Grey water reclamation using solar thermal energy

Gerhard Hartwig
Stellenbosch University

Centre for Renewable and Sustainable Energy Studies

Abstract
Finding ways to reduce our demand for water and energy is an important step towards a sustainable future. This is especially true for South Africa in which current electricity constraint are hampering economic growth and the future outlook on water supply is not favourable.

Following the principles of the Energy Conservation Hierarchy, the first step towards sustainability is to look at conservation through consumer behaviour change. Lynedoch Eco Village near Stellenbosch was chosen as a case study. With a culture of conservation already in place at Lynedoch, focus shifted towards the second step, namely reducing demand by using renewable energy.

Borrowing ideas and technologies from solar desalination, the goal is to obtain clean water from wastewater from treatment facilities similar to the systems at Lynedoch. An evaporation condensation cycle in a multiple effect configuration is utilised as the distillation mechanism. A mathematical model implemented in Trnsys simulation software is developed to predict the production rate of the proposed system. A prototype will validate the simulation, with laboratory tests demonstrating water quality. Successful results would suggest that the proposed design could be utilised to reduce water and electricity demand through using output as feed water for a hot water geyser.

Keywords: Solar, distillation, grey, water, treatment

1. Introduction

It is evident that South Africa is in an energy supply crisis. Anybody watching television between six and eight at night can confirm the constant reminders that we need to switch off our non-essential appliances since our electricity supply is under pressure. We are in a situation where our planning has let us down in terms of providing a constant supply to meet our growing demands. To complicate matters further is the fact that South Africa is an energy intensive economy. Add to that a water scarce country and you have a clouded future for a country requiring high economic growth rates to stem unemployment and reduce inequality.

Unfortunately, both the energy and water supply aspects have been taken for granted. For the past few years, government has had to play catch up in the supply department. We are in a dire situation concerning electricity with Eskom again issuing warnings in early 2012 about tight supply margins due to required maintenance (Lazenby, 2012). Even worse is the fact that we are keeping up with the demand by building more coal fired power stations, a serious step in the wrong direction in an ever increasing environmentally conscience world.

Consequently, in terms of electricity and water, South Africa is at a tipping point in terms of future energy and water supply. We do not live in world were one can continue to dam rivers and burn fossil fuels to feed demand anymore. Our future resources will need to come from sustainable sources and we will need to look at how we are using what we already have.

We therefore need to set out a detailed plan of how we as a country can become a more sustainable society. Following the principles of the Energy Conservation Hierarchy, a guideline towards sustainability published by the Institution of Engineering and Technology (IET, 2009) in the United Kingdom, the first step towards sustainability is to look at conservation through consumer behaviour change. Conserving what we already have is the easiest and most cost effective solution. The second step focusses on reducing our demand through efficient energy use and the third utilising renewable energy sources. If we can apply these principles to our everyday lives then a sustainable society will not just be a dream but a reality.

In order to put these principles into practice, a suitable research area is required where sustainable ideas can be implemented. The case study in this project was chosen as the Lynedoch Eco Village near Stellenbosch. Being an excellent example of a community striving towards sustainability, Lynedoch provides an ideal environment to implement sustainability ideas and projects. Investigating the processes at Lynedoch revealed various practices that are already in line with the first step of the energy hierarchy. With a culture of conservation already in place at Lynedoch, focus shifted towards reducing demand by using renewable energy.

Borrowing ideas and technologies from solar desalination, the idea came about to obtain clean drinking quality water from household grey water. Instead of using salt water as the feed water, it is postulated that the grey water act as the feed source. The distillation process involved in desalination should be capable of distilling out not only the chemical contaminants, but also the biological contaminants. At Lynedoch, waste water treatment facility focussing on natural treatment options are already in place. Since this treated water is currently used for toilet flushing and irrigation, it is suggested that this treated water, henceforth referred to as grey water, could act as the feed water to the prototype.

The objective of this project is therefore to reduce the water and electricity demand of domestic households. This is realised through the recovery of grey water by making use of renewable energy. Not only is the proposed design capable of reducing the demand for fresh water supply systems and wastewater treatment facilities, but also the demand for electricity. A reduced electricity demand is due to the produced fresh water being at an elevated temperature, ready for use as feed water for a domestic hot water geyser. The project involves the design, construction and testing of a prototype system together with the modelling the whole system with software. This allows future production predictions to be made for different locations.

However, it must be mentioned that this proposed design is a complimentary system that should be incorporated into a more complete strategy for sustainability such as the previously mentioned energy hierarchy. Together, all of the system should encourage a change in the behaviour of society towards living a sustainable life.

2. Solar desalination

As mentioned before, the idea for the project came about from previous research into solar desalination. Distillation systems used in solar desalination should therefore provide a good platform from which to design the new system. The most basic desalination system is a simple still composed of a water basin cover with a transparent material. The water heats up, evaporates and condenses on the transparent material and gets collected.

More complex systems utilises the latent heat of condensation to heat up another body of water, thereby recovering otherwise wasted heat. These systems are referred to as having more than one stage, with the amount of stages referring to the amount of times the latent heat is recovered. Some systems have direct solar collection abilities included in the design and some have indirect solar energy collection through using normal solar panels for heating up the water. Specialized systems have incorporated vacuum systems to lower the ambient pressure inside the evaporation chamber, thereby increasing evaporation rates.

