Performance of a simple basin solar still under the South African climate: a baseline study

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by

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EXECUTIVE SUMMARY

BACKGROUND

South Africa is considered a water-scarce country and some regions are also under-developed in terms of the availability and distribution of potable water. Small-scale solar desalination of sea water and brackish water sources is a viable option to produce fresh water for rural communities that do not have access to municipal water, since South Africa has some of the highest solar fluxes on the planet. Simple basin solar stills are a well-developed method for improving the water quality from saline or brackish water sources, however, there is little research on the topic based on the South African climate. Most literature sources are from research institution located in the northern hemisphere such as India, Egypt and countries in the Middle-East. The use of simple basin solar stills can be beneficial to rural settlements to produce clean water due to the simplicity in manufacturing and operating these stills. These units can be operated by individuals to produce small quantities of clean water for their own use. Unfortunately, small-scale desalination by means of basin solar stills is very inefficient and only utilises approximately 25-30% of the total solar irradiance per day. Even though the input energy is essentially free, much higher yields can be achieved with an optimised design and better material selection. Yields of 2-4 $L.day^{-1}.m^{-2}$ have been reported in literature for various still designs of varying complexity.

AIM OF THIS STUDY

This investigation aims at identifying the shortcomings of simple basin solar stills reported in literature and to achieve the ideal maximum yield of 11.8 $L.day^{-1}.m^{-2}$ by means of a cost effective, efficient passive basin solar still. If this cannot be achieved by means of a passive basin still, attempts will be made to improve performance of the same design by introducing active components to the design. In this context, active components refer to water pumps, air circulation fans or a combination of both. Finally, the investigation will aim at introducing heat recovery and attempt at exceeding the performance of both active and passive stills. However, this will only be considered if it is economically feasible or if any gain in yield is greater than that of merely increasing the area of a passive or active still at the same monetary cost.

DESIGN, CONSTRUCTION AND EVALUATION OF THE SIMPLE SOLAR BASIN STILL

Simple solar basin stills are to be constructed and evaluated by means of a detailed and accurate energy balance. All modes of heat and mass transfer should be included, and each component of the energy balance should be determined. The results from this analysis will determine the key areas for improvement to solar basin stills. Based on the results obtained in the energy balance analysis, improvements were made to the solar basin still design to address the determined shortcomings. It is important to obtain the most effective still design with a low capital expenditure and reasonably long lifespan. Still efficiency should be further evaluated with the use of forced flow of the air inside the still, brine inside the still and ambient air outside the still. The latter would be relevant when external condensers are utilized to condense the water vapour.

Simple solar basin stills were designed and built to specifications that are recommended in literature for efficient performance. The stills were equipped with temperature, humidity and mass measuring sensors to determine all modes of heat and mass transfer over the control volume boundaries. The information obtained from these measurements can provide more information on the areas that require improvement in terms of energy losses and will indicate what measures should be taken to reduce these energy losses. Improvements to the stills were focused on the energy loss modes that governed the still performance. Other improvements and additions were considered to indirectly manipulate large energy loss terms, for example, reducing the still operating temperature to reduce heat losses, but with the direct consequence of affecting the still yield.

Global horizontal solar irradiance data was collected over several months in 2018, the data showed that a maximum yield of 9.15 $L.day^{-1}.m^{-2}$ was attainable if no energy losses to the environment was considered.

A thorough investigation into the energy balance over a simple basin solar still showed that energy losses from the cover of these stills were the largest of all and can amount to as much as 50% of all the associated heat and mass transfer components. It was also estimated that approximately 27% of these energy losses are due to radiation. A portion of the energy losses from the still cover are not considered as losses as this is necessary to condense the water and this latent heat must be rejected through the cover.

The first version of a simple solar basin stills was designed and built based on recommendations found in literature. Each revision was based on data obtained from the previous version. The first version of the stills tested produced, on average, 1.25 $L.day^{-1}.m^{-2}$ and was later improved to yield a maximum of 1.95 $L.day^{-1}.m^{-2}$. The second revision produced a maximum of 1.45 $L.day^{-1}.m^{-2}$ when equipped with a PMMA cover. The third revision produced a maximum of 2.55 $L.day^{-1}.m^{-2}$ with a thermal efficiency of 26.5% when equipped with a PMMA cover. At a later stage, revision 2 and 3 of the first version were equipped with a 4 mm single pane glass cover and a 4 mm double pane glass cover, with a 2 mm air gap, respectively. The change in the cover material proved too advantageous and revision 2, with the single pane glass cover, produced a maximum yield of 3.55 $L.day^{-1}.m^{-2}$ with a thermal efficiency of 38.1%. The use of the double pane glass cover was intended to reduce the energy losses through the cover, however, this proved to be a disadvantage when operated as a passive basin solar still and reduced the yield to only 1.45 $L.day^{-1}.m^{-2}$. A second version was built based on the initial design geometry; however, this design was intended to use of the shelf components to reduce cost and simplify the manufacturing process. This version does not produce as much clean water as version 1 but does so at a much lower initial cost. Material cost amounts to less than R300 per unit for these stills. These stills produce as much as 1.37 $L.day^{-1}.m^{-2}$ with inferior insulation thickness when compared to version 1. Additional insulation can improve this version and could be a viable option for mass production.

SUMMARY OF FINDINGS

Passive basin solar stills cannot achieve the ideal maximum yield of 11.8 $L.day^{-1}.m^{-2}$ but can achieve high yields when appropriate materials of construction are used. The main disadvantage in the use of these stills are due to the high internal temperatures in comparison to the surroundings. Energy losses through conduction, convection and radiation are substantial and cannot be reduced significantly without the use of expensive proprietary materials. Active components were added to the passive still that achieved the highest yield in an attempt to improve the still performance. This was done in conjunction with the double pane glass cover mentioned previously. The use of external heat exchangers or circulation of the water proved to increase the yield by as much as 41%, however, this increase is still not comparable to that of the passive still that was equipped with the single pane glass. Different heat exchanger designs were considered but proved to reduce the air temperature too much and is not deemed feasible due to the additional cost incurred with these additions. It is therefore recommended that an optimised passive solar basin still be used to achieve the highest yield at a minimal monetary investment. These units are also very easy to operate and maintain.

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ACRONYMS & ABBREVIATIONS

DPG	Double pane glass
LED	Light emitting diode
PC	Polycarbonate
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
PS	Polystyrene
UV	Ultra-violet

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CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Portions of South Africa experience very low average annual rainfall and on average South Africa experience relatively low rainfall when compared to the global average (Hedden and Cilliers, 2014). Low rainfall has a direct influence on the availability of fresh and potable water. On top of the fact that South Africa has a relatively low rainfall, the country is also affected by low water quality and accessibility to clean water, specifically in rural areas. Nare *et al.* (2011) suggest that it is imperative that communities in rural areas be involved with water quality management and in the overall management of the scarce resource. The availability of fresh, or potable, water directly impacts the socio-economic development of a country and influences the well-being of the population (Corrigan, 2009). It is also necessary to state that South Africa has very high solar irradiance in comparison to the global average, this is in part the cause of the water scarcity in South Africa but could also be used for local small-scale water purification. Water purification at the point of use could be aid in the improvement of water quality in rural areas that do not have access to safe drinking water.

One method of supplementing South Africa's relatively small amount of available fresh water is by means of small-scale solar desalination. This process involves the evaporation and subsequent condensation of saline or brackish water to produce distilled water. Commercial desalination primarily involves extreme temperatures or extreme pressures which is associated with high energy inputs. The use of solar energy would be very beneficial for the desalination process but still shows some deficiencies on a commercial scale. However, the use of solar energy is very beneficial and appropriate when utilised on a small-scale system. These systems have been well documented in the literature (Ayoub and Alward, 1996; Mathioulakis, Belessiotis and Delyannis, 2007; Abdallah, Badran and Abu-Khader, 2008; Kalidasa Murugavel, Chockalingam and Srithar, 2008; Bhardwaj, ten Kortenaar and Mudde, 2013; Kabeel, Omara and Essa, 2014b; Bhardwaj, Ten Kortenaar and Mudde, 2015; Elango, Kannan and Kalidasa Murugavel, 2015; Ibrahim and Elshamarka, 2015; Rabhi *et al.*, 2017; Feilizadeh *et al.*, 2017).

Although solar stills show promising characteristics, these units still provide a relatively low yield of approximately 3 $L.day^{-1}.m^{-2}$ (Bouchekima, 2003; Li, Goswami and Stefanakos, 2013; Yadav and Sudhakar, 2015; Chandrashekara and Yadav, 2017). The relatively low yield of these units also severely impacts the cost of the water produced. This is not due to the cost of energy, as with industrial desalination systems, but rather due to the materials and methods of construction that must be considered for good weatherability and a prolonged lifespan. It is also not conclusive why solar stills fail to produce clean water at efficiencies greater that 35% (Kalogirou, 2014, p. 442). It is evident that it is important to identify the key factors (energy losses) that cause simple basin solar stills to achieve low yields in order to improve their efficiencies. Once the most significant key factors are identified, improvements can be made to specifically target areas of concern. Reducing the most significant losses will inevitably improve the performance and yield of these stills. However, any suggested improvements should still be considered from a monetary point of view. Incurring significant costs to improve still performance is not feasible. It should also be noted that the operational lifetime of any improvements should not drastically reduce the lifespan of the overall system, especially considering the harsh environment of operation.

1.2 PROJECT AIMS

The objective of this investigation is to identify all energy transfer modes in the system and to identify key areas for the most impactful improvements. Improvements are to be evaluated on a monetary basis as well as the longevity of the system. These objectives will be evaluated by means of the following:

1. Determine if it is possible to achieve the ideal yield of 11.8 $L.day^{-1}.m^{-2}$ using a well-insulated simple basin solar still without heat recovery.
2. Determine if it is possible to achieve the ideal yield of 11.8 $L.day^{-1}.m^{-2}$ using a well-insulated continuous flow, simple basin solar still without heat recovery.
3. Determine if it is possible to economically achieve more than the ideal yield of 11.8 $L.day^{-1}.m^{-2}$ using a continuous flow, simple basin solar still with heat recovery. The definition of economical in this context implies that the increased production rate achievable with energy recovery raises cost by a margin less than simply increasing collector area to achieve the same production rate using the cheaper system mentioned in Aim 2.

To ensure comparable results between system 1 and 2, the basic design of the basin still will be kept constant or, at minimum, will be maintained at a similar state.
Further objectives that must also be considered in all still designs include:

1. The simplicity of the design to ensure easy operation of the unit.
2. An easily maintainable unit with respect to cleaning and repairing.
3. A robust design that is not fragile.

The above-mentioned objectives are considered in the event of such units be made available for domestic use in rural areas without readily available fresh water. Optimised and efficient still designs are available in the literature, however; these designs do not necessary conform to all the mentioned objectives of this investigation. It is therefore important to note that the base design will be selected in terms of ease of manipulation and alteration rather than the most efficient design available. Although the cost and longevity of any alterations are important, these aspects will not hinder the use and testing of potentially elaborate or costly ideas.

CHAPTER 2: LITERATURE REVIEW

2.1 SOLAR DESALINATION

As the use of alternative energy sources is increasing, solar energy is rapidly becoming more viable as an energy source for desalination processes (He and Yan, 2009). This is particularly relevant in developing countries where population growth requires large amounts of water but there are insufficient funds for traditional desalination to be feasible. Typically, high levels of solar irradiation are experienced in most of these countries, promoting the use of solar desalination even further (Li, Goswami and Stefanakos, 2013). South Africa has a high potential for implementing solar desalination with the majority of South Africa receiving more than 5.0 kWh.m^{-2} of global horizontal irradiation per day (Pugsley *et al.*, 2016) as seen in Figure 2-1 (SOLARGIS, 2017). Clean water is more commonly being produced with renewable energy resources rather than fossil fuels due to the rising cost of fossil fuels and the environmental concerns associated with it (Elimelech and Phillip, 2011; Ghaffour *et al.*, 2015). A number of Middle Eastern countries rely almost solely on desalination plants and have shown that desalination can be market competitive with an increase in efficiency and improved technology (Karagiannis and Soldatos, 2008; Khawaji, Kutubkhanah and Wie, 2008). Typically, the production rate of a desalination system is proportional to the area of solar collection and therefore improvements due to economy of scale do not apply. For these reasons, solar desalination is favourable when considering a small scale system (Kalogirou, 2005)

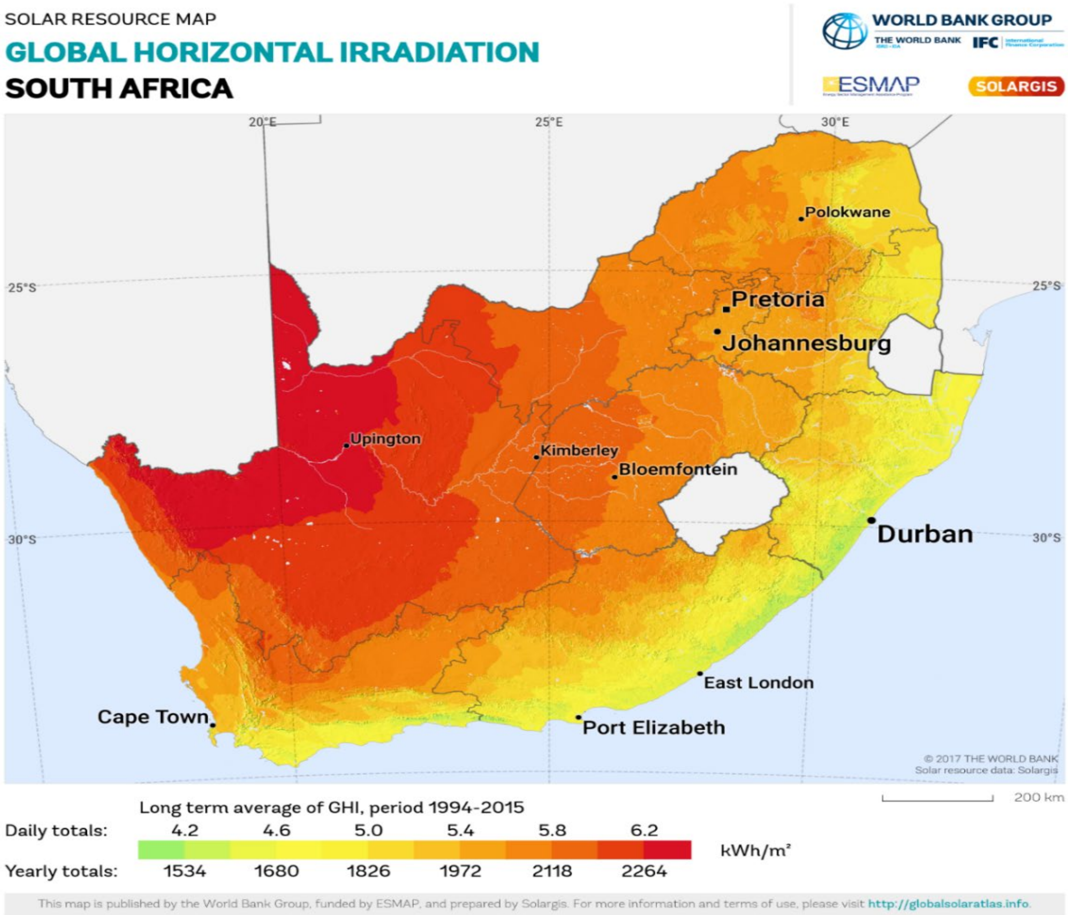

Figure 2-1: Long term average GHI of South Africa (downloaded from https://solargis.com, 2019)

2.2 SMALL-SCALE DESALINATION

Small-scale desalination has been researched for several decades and has seen numerous design iterations and alterations over the years. These designs can be subdivided into direct or indirect solar desalination, active and passive stills, concentrating or non-concentrating, basin stills, or multi-effect stills to name but a few. All the mentioned variations have their advantages and disadvantages, in almost all instances, the cost of the water produced is more than that of transportation from a fresh water source or through conventional water treatment systems (Ayoub and Alward, 1996; Karagiannis and Soldatos, 2008). For the purpose of this investigation, only simple, direct desalination through passive and active stills will be considered. The following sections will discuss the different design features of each variation and the advantages and disadvantages associated with each.

In direct solar desalination the most commonly used method is a basin solar still (Bouchekima, 2003; Chandrashekara and Yadav, 2017), the typical setup is shown in Figure 2-2 (Sharon and Reddy, 2015). Basin solar stills typically operate in such a manner that heat collection and distillation occur in the same system; the water evaporates and condenses on the transparent cover through which solar radiation enters the system (Li, Goswami and Stefanakos, 2013). This is also the cause for the major disadvantage of simple basin stills. It is brought about the fact that the energy dissipated for condensation to occur, must be rejected through the cover. As this forms part of the same system, the cover is inevitably at a higher temperature. Due to these disadvantages, passive solar stills produce low yields of around 3 $L.m^{-2}day^{-1}$ to 4 $Lm^{-2}day^{-1}$. Due to the low yields achieved in these stills, desalination is not considered viable to address the water shortages on a regional scale (Yadav and Sudhakar, 2015). However, solar still desalination is the cheapest desalination method available and is feasible when water is desired in very small quantities (Kalogirou, 2005). Additional disadvantages of solar stills are that they require a large amount of area to produce sizeable amounts of distilled water, require a large initial investment, and require daily maintenance to clean the cover and flush the basin. The maintenance requirements are simple but necessary in order to ensure that the still continues to operate at its optimum; a build-up of dust on the cover hinders incoming radiation and an excess of salt in the still makes evaporation more difficult (Malik *et al.*, 1982, pp. 40-41).

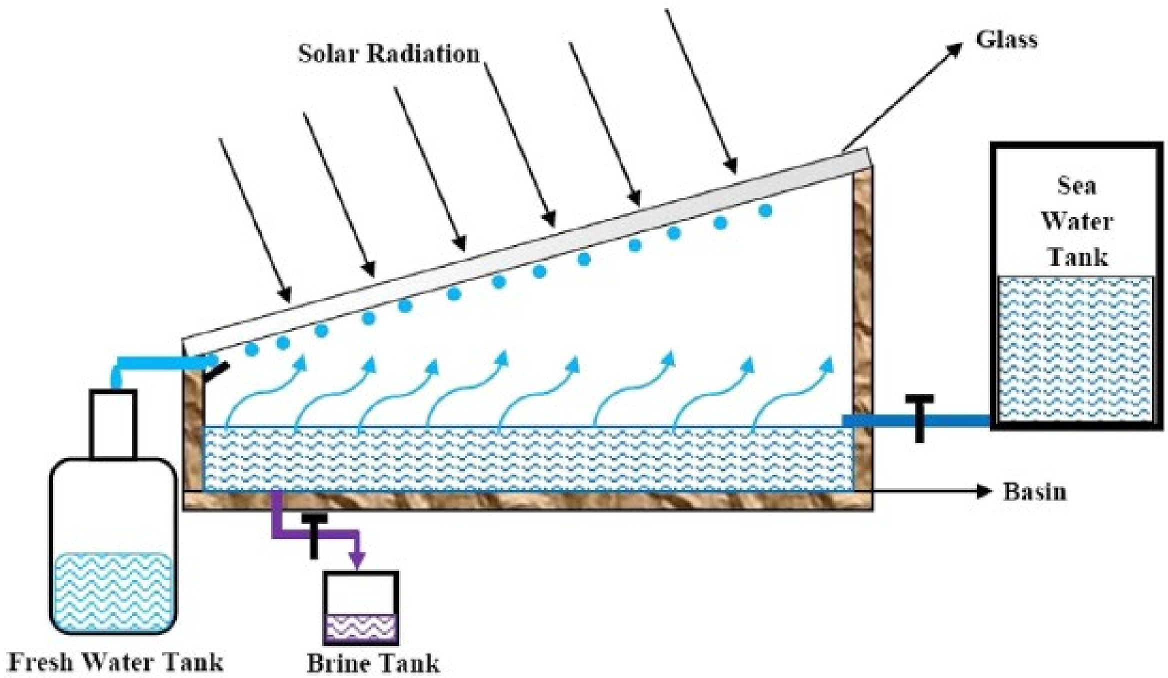

Figure 2-2: A simple, passive, direct-, basin-type solar still (Sharon and Reddy, 2015).

2.3 PRINCIPLES OF OPERATION

The operation of a simple basin solar still is as follows: a transparent cover allows for solar radiation to enter the still where it is absorbed by an absorber plate beneath the water. The absorber plate causes the water to heat up and evaporate where it can then condense on the cover (Malik *et al.*, 1982, pp. 3-5). This is a simplistic view of the actual energy transfer occurring in the still.

2.3.1 General Heat Transfer Processes

In the solar still system, there is both external heat transfer and internal heat transfer occurring. The external heat transfer is losses from the still to the environment and includes convection, conduction and radiation. Internal heat transfer deals primarily with the energy transfer from the water to the cover, as well as the absorber to the water, and includes convection, conduction and radiation. Conduction is described by Equation (1), where *k* is the thermal conductivity of a material and has only a weak dependence on temperature.

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \qquad (1)$$

The driving force for condensation is the temperature difference in the direction of interest.
Convection also uses a temperature difference as the driving force for heat transfer, as shown in Equation (2) (Cengel and Ghajar, 2015, p. 26):

$$\dot{Q}_{conv} = h_{conv}A\Delta T \qquad (2)$$

However, h_{conv} is a complicated function of the geometry of the surface, the flow and physical properties of the fluid, as well as the temperatures of operation.

For natural the relationship,

$$Nu = C(GrPr)^n \qquad (3)$$

can be used to describe the heat transfer coefficient (Malik *et al.*, 1982, p. 9; Cengel and Ghajar, 2015, p. 539). Where *C* and *n* are constants describing geometry and the physical behaviour of the system. Empirical relationships are commonly used for these constants. In the case of forced convection Equation (4) can be used to describe heat transfer (Cengel and Ghajar, 2015, p. 440);

$$Nu = CRe^mPr^n \qquad (4)$$

where the dimensionless parameters are calculated as:

$$Nu = \frac{h_{conv}L_c}{k} \qquad (5)$$

$$Gr = \frac{g\beta L_c^3\rho^2\Delta T}{\mu^2} \qquad (6)$$

$$Pr = \frac{\mu C_P}{k} \qquad (7)$$

$$Re = \frac{\rho v L_c}{\mu} \qquad (8)$$

The convective heat transfer coefficient is strongly dependent on the wind speed in the case of forced convection.

Radiative heat transfer from the cover of the still is modelled using the Stefan-Boltzmann law shown in Equation (9) (Cengel and Ghajar, 2015, p. 29),

$$\dot{Q}_{rad} = \sigma\epsilon\left((T_s + 273)^4 - \left(T_{sky} + 273\right)^4\right) \qquad (9)$$

where the subscript *s* refers to the temperature of the surface from which radiation is occurring.

2.3.2 Internal Heat Transfer

The most important heat transfer processes occurring inside the still are conduction from the absorber surface to the water, evaporation from the water surface, convection from the water surface to the cover surface, and condensation of water onto the cover surface. In a solar still convection occurs, most commonly, in the form of natural convection. Equation (3) is used to describe this process. However, as simultaneous mass and heat transfer is taking place inside the still a modified Grashof number should be used. A common form of this modified Grashof number is shown in Equation (10) (Malik *et al.*, 1982, p. 10).

$$Gr' = \frac{gL_c^3\rho^2}{\mu^2}\left(\frac{M_\infty(T_o + 273)}{M_o(T_\infty + 273)} - 1\right) \tag{10}$$

The subscripts *o* and ∞ refer to the conditions at the evaporation surface and at a point far away from the surface respectively.

Manipulation of the equations and relevant empirical correlations yields Equation (12) to describe the heat transfer by convection inside the basin solar still (Malik *et al.*, 1982, pp. 10-11):

$$\dot{Q}_{conv} = h_{conv}A(T_w - T_{ci}) \tag{11}$$

$$\dot{Q}_{conv} = 0.884\left[T_w - T_{ci} + \frac{(P_w - P_{ci})(T_w + 273)}{(269.9 \times 10^3 - P_w)}\right]^{\frac{1}{3}} A(T_w - T_{ci}) \tag{12}$$

where the subscripts *w* and c_i refer to the conditions at the water surface and at the inside cover surface respectively.

While many models exist to model the evaporative heat transfer occurring in a basin solar still (Elango, Gunasekaran and Sampathkumar, 2015), most commonly used model for evaporation in a basin solar still is that of Dunkle (Dunkle, 1961),

$$\dot{Q}_e = 16.273 \times 10^{-3} h_{conv}A(P_w - P_{ci}) \tag{13}$$

where the vapour pressures are calculated with the following relationship:

$$P_i = exp\left[25.317 - \left(\frac{5144}{T_i + 273}\right)\right] \tag{14}$$

The rate of evaporation in kg.s^{-1} can further be calculated using the latent heat of vaporisation and the evaporative heat transfer rate.

$$\dot{m}_e = \frac{\dot{Q}_e}{\lambda_{vap}} \tag{15}$$

This relationship is largely empirical but is widely used in the field and has been tested extensively. It is clear from these relationships that the driving force for evaporation is the temperature difference between the water and the surface for condensation.

