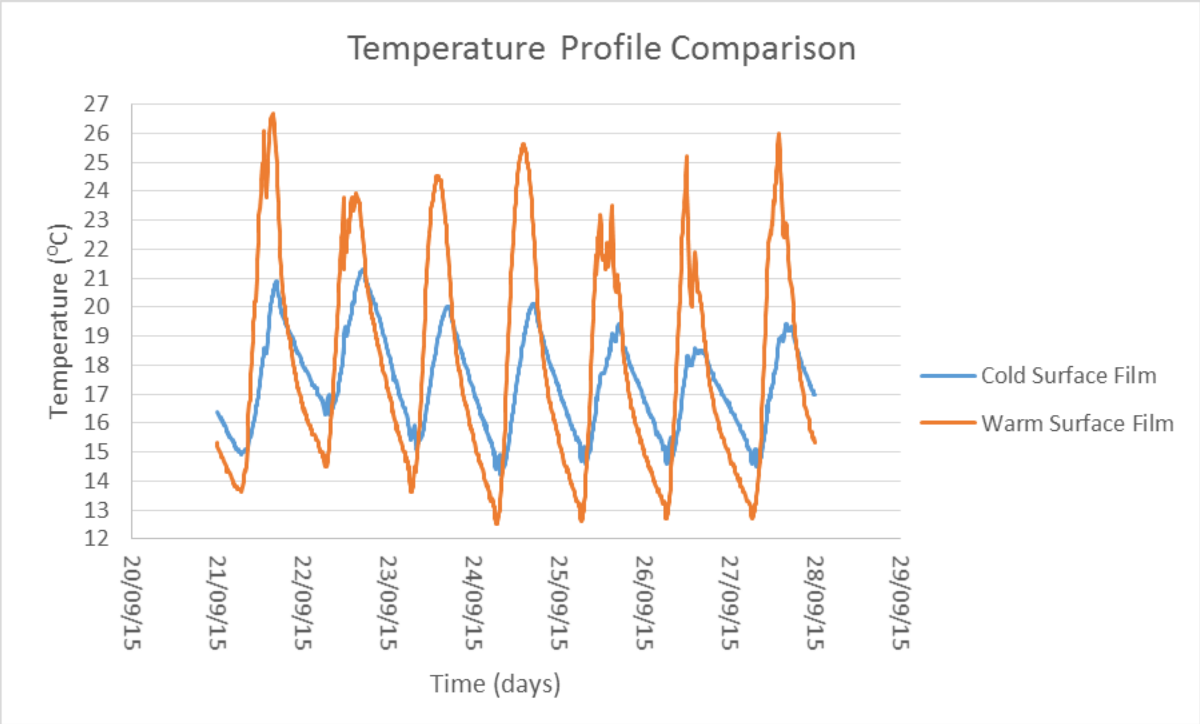

Figure 6.17: Test 1 - Surface thermocouple comparison plot

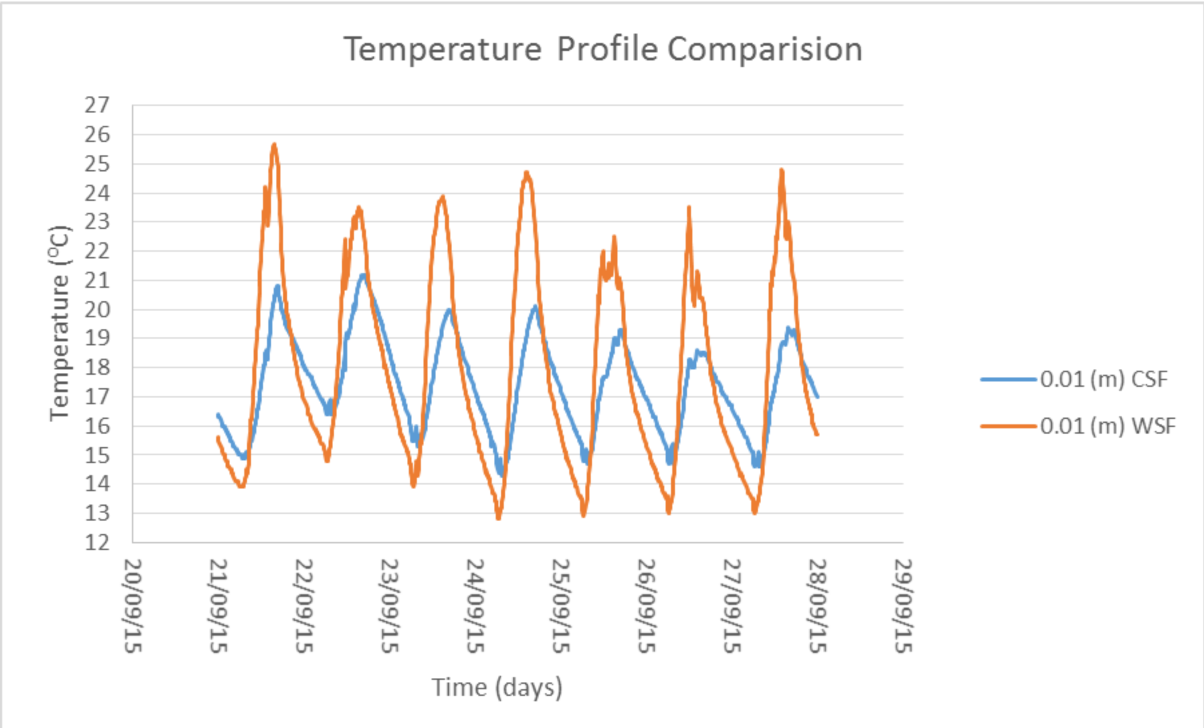

Figure 6.18: Test 1 - 0.01(m) thermocouple comparison plot

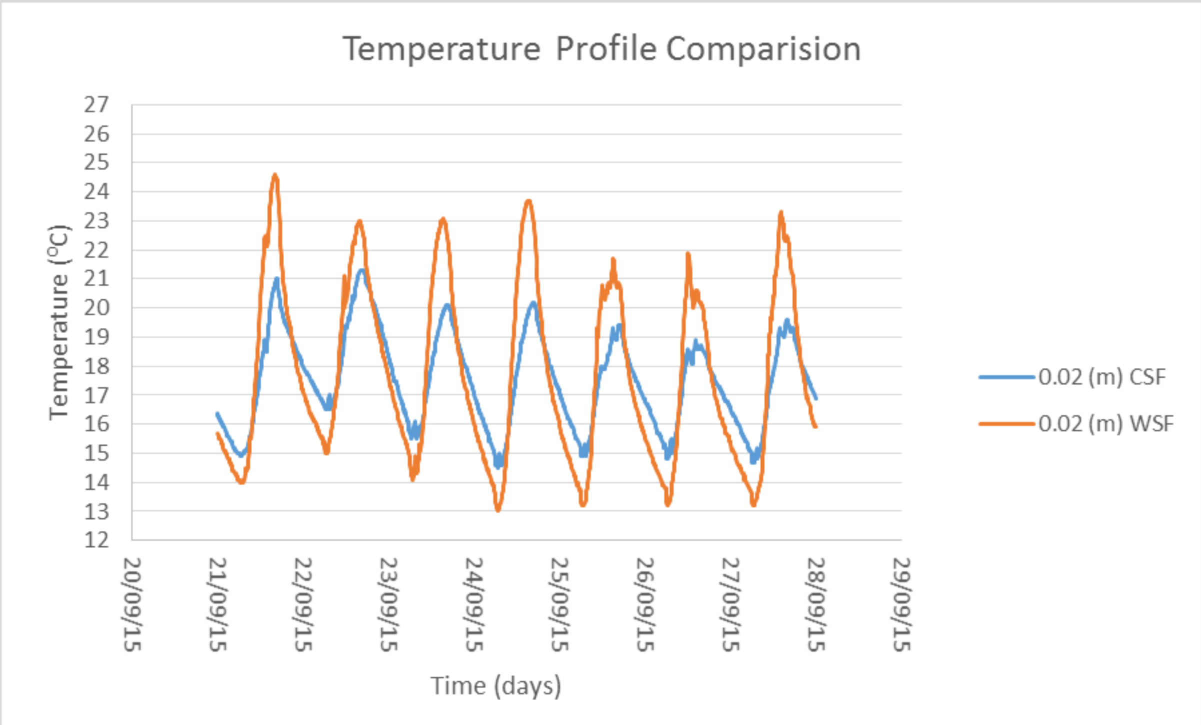

Figure 6.19: Test 1 - 0.02(m) thermocouple comparison plot

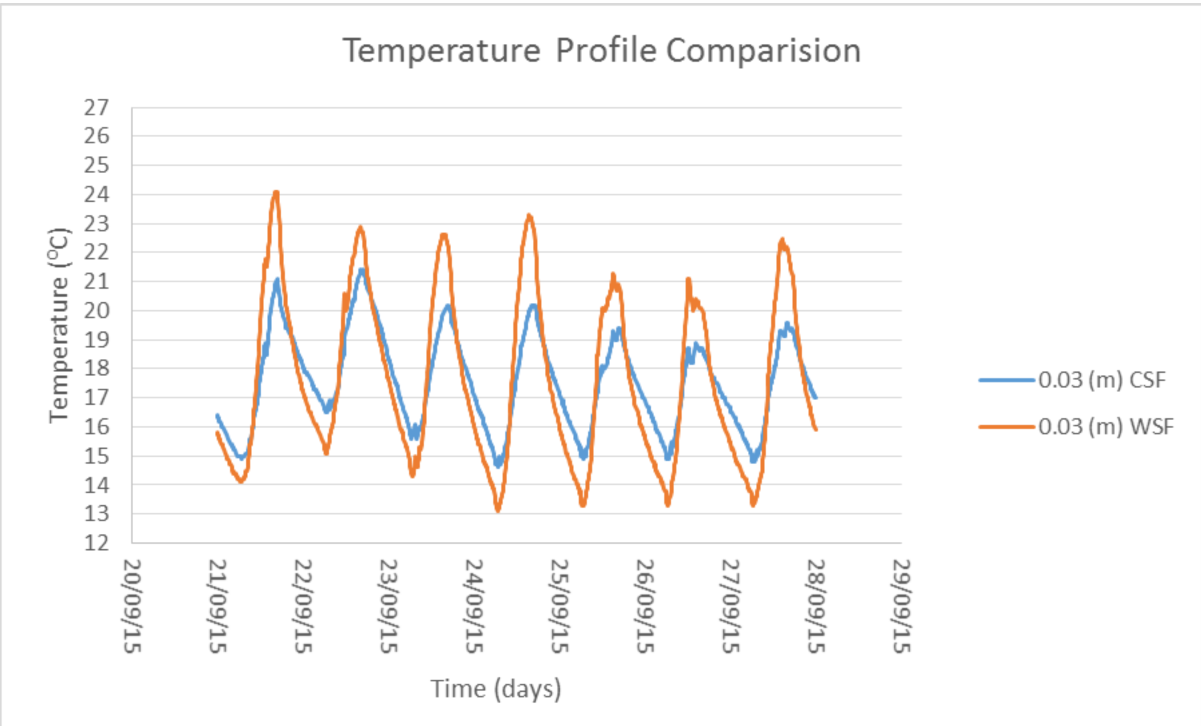

Figure 6.20: Test 1 - 0.03(m) thermocouple comparison plot

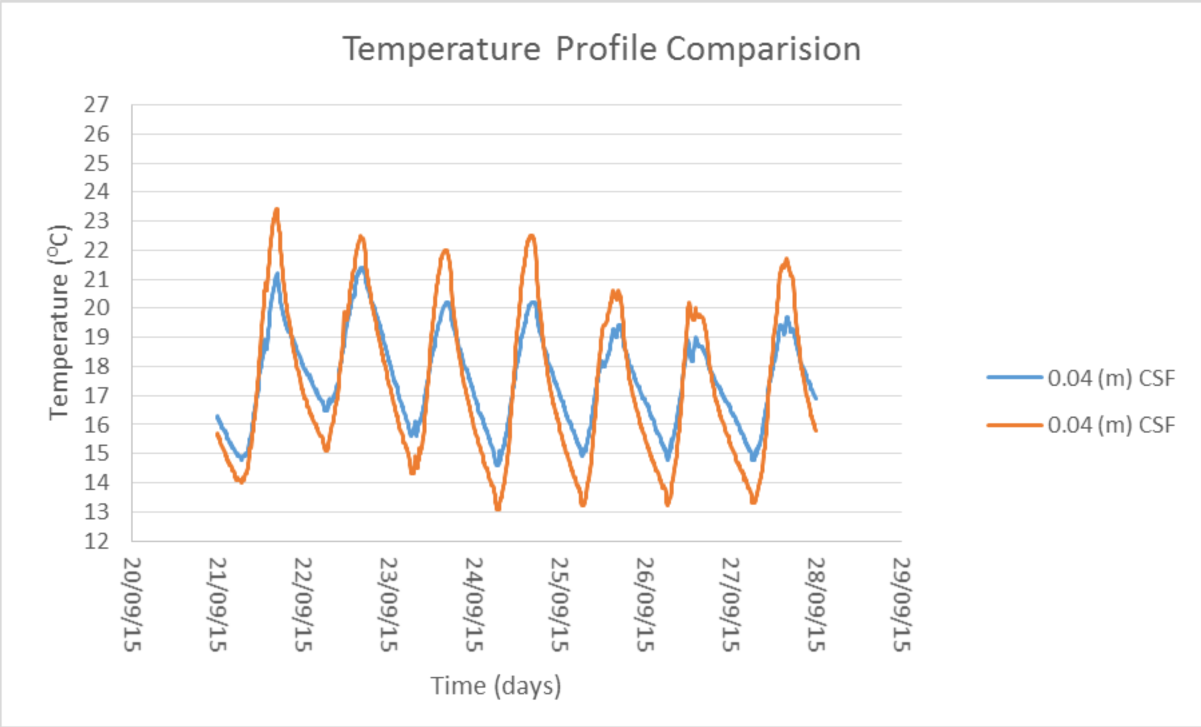

Figure 6.21: Test 1 - 0.04(m) thermocouple comparison plot

Appendix D – Restoral of NCEA Facility

Considerable progress was made on restoring the three large ponds at NCEA Evaporation Compound Facility. As the site had not been used for evaporation research since 2005 the facility was highly dilapidated and was in considerable disrepair. On first inspection of the facility obvious issues were identified and these included; lining punchers and tears, rodent undermining of tank floor, vegetation and wed growth around the perimeter of the tank and stagnate waste water pooled within the tanks.

The following illustrations show the initial state of the ponds on arrival at the site.

Stagnate water pooled on plastic liner

Significant vegetation and weed growth occurred around tank perimeter

The main works undertaken was the removal and realignment of the tank liners. There was a significant amount of vegetation build up around the perimeter of the tanks and this was firstly removed. The vegetation growth had harboured rodent activity. Rates and mice had formed tunnels and nest beneath the plastic greatly affecting the foundation of the storage ponds. The major area affect comprised of a two metre strip around the inside of the tank wall. The follow figures illustrate the before and after shots.

Once the sand floor had been re-levelled. Holes were patch (in the lining) and the tank liner was realigned.