For the task at hand it is decided to focus on simple elements which can be configured to create a robust system capable of operating independently. To realise this, a two stage indirect solar system is envisioned. This falls into the category of a Multiple Effect Humidification Dehumidification (MEHDH) system. Different configurations for the MEHDH system have been found in literature and will be investigated.

After looking at various designs and configurations in literature, a new unique design is formulated. The proposed design starts with positioning the evaporation and condensation area configuration, seen in the system of Bouchekima et al. (1998) and Ahmed et al. (2009), in the vertical rather than the horizontal position. This creates a distillation cell similar to the cells used by Jabrallah et al. (2005). Such distillation cells have been thoroughly investigated and proven to be effective by Jabrallah et al. (2005).

Finally, a circular configuration is proposed by taking the distillation cell and rotating it in a full circular configuration. This reduces areas of possible losses as well as increasing the condensing surface area to the coinciding evaporator area. Also created is a suitable central storage tank. The evaporator will however be fitted with jute cloth to increase the evaporation surface area and allow a water film to form on the outside of the evaporator plate. The overall system layout will be similar to the system of Badran et al. (2005).

Figure 1 provides a section drawing of the proposed circular design. The left hand drawing shows a centre hatched area, which represents the storage tank. The hatched areas represent water. The dashed lines represent the jute cloth. The cloth will be folded over the top to be in contact with the water. This initiates the capillary action of the cloth ensuring a feed water rate. Opposite the dashed lines is the condensing surface. The bottom of this cavity will have a divider keeping the brine and the condensate separate. The outflow will flow out of holes in the bottom plate.

The proposed design is a new approach using already proven techniques. This needs some more in depth analysis on the characteristics and operation of the proposed design. To facilitate this, a mathematical model is required to allow characterization and comparison of the design. The model would also be helpful in simulating the proposed design.

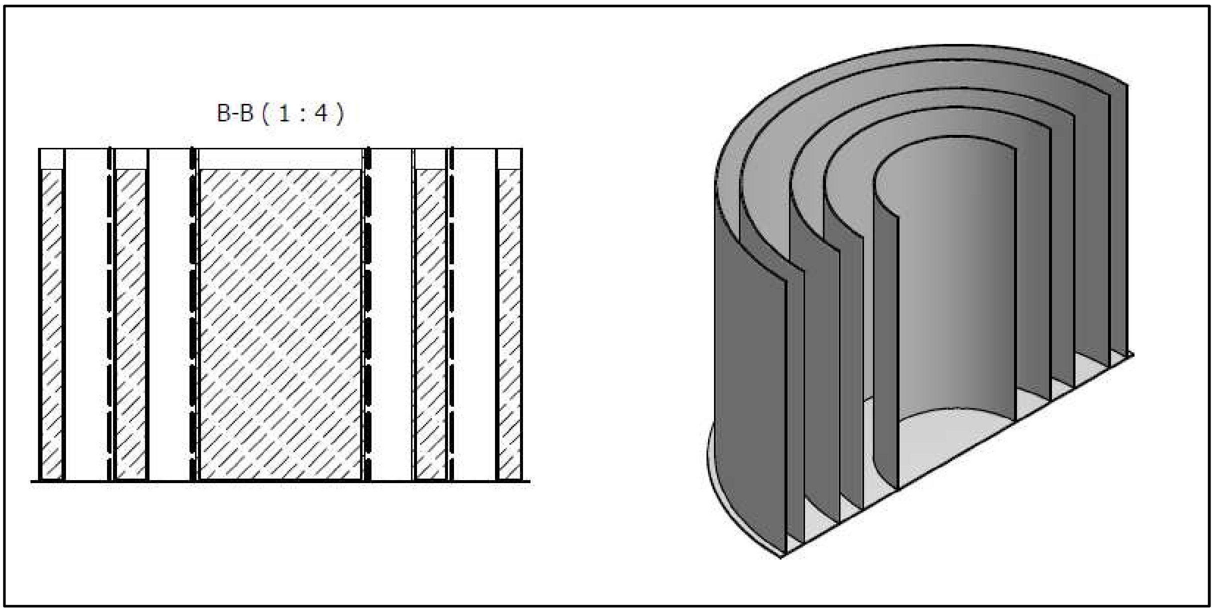

Figure 1: Section view of proposed circular design

3. Mathematical model

Solar distillation is an example of utilising solar energy on a basic level. It was one of the first techniques used to harness energy from the sun. The mechanisms involved are, however, much more complicated. It involves a temperature rise in the water due to absorbed solar energy. The water in turn starts to evaporate into the air at the air-water interface. This increases the humidity of the air. This process depends on the water temperature, vapour pressures, initial air humidity and a variety of moist air properties including specific heat capacity, thermal diffusivity, thermal conductance, density, viscosity and the Prandtl number of the air.

The first person to provide a mathematical model for natural convection distillation was Dunkle (1961) in 1961 and this relation still holds credibility today for specific conditions. This was followed by among other Kumar and Tiwari (1996), Chen (1984) and Adhikari (1990). Zheng et al. (2002) followed a similar path to Kumar and Tiwari (1996) in using the Nusselt Rayleigh relation as a basis to formulate their model. Each researcher tends to define their own model specific to their own needs and thus it is difficult to evaluate which model is the best suited to the current project. However, some of the models are used by other researchers such as Kalogirou (2004) who uses the model proposed by Kumar and Tiwari (1996). Tsilingiris (2007) has done extensive work on the analysis of heat and mass transfer in solar stills and uses the model proposed by Zheng et al (2002) although with different constants for use with the Nusselt Rayleigh relation.