The two main mechanisms for condensation are film condensation and dropwise condensation. In a simple basin solar still dropwise condensation is the observed mode of condensation. In dropwise condensation the vapour condenses as droplets of varying sized which slide down the surface when they reach a specific size, exposing the surface to allow for more drops to form. As there is no film of water hindering heat transfer between the vapour and the solid surface the rate of heat transfer is orders of magnitude larger than that associated with film condensation (Cengel and Ghajar, 2015, p. 612; Coulson *et al.*, 2018, pp. 476-478). For these drops to move along the condensation surface they must become large enough to overcome adhesive forces due to surface tension.

The presence of non-condensable gases in the system can cause a drastic reduction in the rate of condensation. The non-condensable gases collect near the surface and form a barrier which the vapour must first diffuse through subsequently hindering condensation. However, a higher velocity of the gas mixture aids in removing the non-condensable gases from the area adjacent to the surface which reduces this effect (Cengel and Ghajar, 2015, p. 620). This is a problem in the simple basin still as the only movement of the air within the still is due to buoyancy forces and natural convection. Increased temperature differences between the absorber and the cover would aid in increased movement of air within the still.

2.3.3 The Energy Balance

In order to understand the system and determine where inefficiencies and losses are most prevalent it is important to do an energy balance of the system.

The general form of the energy balance is given in Equation (16) (Smith, Van Ness and Abbott, 2005, p. 48),

$$\frac{d(mU)_{cv}}{dt} = \dot{Q} + W - \Delta\left[\dot{m}\left(H + \frac{1}{2}v^2 + zg\right)\right]_{fs} \tag{16}$$

Where subscripts *cv* and *fs* refer to the control volume and flowing streams respectively.

For a passive basin solar still there is only an outlet stream, no inlet, and kinetic and potential energy of this stream is negligible. Additionally, there is no work input or output in the system. This reduces the energy balance equation for a passive basin solar still to:

$$\frac{d(mU)_{cv}}{dt} = \dot{Q}_{net} - \dot{m}_{out}H \tag{17}$$

However, in the case of an active basin solar still, Equation (17) should include the electrical work done by any pumps or fans added.

The terms of Equation (17) can be expanded to a place where the fundamental laws of heat transfer can be applied. Working from left to right, the first term represents the internal energy change of the system. The internal energy change of the system will be the sum of the internal energy changes of the various components included in the control volume. The control volume is not a general control volume and will be discussed in depth in Section 3.3.

Expanding the heat transfer term,

$$\dot{Q}_{net} = \dot{Q}_{in} - \dot{Q}_{out} \tag{18}$$

Where the subscripts *in* and *out* could be replaced by *incident radiation* and *losses*. In a passive solar still the only significant heat input to the system is in the form of solar irradiation, thus allowing for the $\dot{Q}_{in}$ term to be replaced with $\dot{Q}_I$ where $\dot{Q}_I$ is the incident solar irradiation.

Losses from the system are numerous, and dependent on the control volume selected. They can include convective losses from the cover plate, radiative losses from the cover, reflective losses from the cover, and conductive losses through the insulation. These can in turn be expressed using the heat transfer relations described previously.

2.3.4 Thermal Efficiency

The thermal efficiency of a solar still is traditionally calculated as the ratio of water produced to the input of solar energy. In a passive solar still the instantaneous thermal efficiency can be calculated as the ratio of the rate of heat transfer related to evaporation to the rate of incident solar irradiation, this is seen in Equation (19) (Tiwari, Tiwari and Shyam, 2016, pp. 523-524),

$$\eta_i = \frac{\dot{Q}_e}{\dot{Q}_i} \quad (19)$$

And can be rewritten as

$$\eta_i = \frac{h_e A(T_w - T_{cover})}{\dot{Q}_I} \quad (20)$$

Showing that as the temperature difference between the water and the cover increases, the theoretical thermal efficiency of the still increases. Similarly, an overall thermal efficiency can be determined by Equation (21):

$$\eta = \frac{\lambda_{vap} \int_{t_0}^{t_n} \dot{m}_e dt}{\int_{t_0}^{t_n} \dot{Q}_I dt} \quad (21)$$

2.4 PASSIVE BASIN SOLAR STILL

The performance of a solar still is a function of many different parameters which can be classified as design, operational, and meteorological parameters. As the meteorological parameters are not controllable variables within the system they will not be discussed in detail. However, it is known that as the wind velocity increases the yield of the still increases, and as ambient temperature increases the yield also increases (Malik *et al.*, 1982, p. 52). The design parameters include the size of the basin, the material of the absorber plate, the inclination angle of the cover, the material and thickness of the cover, and the type and thickness of insulation. While operational parameters include the depth of water in the still, and the temperature of water fed to the still (Taghvaei *et al.*, 2014; Jamil and Akhtar, 2017). Optimisation of the design and operational parameters are key to maximising the yield of the solar still.

The following subsections discuss many of the modifications that can be made regarding both design and operational parameters in order to improve the yield of a simple basin solar still.

2.4.1 Basin Geometry

Optimisation of the geometry of the basin still is of utmost importance to this work as an exploratory investigation in the various still geometries is time consuming and costly. Various aspects of the still geometry should be considered for the optimal still design.

2.4.1.1 *Basin Height*

The height of the basin is an important parameter in the design of the solar still. The main effect of changing the basin height are that the volume available for evaporation increases, the distance water vapour must travel to condense increases, and additional shadows are added to the still. Various studies into the effect of the basin height on the yield of the solar still showed that the yield is inversely proportional to the height of the back wall (Estahbanati *et al.*, 2016; Feilizadeh *et al.*, 2017; Jamil and Akhtar, 2017; Rajaseenivasan *et al.*, 2017). The explanation for this increase in yield for decrease in height is that the distance for the vapour to travel before it condenses decreases while the driving force remains relatively constant, a lower basin height also promotes convective heat transfer within the still due to the reduced distance between evaporation surface and condensation surface. Decreasing the volume of air in the still causes there to be more heat available per unit volume of vapour in the still and for there to be less volume that must be saturated before condensation can occur. An increase in the basing height also increases the distance condensate droplets must travel on the cover surface. An increase in this distance could lead to droplets detaching before they reach the condensate collection area and are consequently lost. Finally, the additional shadows caused by higher walls, hinder incoming radiation and decrease the temperature, and consequently yield, of the still.

2.4.1.2 *Basin Aspect Ratio*

The basin aspect ratio is the length to width ratio of the bottom of the basin. For clarity, the length of the still is the dimension parallel to the equator while the width is defined as the dimension normal to the equator. Varying this parameter can increase or reduce the area of the still that would be shadowed by the walls. It should also be noted that for a specified cover angle, changes in the aspect ratio could lead to a change in the basin height. Literature (El-Swify and Metias, 2002; Feilizadeh *et al.*, 2017) shows that an aspect ratio of approximately 2 is optimal. Decreasing the aspect ratio introduce large areas that are shadowed by the walls and increasing the aspect ratio beyond 2 shows no markable increase in productivity.

2.4.1.3 *Angle of Inclination of Cover*

The tilt angle of the cover is harder to discuss than some other factors as the optimum depends on both the latitude and season of where the tests are being conducted. Changing the angle of inclination causes a number of changes within the still such as the speed at which condensate runs down the cover, the volume available for water to evaporate into, the cover area available for heat transfer, and the amount of radiation that is reflected by the cover (Khalifa and Ahmad M. Hamood, 2009; Lal *et al.*, 2017). The speed of the water collection is important because if the water travels too slowly along the cover it is more likely to fall from the condensation surface back into the still. Additionally, slow movement of the water on the cover can result in a lack of cover space for new water vapour to condense on. It is proposed that a minimum cover angle of 10° is used to prevent condensate falling back into the still (Tiwari, Thomas and Khan, 1994). It is evident from several investigations that the optimum cover angle for a single slope basin still is equal to the latitude of the locale of operation (Tiwari, Thomas and Khan, 1994; Nafey *et al.*, 2000; Singh and Tiwari, 2004). This set angle does have reduced productivity in mid-summer and winter, however, it is optimal when considering the operation of the still throughout the year.

2.4.2 Absorber Surface

In a conventional basin solar still the bottom of the basin, or the absorber surface, is responsible for capturing energy from the incident solar radiation in the form of heat and transferring this energy to the water in the basin. Evidently the properties of this surface will affect the still performance. One of the main things to consider is the surface area of the absorber, increasing the surface area improves the transfer of heat between the absorber surface and the water within the still due to increased area for heat conduction. An increase in area can be achieved through many different means such as corrugating the absorber plate, adding fins, pins, or wicks to the plate, or by the addition of a porous medium such as a sponge. It was observed that a still with a corrugated wick absorber reached higher internal temperatures and consequently higher yields than a conventional still. The modified still achieved as much as 5.9 $L.m^{-2}.day^{-1}$ which is equivalent to an increase in yield of 35% (Matrawy, Alosaimy and Mahrous, 2015). This was also reported in a study where an increase in yield of 30% was observed when using wicks on the absorber plate (Velmurugan *et al.*, 2008).

Literature reports an increase in yield of between 15% and 49% (2.83 $L.m^{-2}.day^{-1}$ and 2.81 $L.m^{-2}.day^{-1}$ respectively) when the stills were fitted with fins and pins on the absorber surface (Velmurugan *et al.*, 2008; Rabhi *et al.*, 2017). The addition of a porous medium serves to increase the exposure area of the water to the absorber surface. An example of this is the use of sponge cubes at the bottom of the basin still. The sponge is most useful when it protrudes from the water surface allowing capillary action to draw water in the sponge. This area is heated more quickly and allows for easier evaporation (Abu-Hijleh and Rababa'h, 2003; Kalidasa Murugavel, Chockalingam and Srithar, 2008). Other investigations show similar improvements (Velmurugan *et al.*, 2008) while another study made use of soot in the basin to improve heat transfer and evaporation with an increase in yield of approximately 35% (Madani and Zaki, 1995).

While the absorbing surface is typically the bottom of the still it is of great benefit if the heat can be absorbed near the surface of the water instead of the absorber plate at the bottom. This can be achieved using a suspended absorber which separates the water into two sections causing a smaller volume to receive heat and for the heat to be added nearer the surface. The use of a suspended absorber is advantageous as it removes the need for the entire volume of water in the still to be heated before evaporation can begin. Small volumes of water above the absorber are heated much quicker allowing for evaporation to occur at an increased rate due to the effective decreased thermal mass of the water capturing heat.

A disadvantage of the warm-up period experienced when heat is absorbed from the bottom is that heat is lost in this period largely by conduction through the basin to the environment. Maintaining the still at a cooler temperature reduces losses to the surroundings (Szulmayer, 1973). Investigations in the use of a floating absorber material has shown promising results. These can either be suspended beneath the surface of the water or floating such as with plastic shade cloth or felt-like materials. These studies show that the use of such an absorber increases the rate of evaporation and claims to increase the productivity of the still (Szulmayer, 1973).

In general the absorber material is required to have a high radiation absorbance, to be corrosion resistant and to have a low cost (Madani and Zaki, 1995). The absorber is one of the most important parts of the still and extensive research has been done on modifications to enhance the absorber performance. The modifications that have been investigated in this section all involve improving the absorbance of the solar irradiation or improving the rate of heat transfer from the absorber to the water.

2.4.3 Cover Surface

In a conventional solar still the cover of the still is the same surface on which condensation occurs. This results in a decrease in the amount of solar radiation entering the still as more condensate is generated due to increased reflection of the incident radiation. Reflection occurs on both the surface itself and the condensed water on the surface; characterising the amount of reflected radiation is non-trivial due to the dependence on the shape and size of the water drops.

The material of the cover surface can have a significant effect on the productivity of the still. Studies up to now indicate that glass is preferential to other transparent plastics due to properties such as transmittance and roughness. The use of different materials for the cover surface has been investigated and has shown that the use of glass for the cover produce 27% more water than that of polyethylene terephthalate (PET) (Bhardwaj, ten Kortenaar and Mudde, 2013). The reasons for this are the droplet shapes on the respective materials; on glass the drops are flatter and more spread out which allows for more light to pass through compared to the drops on the PET surface.

Additionally, the water vapour that collects on the PET remains in place for much longer that does on the glass due to the higher contact angle of water on PET. This decreases the yield as the water fails to collect and allows additional condensation to occur. Glass is generally the preferred cover material due to its high transmittance for a wide range of angles of incidence (Kalidasa Murugavel, Chockalingam and Srithar, 2008). The contact angle of a material is important to the performance of a still for more than the above-mentioned reason; in the wetted condition materials with low contact angles allow more solar irradiation to pass through them than materials with high contact angles. The contact angle is therefore directly related to the production rate of distilled water (Bhardwaj, ten Kortenaar and Mudde, 2013).

Another factor to consider about the cover surface is the thermal conductivity. A higher thermal conductivity is better as it is easier for the cover to reject heat (Dimri *et al.*, 2008). The thickness of the cover is also of concern, a thinner cover surface produces better yields than the same still with a thicker cover surface (Bhardwaj, ten Kortenaar and Mudde, 2013), this is again explained by the ability of the cover to lose heat to the surroundings (Dimri *et al.*, 2008). Two glass covers of 3 mm thickness and 6 mm thickness were compared and it was observed that the thinner cover resulted in an increase in yield of 16.5% (Kalidasa Murugavel, Chockalingam and Srithar, 2008). Increasing the area of the cover can also affect the yield; an increase in area increases the amount of radiation which enters the still but also increases the area through which energy can be lost to the surroundings. Additionally, increasing the condensation surface area improves the yield of the still by providing additional area for the vapour to condense on, increasing the condensation rate results in a decrease in vapour pressure which consequently increases the rate of evaporation.

Bhardwaj, Kortenaar and Mudde, (2015) increased the area for condensation without significantly increasing the entry area for solar radiation using an irregularly shaped cover. They observed that as the area increased, initially a large increase in yield was obtained but that after a point the effect of changing the area became less and a very large change in area was required for a small change in yield. Part of the reason for the claimed increase in yield was that more heat could leave the still which increased the rate of condensation. Recall that a problem with conventional solar stills is optimising the operating temperature between the optimum evaporation, and condensation, temperatures. Thus, increasing the condensation surface area without increasing the incident radiation will result in a decrease in still temperature. This effect explains why Bhardwaj *et al.* (2015) also observed that the yield of water versus condenser area went through a maximum, as there is an area above which too much heat is lost and there is insufficient energy for evaporation to proceed at a satisfactory rate.

There are many factors to consider regarding the cover surface of the still as it is responsible for both energy entering the system and energy leaving the system. It is not a simple parameter to optimise in the design of the still, and much work has been done on trying to understand the different ways it affects the still's performance. Modifying the cover surface is one of the few ways to directly influence the condensation rate in the system, either by changing the amount of time which drops spend on the cover, or by changing the amount of area available for drops to form on.

2.4.4 Insulation

Insulation is an important part of a basin solar still as it ensures that minimum amounts of heat are lost from the still to the surroundings. It is undesirable to lose heat and preferential that the energy be retained within the system and used to heat the water. Basin type solar stills are typically insulated on both the sides and the bottom of the still. There are certain requirements that the insulating material must meet; it must be strong enough that the weight of the basin does not cause it to compress of deform, and it must be capable of withstanding high temperatures (Khalifa and Ahmad M Hamood, 2009a). Studies have been done on determining the degree to which the insulation improves the performance of the still, as well as determining the optimum thickness of the insulation material. Khalifa & Hamood (2009a) used polystyrene insulation and investigated three thicknesses: 3 cm, 6 cm, and 10 cm. The insulated stills were compared to a still with no insulation. They found that the stills with insulation had a larger yield than the still without, and that the presence of insulation could improve the performance by more than 80%. They also observed that the increase in yield from 3 cm insulation thickness to the 6 cm thickness was larger, but that from 6 cm to 10 cm there was practically no change in the productivity of the still. This is in agreement with the results shown by Malik *et al.* (1982, p. 31) where the yield of the still increases rapidly up to an insulation thickness just larger than 4 cm, after which the effect the additional insulation has on the yield is minimal.

The above results can be generalised in terms of the thermal resistances. Polystyrene has a thermal conductivity of 0.04 $W.m^{-1}.K^{-1}$ (Cengel and Ghajar, 2015, p. 914), the thermal resistances calculated for a unit area of material and corresponding to thicknesses of 3 cm, 6 cm, and 10 cm are 0.75 $K.W^{-1}$, 1.5 $K.W^{-1}$, and 2.5 $K.W^{-1}$. It can now be suggested that around a thermal resistance of 1 $K.W^{-1}$ the insulation is at an optimum thickness. There are many different types of insulating material that can be used, and the thermal conductivity of the insulating material will determine how effective it is as an insulator. A material with a lower thermal conductivity will keep more of the heat inside the still than a material with a higher thermal conductivity. Madani & Zaki (1995) evaluated the effect of the presence of a 4 cm layer of glass wool insulation on the yield of the still and found that the presence of insulation resulted in approximately a 15% increase in yield which appears low compared to the increases reported by Khalifa & Hamood (2009a) with polystyrene. Adding insulation to the system seems like an obvious addition to the still in order to reduce energy losses from the system. It is, however, important to understand the effect which it has on the system in order to optimise the still economically as well as to obtain the maximum yield. Knowing that after a certain thickness the effect of adding additional insulation is negligible is of great benefit to the economic optimisation of the still.

2.4.5 Still Feedstock Depth

The depth of water in the still has a large impact on the performance of the still. This is because the volumetric heat capacity of the still is largely determined by the volume of water available to absorb heat; if the incident radiation remains constant a larger volume of water will achieve lower temperatures than a smaller volume would. The depth of water is a parameter that is easily adjusted and is a cheap way to improve the performance of the still as it does not require additional components. All literature indicates that increasing the depth of the water in the still decreases the yield. This has been observed by Badran & Al-Tahaineh (2005) who investigated water depths ranging from 2 cm to 5 cm and found a constant decrease in productivity as the depth increased, Tiwari and Tiwari (2006) who looked at larger water depths of 4 cm to 16 cm and observed approximately a 30% decrease in the yield of the still, and Khalifa and Hamood (2009) who found a linear relationship between the productivity of a solar still and the brine depth and found that reducing the depth of the brine can increase the productivity of the still by 33% for depths between 10 cm and 1 cm.

Feilizadeh *et al.* (2016) investigated water depths of 2 cm, 4 cm, 8 cm, and 16 cm, while keeping the distance between the water and the cover constant and found a 75% decrease in yield as the depth increased from 2 cm to 16 cm in summer and 68% decrease in winter. In general, the relationship between water depth and still productivity is that as the depth increases the productivity decreases (Phadatare and Verma, 2007; Khalifa and Ahmad M Hamood, 2009b). The studies mentioned above all focused on water depths larger than 1 cm and there are very few studies which have been done on fluid depth less than 1 cm. Sharshir, Peng, *et al.* (2017) did a study on depths ranging from 0:25 cm to 5 cm and observed an optimum water depth within the still of between 0:5 cm and 1 cm. It is likely that below 0:5 cm dry spots develop in the still which negatively affect the yield of the still (Sharshir *et al.*, 2017).

There is one advantage of a larger water depth; stills with a small depth of water are extremely sensitive to small changes in solar irradiation due to cloud cover or other fluctuations because of their low volumetric heat capacity, this can severely affect the yield. On the other hand, stills with more water are not as sensitive due to the higher thermal capacity of the system (Kalidasa Murugavel, Chockalingam and Srithar, 2008). The depth of brine in the still adds no significant cost to the still and is therefore an attractive way of optimising the yield. It is clear from the above discussion that it has a large impact on the performance of the still and is worth careful consideration. Due to the varying volumetric heat capacity with varying depth, it is possible that the maximum temperature can be influenced thus affecting the evaporation rate.

2.5 ACTIVE BASIN SOLAR STILL

2.5.1 Agitation of Fluid

The use of agitation to improve the productivity of a simple basin solar still in an active modification as additional energy is required to power the agitation tool. The purpose of the agitator is to increase the contact area of the water and the air, and to break the surface boundary layer. These result in an improved rate of evaporation. The slight vibration of the still can also increase the frequency at which condensate runs off the cover and collects as distillate. This could potentially reduce the number of droplets which fall back into the still by reducing the time that a drop spends on the cover surface. (Eltawil and Zhengming, 2009; Rajaseenivasan *et al.*, 2017). The most common way of agitating the fluid is with a rotating shaft (Abdel-Rehim and Lasheen, 2005; Eltawil and Zhengming, 2009; Kumar, Esakkimuthu and Murugavel, 2016). Comparison of a conventional still with a still modified to have a rotating shaft showed that the yield was increased by on average 25% in the modified still (Abdel-Rehim and Lasheen, 2005). Rajaseenivasan *et al*. (2017) achieved similar results and saw a 30% increase in yield due to the addition of rotating shaft stirrers to the solar still.

There are other methods of achieving agitation within the still, an example of this is seen in the research done by Eldalil (2010) where the use of harmonic vibrations within the still was investigated. It was found that the yield was increased by 70% when compared to a solar still without vibrations. Another method of brine agitation is the use of pump that circulates the brine over an absorber surface. Kaviti, Yadav and Shukla (2016) reviewed the use of active solar still with inclined absorber surfaces, single and multi-effect active stills and multiple pass active stills. The still performance is improved in all variations but at an increased capital cost, cost of operation, and cost of maintenance. Another drawback with the use of these complex units is the complexity of material selection and manufacturing. One should keep in mind that these units are under severe thermal stress, which is incurred over several expansion-contraction cycles (day-night cycles), and it is extremely difficult to maintain air tight seals on all joints. Among the simplest of active designs are the inclined solar still. Figure 2-3 shows a schematic of a simple inclined solar still. In these stills, brine is pumped over the absorber surface and is heated up, essentially all other operation is exactly as with a simple basin solar still.

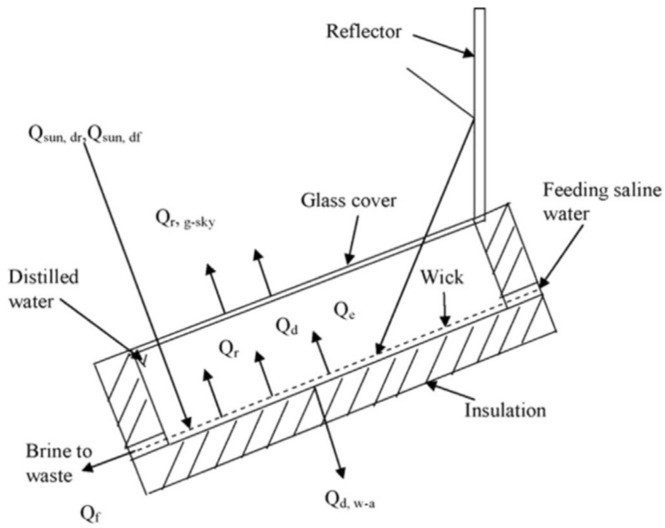

Figure 2-3: Schematic of an inclined solar still (Kaviti, Yadav and Shukla, 2016).

2.5.2 External Condenser

The addition of an external condenser can be advantageous to the performance of the still. Based on one of the primary drawbacks of a simple solar still being that evaporation and condensation must occur in the same unit it is likely that using a separate condenser unit could be a key aspect to improving the performance. An external condenser acts as a heat and mass sink which results in a decrease in heat loss by convection from the water to the transparent cover, increases the condensation rate, and can theoretically increase the distillate yield by 56% compared to a traditional solar still (Kabeel, Omara and Essa, 2017). Rabhi *et al.* (2017) compared a conventional unmodified solar still to a solar still with an external condenser, and an inlet to allow for air to move into the condenser. They observed that both the cover and absorber temperatures were lower in the still with the external condenser, and that the still with the condenser produced 3.15 $L.m^{-2}.day^{-1}$ compared to the conventional still which produced 2.38 $L.m^{-2}.day^{-1}$, a 32% increase in yield.

Parameters such as the volume and area of the condenser are important to its performance. Al-Kharabsheh & Goswami (2003) found that varying the condenser area influenced the evaporation rate; doubling the fin area on the condenser increased the yield by 9%. In practice the use of an external condenser is usually combined with a vacuum fan to aid circulation of air from the still into the condenser. A study by Kabeel, Omara & Essa (2014a) investigated a basin still with an external condenser and a vacuum fan drawing the evaporated water from the still to the condenser. They tested the still with and without the vacuum fan and found that the presence of the fan increased the yield by up to 53% depending on the power of the fan. Similarly, Monowe *et al.* (2011) investigated a solar still with an external condenser and a vacuum fan pulling humid air from the still into the condenser. The vacuum fan was powered by a PV panel of 1 m^2. They found that the presence of the vacuum fan increased the yield by 60% compared to the still with just the external condenser.

If a vacuum fan is used in the still there are a few additional advantages. The vacuum fan can increase the turbulence of the air above the water which results in an improved evaporation rate (Omara, Kabeel and Essa, 2015), the reduction in pressure can decrease the operating temperature which can result in a decrease in losses (Al-Hussaini and Smith, 1995; Ibrahim and Elshamarka, 2015), and the movement of air within the still can also reduce the effect non-condensable gasses have on condensation (Al-Hussaini and Smith, 1995).