In finding the best suited model, the Nusselt Rayleigh relation used in some mathematical models will not be evaluated. This is because the constants in Nusselt Rayleigh relation is derived from experimental results and these experimental results are from specific experiments utilising certain geometrically shaped devices. The best suited Nusselt Rayleigh relation will therefore be investigated separately.

It must also be stated that the models are not evaluated according to which one provides the most exact theoretical representation but to their applicability to the proposed circular system. With this in mind the most applicable model is the model of Zheng et al. (2002). This model is therefore chosen as the applicable mathematical model and is presented below.

$$\dot{m}_e = \frac{h_c}{\rho_f c_{paf} Le^{(1-n)}} \frac{M_w}{R} \left(\frac{P_w}{T_w} - \frac{P_g}{T_g} \right)$$

$$h_c = C(Ra')^n \frac{k}{d}$$

$$Ra' = \frac{X^3 \rho g \beta}{\mu \alpha} \Delta T''$$

$$\Delta T'' = \left[(T_w - T_a) + \frac{(P_w - P_a)(T_w + 273.15)}{\frac{M_a P_t}{M_a - M_w} - P_w} \right]$$

where

$\dot{m}_e$ = distillate flow rate [kg/s.m_{eva}^2]

As mentioned before, a suitable Nusselt Rayleigh correlation used in the mathematical models will be evaluated separately. This is due to the chosen Zheng et al. (2002) model using the simple Nusselt Rayleigh relation. For the proposed circular design a more representative relation is needed hence further research. Investigations into circular enclosures are limited and even less Nusselt Rayleigh relations are available as compared to the more common rectangular enclosures. However, circular correlations are provided by Kumar & Kalam (1991), Reddy & Narasimham (2008), Vahl Davis & Thomas (1970), Prasad (1986) and Weng & Chu (1996). The correlation for circular designs is presented below. Different constants are used for different configurations.

$$Nu = C(Ra)^n \left(\frac{H}{W} \right)^b \kappa^{\left(d + \frac{e}{\kappa} \right)}$$

with radius ratio $\kappa = \frac{r_o}{r_i}$

After evaluations, the correlation constants of Kumar & Kalam are chosen. The constants are C = 0.18, n = 0.278, b = -0.122, d = 0.34 and e = 0.329

4. Prototype

Since the prototype configuration and mathematical model are now available, the actual size of the prototype needs to be established. The simulation software used for this project is TRNSYS, a versatile and very powerful software package. Various parameters have an effect of the efficiency of the system and TRNSYS is used to investigate the relationships between these parameters to produce a suitably sized system capable of being used in a domestic environment.

The first aspect to look at is the average tank temperature. The temperature of the storage tank is the main driven of the rate of evaporation, hence a higher temperature results in higher evaporation rates. The average tank temperature is influenced by the size of the tank and the area of the solar collector. This is portrayed below with the f denoting "a function of".

$$\text{Average tank temperature} = f\,(\text{tank volume, collector area})$$

Ideally we would like to minimize the tank volume and maximize the collector area. Unfortunately the evaporation area, another factor in the overall production rate, is in turn a function of the tank volume. In this instance increasing the volume is more beneficial towards maximizing production rates as it increases the evaporation area.

$$\text{Evaporation area} = f\,(\text{Tank height, Tank diameter}) = f\,(\text{Tank volume})$$

Using TRNSYS to simulate the relationship between the tank volume, collector area and evaporation area a midpoint is found where temperatures of 70 Celsius can be reached using a 100 litre tank coupled to a 2 m^2 solar panel. The next step is to define the height and diameter of the tank to maximize the evaporation area with the given volume. Unfortunately the height and diameter plays a vital role in the aspect and radius ratios. These ratios have a large influence on the Nusselt number, as used in the mathematical model. The Nusselt number indicates the heat transfer rate and higher heat transfer rates translate into higher production rates. Accordingly, the following statements must also be taken into account.

$$Aspect\ ratio = \frac{H}{W} = f\,(Height,\ Width)$$

$$Radius\ ratio = \kappa = f\,(Tank\ diameter,\ Width)$$

$$Rayleigh\ number = f\,(Width)$$

With all of these relationships in place, a general optimization procedure is performed using TRNSYS as well excel spreadsheets. The results from the optimization process results in a system height of 1 m, an inner tank diameter of 0.3 m and an air cavity width of 0.2 m. This translates into an aspect ratio of 5 and a radius ratio of 2.12.

5. Experiments

The goal of the experiments is to indicate the accuracy of the simulation and mathematical models but most importantly to indicate the quality of water produced by the distillation of grey water. In order to accomplish this, different parameters will be investigated and compared against the experimental data gathered from the prototype. Three crucial areas of investigation will be looked at and are discussed in the next paragraphs.

The first crucial area of investigation is the accuracy of the mathematical model in predicting a distillate flow rate given two temperatures as inputs, namely the evaporation and condensation temperatures. This is done by using the experimental temperature data as inputs to the mathematical model. The production rate output of the mathematical model will then be compared to the experimental production rate data gathered at the same time as the temperature data. This will provide an accurate comparison in whether the mathematical model can accurately predict the distilled water production rate based on only two temperatures and the prototype parameters.

Secondly, the ability of the humidification dehumidification process to distil the grey water into water of a drinking grade. This requires taking water samples and testing them against the national drinking water standard, the SABS 241 standard. Samples of the input cold grey water, grey water after being exposed to the high temperatures reached in the storage tank and the distilled water will be taken and analysed. The reason for sampling the high temperature exposed grey water is to see what impact the high temperature water has on the biological elements present in the grey water.

Finally, the ability of the TRNSYS simulation to accurately predict the operation of the prototype. The focus here will be on the accuracy of the TRNSYS data to predict the different tank temperatures over a period of a couple of days. These temperatures are the driving force of the whole concept and reflect the operational ability of the prototype. Agreement in this instance will validate the TRNSYS components used, the heat and mass transfer configurations as well as all of the various assumptions made in constructing the entire simulation model.

Agreement on all of the above criteria will provide a simulation model capable of accurately predicting water production using the proposed model together with applicable solar radiation data. Prediction of the energy and water savings realised by using this system can also be provided.

After initial experiments, problems arose due to leakages and bending of the system rings. It was decided to reduce the height of the system to 0.5 m. This solved the problem without reducing functionality although the production rate is now half of the original design. Experiments and validating data are therefore based on a system with a height of 0.5 m.

5.1 Mathematical model validation

The following graph, Figure 2 , shows the temperature profiles for different points of operation for one experiment. T_eva refers to the evaporating temperature measured by the probes interwoven into the hessian fabric. Tank_1 is the temperature of the central storage tank with T_cond the second storage tank. Both Tank_1 and T_cond are measured in the middle of their respective water cavities. Detailed information on the placement can be found in Appendix A. T_air represents the air temperature measured in the middle of the cavity as outlined above. The dip in some of the temperature readings at a time of 06:30 occurred due to a visual inspection of the process in action. At this point, the auxiliary heater is also switched off resulting in the steady lowering of the temperatures.

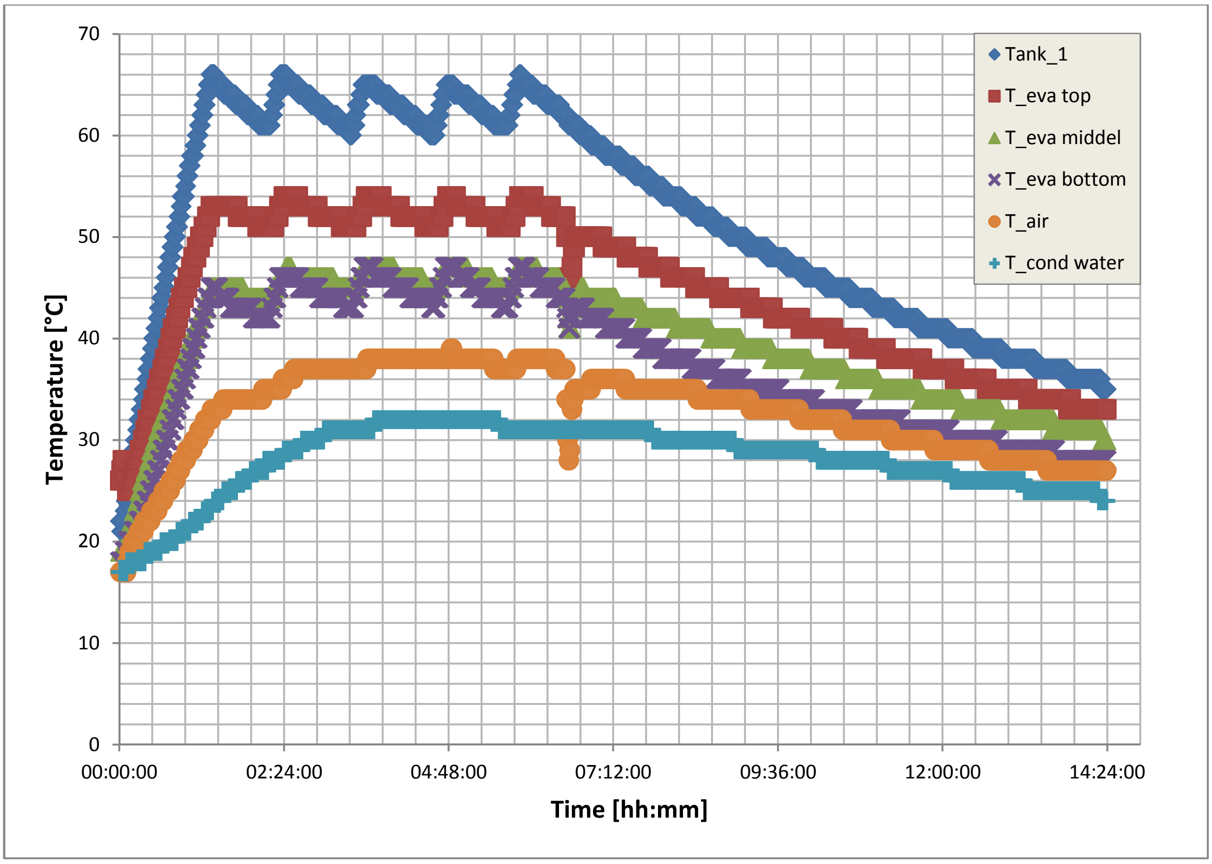

Figure 2: Temperature data for auxiliary heated operation

We are now able to comfortably input the temperature data into the mathematical model and compare the results with the measured distillate flow rate. Figure 3 shows the typical results from one specific experiment. It is evident that the mathematical model is dependent only on temperature inputs since the modelled data resembles the temperature profiles as found in Figure 2. Also visible is the initial warm up period where the measured flow rates are much lower than the predicted flow rates. This is as mentioned earlier, expected since the mathematical model does not take into account the specific heat capacity of the air or the system itself.