It is easy to understand how the use of vacuum and an external condenser in a solar still will increase the yield, research shows that it has a significant effect on the performance. Adding only an external condenser is a once off capital cost while the addition of a vacuum fan adds to the operating costs. It will be necessary to consider the economic implications of these modifications, but purely considering maximising the yield both are effective and worthwhile.

2.6 A SIMPLE BASIN SOLAR STILL

2.6.1 Basin solar still design

A simple basin solar still is essentially an enclosed container with an inclined, transparent cover to allow for the transmittance of solar irradiance. These stills all have very similar design features as annotated in Figure 2-4.

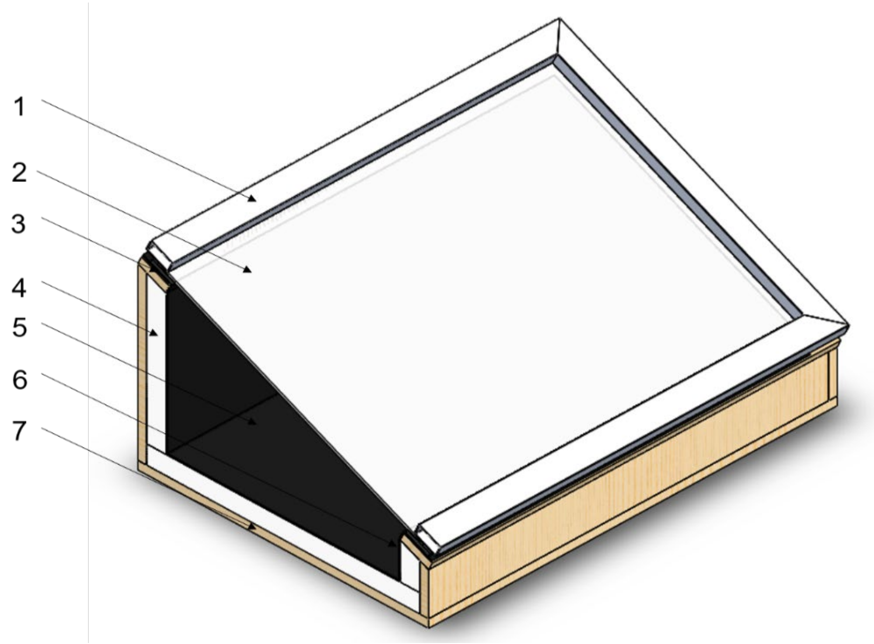

Figure 2-4: A cross-sectional, scale drawing of a simple basin still.

The annotated items are described as follow:

1. A rigid frame to secure the cover to the body of the basin still. The frame also allows for uniform pressure to be applied on the cover. The uniform pressure is essential to ensure a sealed system.
2. A transparent cover to allow for the transmittance of solar irradiance. It should be noted that the cover is not necessarily required to be transparent in the visible spectrum only. However, it is essential to be as transparent as possible through the full range of the solar spectrum. The complete solar spectrum is shown in
3. Figure 2-5.
4. Water resistant seal. A simple basin solar still is, usually, exposed to atmosphere through the condensate collection system. However, it is important to seal the warmest, most humid areas from atmosphere to reduce unnecessary temperature losses.
5. The use of effective insulation material is imperative to the optimal operation of a basin still. Heat lost by means of conduction through the still body is not utilised to produce condensate and should be minimised as far as possible.
6. The absorber material is the surface responsible for absorbing the solar irradiance and transferring this energy to the rest of the system through conduction, convection and radiation. This material should have a high absorbance, low reflection and low emissivity.
7. Typically, condensate runoff from the cover of the still will collect at the front of the still and channelled to a central collection point. This channel cannot be seen in
8. Figure 2-4.
9. The insulation material described in 4 is typically a lightweight, aerated material and does not provide much resistance to deformation and can be fragile. Therefore, a rigid, hard-wearing body is shown to provide protection from bumps from transportation and to increase the durability and weatherability if the unit.

Figure 2-5 is shown for reference and additional information. It should be noted that the visible range is a relatively small band of the entire solar spectrum.

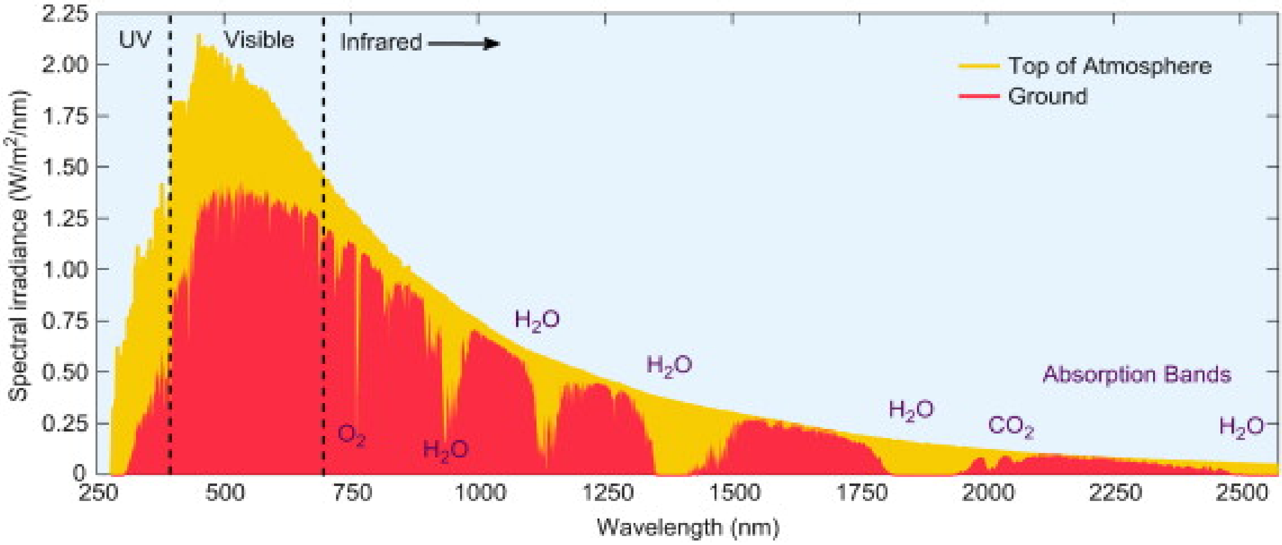

Figure 2-5: Spectral irradiance as measured at the top of the atmosphere and at ground level. Image obtained from https://www.sciencedirect.com/topics/engineering/spectral-irradiance.

2.6.2 Still Cover

The transparent still cover should exhibit several important properties to enable the successful operation of a still. Apart from the obvious function of transmitting a large portion of the spectral irradiance, it is also the surface where condensation would occur. Consequently, the cover material should not exhibit a very high resistance to heat transfer as this will impair the heat rejection required to condense the water vapour (Dimri *et al.*, 2008). As condensation occurs on the cover material, it is also preferential to exhibit some hydrophilic properties. This property favours the runoff of condensate in a film-wise manner. Dropwise condensation and runoff typically occur on hydrophobic surfaces and can be advantageous as well as disadvantageous.

This can be explained by the fact that hydrophilic surfaces would expose less surface area for condensation whereas dropwise condensation on a hydrophobic surface would expose more available surface area for condensation. However, the retention time is prolonged when runoff occurs in a dropwise manner and there is a potential for large droplets to detach from the surface before reaching the collection point (Bhardwaj, ten Kortenaar and Mudde, 2013). Lastly, any material to be considered as the still cover must be able to withstand elevated temperatures and should provide a high resistance to UV radiation and weatherability. From the above-mentioned discussion, it is evident that the selection of cover material is not trivial. Literature (Kalidasa Murugavel, Chockalingam and Srithar, 2008; Bhardwaj, ten Kortenaar and Mudde, 2013) suggest the use of glass, polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), polycarbonate (PC) and in some instances polystyrene (PS). It is also reported that glass is used most often and exhibits good optical properties, is hydrophilic, shows good weatherability and resistance to UV but is fragile.

2.6.3 Insulation Material

Albeit the use of insulation material does not directly influence the transmittance, absorbance or transferring of heat to the brine or from the condensate, it is extremely important in the proper functioning of a still. Since the stills operate at temperatures significantly higher than ambient conditions, a large portion of energy will be lost through conduction is the stills are not properly insulated. Therefore, the selection of insulation material and thickness thereof is also considered as a design parameter in the basin still. If the insulation material is subject to direct sunlight, it should also be resistant to UV degradation, tolerant of elevated temperatures and must be suitable for use in humid areas. The thermal resistance should also be considered in the still design. Literatures shows that an increase in thermal resistance has diminishing return above a value of approximately 1 $K.W^{-1}$. Increasing the insulation thickness beyond this point incurs additional cost at a relatively low increase in productivity (Malik *et al.*, 1982; Khalifa and Ahmad M Hamood, 2009a).

2.6.4 Absorber Material

The absorber material/surface is essentially the area that should absorb all solar radiation and rejects it as heat energy into the brine. This material should therefore be highly absorbent, non-reflective and should, preferably, exhibit a low emissivity. It should also be water resistant, UV stable and should tolerate elevated temperatures. Matt black surfaces exhibit the optical properties required as absorber material. Typical materials used as absorber area are gravel, soot, carbon black, charcoal, black paint and several forms and types of black polymers (Madani and Zaki, 1995; Kalidasa Murugavel, Chockalingam and Srithar, 2008; Matrawy, Alosaimy and Mahrous, 2015).

2.6.5 Geometric Design Parameters

The geometric design parameters influence various aspects of the still performance, the ease of manufacturing and maintenance of the still. The obvious dimensions include the still width, length and height (refer to Figure 2-4).

- The length and width of the still defines the area available for the absorber material. Consequently, an increase in these values increase the area proportionally. However, literature (El-Swify and Metias, 2002; Feilizadeh *et al.*, 2017) recommends a length to width ratio of 2. Ratios smaller than 2 impose significant shadows cast by the sides of the still. An increase in the width is also limited by the distance that droplets must travel before being collected.
- The height of the still is somewhat fixed by the cover inclination angle. The cover inclination angle is determined by the latitude of the location intended for still operation. Pretoria, South Africa is located at 25°43’48’’S and 28°13’12’’E and it is generally accepted that the optimal, year round, inclination angle is equal to the latitude (25° in this case) (Nafey *et al.*, 2000). Once the cover angle has been determined, the basin height can be fixed at the minimum height that would provide the desired angle and enough space for condensate collection (Feilizadeh *et al.*, 2017). Increasing the basin height increases the total volume of the still and area exposed to conductive heat loss, which, in both cases, negatively affects still performance.

2.6.6 Material Selection Considerations

While the design considerations are primarily focused on dimensions, optical properties and thermal properties, it is imperative to consider the durability of the equipment, ease of cleaning and maintaining and the durability of each individual component. The factors are extremely important to consider as the operation of such a device is subject to very high UV irradiation, high temperatures, a saline (corrosive) environment and there will also be fouling of the wetted surfaces during normal operation. It is therefore important to consider materials that are:

- Very durable in direct sunlight and can withstand prolonged exposure to direct sunlight.
- Wetted materials must be easy to clean, smooth and not susceptible to fouling. This would imply that the surfaces must be easy to clean using a soft, damp cloth and should not require scrubbing as this would cause the surfaces to be damaged and provide breeding areas for thermophilic bacteria.
- Outside surfaces must be sealed and should not be damaged by rain or condensation.
- Materials should also not be susceptible to cracking or breaking during transport or when bumped as this could occur frequently during normal operation.

2.6.7 Additional Design Parameters

The most important design parameters were noted in the above-mentioned section; however, numerous other additions and designs can affect still performance. Among these are transparent side panels (to the left and right of the still body), reflectors on the inside of the still, assembling the still in panels at angles less than 90°. Although there are other design parameters worth mentioning, these are omitted due to the fact that it either show significant disadvantages with seasonal or time changes or have a severe impact on the manufacturing cost of the system.

CHAPTER 3: EXPERIMENTAL METHODS

3.1 CONFIGURATION OF A SIMPLE BASIN SOLAR STILL

The basin solar still was designed using as far as possible the optimum geometric parameters obtained in literature (Section 2.6). In specific:

- The ratio of length to width was designed to be 2, as recommended in literature (El-Swify and Metias, 2002; Feilizadeh *et al.*, 2017).
- The average height of the still was minimised within practical constraints; primarily the need for a water catchment system with sufficient angle to allow flow of condensed water (Feilizadeh *et al.*, 2017; Jamil and Akhtar, 2017; Rajaseenivasan *et al.*, 2017).
- The inclination angle of the cover was designed to be 25°; the latitude of Pretoria, South Africa, the location where the experiments would be conducted (Tiwari, Thomas and Khan, 1994; Singh and Tiwari, 2004).

The stills were designed to have a cover area of 0.5 m^2, this being the area through which solar irradiation enters the still. Figure 3-1 indicates the dimensions used for to manufacture the reference and first version of the stills. These dimensions are based on the guidelines recommended in the literature. The length and width were also chosen such that the still can be easily manoeuvred and transported by two persons. The height of the panel at the front of the still was chosen such that the condensate collection channel has a sufficient angle to ensure that condensate runs off toward the condensate collection container below the still. By selecting the height of the front panel, the height of the rear panel is fixed by the inclination angle of the cover. The basin indicated in Figure 3-1 was constructed form a cheap plywood material and sealed with a non-toxic, black sealant on the inside and well-insulated on the outside.

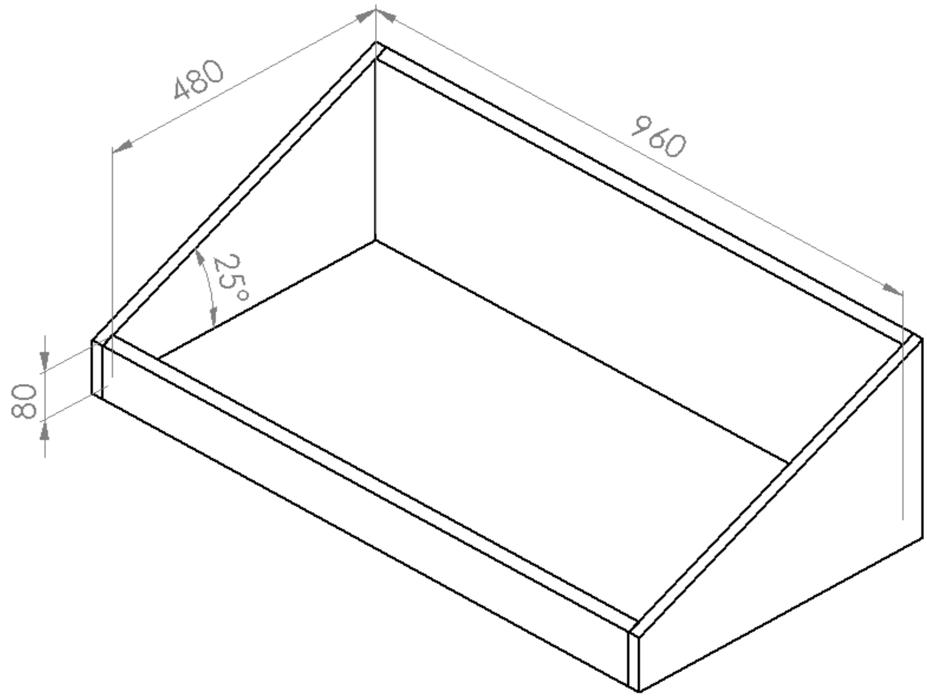

Figure 3-1: Dimensions used for manufacturing of the reference still and the first version for testing.

An expanded foam sealant was applied to the edges of the basin to ensure that the cover would form a tight seal when closed. For convenience, the cover was attached to a rigid frame, hinged on one side and fastened with eccentric latches on the opposite side. This ensured that the basin could be opened and maintained with minimal effort. Further details on each revision of the still design will be given in the relevant section with the performance evaluation of that particular still revision.

3.2 APPARATUS

3.2.1 Basin Stills with Induced Flow

Inducing flow in a solar basin still has the advantage of manipulating the rate of heat transfer due to fluid flow or the lack thereof. It is believed that the rate of condensation limits the overall production of condensate in the system (Marais, 2018) and this limit can be manipulated by means of forced convection and consequently the heat transfer. The proposed method of improving the rate of condensation is to include electrical fans that would induce flow over an external heat transfer surface. This can be achieved through a tube bank or over a flat surface. The design of this unit is, however, not as easy as one might think. This is due to the need to condense the water vapour without decreasing the still temperature drastically. To achieve this, the heat exchange surface area must be optimised for a varying range of still operating temperatures. To further complicate the task, the temperature and wind conditions of the surroundings must also be considered. Three options were considered in this investigation;

- air flow through a tube bank, with and without forced air flow over the tube bank,
- air flow over a finned, flat plate, with and without forced air flow over external fins, and,
- air flow over a finned, flat plate with controlled cooling by means of thermoelectric coolers.

Option 3 was evaluated further to attempt to recover the energy from the condensate through the heated side of the thermoelectric cooler. Thermoelectric coolers operate on the so-called Peltier effect, which is, in short, heat being generated on one side of adjacent conductors of different materials while the other side is cooled. Thermoelectric coolers that are commercially available can generate a temperature difference of approximately 65°C when a current is passed through the device. These devices typically operate at 12 VDC and at 5 A. If such a system is managed correctly, slightly less than 60 W of energy can be withdrawn from the hot, humid air and reintroduced into the same stream that is now dryer due to condensation on the cold surface. This is obviously stated in the ideal case where now thermodynamic consideration is given. All options of induced fluid flow were installed on the existing simple solar basin stills and any improvements are to be considered at the cost of the additional electrical input.

3.2.2 External Area for Condensation

Different designs of heat exchangers were considered for installation onto the solar basin stills. Two designs were considered; heat sinks are designed to transfer heat very efficiently due to the finned surface (Figure 3-2); tube banks expose a large surface area to both internal and external heat transfer and can be distributed in various ways to allow for better movement of fluid over the tube bank (Figure 3-3). Both these designs show merit and can be installed onto the simple basin solar stills.

Figure 3-2: Heat sinks used as external condensers. The unit on the right is equipped with a fan for forced convection.

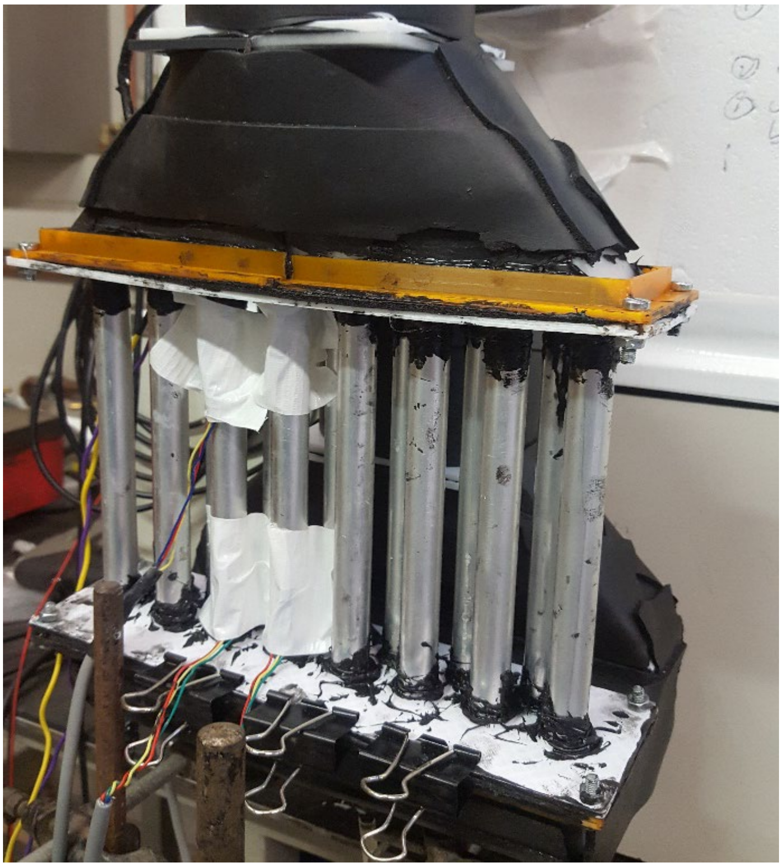

Figure 3-3: An image of the tube bank used in place of the heat sinks. The tubes are staggered to allow air to pass freely over the tube bank.

3.2.3 Data Acquisition and Measuring Sensors/Instruments

Data acquisitioning and logging was done by means of Arduino Mega 2560 R3 microcontrollers with the addition of a SD-card datalogging shield. These microcontrollers can read the various data from various sensors, low-level calculations and text file manipulation. The use of these microcontrollers allowed for easy and reliable field installation at a low cost. Various types of sensors were used to measure several variables on each still;

1. Temperatures were measured by means of DS18B20 One-wire sensors. These sensors can measure temperatures in the range of -55°C to 125°C with an accuracy of ±0.5°C. The One-wire functionality allows multiple sensors to be installed on one communication pin on the microcontroller, which allows the measurement of numerous temperatures without many pin allocations. These sensors were installed as a waterproof version to measure the water temperature as well as the TO-92 form factor to measure surface temperatures.
2. DHT22 humidity and temperature sensors were used to measure the air temperature and humidity inside the still. These low-cost sensors can measure temperatures in the range of -40°C to 80°C with an accuracy of ±0.5°C, and humidity in the range of 0% to 100% with an accuracy of ±2-5%.
3. The mass of the condensate collected was measured in real-time by means of TAL220 type load cells. The load cells can measure 5 or 10 kg, two versions were used, with a combined error of ±0.05% of the full scale. HX711 load cell amplifier shields were used to convert the analogue signal to a digital signal.
4. An Apogee SP-215-SS silicon-cell pyranometer was used to measure global solar radiation. These instruments measure solar radiation in the range of 360 to 1120 nm with a field of view of 180°. The measurement range is limited at 1250 $W.m^{-2}$ by the maximum voltage on the analogue pins on the Arduino Mega 2560 R3 microcontroller.

A StellerNet BLUE-Wave VIS-25 spectroradiometer was used to measure spectral irradiance in the region of 350-1000 nm by means of a cosine-corrected detector. Reflectance data was measure with the same instrument by means of an additional reflectance probe. The functionality and instrument specifications can be viewed at the manufacturer’s website https://www.apogeeinstruments.com/lab-spectroradiometer/

3.3 SYSTEM ENERGY BALANCE

In order to understand the system and determine where inefficiencies and losses are most prevalent it is important to do an energy balance of the system. It is also important to understand the selected control volume for determining the various components comprising the total energy balance. In Figure 3-4, the dashed red line depicts the boundary of the control volume chosen for evaluating the transfer of energy to and from the still. The annotated items are; 1) the still cover, 2) insulation surrounding the still body, 3) the still body when Still 1, 2 or 3 is referred to, and 4) the body of brine at the base of the still. The selection of the control volume indicated in Figure 3-4 is arbitrary but necessary for the intended purpose of the energy balance analysis. The boundaries are chosen such that all modes of heat transfer can be considered.

1. Conductive heat transfer through the body is the primary mode of heat losses through the body and therefore crosses the control volume boundary.
2. Convective heat transfer is a primary mode of heat transfer, in conjunction with radiative heat losses, from the still cover and is bounded by the control volume.
3. Radiative energy transfer, to and from the still, crosses the control volume boundary through the still cover.

Lastly, the only mass transfer that occurs over the control volume boundary is the condensate collected from the collection channel which is not indicated in Figure 3-4.

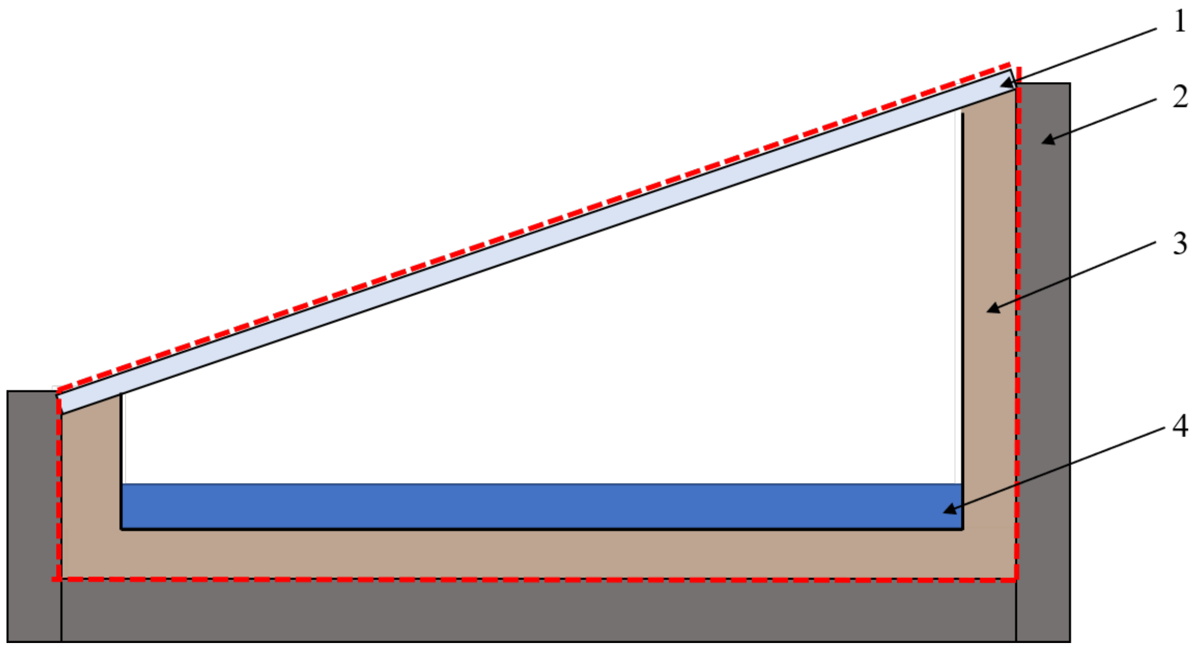

Figure 3-4: The control volume considered for the evaluation of energy transfer to and from the still.

3.4 INVESTIGATIONS BASED ON PRELIMINARY OBSERVATIONS

3.4.1 Loss of Condensate

During the operation of the solar basin stills it was observed that a significant portion of the condensate dripped back into the still before the droplet reached the collection channel. This is a significant energy loss since the latent heat of condensation is rejected through the cover with zero increase in productivity. Experiments were planned to determine the maximum travel distance of water droplets before they would detach from the cover material. It was assumed that the cover material, cover inclination angle and still temperature could affect the outcome of the investigation.

3.4.2 Reducing the Energy Losses through the Still Cover

Based on results obtained from the energy balance analysis of the solar basin stills, improvements to the cover material were considered to reduce unwanted energy losses through the cover. Different cover materials were considered and variations in thickness and layering of the cover material, in the case of a glass cover, were also considered.

3.5 EXPERIMENTAL PROCEDURES

Due to the stills operating in varying conditions throughout any given day and with seasonal change, it was deemed necessary to run at least two stills for a minimum of five days at a time. The stills can then be compared over several days to determine the effect of any changes made to a still. One unit was always kept unchanged to quantify and compare the effects of the improvements made. Periodically, baseline experiments were conducted on all operational still to ensure that the productivity of the stills did not deviate from their reference state and to further ensure reliable and comparable results.

3.5.1 Simple Basin Solar Still Operation

Stills were operated in an open environment on the roof of Engineering 2 Building, University of Pretoria, Pretoria, South Africa. The surroundings do not significantly hamper natural air movement and does not cast any shadows on the stills. All experiments were initialised between 06h00 and 09h00. Stills were occasionally operated over weekends and were then left to operate unattended. Data, for comparative purposes, was only used from the Friday morning to the Saturday morning. The additional data did, however, prove insightful as they were essentially operated with a smaller starting volume of water. The typical operational procedure was as follow;

1. Clean the still cover from any condensate, dust or debris and let the still stand open.
2. Add 9 L of water to the basin or top the water level up to a depth of approximately 25 mm.
3. Close the still cover and ensure that it is properly sealed.
4. Attach empty collection container to the load cell and wait until the container is still.
5. Power the microcontroller unit up. An LED indicator will switch on once the load cell was correctly zeroed.
6. Once zeroed, the collection containers were removed, and a reference mass was attached to the load cell. A switch was used to signal the microcontroller that the calibration of the load cells can be done. Another LED indicator would switch on once the load cells were correctly calibrated. The empty collection containers were then attached to the load cells.
7. A known mass of water, usually 200 g, was added to the collection containers to verify the load cell calibration factor and to stabilise the containers. This reduced the measurement noise due to windy conditions.
8. A second switch was thrown to start data collection and logging.
9. LED indicators were also employed to indicate any error conditions during operation. Error conditions were defined as unreadable or disconnected measurement sensors or errors in initialising the memory card.
10. The stills were then left to operate until the following morning. The volume of condensate collected was manually measured to verify that the real-time mass measurements were accurate.

Stills were operated for a minimum of three days with clear conditions when any improvements or additions were made. It should be noted that the stills were started with equal amounts of water every day, and not operated for three consecutive days. Comparison of data of cloudy or rainy days was difficult and could lead to inconclusive or biased results.

3.5.2 Basin Solar Still with Forced Fluid Flow Operation

Induced fluid flow system was operated the same as a simple solar basin still. Additional measuring sensor was installed to measure all additional variables and the electrical inputs were noted as this energy component must be incorporated in the total energy balance. The effect of external forced convection must be quantified by means of a parametric study while considering the temperature of the system and the flow rate of the internal humid air, as well as the flow rate of any external ambient air flow. Any performance improvements must be critically evaluated against the increase capital cost and operational cost.

3.5.3 Procedures Involving Simulated Basin Stills

The simulated basin stills were employed to reduce development time for still additions and improvements. These experiments could be conducted at the operating temperature and maintained at a steady operating condition with an hour, unlike the solar basin stills. These stills were used to evaluate several different aspects of the stills.

3.5.3.1 *Quantifying the Amount of Condensate Lost*

Fourteen small containers were placed inside a water bath to determine the amount of condensate lost back into the still. These containers are 40 mm wide and were placed adjacent to one another. The water bath was set to the desired temperature and was operated for 2 hours. The operating temperatures were 50°C, 60°C and 70°C which is comparable to the operating temperatures of solar basin stills. Still cover inclination angles were also varied between 15°, 20° and 30°. Condensate collected in the first container represented droplets that reached the collection channel in the solar basin stills, while the contents of all other containers were considered lost energy.

3.5.3.2 *Reducing the Energy Losses through the Still Cover*

In conjunction with the experiments described in the preceding section; the cover material was also investigated. The use of 4 mm window glass was considered to compare to the conventional 5 mm PMMA cover material. Ultimately, the use of a layered glass cover, with a 2 mm air gap in between, was considered to increase the thermal resistance and reduce energy losses. These experiments were carried out in the same manner as described in the preceding section.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 INTRODUCTION

To determine the success of any additions or modifications made to a still it is necessary to know what the ideal scenario is (assuming no energy losses), where and why energy losses occur and how well any given addition or modification performs when compared to a standard reference still. For these reasons the results reported will include sections on the solar irradiance as measured at the locale of operation, analysis of a complete energy balance performed on a reference still, and modifications made to passive stills. Further modifications are made to the passive stills to convert these to active stills. These modifications include the addition on water circulation pumps, air circulation fans and a combination of both. The conversion of the passive stills to active stills enables the direct comparison of the results obtained from the active stills to that of the reference passive still without the addition of unnecessary variables in design or geometry.

4.2 TOTAL SOLAR IRRADIANCE FOR PRETORIA, SOUTH AFRICA

Global tilted irradiance data was collected from mid-June 2018 to the end of September 2018 by means of an Apogee SP-215 pyranometer and thirty days were identified as days with zero cloud cover or interference. A total daily average of 6.06 $kWh.m^{-2}$, with standard deviation of 0.24 $kWh.m^{-2}$, was determined from these datasets. This equates to an ideal maximum achievable condensate volume of 9.15 $L.m^{-2}.day^{-1}$ when evaluated at the water temperature at the maximum rate of condensation. The value indicated above assumes that no energy is lost to the environment apart from the latent heat of condensation necessary to condense the evaporated water and that no incoming irradiation is reflected from any surface. This is inevitably not possible since there are always energy losses present in any physical system which is not at equilibrium with its surroundings. However, the presented value gives valuable insight into the performance of the solar stills presented in remainder of this text.

The locale of operation of this work falls in the region of 5.4-5.6 $kWh.m^{-2}$ as indicated in Figure 2-1. Assuming the performance of the stills are scalable on the total daily irradiance, one can assume that the solar stills presented here will perform slightly worse along the north-eastern parts of South Africa, along the coastal regions of Kwa-Zulu Natal and the Eastern- and Western Cape. However, one can expect equal or improved performance in the Free State, North-West, portions of Limpopo province and Northern Cape.

4.3 COMPREHENSIVE ENERGY BALANCE FOR A SIMPLE BASIN SOLAR STILL

Analysis of a few datasets, with respect to the energy balance, indicates which areas are subject to high energy losses and what portion of the solar irradiance is utilised in producing condensate. Figure 4.1 represents the proportions of energy leaving the control volume with reference to total solar irradiation over the time period 06h00- 05h59 for a random selection of days. From Figure 4.1 the losses from the still cover are the largest contributing term to the energy balance and is cumulatively responsible for approximately 50% of all the energy transferred. The bundled value comprises of the light reflected from the cover surface and heat transferred through convection and radiation from the cover. The portion of losses due to reflection are inevitable and is a physical property of the cover material used. Both radiative and convective losses are primarily governed by the cover temperature and can be influenced by a reduced operating temperature. Temperatures in excess of 50°C are not uncommon and provide a large driving force for heat transfer, especially since radiation is a function of the cover temperature to the fourth power.

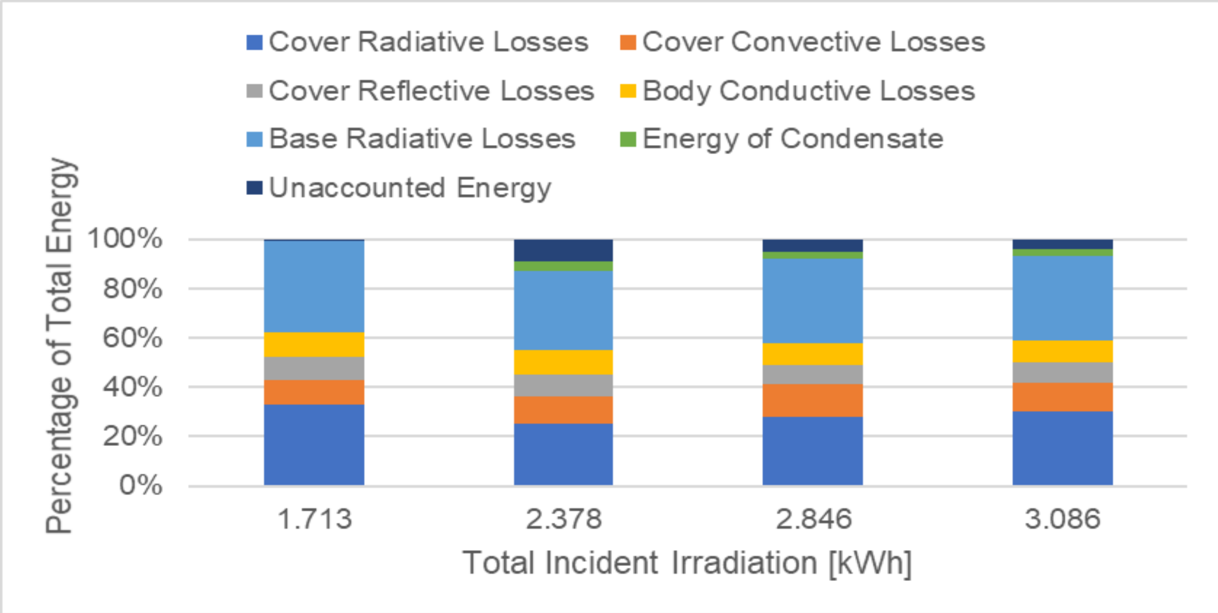

Figure 4-1: The energy balance analysis, over a simple basin still (reference still), for a random selection of days with the solar irradiation on the still as independent variable.

The base radiative losses are somewhat speculative due to the complexity of the analysis of the geometries involved and the uncertainty of the material properties. The magnitude of these losses may be inaccurate but is most definitely a portion of the energy lost to the surroundings. However, reducing the radiative losses from inside the still can only be achieved by means of a reduction in the absorber surface temperature or by means of modifications to the cover material. Reducing the absorber temperature will affect the performance of the still negatively as this is the driving force for evaporation and will also decrease the temperature difference between the area of evaporation and condensation. Modifications to cover can be made by adding infrared reflective films on the inside of the still. However, these materials are costly and could also affect the amount of incoming radiation, mode of condensation (dropwise or film condensation) and heat transfer through the cover. For these reasons, it was not considered to investigate improvements in reducing the radiative losses from inside the still. Also noticeable from Figure 4-1 is the relatively small proportion of losses through the insulation. Additional insulation will not be economically feasible and will not be considered any further. It should be noted that the convective losses over the insulated surfaces are not considered. These losses are erratic and relatively inaccurate purely because of the complexity in analysis of convection over the geometry of the stills and velocity (speed and direction) of the wind. The heat conduction through the insulation is the limiting factor and is therefore considered the overall rate of energy loss through the walls and bottom.

The energy content of the condensate leaving the system represents utilised energy. This value seems very low for all indicated days; however, it should be stressed that a portion of the energy losses through the cover is needed for condensation to occur and to maintain the driving force for condensation and this portion of energy is not included in the energy of the condensate. The unaccounted energy is a bundled term to indicate the portion of energy lost or utilised that cannot be determined accurately. To mention a few possibilities:

1. Evaporation from the collection container.
2. Uneven temperature distribution over surfaces (surface temperatures are assumed constant where one sensor is used and linearly distributed if multiple sensors are used).
3. Inaccuracies with respect to measurements in ambient conditions.
4. Assumptions made with respect to convective and radiative losses from the cover.

The results obtained from the energy balance analysis gives valuable insight into the typical operation of a basin solar still and identifies the areas to consider for effectively improving the performance of such a still. It is evident that the cover surface or material can be improved to provide increased efficiency of the solar stills.

Some of the shortcomings of the polymethyl methacrylate covers used in the energy balance analysis will be discussed in the following sections.

4.4 OBSERVATIONS FROM EXPERIMENTS ON THE REFERENCE STILL

During the several months of experimental work there were various observations made during the operation of the reference still that are necessary to note. Condensate began forming on the covers within minutes of closing the still. The droplet size increased until the drops began running consistently down the cover every few seconds. As soon as a drop had run and cleared the area in its path, condensate reformed on this area immediately, drop formation could be observed in real time. All the stills fitted with a PMMA cover had problems with drops dripping back into the stills from the cover. If the drop began to run from the top half of the cover it would become too large to adhere to the cover and would fall back into the still before reaching the channel where condensate was collected. Counting, for a few minutes, the drops that ran all the way to the bottom and the drops that fell into the still indicated that for every drop collected a portion of another drop could be lost. This was for the period when the cover was most saturated with large drops, when smaller drops exist on the cover there is less water for them to collect as they run down and fewer drops are lost in this manner.

4.4.1 Material Incompatibilities

The *Durapond™* sealant caused numerous problems. The surface looked like the sealant had bubbled (Figure 4-2). It is unclear if this was due to poor adhesion of the sealant to the wood, the temperatures experienced inside the still causing degradation of the polyurethane sealant, air pockets trapped beneath the sealant, or solvent which had not evaporated properly when the sealant was drying. Regardless of the reason, the *Durapond™* sealant began to leak at some point in time and had to be replaced with the PVC tarpaulin used in the later experiments. Due to the design of Revision 2 the leak was not noticed until much later, this resulted in the polyurethane foam becoming wet and inconsistent results being obtained from a selection of experiments done in that still.

Figure 4-2: Deterioration of the Duram Durapond sealant.

4.4.2 Effects of Disturbance Variables

It is necessary to understand the effects which disturbance variables have on the performance of the still. These variables are the wind speed, wind direction, ambient temperature, and intensity of solar irradiation. Many of the independent variables in the system can be classified as disturbance variables making it even more important to understand their effects. The discussion in this section will focus primarily on the results from the reference still as it remained unmodified throughout most of the project and for that reason its results can easily be compared.

4.4.2.1 *Ambient Conditions*

Theory suggests that the wind speed will affect the convective heat losses from the cover plate and change the temperature of the cover. Wind speed and direction changes erratically during a day and characterising the wind behaviour over a day using simple averages or variances did not yield any direct observable correlations with still performance.

Figure 4-3 shows the amount of water produced in the reference still as a function of the total solar irradiation received by the still in that day. The data points in Figure 4-3 are coloured based on the average daily ambient temperature with the dark red dots representing the warmest temperatures and the dark blue dots the coldest. The points with incident irradiation values in the excess of 4 kWh per 0.5 m^{-2} are possibly anomalies; the irradiation measurements for several consecutive days was abnormally high, the measured values decreased again after this period. However, the linear relationship observed would support the validity of the points despite their larger irradiation intensities.

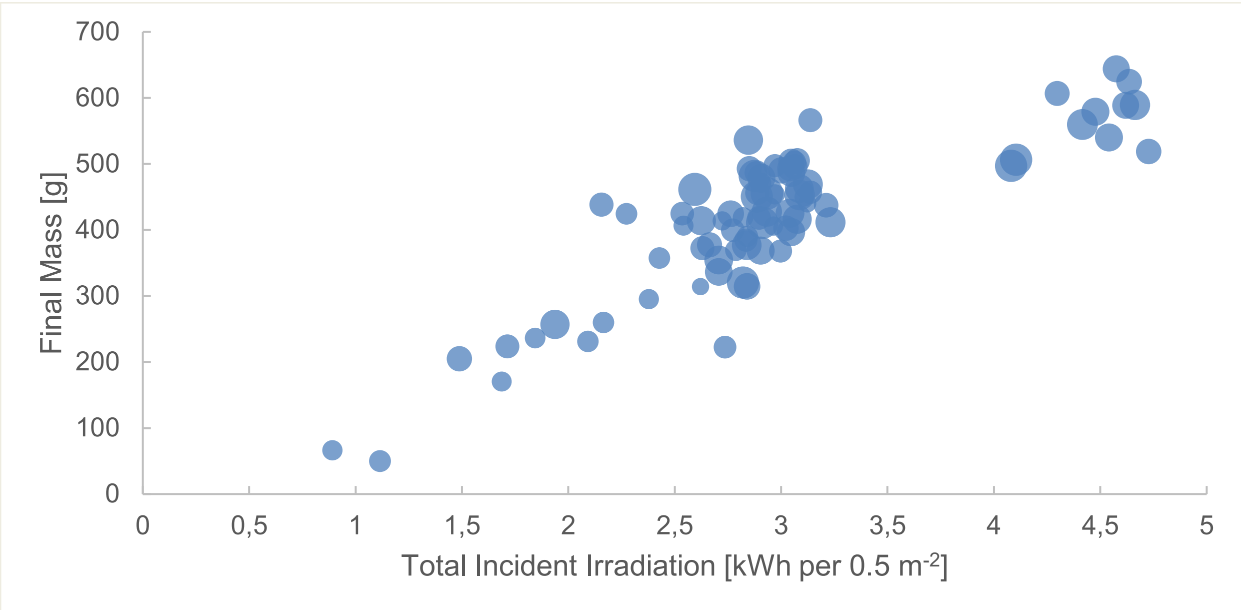

Figure 4-3: Mass of condensate versus total irradiation seen by the still, considering the 0.5 m^2 area, with bubble diameter indicating average daytime ambient temperature.

The data strongly suggests a linear relationship between the incident solar irradiation and the yield of the still. However, it can also be seen that the days with the lowest yields experienced cooler temperatures than the days with higher yields. This is however not conclusive as suggested by the data shown in Figure 4-4. No clear relationship or trend can be determined from the presented data. Wind speed and direction was also considered as a disturbance variable but was found to be too erratic and no clear conclusions could be drawn from the collected data. This variable does influence the operation of the stills, however, with the data being collected on the minute, every minute, measurement uncertainty and the erratic wind effects in the urban environment it was not possible to obtain any meaningful or accurate relationship.

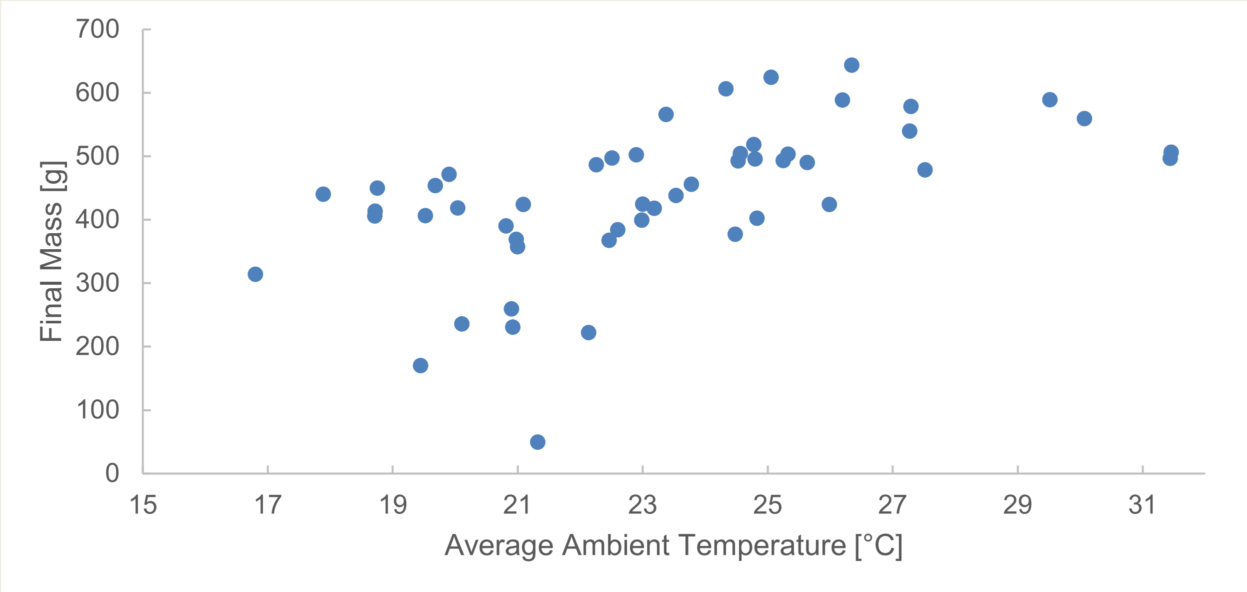

Figure 4-4: Mass of condensate versus average daytime ambient temperature.

4.4.2.2 *Seasonal Variation*

A large variation in still performance is expected for different seasons of the year. This variation was not observed and show the still performance being relatively independent on the season (Figure 4-5). This can be explained due to the relatively clear skies observed during winter months and more cloudy days during summer months. Other possibilities are the positive (or negative) effect of ambient temperature, the temperature difference between still components and the ambient temperature or wind, however, these are all speculative and cannot be considered as the actual- or only effect through the seasonal changes.

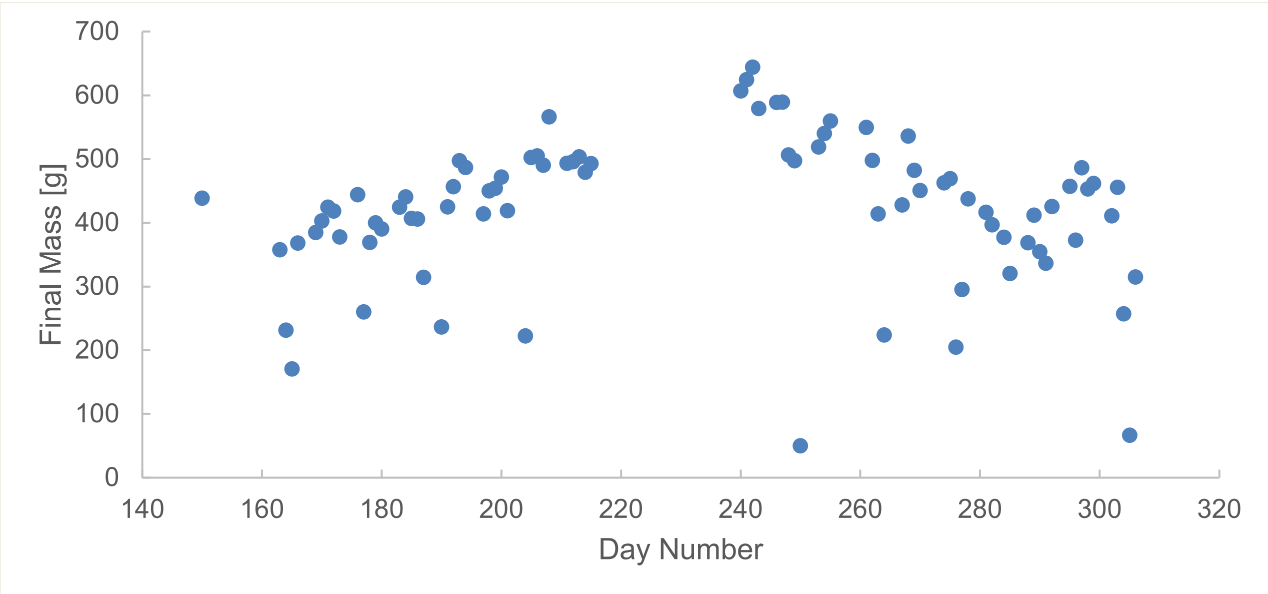

Figure 4-5: Mass of condensate plotted against day number to observe the change in performance over the change in season.

4.4.3 Reflection and Transmittance of the Still Cover

From the data obtained in the previous sections it was determined that the cover material should be critically evaluated with respect to condensate losses and energy losses. For these reasons the following work was included in the investigation. The optical properties of some materials considered are shown in Table 4-1. The cost of these materials is also shown for reference. Initially it was considered that PMMA would be the best material for use in the solar stills. This decision was based on the face value of the optical properties as well as the fact that glass is extremely fragile and could incur high maintenance costs during the lifespan of a still. However, it was not considered that the condensation formed on the cover would greatly affect the reflection or transmittance of sunlight. The portion of energy lost from reflection reported in Figure 4-1 is calculated based on the optical properties of the PMMA material.