However, as the system reaches steady state the measured flow rates become more aligned to the predicted flow rates. It is also observed that the measured results do not show any real signs of following a saw tooth pattern as is visible in the modelled results. The model also over predicts the flow rates slightly. Figure 4 shows the same results as in Figure 3 but with four other experimental data sets as well. Similarities exist between the patterns of the experimental data sets but each set is distinguishable. This shows the difficulty in repeatability of the experiments since so many uncontrollable parameters, such as the natural environmental parameters, are involved.

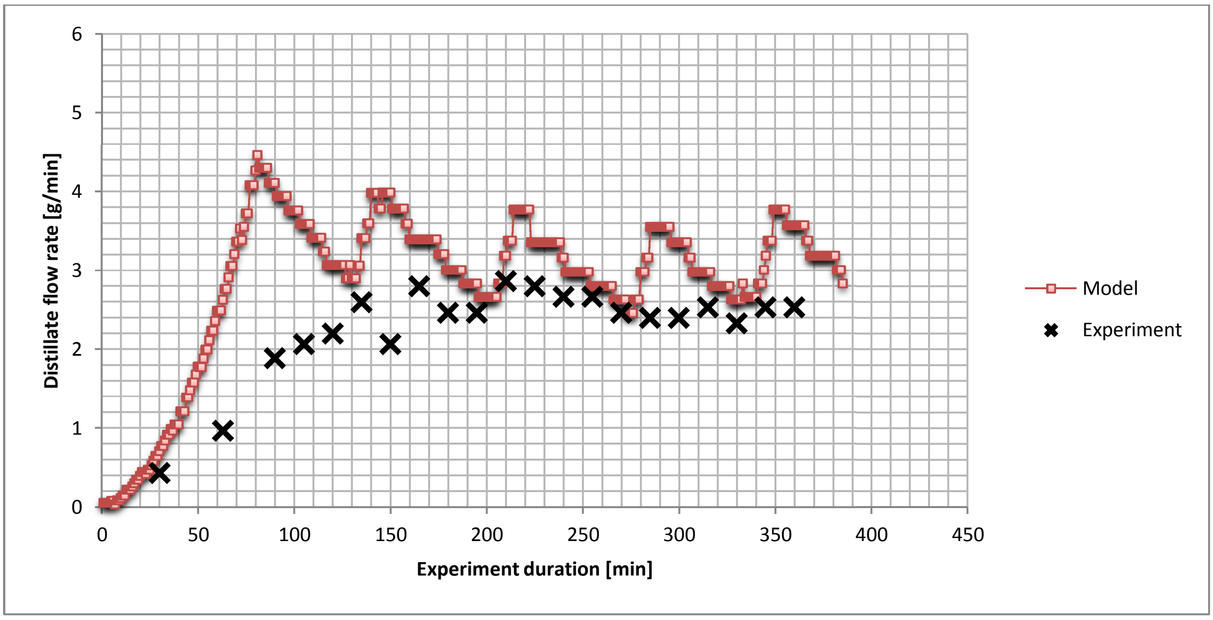

Figure 3: Experiment distillate flow versus mathematical model prediction

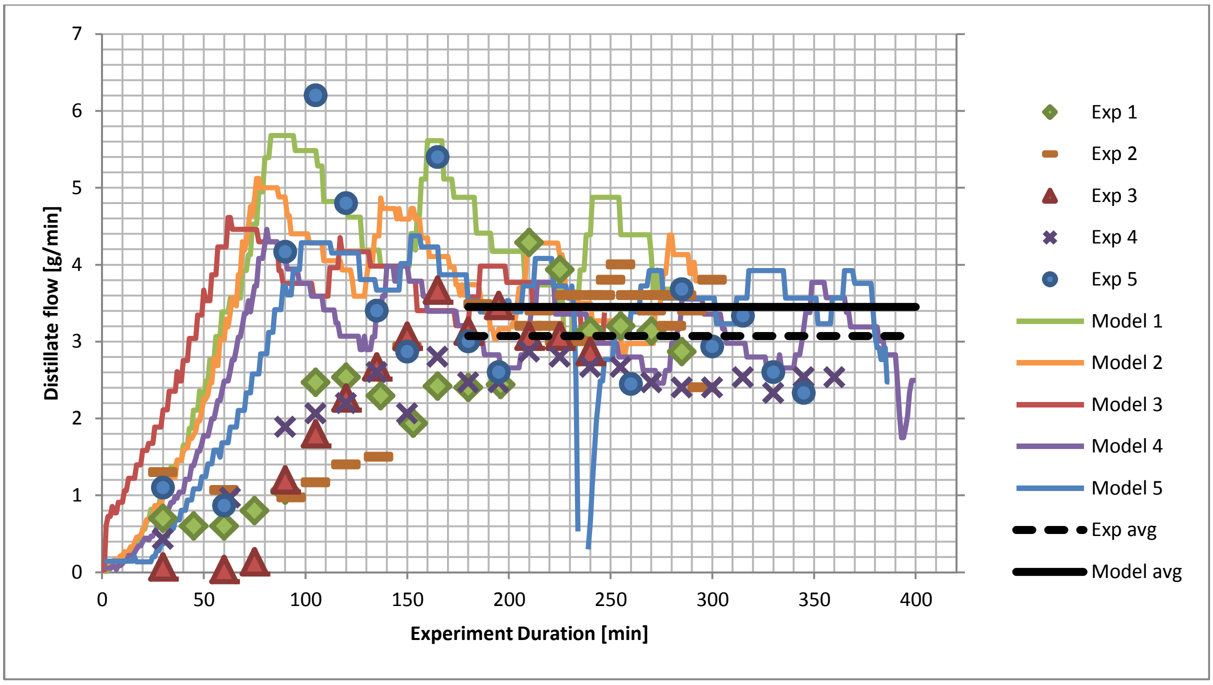

Figure 4: Experimental versus modelled flow rates

Also visible in Figure 4 is the average flow rates of the experimental and modelled data sets after the initial warm up period. It is assumed that steady state conditions is reached after 180 minutes and therefore the average rates are calculated from this point onwards. The average modelled flow rate is 3.45 grams per minute with the experimental data coming in at 3.07 grams per minute. The model thus over predicts the flow rates by 12.34 %.

5.2 Water Quality

The next experimental focus area is the quality of the produced water. The grey water used in the experiment comes directly from the treated water tanks at Lynedoch. Water samples were taken not only of the input grey water and the distillate produced, but also of the grey water after it has been exposed to the high temperatures encountered in the central storage tanks. This would indicate the impact of the high temperature exposure on the biological contaminants in the water. All samples are compared to the SANS 241 national drinking water quality standard.

The first sampling tests were conducted using the auxiliary heating element as a heat source. The main focus is to analyse the chemical levels found in the water. Samples were sent to the in house Stellenbosch Central Analytical Facility. Table 1 shows the results of the initial grey water (GW 1A), the heated grey water (GW 1B) as well as the distilled product (DW 1).