Table 4-1: Conductive and optical properties of materials considered for solar still covers.

Material	k ($W.m^{-1}.K^{-1}$)	ε	T_{solar}	R_{solar}	A_{solar}	$R.m^{-2}$
Glass	0.7	0.9-0.95	0.79	0.07	0.14	~ 259 (4 mm)
PMMA	0.19	0.86	0.92	0.08	< 0.005	~ 1100 (5 mm)
PC	0.19		0.89			~ 1000 (5 mm)

Differences in light transmittance may exist between stills equipped with glass and PMMA covers due to the different mode of condensation observed on these covers. This can be verified visually but not quantified with the naked eye as shown in Figure 4-6. However, the effect of the droplets and film can be quantified by means of an UV-Vis spectroradiometer.

Figure 4-6: Different modes of condensation observed on PMMA and glass covers.

Solar irradiance measurements were taken at different times during the day and was compared to the spectra obtained when measure inside the still. This was made possible with the use of a fibre optic cable and a cosine-corrected detector. A comparison between the different spectra is shown in Figure 4-7. The effect of the different cover material and condensation mode can be quantified by integration of the solar spectrum.

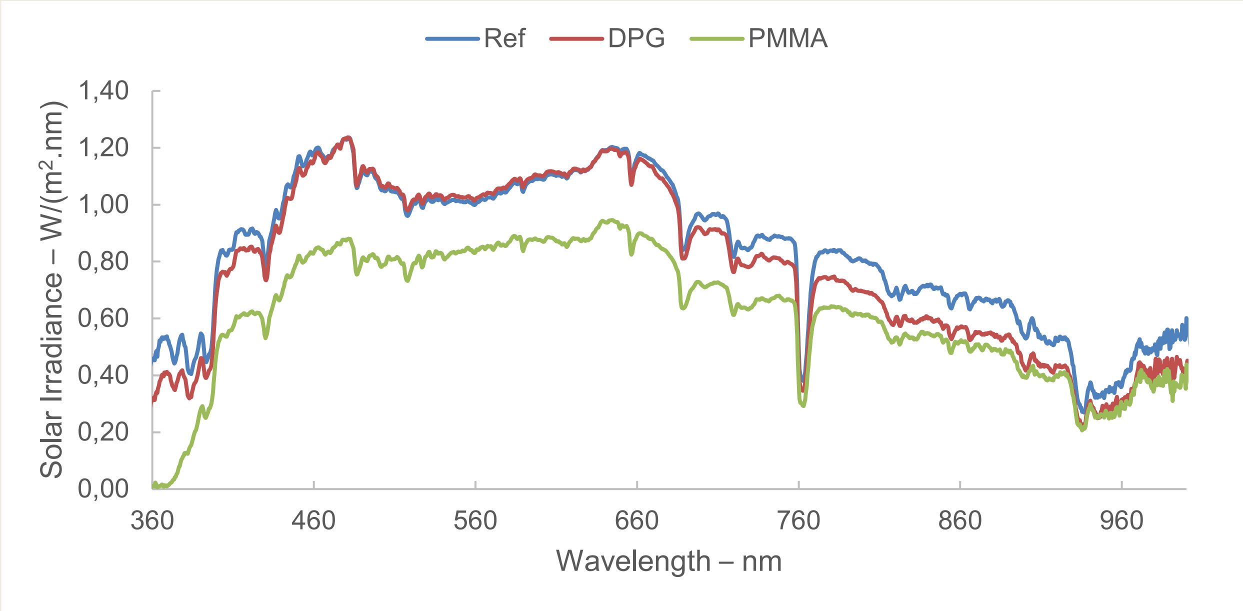

Figure 4-7: Difference in the solar irradiance due to different cover material and condensation mode. Measurements were taken at 14:30 PM

Integration of the solar spectra measured at various times during the day shows promising results for the use of a double pane glass cover. The results shown in Figure 4-8 is based on the solar irradiance measured at the same time of day and measured normal to the still cover.

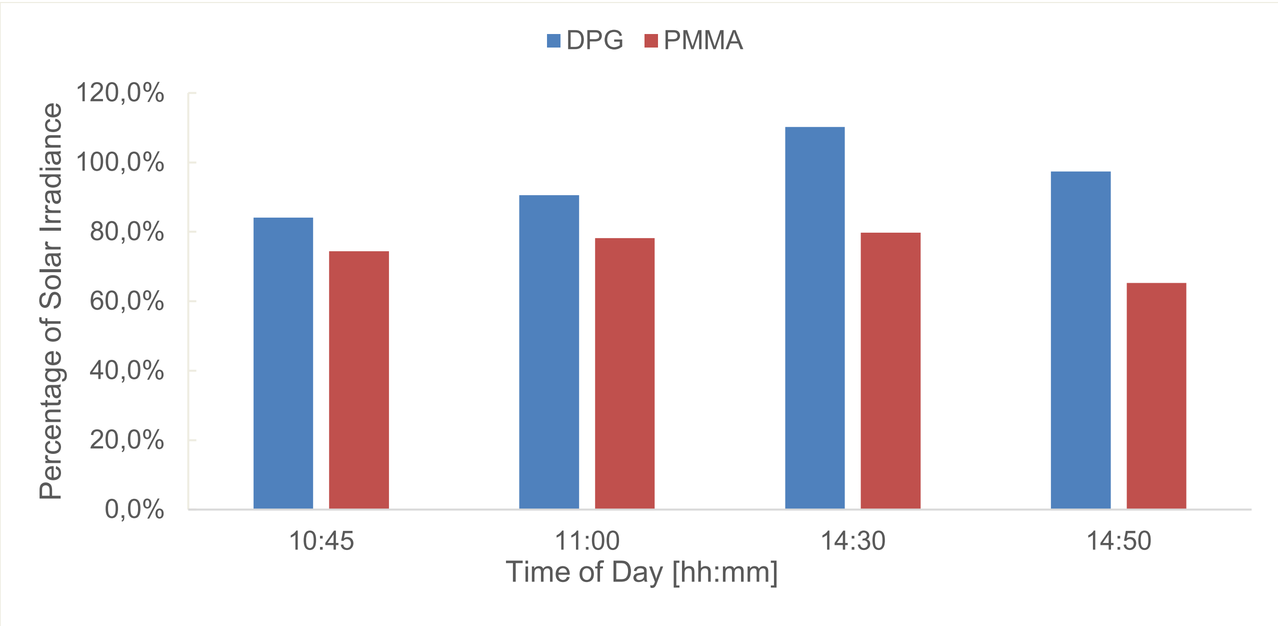

Figure 4-8: Portion of solar irradiance transmitted through different cover materials, with condensation on the cover, at different times of the day.

It is evident that the double pane glass cover has superior transmittance of solar irradiance during operation. This contradicts the optical properties shown in Table 4-4, however, these properties are for the cover material only and does not consider the additional reflectance or absorbance of the condensate. This is also the reason for the difference in reported values for reflective losses in Section 4.3. It should also be noted that solar irradiance measured for the glass cover at 14:30 is in excess of the actual reference irradiance. This can be attributed to the use of the cosine-corrected detector that measures the irradiance normal to the detector surface. If the condensate on the glass cover concentrates and reflects more irradiance that should be measured, higher than theoretically achievable results could be obtained. Measurement at different positions in the still should eliminate such outliers but is not possible since large holes had to be made in the still wall to accommodate the detector.

4.4.4 Condensate Losses from the Still Cover

It was observed that droplets at the top of the still cover is predominantly larger than anywhere else on the cover. This can be explained with the aid of Figure 4-9, any droplet that acquires enough mass will start to run down the cover and accumulate all other droplets in its path. This concludes that the bottom section of the cover will be cleared more frequently and that the droplets at the top of the still will grow much larger than those lower on the cover. If any of the large droplets at the top of the still starts to run down, it will rapidly gain mass and has a higher potential to drip back into the still before reaching the bottom.

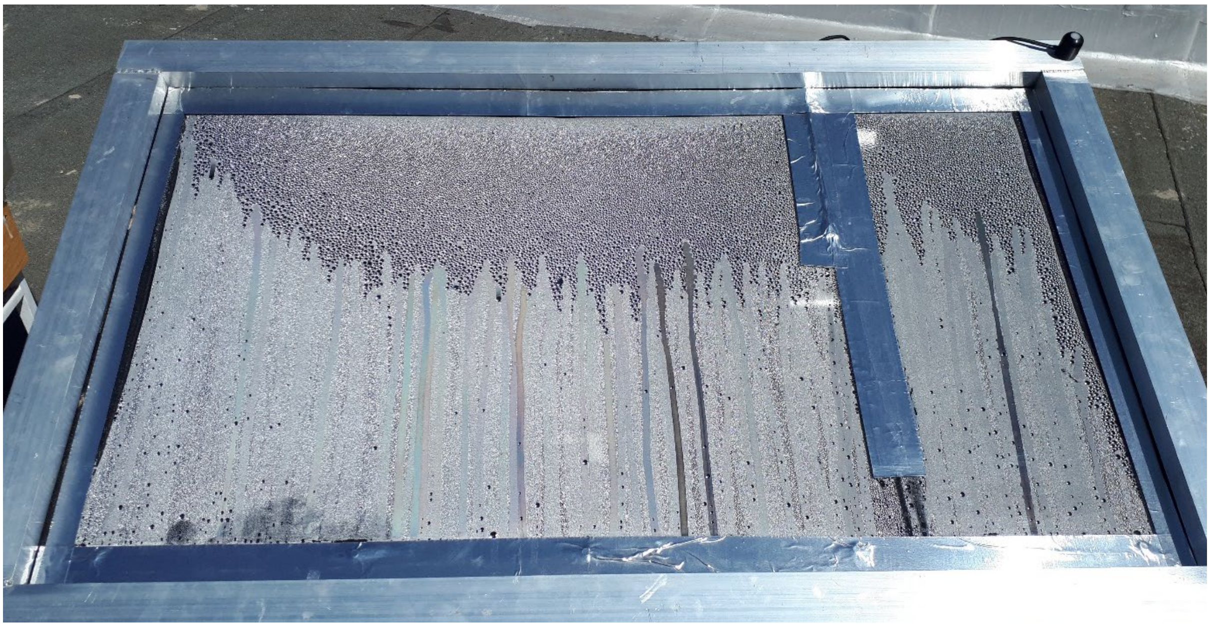

Figure 4-9: Condensate growth and runoff from solar basin still cover.

The amount of condensate lost was determined in a simulated basin still for various cover angles and water temperatures. The still dimensions can be optimised to reduce or eliminate energy losses incurred by this loss of condensate. Figure 4-10 and Figure 4-11 show the fraction of condensate collected at various positions from the collection channel for a PMMA and double pane glass cover. The cover inclination angle was set at 15° and 30° respectively. These results were also obtained at various water temperatures. It is expected that more condensate will be lost at lower angles of inclination, however, it should be noted that less than a quarter of all the condensate collected on the PMMA cover at an angle of 15° was in the condensate collection channel. Less condensate was lost at the higher cover angle, but it was still not optimal. It is also evident that the amount of condensate lost on a PMMA cover is affected by the water temperature in these experiments. This is not necessarily correlated to the actual water temperature but could rather be correlated to the rate of evaporation or condensation.

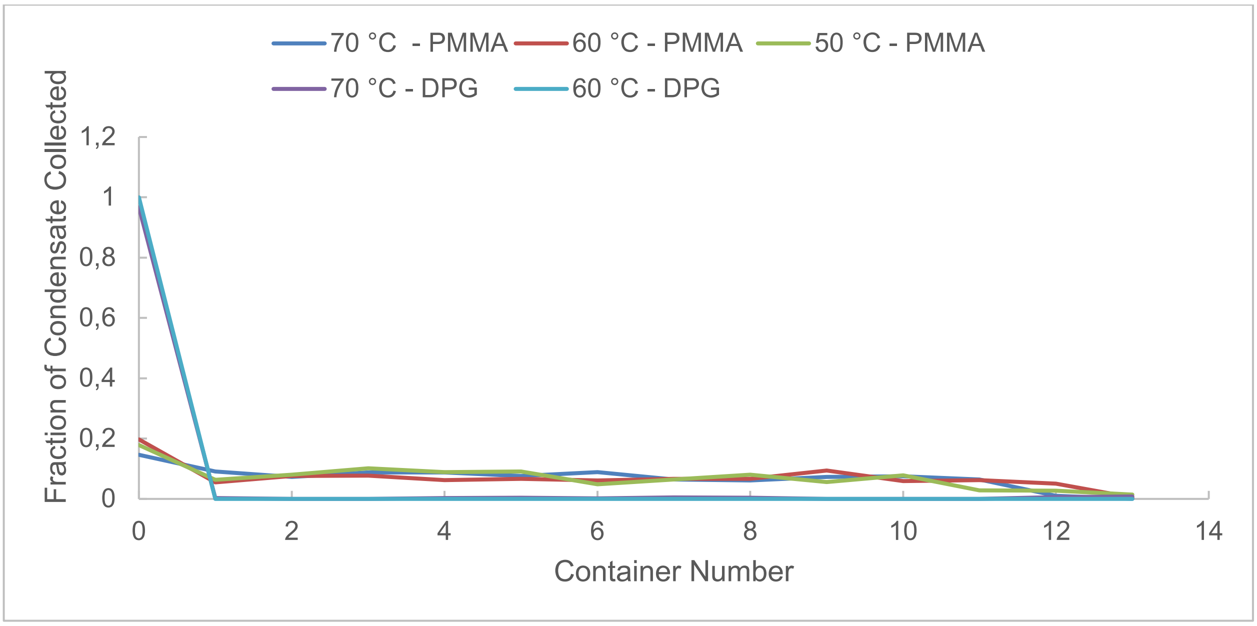

Figure 4-10: Condensate collected at various position in the still basin of a cover inclination angle of 15°. Container 0 indicates condensate collected in the collection channel during normal operation and each container has a width of 40 mm.

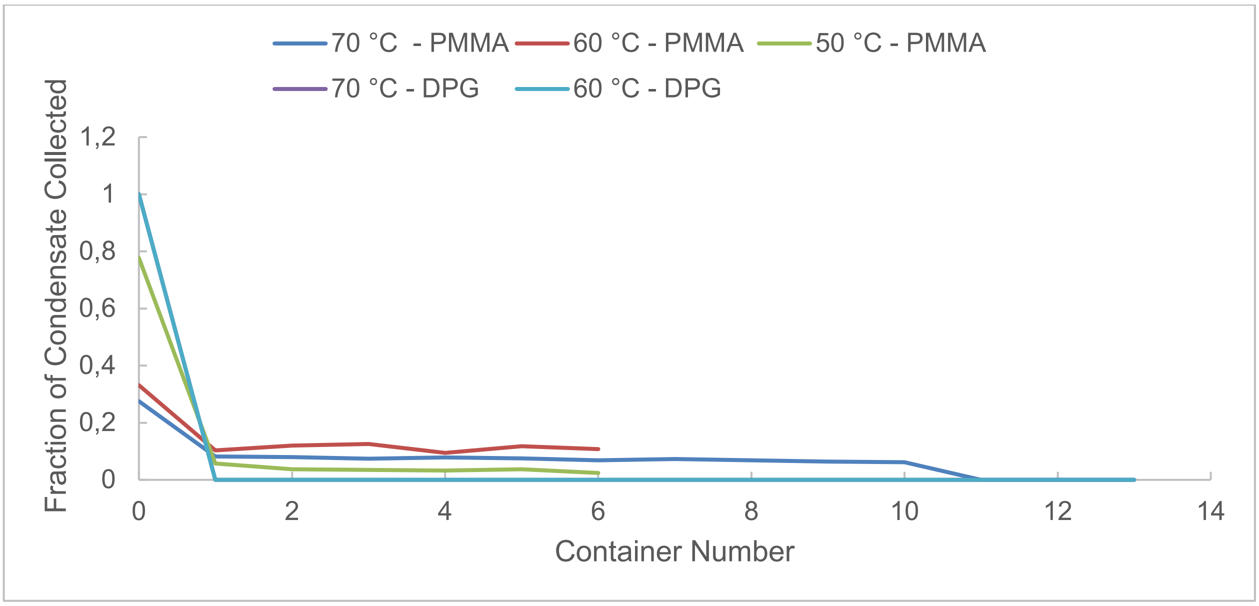

Figure 4-11: Condensate collected at various position in the still basin of a cover inclination angle of 30°. Container 0 indicates condensate collected in the collection channel during normal operation and each container has a width of 40 mm.

In all cases the double pane glass produced 100% recovery, except for a cover angle of 15° and at a bath temperature of 70°C. This is possibly also due to the increase rate of evaporation and / or condensation. The higher recovery of condensate from the glass cover can be contributed to the hydrophilic nature of the glass surface. Condensate forms thin films on the glass and runs down as a thin continuous stream rather than in well-defined single droplets as is the case for the PMMA surface. However, dropwise condensation poses much less resistance to heat transfer than film condensation. The liquid films on the glass surface does hold another advantage, upon observation the glass with liquid film appears clear and transparent, whereas the droplet covered PMMA surface appears somewhat opaque.

4.4.5 The Effect of Insulation on Still Performance

Various insulation materials and thicknesses were tested to quantify the effect of the insulation on the still body on the amount of water produced. Literature (Section 2.4) suggest a thermal resistance of around 1 $K.W^{-1}$ as an optimal balance between efficiency and cost. Several experiments were conducted to verify this result and the condensate mass collected is shown in Figure 4-12. These data are comparable with respect to the specific still used, the amount of solar irradiance and ambient temperatures experienced during operation. From Figure 4-12 it is clear that an increase in insulation thickness (or change in material) does have an impact on the mass of water produced during operation. The cost of these materials can be seen in Table 4-2.

Table 4-2: Comparison of various insulation materials used.

Material	Thickness [mm]	*R* [$K.W^{-1}$]	Cost [$R.m^{-2}$]	Cost [$R.(K.W^{-1})^{-1}$]
Plywood	19	0.16	131	819
Armaflex	13	0.34	120	353
PU Foam	40	1.1	193	175
Extruded PS	50	1.6	209	131

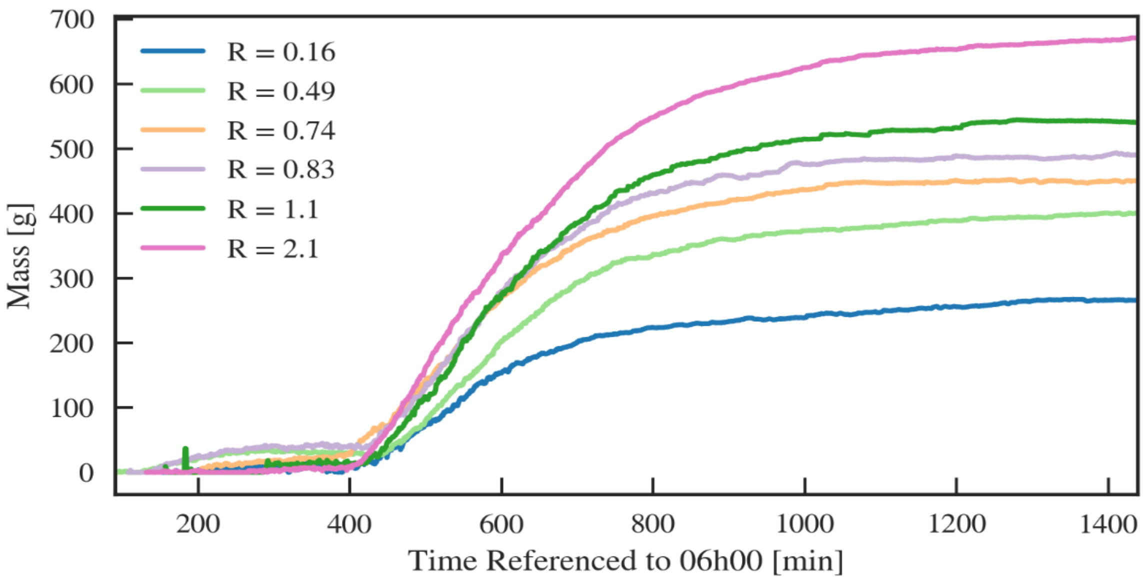

Figure 4-12: Mass of condensate for stills with specific thermal resistances, calculated for a unit area of the still, selected from various days over the course of the project.

The thermal resistance data from Table 4-4 and Table 4-5 do not correspond on directly with those shown in Figure 4-12 due to layers of the different materials, for instance stills with plywood and one or multiple layers of insulation.

4.4.6 Increasing Evaporation Rate

A few attempts were made to influence the rate of evaporation by means of materials such as a carbon black nanofluid, charcoal and a carbon felt material. In all instances, still efficiencies and mass of water produced increase when compared to the reference still. The addition of more absorbent materials to the basin still should increase water temperature and consequently increase the evaporation rate. This is observed when considering the data in Table 4-3.

Table 4-3: Comparison of still efficiencies with the addition of more absorbent materials to the water or basin surface. The increase in efficiency is referenced to the Duram Durapond material.

Material	Average Reference Still Efficiency [%]	Average Rev. 1 Efficiency [%]	Increase in Efficiency Rev. 1 [%]
PVC Tarpaulin	10.2	21.4	8.6
Carbon Black	11.6	21.6	8.8
Charcoal	8.7	20.7	7.9
Carbon Felt	8.6	21.4	8.6

In all instances the material added showed an increase in efficiency when referenced to the Durapond™ sealant used initially. When considering the addition of the carbon felt, the increase in efficiency is comparable to that of the PVC tarpaulin, which is a modification to the still rather than an addition to the still. However, the reference still also shows an increase in efficiency for the experiments conducted with the PVC tarpaulin which could imply that the ambient conditions were more favourable for still operation during these experiments. The addition of charcoal and a carbon black nanofluid does not provide sufficient improvement to consider the continuous use of these materials, especially in the case of the nanofluid as it was prone to settling through the thermal cycle.

4.4.7 Increasing Condensation Rate

Several attempts were made to increase the rate of condensation of the simple basin solar stills. Grooves were machined into a portion of the still cover to introduce more surface area and to promote droplet agglomerating and to increase the rate of droplet runoff. An aluminium heat sink was also added to the outside of a still cover to promote heat transfer at the top off the cover. Both alterations are shown in Figure 4-13. The addition of the heat sink shows condensate runoff in that area whereas the area not covered by the heat sink does not show any condensate runoff. This observation should imply an improved operation and efficiency, however, the data collected during these experiments show erratic behaviour and cannot be concluded as positive. The increase in yield relative to the reference still was determined as -2% up to 36% with an average of 12.6% and standard deviation of 13.9%. The large standard deviation is evidence of the erratic behaviour of the still during these experiments. The addition of the grooves in the cover also showed an increase in the yield of Revision 2. However, in this case the increase cannot be justified due to the labour of machining the grooves. Alternative materials with similar characteristics as the grooved PMMA cover was considered but could not be found as an “off the shelf” solution.

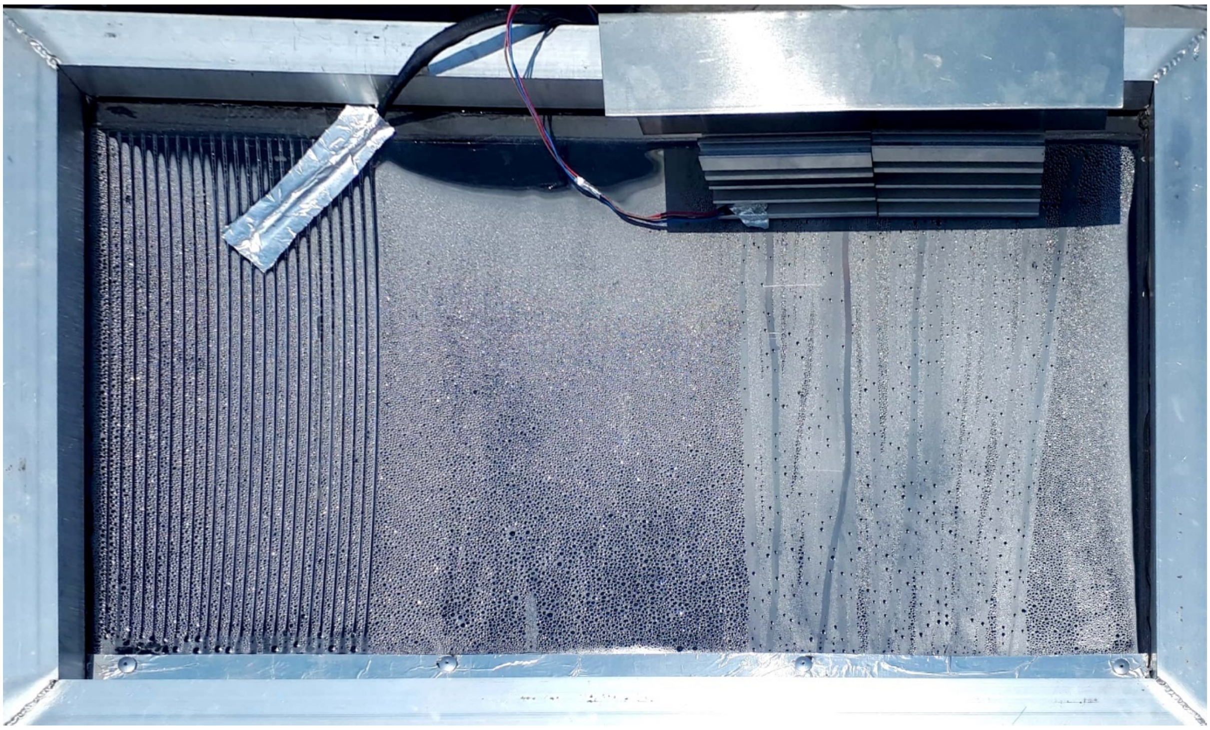

Figure 4-13: A still fitted with a heat sink and grooves added to improve the rate of condensation and condensate runoff.

4.5 PERFORMANCE EVALUATION OF SIMPLE BASIN SOLAR STILL

4.5.1 Overview

Inherent differences exist in the stills as a result of small differences in materials of construction or inaccuracies introduced during construction. Baseline tests were run to determine the extent of these differences and to quantify the effect which they have on the performance of the stills to allow for comparison of results.

4.5.2 Simple Basin Solar Still Version 1

4.5.2.1 *Revision 1 Design*

The still body was made of 18 mm *ShutterPly*, a type of plywood. It was chosen as it is cheap, strong, and readily available. The still body needs to be rigid and sufficiently durable to withstand exposure to ambient conditions. The wood was coated on the inside with black *Duram™ Durapond™* which is a non-toxic, polyurethane waterproofing with a service temperature range of is -44°C to 120°C making it suitable for the use in the solar stills. *Durapond™* was selected for its ability to act as both the waterproofing and the absorber surface. Due to a lack of available data for the emissivity of *Durapond™* a value of 0.97 was used in later analysis, as this is the commonly used emissivity of black paint, the corresponding absorptivity for black paint is also taken as 0.97 (Cengel and Ghajar, 2015, p. 743). The stills were later coated with polyvinyl chloride (PVC) coated textiles, such as those used in dam linings, to replace the *Durapond™* absorber. The *Durapond™* proved to be unreliable and the quality of the waterproofing deteriorated over time, it is uncertain if this was due to an incorrect service temperature range of the *Durapond™* or if there were unfavourable interactions between components of the still. The PVC is a black coated fabric which is UV stabilised to discourage degradation of the polymer. Initially, PMMA was used as cover material due to its favourable optical properties and its durability. Glass was considered but deemed too fragile and could easily be broken or cracked due to thermal stress, hail or bumps during transportation, cleaning or operation. The material properties for PMMA and other potential materials are shown in Table 4-4. From these properties, the most notable are the thermal conductivity, transmittance, UV stability and flexural strength. These properties are what favoured the use of PMMA in the initial design of the stills.

Table 4-4: Comparison of relevant material properties for common transparent materials.

	PMMA	PC	PS	Glass
Thermal conductivity [$W.m^{-1}.K^{-1}$]	0.19	0.22	0.128	0.7
Transmittance [%]	92	82-91	89-90	79-88
Refractive index	1.49	1.58	1.6	1.52
Contact angle with water	69.1-74.7	81.3-84.0	85.3-88.5	~55
UV Stability	Yes	Limited	Limited	Yes
Flexural strength [MPa]	107-117	94-120	66-95	55-70

The first revision is shown in Figure 4-14. This version was manufactured as described in the preceding text. After failure of the *Durapond*™ sealant, the stills were retrofitted with PVC tarpaulin. It is not clear from Figure 4-14, but the stills' rigid, plywood body is on the inside of the insulation material. This version was equipped with foamed nitrile rubber insulation with a maximum thickness of 26 mm.

Figure 4-14: First basin stills manufactured and tested.

4.5.2.2 *Revision 1 Performance Evaluation*

The first version was manufactured in duplicate and the second unit was used as an unmodified still for comparative purposes. Table 4-5 shows the difference between the two, seemingly identical, stills built. The relatively low yield of these stills can be attributed to the inferior insulation material thickness and the method it was applied. The design also included a large mass of plywood that had to be heated which contributes to the low yield and poor efficiencies.

Table 4-5: Efficiencies and Water Produced from the Revision 1 still.

Day Number	Ref. Still Yield (*kg*)	Revision 1 Yield (*kg*)	Difference in Yield (%)	Ref. Still Efficiency (%)	Revision 1 Efficiency (%)
204	0.22	0.25	12	7	8
205	0.50	0.59	17	11	14
206	0.50	0.60	18	12	14
207	0.49	0.56	14	12	13
208	0.57	0.59	3	13	13
211	0.49	0.57	16	11	13
212	0.50	0.57	15	11	13
213	0.50	0.59	18	12	14
214	0.48	0.59	22	12	14

Comparison of the energy balance considered over both Revision 1 still can be seen in Figure 4-15. Although some differences are observed in the energy balance, no clear conclusion can be drawn as to why the two stills perform somewhat differently. The large portion of unaccounted energy for this version of the stills can, to some extent, be contributed to a poor design in the collection channel. The collection channel was made from a rectangular aluminium extrusion and the flat surface was conducive to droplets accumulating rather than running down toward the collection vessel. Later designs were fitted with a 90°, V-shaped channel. This version also directed the collected condensate to either side of the still whereas in later designs, condensate was directed to the middle of the still. This reduced the length of tubing required to direct the condensate to a single collection vessel.

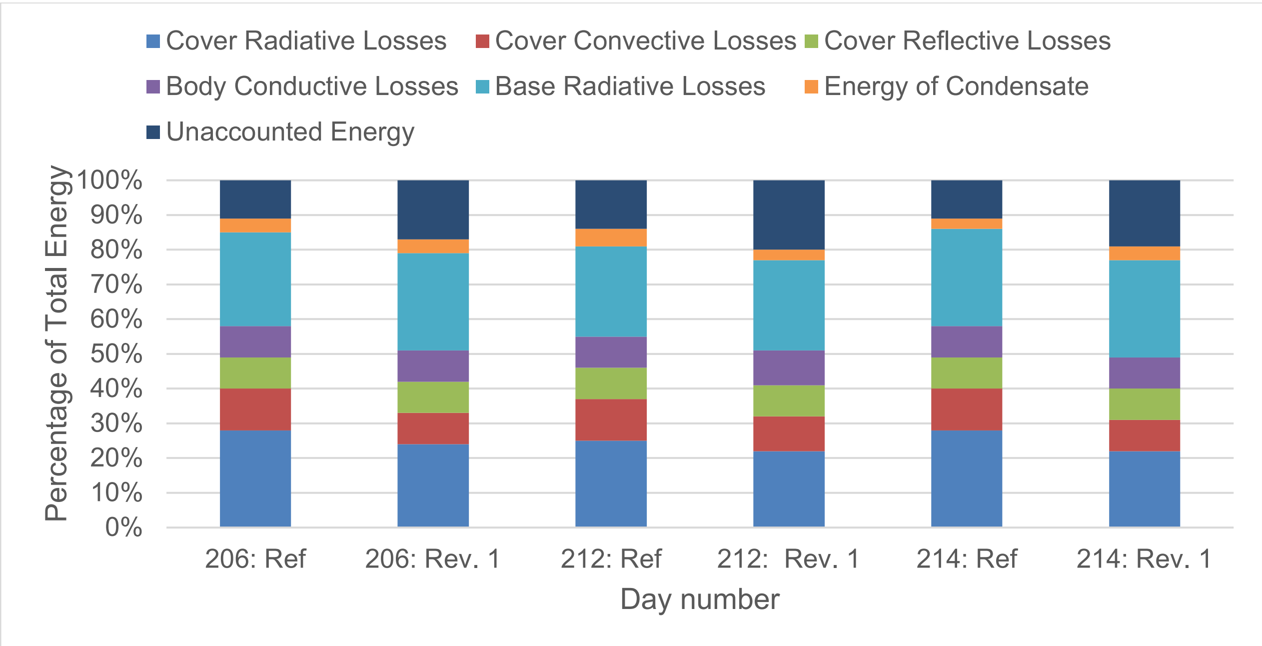

Figure 4-15: The energy balance for the Version 1 still and the reference still for a random selection of days.

When considering the still performance, the two most notable variables are the still cover and water temperatures. Figure 4-16 and Figure 4-17 show the variation of these temperatures for a few days for the Revision 1 still. A lower cover temperature and higher water temperature should infer higher yield which is observed in the data for Revision 1. The lower cover temperature could be caused since more water condenses in this still which implies more heat transfer through the cover. This is not observed in the energy balance analysis but could be contributed to the uncertainty of the unaccounted energy.

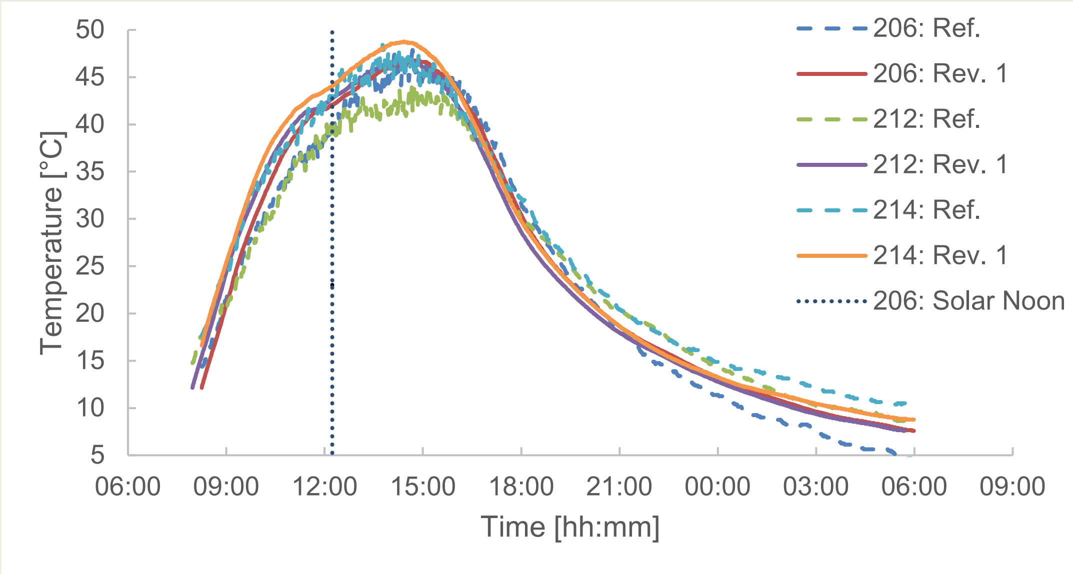

Figure 4-16: Cover temperature for the Version 1 still and the reference still.

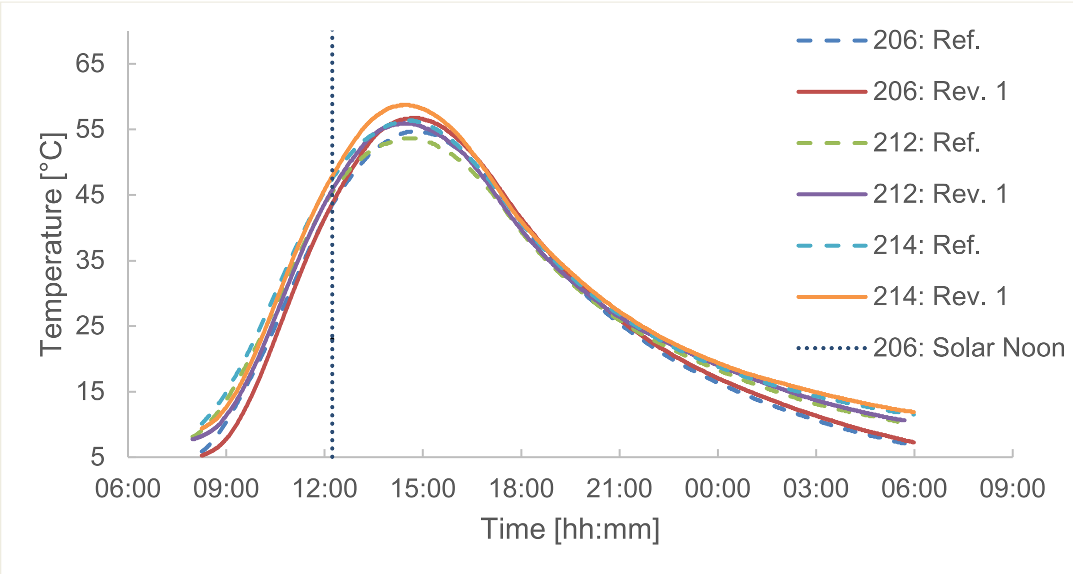

Figure 4-17: Water temperature of the Version 1 still and the reference still.

It is evident that the temperature difference between the still cover and the water temperature is not appreciable when considering the reference still, however, this value is significant for Revision 1. The average difference is around 6°C for Revision 1. The onset of condensate collection and rate of condensate collection should also be observed and compared when considering modifications in the stills. Figure 4-18 shows no distinct difference in the onset of condensate collected during operation of the two stills. However, it is easily observed that the rate of condensate collection is increased for Revision 1.

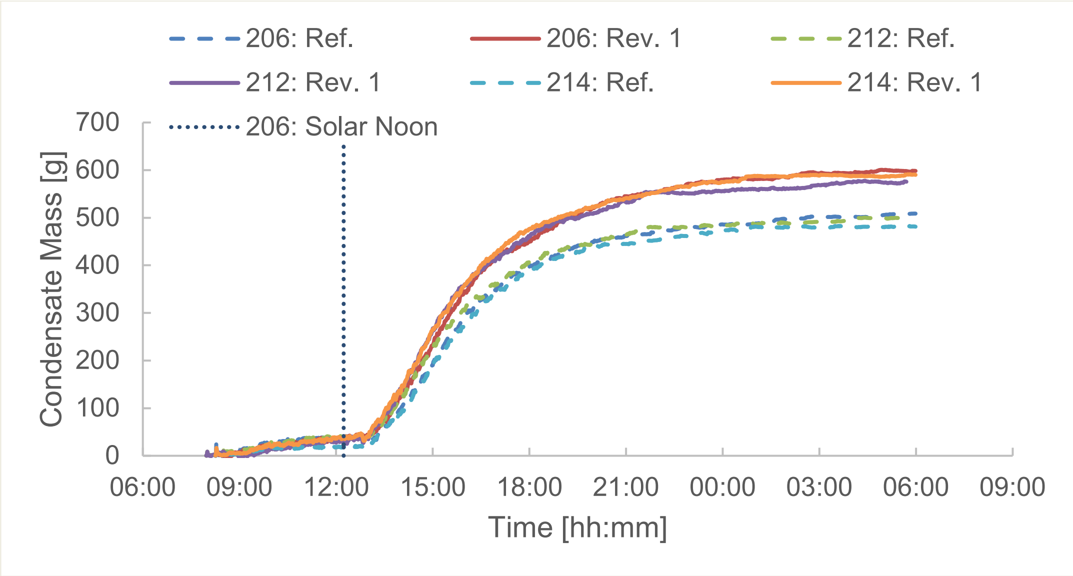

Figure 4-18: Mass of condensate versus time for the Revision 1 still and the reference still.

4.5.2.3 *Revision 2 Design*

Essentially, revision 2 is identical to the first design with minor changes to the insulation material and thickness. The still had a plywood inner shell and a thin aluminium sheet outer shell. The void between the inner and outer shells was injected with expanding polyurethane (PU) foam with an ultimate thickness of 50 mm. This version was also coated with *Durapond*™ sealant and was also retrofitted with PVC tarpaulin. This still was not properly sealed between the inner and outer shells and got waterlogged over time. It was therefore discontinued due to the erratic data that was obtained from its operation.

4.5.2.4 *Revision 2 Performance Evaluation*

In summary, the most notable difference between Revision 1 and 2 is the use of a thicker (26 mm versus 50 mm) and different insulation material (Armaflex foamed nitrile versus foamed PU). All other design parameters are the essentially the same. Table 4-6 indicates the significant difference in still operation when adequate insulation is used and indicates the possibility of losses occurring from the condensate collection channel and tubing that was used in the first revision. Still cover and water temperatures where different but not significant enough to draw definitive conclusion from. The onset of condensate collection did not change for Revision 2 and this version also show an increased rate of condensate collection as in the case of Revision 1 when compared to the reference still.

Table 4-6: Efficiencies and water produced in the reference still and the Revision 2 still.

Day Number	Ref. Still Yield (*kg*)	Revision 2 Yield (*kg*)	Difference in Yield (%)	Ref. Still Efficiency (%)	Revision 2 Efficiency (%)
206	0.50	0.74	47	12	17
207	0.49	0.66	34	12	16
208	0.57	0.69	22	13	15
211	0.49	0.67	35	11	15
212	0.50	0.65	30	11	15
213	0.50	0.66	31	12	15
214	0.48	0.63	31	12	15
215	0.49	0.61	23	12	15

4.5.2.5 *Revision 3 Design*

The major difference between this version and the previous versions was the use of hard, extruded polystyrene as the insulation material and the inner shell. The polystyrene layer was protected by a plywood outer shell. PVC tarpaulin was used as absorber and waterproofing.

4.5.2.6 *Revision 3 Performance Evaluation*

Version 3 was introduced with the rigid wooden structure on the outside of the still and the insulation material on the inside. Extruded polystyrene insulation board was used as an insulation material and has a thickness of 50 mm. The absorber material was PVC tarpaulin. Table 4-7 shows the drastic improvement in the still design when compared to the reference still. The main difference is the mass of wood that must be heated in all previous versions. This increase in thermal mass introduce a delay in the onset of condensate collection and harbours energy inefficiently. The average amount of water collected for this dataset was 1.02 $kg.day^{-1}$ and amounts to 2.13 $kg.day^{-1}.m^{-2}$.

Table 4-7: Efficiencies and water produced in the reference still and Version 3 still.

Day Number	Ref. Still Yield (*kg*)	Version 3 Yield (*kg*)	Difference in Yield (%)	Ref. Still Efficiency (%)	Version 3 Efficiency (%)
297	0.47	1.29	164	11	27
298	0.45	1.25	176	10	27
299	0.46	1.24	169	11	28
302	0.41	1.20	193	9	26
303	0.46	1.18	158	8	26
304	0.27	0.73	183	8	25
305	0.07	0.23	250	5	17
306	0.31	1.05	232	8	25

Figure 4-19 indicates the rapid increase in water temperature for the revised still design. Also notable is the increase rate of heat loss during the evening. This is attributed to the reduced thermal mass inside the still; the wood in the reference still acts as a heat sink during daytime and as a heat source during night time, keeping the water warmer for longer.

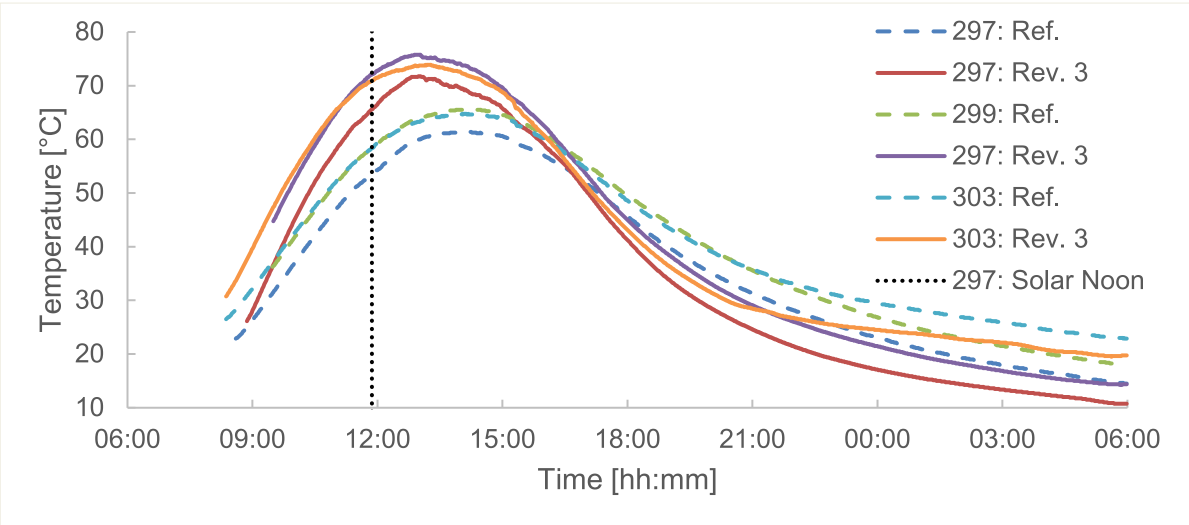

Figure 4-19: Water temperature of the reference still (Still 2) and Version 3 (Still 4) for a selection of days.

Even though this seems favourable, the still efficiencies and yield shown in Table 4-7 proves otherwise. A disadvantage of the increase operating temperature is, unfortunately, a higher rate of degradation of the materials of construction and may reduce the lifespan of the still. The onset of condensate collection is almost an hour earlier for Version 3 than all the previous versions (Figure 4-20). It is also notable that the rate is much higher due to the increased water temperature and consequently, water to cover temperature difference.

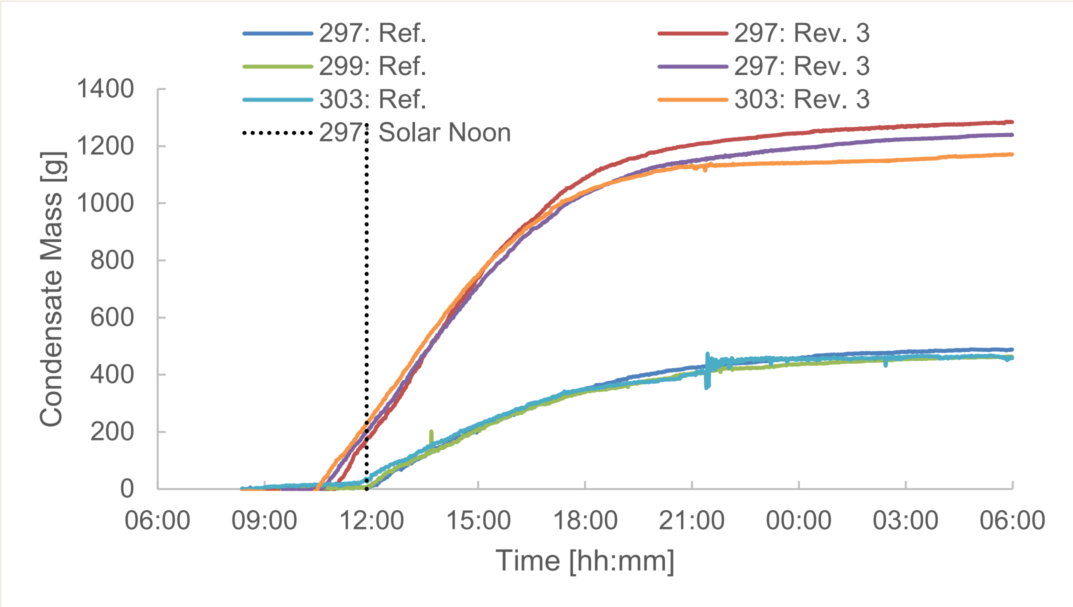

Figure 4-20: Comparison of the mass of condensate collected between the reference still (Still 2) and Version 3 (Still 4).

4.5.3 Simple Basin Solar Still Version 2

This version of a simple basin solar still was aimed at reducing material cost, manufacturing time and to introduce simplicity in design and operation. The still body was cut from a polystyrene cooler box with dimensions of 620 mm × 300 mm × 220 mm which is similar to the length-width ratio of the first versions of the stills and also has a cover inclination angle of 25°

4.5.3.1 *Solar Basin Still Version 2 Design*

Two units were modified to resemble the typical basin still design, however, are much smaller with a cover area of 0.18 m^2. PVC tarpaulin was used as absorber surface and was installed at the bottom of the stills only (Figure 4-21). It is believed that the white polystyrene walls will reflect more solar irradiance to the base of the still and consequently reduce the wall temperature, increase the water temperature and potentially increase the temperature difference between the water and cover surface. These stills were fitted with a PMMA cover and another with a window glass cover respectively.