The initial observation is that the grey water on its own is chemically within the limits of the SANS 241-1 standard except for the levels of NO_3. Looking at the produced distilled water, it is easy to see the effect of distillation on reducing the chemical contaminant levels. This is summarized by a reduction in electrical conductivity (EC) of around 90 %. Interestingly the grey water itself is within the most of the limits of the SANS 241.

Table 1: Grey water distillation Test 1: Chemical contaminant removal results

Water quality Test 1 Lab: Central Analytics Facility			Standard		Samples					
			SANS 241-1		GW 1A	Within limits	GW 1B	Within limits	DW 1	Within limits
CHEMICAL ANALYSIS										
Component	Units									
pH			5 ≤ x ≤ 9.7		8.8	Y	8.1	Y	8.1	Y
EC	mS/m		≤ 170		113	Y	111	Y	11	Y
Na	mg/l		≤ 200		80	Y	79	Y	1.6	Y
K			≤ 50		19	Y	19	Y	0.4	Y
Ca			≤ 150		97	Y	99	Y	4.8	Y
Mg			≤ 70		12	Y	12	Y	0.3	Y
Fe			≤ 2		0.34	Y	0.55	Y	0.13	Y
Cl			≤ 300		95	Y	95	Y	2.6	Y
CO_3			NA		NA		NA		NA	
HCO_3			NA		NA		NA		NA	
SO_4			≤ 250		44	Y	48	Y	bdl	Y
B			NA		NA		NA	Y	NA	Y
Mn			≤ 100		0.2	Y	0.2	Y	0.03	Y
Cu			≤ 2		bdl	Y	bdl	Y	bdl	Y
Zn			≤ 5		bdl	Y	bdl	Y	bdl	Y
P			NA		NA		NA		NA	
NH_4			≤ 1.5		NA		NA		NA	
NO_3			≤ 10		21	N	24	N	bdl	Y
F			≤ 1.5		NA		NA		NA	
Suspended Solids	%		NA		< 1	Y	< 1	Y	< 1	Y
TDS	mg/l		≤ 1200		NA		NA		NA	

The second grey water experiment was again conducted with grey water from Lynedoch. For this experiment the focus is on the biological contaminants although chemical analysis is also conducted. Bemlab was used as the testing laboratory since they are a SANAS accredited laboratory. Results are tabulated in Table 2 with the cold grey water (GW 2A), warm grey water (GW 2B) and the distilled product (DW 2) again being the samples investigated.

The chemical tests revealed similar results as the first experiment in reducing the chemical contaminants to lower values. The only element outside of the acceptable range is ammonium (NH_4) with the distillation process only capable of reducing the levels slightly. An increase in levels of iron (Fe) and Zinc (Zn) is in contrast with the distillation process. This increase can be attributed to the rusting components used on the prototype.

On the biological front, the experiment revealed less conclusive results. The E-coli microbe is not detected in any sample with total coliforms only registering in the cold grey water sample (GW 2A). The coliform level is however still below the acceptable level of 10 counts per 100 ml. The total bacteria level, or bacterial plate count, is unfortunately outside of acceptable limits in all samples including the distillate produced.