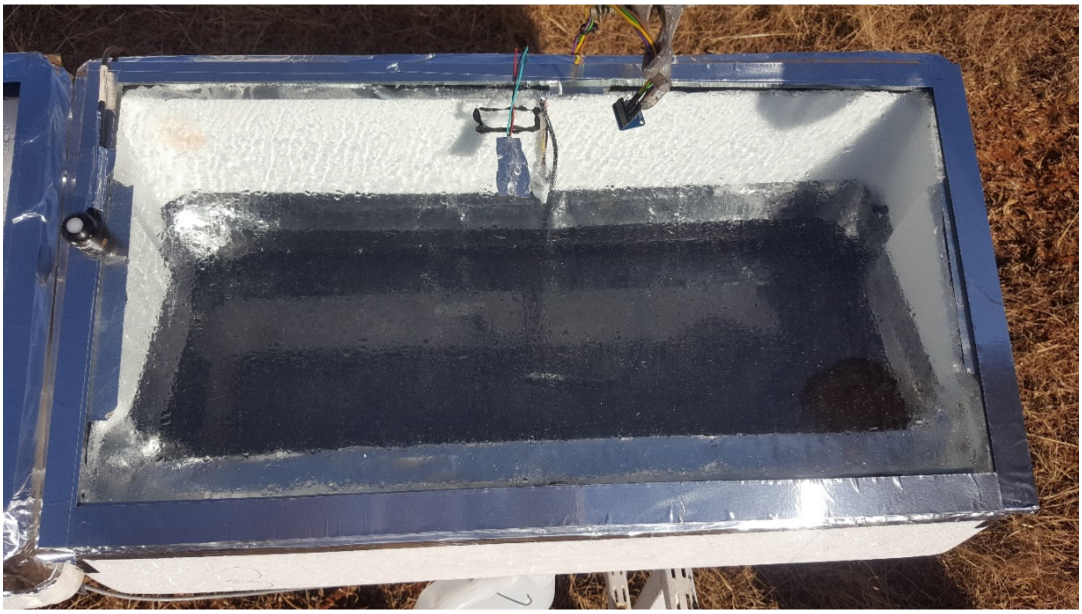

Figure 4-21: Basin Still Version 4, shown with a glass cover and PVC textile absorber.

4.5.3.2 *Solar Basin Still Version 2 Performance Evaluation*

Figure 4-22 shows the cover and water temperatures of this version of the stills and a larger temperature gradient exists between the cover and water. It is also evident that the stills operate at a slightly higher water temperature than the first versions built. However, this is not due to superior insulation as these stills only have a 20 mm thick polystyrene wall. The stills can be improved in performance by increasing the wall thickness of the polystyrene body. It should be noted that this version was not intended to be an improvement in performance to those proposed as Version 1, however, these were investigated as units that could be manufactured in large quantities.

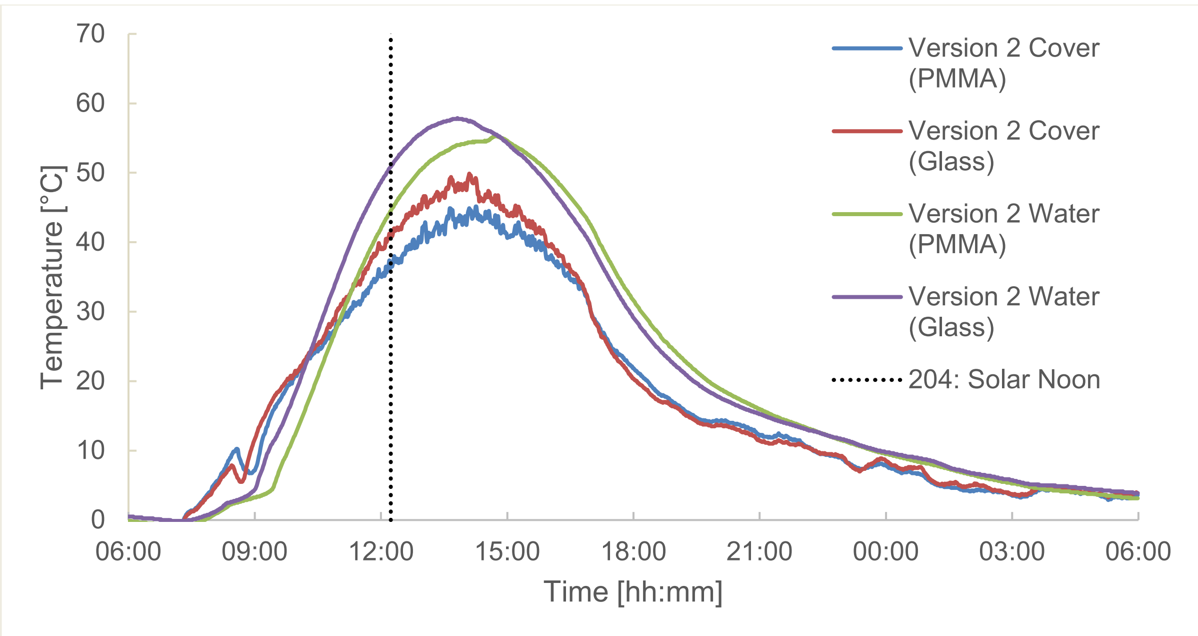

Figure 4-22: Version 2 still cover and water temperatures.

These stills also have an earlier onset of condensate collection. Figure 4-23 shows an increase in the condensate mass as early as 09h00 in the morning. This is due to the much smaller volume of the still and water used, however, maintaining the same depth of water as used with the previous versions. The still efficiency for this particular dataset was 16%, less than that of Version 3, but at a much lower cost. The total amount of water collected amounts to 1.37 L.day^{-1}.m^{-2}, again much less than Version 3 with 2.13 kg.day^{-1}.m^{-2} achieved with similar conditions, however, it should be noted that the insulation was only half of the thickness of Version 3 and at a cost of approximately one order of magnitude less than that of Version 3.

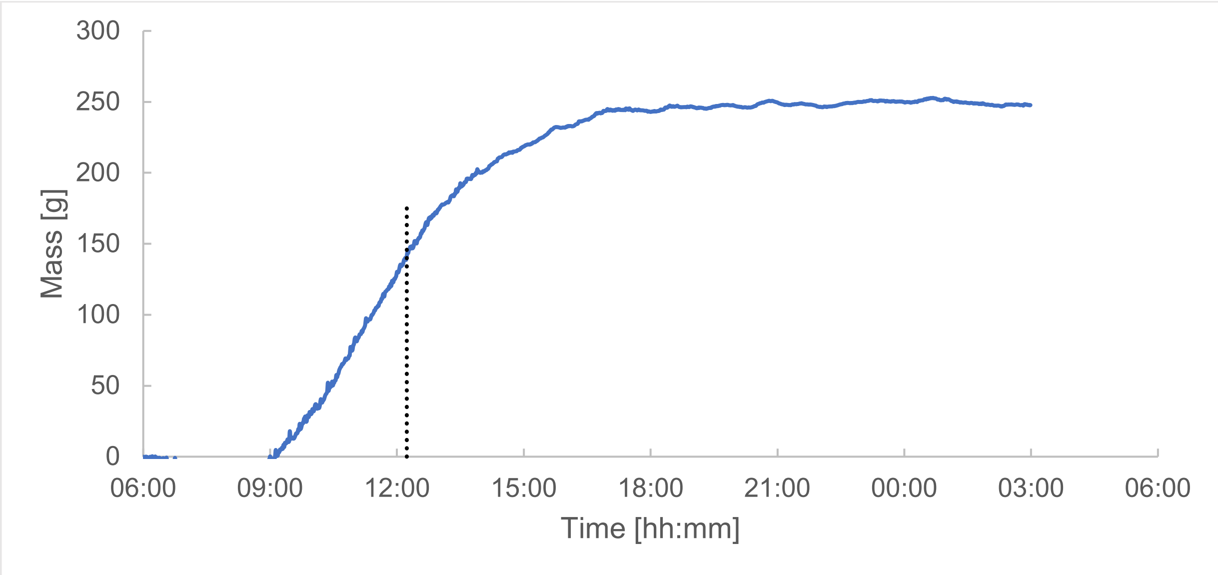

Figure 4-23: Mass of condensate collection for still Version 2.

4.6 MODIFICATION IN PREPARATION OF ACTIVE SIMPLE BASIN SOLAR STILLS

4.6.1 Overview

Results obtained from the operation of the passive simple solar basin stills provided clarity on areas for improvement of the stills in preparation for modification toward active solar stills and is included in this section of the report. Among the improvements to be considered are the type of material used for the cover and additional insulation of the cover to reduce condensation on the cover. The additional insulation of the cover refers to the use of double pane material with an air gap between the layers.

4.6.2 The Effect of Still Cover Material

Still Revisions 2 and 3 were fitted with 3 mm single pane glass and a 10 mm double pane glass with air gap in light of the promising effect of a glass cover material on still performance. The use of the double pane glass was considered with the use of an external condenser. This could reduce energy losses though the large area of the cover and promote condensation on the external heat exchange surface. The data shown in

Figure 2-24 is very promising in both aspects, single pane (fitted to Revision 2) and double pane glass (fitted to Revision 3) covers. The onset of condensation is very early in the experiment and the rate and mass of condensate collected in Revision 2 is the highest achieved yet, 3.55 L.day^{-1}.m^{-2} with an efficiency of 38%.

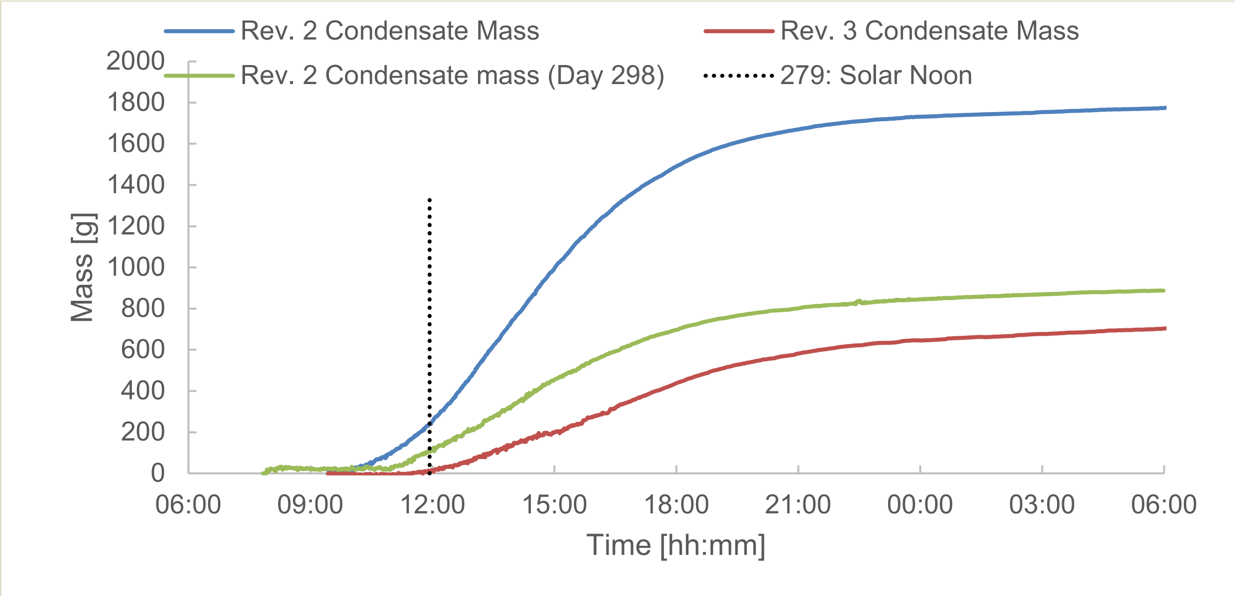

Figure 4-24: Mass of condensate collected with Revision 2 and 3 with 3 mm, single pane, and 10 mm double pane glass.

The drastic reduction in performance of Revision 3, is due to the additional insulation of the cover. The thermal resistance is approximately three times higher than the previous PMMA cover used (Table 4-8) and is the main reason for the still's performance. Figure 4-25 clearly shows the improved heat retention of the cover, both stills have a high, water temperature, which indicates similar levels of irradiation impinging on the absorber, however, the single pane glass achieves outer surface temperatures as high as 62°C while the double pane glass surface is much cooler at a maximum of 42°C. The consequence of the double pane glass is poor performance when considering a simple solar still with no agitation, however, it should be noted that this cover is to be used in conjunction with external heat exchangers that is designed for these stills and therefore less energy losses can be expected through the still cover.

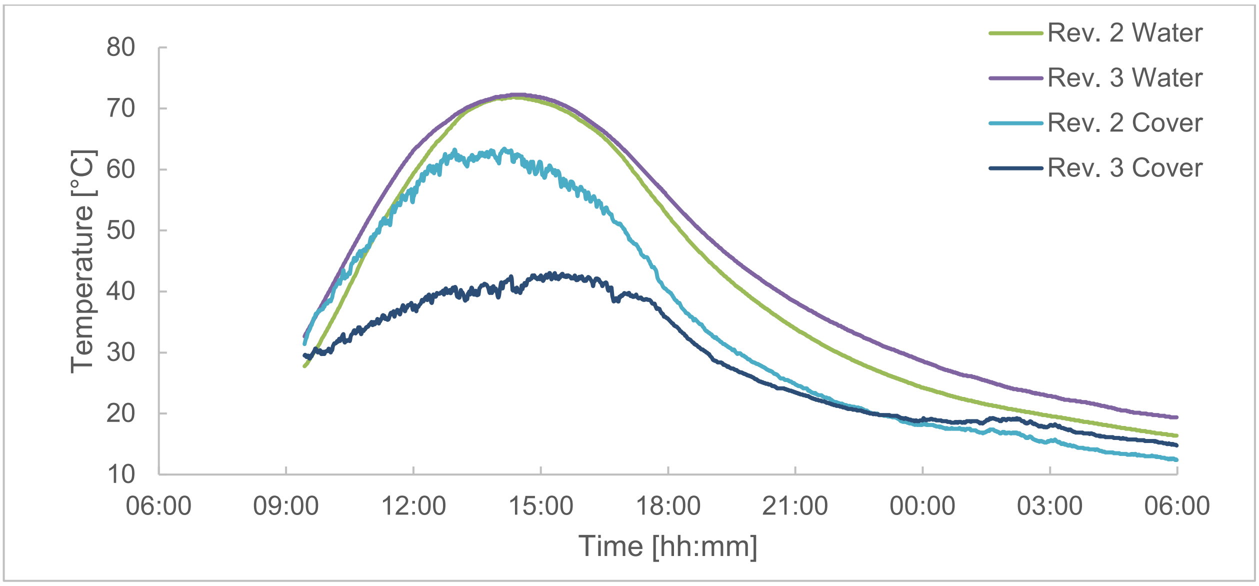

Figure 4-25: Comparison of water and cover temperatures of stills with a single pane glass (Revision 2) and double pane glass (Revision 3) cover.

4.6.3 Reducing Heat Losses from the Cover

A single sheet of 4 mm window glass has a much lower resistance to heat transfer than a PMMA cover with a thickness of 5 mm. However, the use of a double pane glass cover with a 2 mm air gap significantly improves the resistance to heat transfer through the cover. The thermal resistance of the mentioned cover materials can be seen in Table 4-8. The use of double pane glass is evidently beneficial to reduce the heat conduction through the glass, however, the outer surface is also at a much lower temperature because of the higher resistance to heat transfer which reduces the amount of energy lost through convection and radiation from the cover.

Table 4-8: Thermal resistance values of different cover materials.

Cover Material	Total thickness [mm]	Thermal Resistance [K/W]
PMMA	5	0.026
Single pane glass	4	0.006
Double pane glass, no gap	8	0.011
Double pane glass, air gap	10	0.083

4.7 SIMULATED BASIN STILLS WITH INDUCED FLOW

4.7.1 Overview

It was considered to determine the productivity of different heat exchanger designs in a controlled environment rather than to install these heat exchangers directly on a solar still. The heat exchangers were connected to an electrical water bath with temperature control and tested at various bath temperatures. Three variations are considered, a large heat sink with dimensions 200 mm × 150 mm, a tube bank with 12 tubes with an OD of 12.7 mm and a tube bank with 12 tubes with an OD of 9.53 mm. Both tube banks had a length of 150 mm. The heat sink and tube banks aren't comparable with respect to area, mass flux or in any other way, however, the reason for the different setups was cost and the space available in the existing basin solar stills. All three designs were tested with and without forced convection.

4.7.2 Performance Evaluation of a Heat Sink as Condensation Area

The main aim of investigating different heat exchanger designs is to determine the loss of sensible energy while monitoring the amount of condensate collected. If too much sensible energy is lost through the heat exchanger, then the inclusion of such is system us redundant. It is necessary to note that some degree of sensible heat loss is necessary to achieve condensation, however, this should be kept at a minimum to reduce unnecessary heat losses from the system. Figure 4-26 indicates the temperature of the air entering and exiting the heat sink type heat exchanger during the course of an experiment for both natural convection and forced convection on the external heat sink surface. The difference in the inlet and outlet temperature is approximately 1.2°C and 10.5°C for natural and forced convection on the heat exchanger. This should be considered at a very low inlet temperature of approximately 41-42°C which is much lower than the water temperature, controlled at 60°C. The reason for this observation is the very large thermal mass of the heat sinks. The heat sinks conduct a large amount of energy and is therefore too efficient too consider as external heat exchanger surface. Smaller heat sinks can be considered to reduce the overall thermal mass and to reduce the efficiency of operation, however, considering heat sinks on a trial-and-error basis would be a very costly exercise and was not considered further.

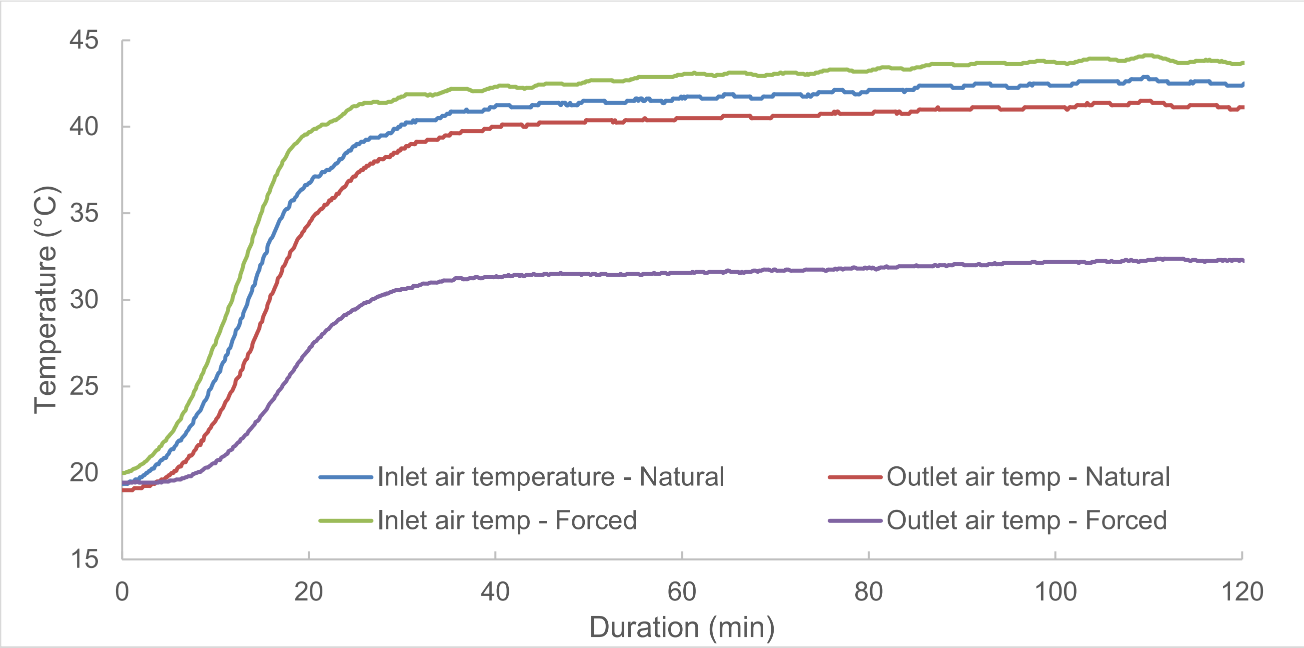

Figure 4-26: Temperature profile of air flowing into the heat sink heat exchanger and out of the heat exchanger for a bath temperature of 60°C.

Figure 4-27 indicates the performance of the heat sink section used for external condensation. The heat sink without forced convection provided a heat duty of approximately 25 W and is almost half when compared to the instance with forced convection, 46 W. However, the major drawback with the use of these large heat sinks is the cost of the material. The heat sink alone amounts to R376 per condenser whereas the tube bank material amounts to less than R20 per condenser.

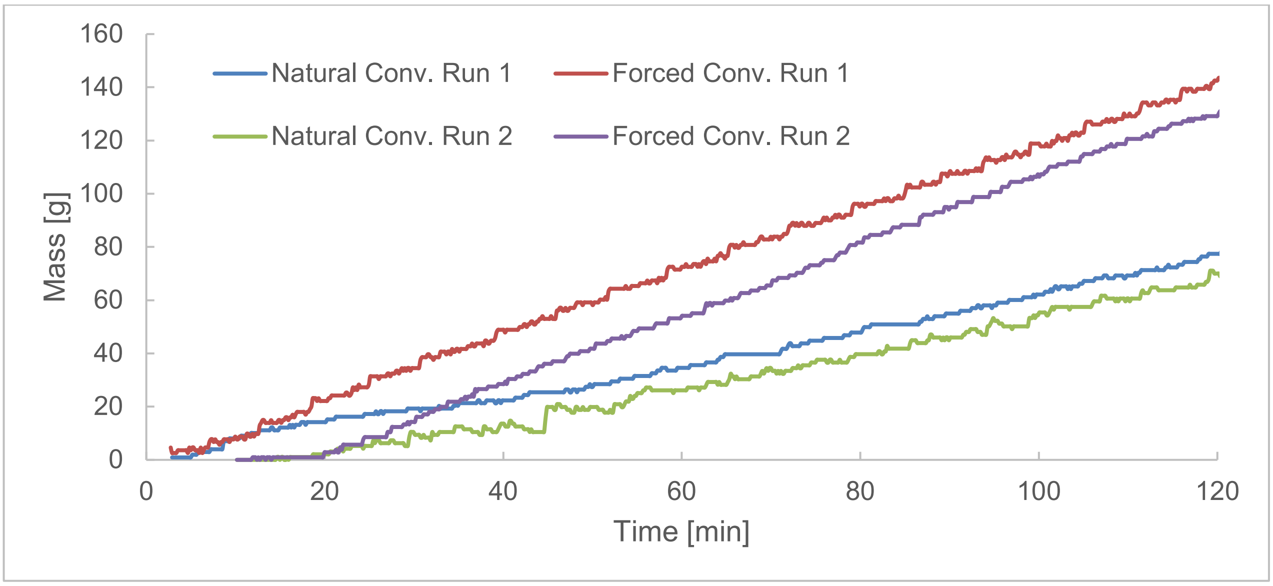

Figure 4-27: Mass of condensate collected with a large heat sink as condenser area. Data includes both natural convection and forced convection.

4.7.3 Performance Evaluation of a Tube Bank as Condensation Area

4.7.3.1 *9.53 mm Tube Bank Heat Exchanger*

Due to the high cost and excess heat lost from the heat sink type heat exchanger a tube bank version was considered in place of the heat sinks. A tube bank of 12 tubes consisting of aluminium tubes with a diameter of 9.53 mm was considered. The temperature of the inlet and outlet air passing through the tube bank are shown in Figure 4-28. The inlet temperature of both experiments, one with natural convection on the outer surface and one with forced convection on the outer surface, are much closer to the water bath temperature of 60°C. The average temperature difference between the inlet and outlet of the two experiments are 5.5°C and 7.5°C, for the natural convection and forced convection experiments respectively. These temperature differences are still considered too high since the tube bank loses 171 W when considering natural convection and 260 W when considering forced convection.

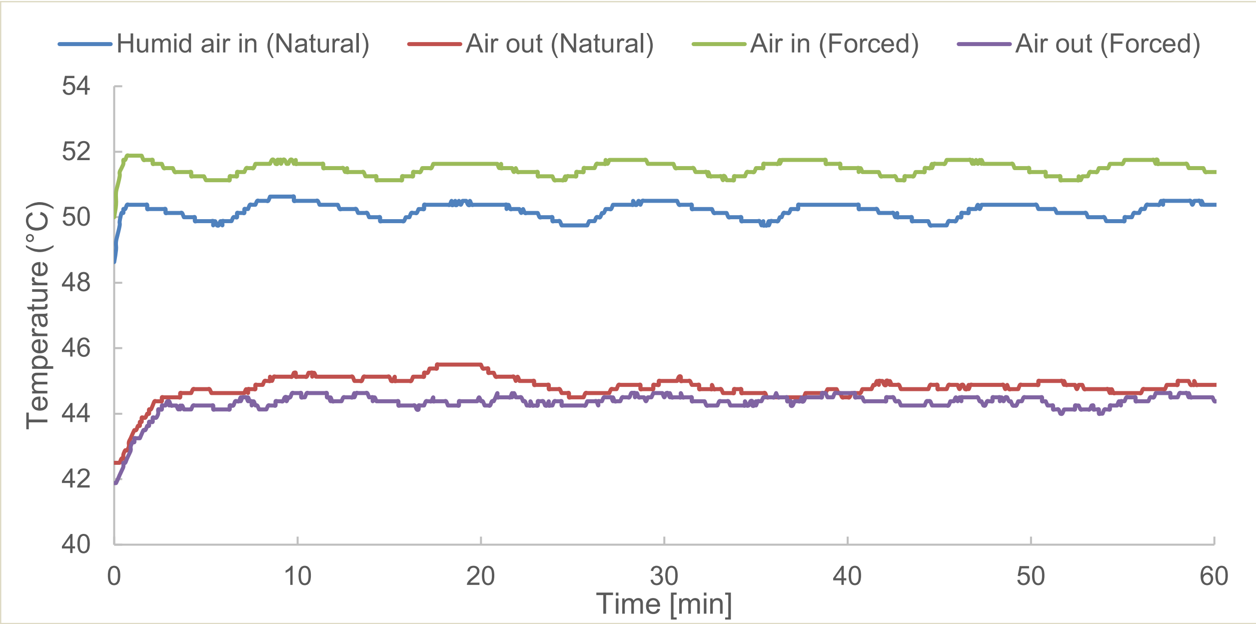

Figure 4-28: Temperature profiles of a 9.53 mm bank of tubes containing 12 tubes in a staggered configuration. The water bath was controlled at 60°C.

When considering the rate of condensate collection (Figure 4-29), the duty of the heat exchanger can be calculated as 28 W and 35 W for the natural and forced convection experiments, respectively. This implies that only 14% and 12% of the energy lost is toward condensation for the natural and forced convection. The remainder of the energy is lost toward sensible energy.

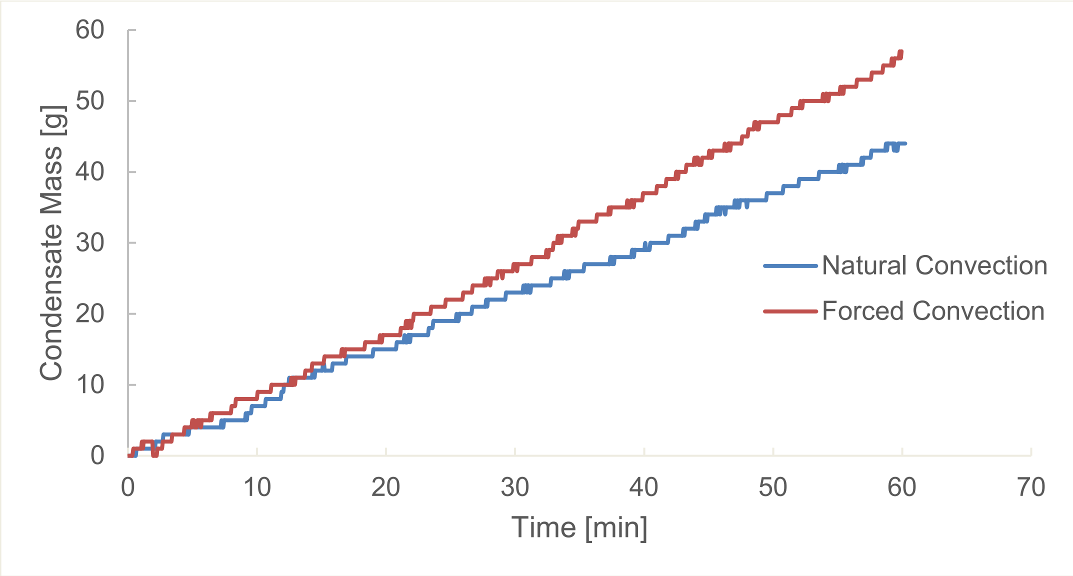

Figure 4-29: Condensate mass collected for a tube bank with 9.53 mm tubes, with and without forced convection over the tube bank.

4.7.3.2 *12.7 mm Tube Bank Heat Exchanger*

A tube bank with tube diameter of 12.7 mm was also tested as an external heat exchanger. The tube bank consisted of 12 tubes in a staggered arrangement with the same tube spacing as the 9.53 mm tube bank. The inlet and outlet temperatures of the tube bank for natural and forced convection can be seen in Figure 4-30. The average temperature difference for natural convection was 2.5°C while the average temperature difference for forced convection was 3.5°C. The temperature difference is less than that for the 9.53 mm tube bank and is counter intuitive since the 12.7 mm tube bank has 1.8 times the surface area of the 9.53 mm tube bank. However, the heat transfer coefficient on both the inside and outside of the tube bank should be less than that for the smaller tube diameter. The energy lost as sensible energy equates to 122 W for natural convection and 171 W for forced convection. In both instances, much less than that for the 9.53 mm tube bank.

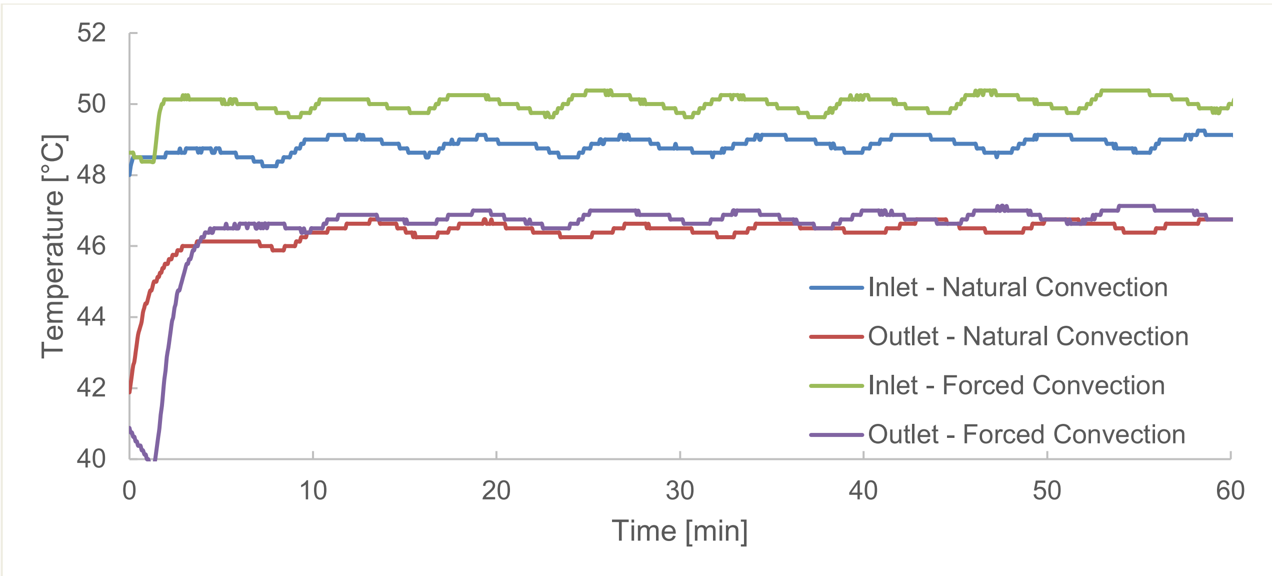

Figure 4-30: Temperature profile of the condenser inlet and outlet for natural and forced convection over a 12.7 mm tube bank.

Although the temperature difference associated with the 12.7 mm tube bank is advantageous, it must be considered with the rate of condensate collection. The condensate collected for these experiments is represented in Figure 4-31. The duty of the heat exchanger is calculated to be 26 W and 40 W for natural and forced convection respectively. This is equivalent to an effective energy usage of 18% and 19% respectively. The reduced temperature difference of the larger tube bank in conjunction with the increased energy efficiency of the tube bank verifies that the 12.7 mm tube bank is preferred over the 9.53 mm tubes.

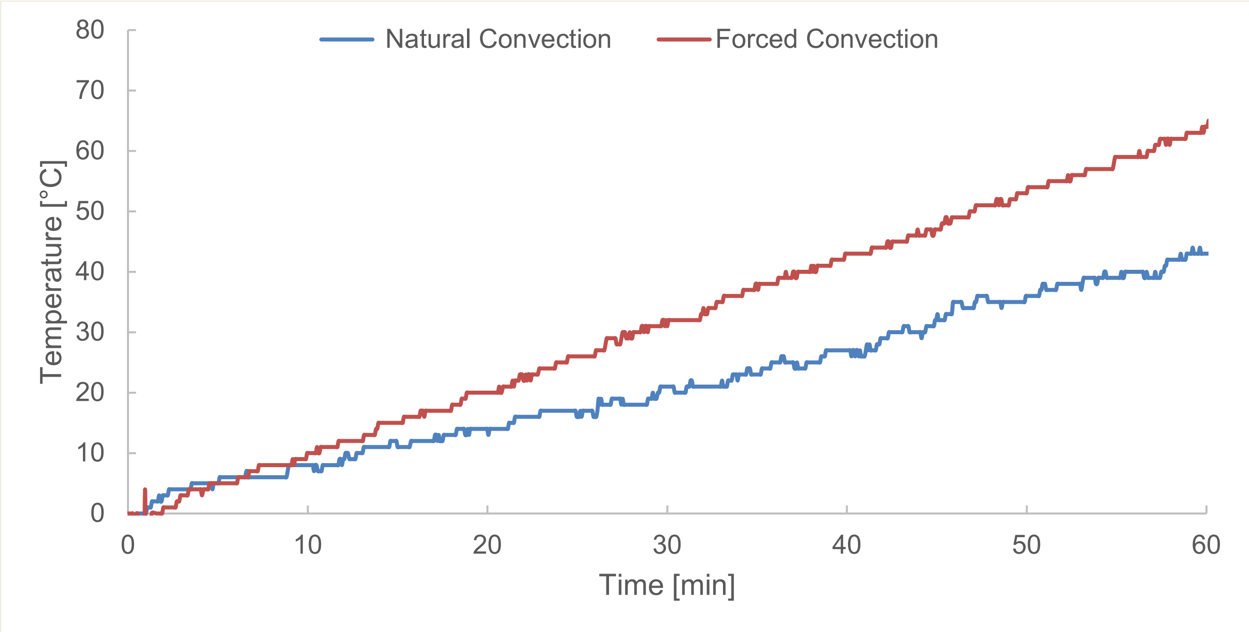

Figure 4-31: Mass of condensate collected with the use of a tube bank without forced convection. The tube bank has 12 tubes of 12.7 mm outer diameter.

4.8 PERFORMANCE EVALUATION OF AN INDUCED FLOW BASIN SOLAR STILL

To investigate the effect of forced flow of the water in the still and the effect of forced convection of the humid air, a 12 VDC water pump and 12 VDC fan was installed on Still 4, Version 3. The water was circulated from the basin to the back wall in an attempt to utilise the heat accumulated on the back wall. The fan was installed in conjunction with an external heat exchanger. Figure 4-32 shows the data obtained from Revision 2 and Revision 3 while Revision 3 was fitted with the water circulation pump. The temperature data shown is comparable to the data shown in Figure 4-25. However, there is a definite increase in water production as indicated on the mass data for Revision 3 with and without flow of water. This equates to a 46% increase in condensate collected but does not compare to the condensate collected in Revision 2 with no flow and with only a single glass pane as cover.

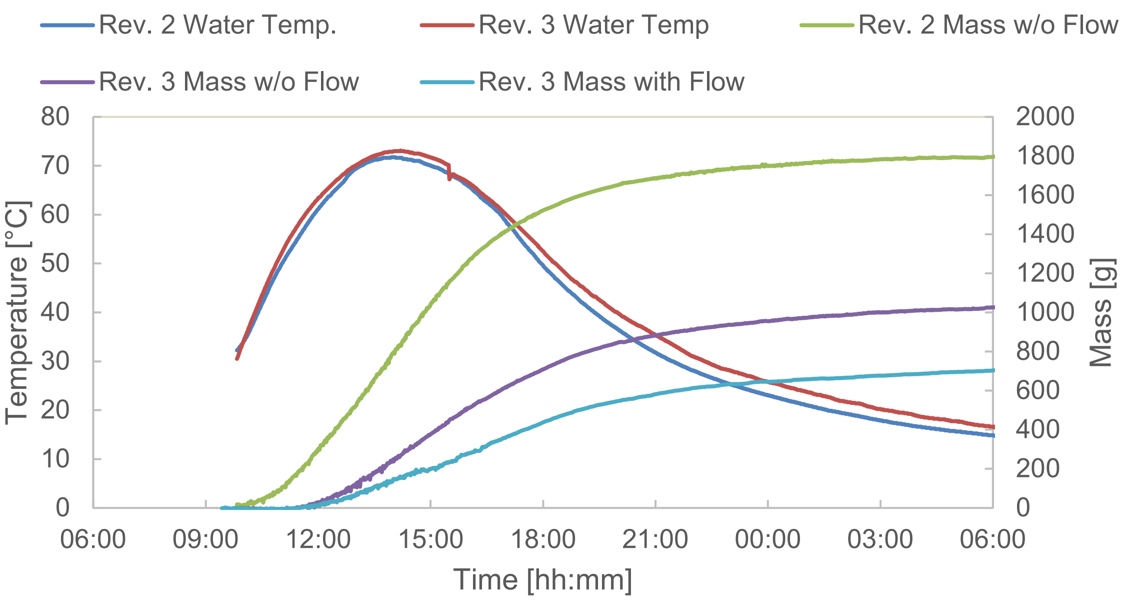

Figure 4-32: Water temperature and condensate mass collected of Revision 2, Revision 3, and Revision 3 with water circulation.

4.9 FEASIBILITY OF HEAT RECOVERY OF A BASIN SOLAR STILL

The original project proposal suggested an investigation into heat recovery with the use of vacuum pumps and low pressure flashing of the humid air. However, due to the need to produce clean water at a competitive cost, this possibility was not entertained. An alternative design was introduced to use with the heat sink condenser system. Instead of having two heat sinks back to back, two thermoelectric coolers were sandwiched between the heat sinks. In theory, the humid air will be cooled and condensed on the one heat sink and then heated on the other. Unfortunately, the operation of thermoelectric coolers requires fast dissipation of the heat that is generated, and all attempts failed at achieving this. This caused several thermoelectric coolers to burn out. Even though there is some merit to the use of thermoelectric coolers in such a system, these units typically require 60 W electrical energy and is relatively expensive. For these reasons the use of thermoelectric coolers was seized.

4.10 COST CONSIDERATIONS OF SOLAR STILLS

In order to determine the feasibility of the use of simple basin solar stills for clean water production from saline or brackish water one must consider the cost implication. Table 4-9 and Table 4-10 summarise the material and labour cost of the two most promising still designs, Version 1, Revision 2 and 3 and Version 2. It should be noted that the data is shown for a combination of still Revision 2 and 3 as the best design would be one with the body of Revision 3 and the cover of Revision 2. In both instances provision is made for the manufacturing of an aluminium stand. This is not strictly required, however, still operation relies heavily on the basin to be level and the still must be elevated to allow condensate to be collected below the still. It is therefore necessary to account for this cost. The major difference in cost of the two versions of stills is the additional support require to house the insulation material for still Revision 3, it is more than double the usable area of Version 2 and the fact that it is very labour intensive to manufacture. Albeit the labour cost is in both instances approximately half of the total unit cost which may be an underestimation. The cost estimation of Version 2 is only base on currently available polystyrene boxes, this cost should increase slightly when made on a larger scale as the wall thickness of these boxes must be increased for better productivity. If a mould could be made to manufacture these stills, the labour required could also be reduced.

Table 4-9: Cost of manufacturing a simple basin solar still

Component	Material	UOM	Quantity	Rand/unit	Total Cost [R]	%
Cover plate	Glass, 4 mm	m^2	0.63	220.15	138.69	4.3
Absorber	PVC Textile	m^2	1.5	34.66	51.99	1.6
Insulation	Isoboard®	m^2	1.65	166.80	275.22	8.5
Support Structure	Shutterply	m^2	1.82	113.63	206.81	6.4
Metal Frame	Aluminium	m	10.1	567.72	567.72	17.6
Sundries			1	368.00	368.00	11.4
Subtotal					**1 040.71**	**49.8**
Labour		hour	8	1 200.00	1 200.00	37.2
Total (excl. VAT)					**2 808.43**	
Total (incl. VAT)					**3 229.70**	

Table 4-10: Cost of manufacturing a simple basin solar still Version 2

Component	Material	UOM	Quantity	Rand/unit	Total Cost [R]	%
Cover plate	Glass, 4 mm	m^2	0.25	220.15	55.04	7.4
Absorber	PVC Textile	m^2	0.18	34.66	6.24	0.8
Still Body	PS		1	70.00	70.00	9.4
Metal Frame	Aluminium	m	3	56.21	168.63	22.6
Sundries			1	50.00	50.00	6.7
Subtotal					**349.91**	**46.8**
Labour		hour	2	150.00	300.00	40.1
Total (excl. VAT)					**649.91**	
Total (incl. VAT)					**747.39**	

Table 4-11 is a comparison of the two most promising still designs. The estimated lifespan was included to be able to determine a monetary value for one litre of water produced and is accepted as a speculative observation. However, the authors are confident that the lifespan is reasonably accurate. It is clear that an increase in the lifespan of Version 2 would make a markable difference to the cost per litre of water produced. Further improvements with respect to additional insulation could improve the productivity of these stills significantly and also improve the cost of the water produced. Due to additional cost involved with the active basin stills investigated and the relatively low improvement in productivity when compared to the passive counterpart, the cost estimation of these stills was omitted as all electrical components would reduce the lifespan and total cost and inevitably increase the cost of the water produced.

Table 4-11: Comparison of still productivity, estimated lifespan and cost per litre of water produced

Still	Estimated Lifespan	Production Cost [R]	Productivity	Cost per Litre
Version 1, Rev. 2 and 3	5 10	3 229.70	3.55 $L.day^{-1}.m^{-2}$	R1.25 R0.63
Version 4	2	747.39	1.37 $L.day^{-1}.m^{-2}$	R5.19

CHAPTER 5: CONCLUSIONS ANS RECOMMENDATIONS

5.1 CONCLUSIONS

5.1.1 Solar Basin Still Performance

Two versions of a simple solar basin still were designed, manufactured and tested during the project timeline. The best performance was achieved by Version 1, Revision 2 and produce a maximum of 3.55 $L.day^{-1}.m^{-2}$ which is comparable to highly efficient designs in literature. This maximum was achieved with a thermal efficiency of 38% and requires no electrical input to operate. Table 5-1 is a summary of the results of all versions and revisions of the stills tested. The maximum yield achieved is much lower, only 30%, than the ideal maximum yield set in the aim of the project with respect to a simple basin solar still. This is due to the fact the ideal yield neglects all forms of energy losses, including the portion of energy required to achieve condensation.Table 5-1: Summary of all versions of stills in terms of yield and efficiency.

Table 5-1: Summary of all versions of stills in terms of yield and efficiency.

Version	Revision	Max. Yield [$L.day^{-1}.m^{-2}$]	Average Efficiency [%]
Reference	-	1.12	11.5
1	1	1.95	13.5
	2 (PMMA)	1.48	15.4
	2 (Glass)	3.55	38.1
	3 (PMMA)	2.50	26.5
	3 (Glass)	1.45	16.2
	3 (Flow)	2.05	21.4
2	1	1.37	13.8

The use of a single pane glass cover on Version 1, Revision 3 could achieve higher yields than that of Revision 2 since this still produced much higher yields during normal operation. However, this cannot be concluded and should be investigated further.

Version 2 is a very promising design purely because of its simplicity and cost. The design is similar to that of Version 1, however, utilising only of the shelf materials. These stills are very easy to build and cost approximately R300 per unit with an average daily yield of approximately 1.35 $L.day^{-1}.m^{-2}$. These stills have an insulation wall thickness of 25 mm, half of the insulation of Version 1, Revision 3 and can therefore be improved by additional insulation.

Optimisation of the cover material, angle and recommended distance proved to be valuable in the design of future stills. If PMMA is used, it should have a cover angle of at least 25° and the distance travelled by condensate must not exceed 30 mm to avoid excessive losses. However, it is recommended that a glass cover should be used instead of a PMMA cover since the use of glass practically eliminates losses back into the still, allows for better transmittance of solar irradiation and produce a much higher yield. The cost of glass is also much less than PMMA, however, introduce some fragility to the design.

The reflective losses from the cover as well as the additional reflective losses and possible absorbance of irradiance by the condensate on the cover was determined. The results show that the dropwise condensation on a PMMA cover increases the total loss of solar irradiance. A PMMA cover with condensate on the cover transmits between 70% and 80% of the total solar irradiance while the use of a double pane glass cover transmits at minimum 10% more.

5.1.2 Active Solar Basin Still Performance

Alterations were made to the passive solar stills to operate as active solar basin stills. These alterations require electrical power to operate and inevitably introduce capital cost and maintenance implications. The addition of a circulation pump to the Revision 3 still produced a yield increase of 46% but did not achieve a higher amount of condensate collected than that of Version 1, Revision 2 with a single pane glass cover. The addition of a double pane glass cover shows promising results with respect to reducing heat losses from the cover, however, the advantage is eliminated through unsatisfactory yields achieved in the external heat exchangers. The small increase in the yield achieved is not feasible when considered with the increase in capital and operational cost. It can be concluded that it is not possible to achieve the ideal maximum yield of 11.8 $L.day^{-1}.m^{-2}$, as set in the project aims, by means of an external heat exchange surface. It is probable that an optimal heat exchanger can be developed, however, the development of such a unit will require sophisticated modelling and testing and this is not deemed feasible when compared to the low cost and reasonable yields obtained with passive solar stills.

Although heat recovery was suggested as a viable method of achieving very high yields, the idea was not entertained after multiple failures. These failures included the use of thermoelectric coolers to improve condensation and reheat the outgoing air stream, however, it proved difficult to provide sufficient control of the hot and cold side of the thermoelectric cooler. Due to the uncontrolled temperature, many units failed and therefore further attempts were halted. The use of thermoelectric coolers in a competitive solar still is also deemed too expensive.

It should also be noted that heat recovery in simple basin solar stills cannot be achieved since the quality of the energy leaving the system is always lower than the energy inside the still. If heat recovery is to be considered, it should be considered in a multi-effect continuous flow system. Very high yields can be achieved using these solar stills, however, the development and manufacturing of complex design does incur additional costs.

5.1.3 Cost Evaluation

It was estimated that the best performing passive basin still produced clean water at a cost of R0.63-R1.25 per litre when considered over a lifespan of 5-10 years. This value is significantly higher than that of the local municipal supply at approximately R0.10 per litre in October 2019. Costs could be reduced with the use of recycled insulation materials, bulk manufacturing and some alternative materials than those listed in Table 4-9. This report does not aim to conclude specifics with respect to costing and cost optimisation, however, it is necessary to report the efficiency and yield of the proposed stills in conjunction with a monetary value.

5.1.4 Recommended Solar Basin Still Design

The final and most productive still is proposed based on all experiments considered and all materials used during the execution of the project. This design should incorporate a low thermal mass insulation material, such as extruded polystyrene, as the basin inner lining and should be enclosed with a rigid, durable, UV resistant outer shell. This outer shell can be manufactured from a cheap plywood, a cheap polymer or thin aluminium sheet metal. Care should be taken to seal the outer shell to ensure that the insulation material does not get waterlogged as this decrease still performance significantly. The dimensions used for Version 1 (960 mm × 480 mm) are appropriate for the recommended design. These still do however require two persons to transport or move and, depending on materials used, can be heavy. If portability is required, it is recommended to use Version 2 or a scaled design of Version 1.

The absorber material is one of the components that drastically influence still performance and it is recommended that black PVC tarpaulin is used. This material is fairly UV stable, very cheap and produced very high yields in comparison to some of the other materials used. It is also very easy to insert into the inner lining of the still and is waterproof. It is not recommended to cut and solvent weld seams in the corner of the stills as this material does not solvent weld easily.

It is recommended to use glass with a thickness of 4 mm as the cover material. Condensate on the cover hinders the transmittance of sunlight and reduced the total transmitted irradiation significantly when hydrophobic PMMA covers were used. Glass is somewhat hydrophilic and provides a thin layer of condensate which allows more irradiation to be transmitted. Another important factor is the fact that a lot of condensate was lost when a PMMA cover was used. Droplets do not acquire enough mass to detach from the glass surface due to a thin continuous film is formed on the glass surface and consequently, losses are reduced. With all advantages considered, the use of glass provided an increase in yield of 100% at a reduced cost. Unfortunately, the use of glass does render the still design somewhat fragile.

It is not recommended that an active still be used since these incur additional capital and operational cost with a relatively low increase in yield, compared to the passive solar stills investigated.

5.2 FUTURE STUDIES

Research on passive basin stills is abundant in literature and provides very useful insight into efficient designs and features. However, in most instances these designs are costly due to the complexity and small scale of operation and production. It is therefore recommended that future studies be pursued in the cost optimisation of basin solar stills. This can be achieved with the consideration of alternative materials, a study into manufacturing techniques to reduce labour costs and evaluating the actual lifespan of basin solar stills.

It is also recommended to investigate the possibility of the use of solar stills manufactured from roto-moulded polymers with a cheap and effective insulation material in the cavity between the inner and outer shells. This technique could be utilised to produce large quantities of stills and can include the use of recycled polymers.

The use of building materials such as bricks and mortar can enable the construction of much larger, permanent structures and some of the findings in this report can be employed in the design of such a structure. It is not foreseen that such a design be more cost effective but could produce sufficient quantities of clean water for more than one consumer per day. It is recommended that a feasibility study of such a design be conducted for secluded rural areas.

Although the use of electric components increased the production of water, it is recommended that further studies and creative ideas be investigated in an effort to improve the cost and productivity of these stills. The data obtained in this investigation is insufficient to conclude all advantages and disadvantages of active basin solar stills.

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