Table 2: Grey water distillation Test 2: Biological and chemical contaminant results

Water quality Test 1 Lab: Bemlab Sanas accreditation (ISO/IEC 17025)			Standard		Samples					
			SANS 241-1		GW 2A	Within limits	GW 2B	Within limits	DW 2	Within limits
CHEMICAL ANALYSIS			NA = not applicable; Y = yes; N = no; ND = not detected							
Component	Units		Bold values are below acceptable detection limits							
pH			5 ≤ x ≤ 9.7		9.3	Y	9.3	Y	7	Y
EC	mS/m		≤ 170		83	Y	79	Y	8	Y
Na	mg/l		≤ 200		78.7	Y	80.8	Y	4.6	Y
K			≤ 50		23.9	Y	20.4	Y	2.4	Y
Ca			≤ 150		87.2	Y	87.3	Y	8.1	Y
Mg			≤ 70		15.6	Y	14.4	Y	0.5	Y
Fe			≤ 2		**0.03**	Y	**0**	Y	**0.18**	Y
Cl			≤ 300		113.7	Y	128.7	Y	8.3	Y
CO_3			NA		180.4		153.3			
HCO_3			NA		166.6		131.4		37.5	
SO_4			≤ 250		53	Y	62	Y	11	Y
B			NA		0.09		0.09		**0.01**	
Mn			≤ 100		**0**	Y	**0.02**	Y	**0.01**	Y
Cu			≤ 2		**0.03**	Y	**0.03**	Y	**0.06**	Y
Zn			≤ 5		**0.02**	Y	**0**	Y	2.28	Y
P			NA		1.25		1.65		0.12	
NH_4			≤ 1.5		2.84	N	2.85	N	2.25	N
NO_3			≤ 10		7.86	Y	7.83	Y	**0.05**	Y
F			≤ 1.5		0.3	Y	0.4	Y	0	Y
TDS	mg/l		≤ 1200		532	Y	510	Y	55	Y
BIOLOGICAL										
Total Bacteria	/1 ml		≤ 5000		>30000	N	9300	N	>30000	N
Coliforms	/100ml		≤ 10		3	Y	ND	Y	ND	Y
E Coli	/100ml		ND		ND	Y	ND	Y	ND	Y

The final water quality test will test the water against the whole SANS 241 standard. This is still on going and is therefore not included in this report. The reason for not testing every sample according to this standard is the high costs of such a test. Results from this test should provide final clarification on the effectiveness of the prototype.

5.3 Simulation validations

As mentioned, TRNSYS is used to simulate the long-term performance of the proposed design. Experimental data required to confirm the simulation is currently still being gathered.

Actual measured solar radiation values will be fed into TRNSYS which will then provide a produced flow rate. These flow rates will be compared to the experimental flow rates. Temperatures recorded in the three storage tanks will also be used to validate the simulation. Figure 5 Figure 6 show TRNSYS results based on solar radiation data for Cape Town.

From this data estimates can be made in terms of how many prototype systems are needed to produce enough fresh water to sustain an average Lynedoch household. Over the summer period, seven prototype systems are capable of satisfying the demand of 250 litres a day.

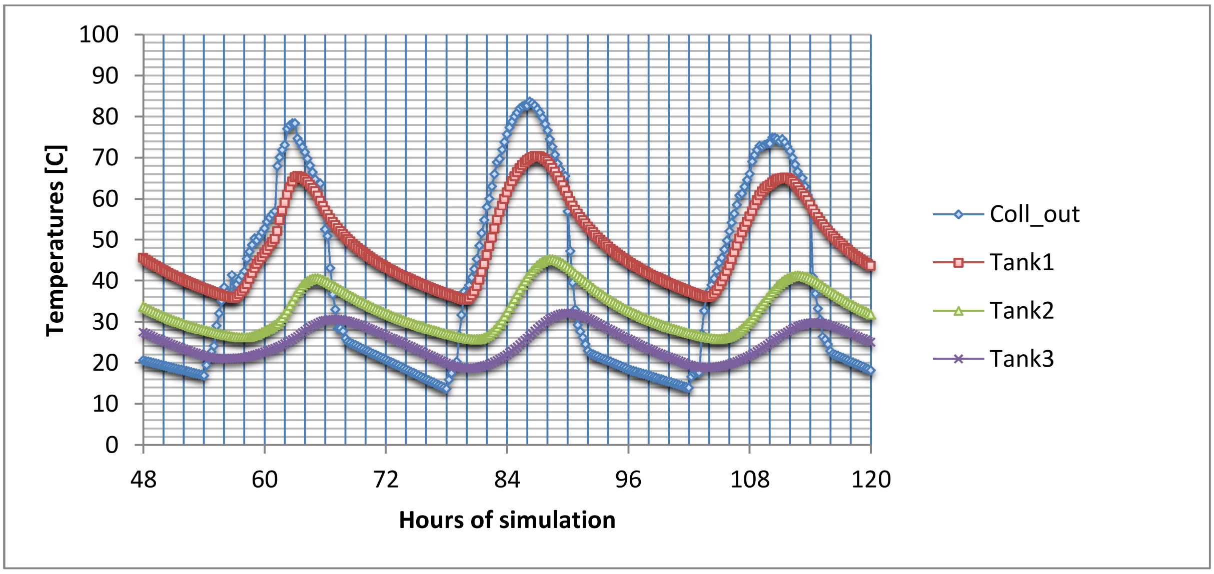

Figure 5: Simulated Tank Temperatures

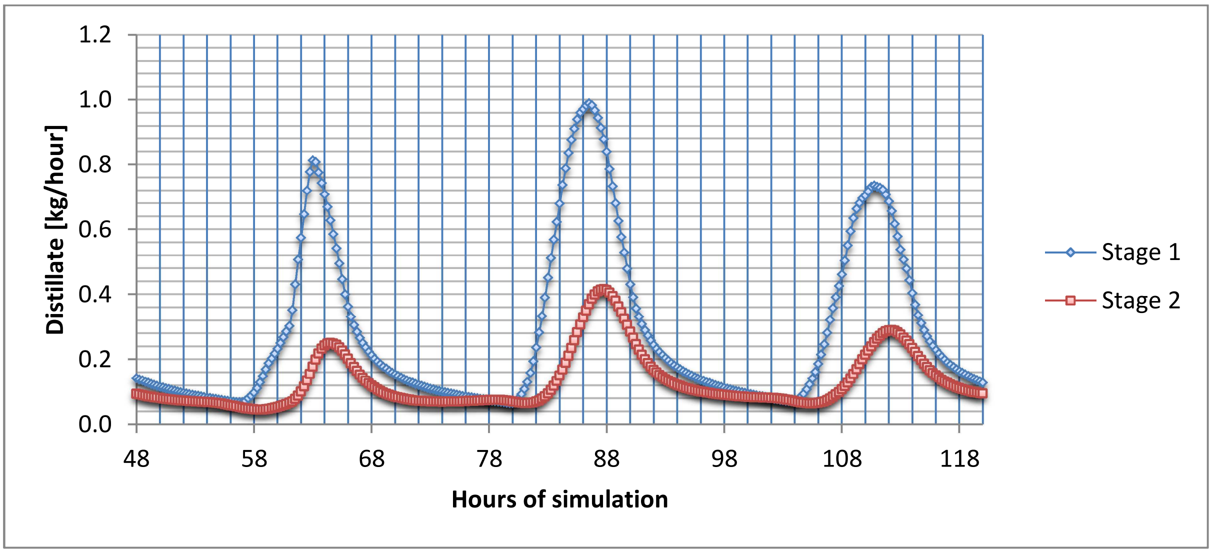

Figure 6: Simulation distillate production

6. Conclusion and recommendations

The initial objectives of the project involves designing, constructing and experimentally verify a device capable of distilling grey water. Although the project is not complete yet, initial results have been encouraging. The design of the prototype combines simple elements into a unique system capable of operating as a standalone device without supervision. This is applicable to the rural environment where it is envisioned the device will operate in.

A mathematical model has been formulated to characterize the device. This allows long term predictions to be made in conjunction with the TRNSYS simulation software. Savings in terms of energy and water can be viewed over extended periods. Incorporating such data into economic models can reveal long term benefits to not only the communities that use the device, but the municipalities as well. Initial results from the quality of drinking water produced shows positive levels in terms of chemical composition. Biologically the results are not yet conclusive since the grey water used proved less contaminated than initially assumed. However, the results are yet to disprove the concept. Recommendations for future research include testing the circular design in a laboratory setup as well as investigating potential larger sized systems.

In the end, the proposed system contributes a large part in creating a sustainable solution to an ever increasing problem facing humanity. The problem of an increase in demand for resources from an ever-increasing population. Together with similar solutions , a sustainable future can truly become a reality.

Nomenclature

M_w = Molecular weight of water vapour
P_w = Saturation vapour pressure of water vapour at evaporation surface
P_g = Saturation vapour pressure of water vapour at condensation surface
P_t = Total pressure of air mixture
h_c = Convective heat transfer coefficient
ρ_f = Density of humid air
c_{paf} = Specific heat capacity of humid air
Le = Lewis Number
R = Universal gas constant
T_w = Temperature at evaporation surface
T_g = Temperature at condensation surface
T_a = Average temperature
Ra = Rayleigh number
k = Thermal conductivity of humid air
d = Characteristic length
X = Distance between evaporation and condensation surfaces
ρ = Density of water vapour
g = Gravity constant
β = 1/T
μ = Dynamic viscosity of humid air
α = Thermal diffusivity of humid air

7. References

Adhikari, R., Kumar, A. & Kumar, A., 1990. Estimation of mass-transfer rates in solar stills. *International Journal of Energy Research,* Issue 14, pp. 737-744.

Ahmed, M., Hrairi, M. & Ismail, A., 2009. On the characteristics of multistage evacuated solar distillation. *Renewable Energy ,* 6(34), pp. 1471-1478.

BADRAN, A., ALHALLAQ, I., EYALSALMAN, I. & ODAT, M., 2005. A solar still augmented with a flat-plate collector. *Desalination,* Issue 172, pp. 227-234.

Ben Jabrallah, S. et al., 2005. Experimental study of the evaporation of a falling film in a closed cavity. *Desalination,* Issue 180, pp. 197-206.

Bouchekima, B., Gros, B., Ouahes, R. & Diboun, M., 1998. Performance study of the capillary film solar distiller. *Desalination,* Issue 116, pp. 185-192.

Chen, Z. et al., 1984. Natural convection heat transfer across air layers at various angles of inclination. *Engineering Thermophysics,* pp. 211-220.

Dunkle, R., 1961. Solar water distillation: the roof type still and a multiple effect diffusion still. *International Developments in Heat Transfer,* Issue 5, p. 895.

IET, I. o. E. a. T., 2009. *Energy.* [Online]
Available at: http://www.theiet.org/factfiles/energy/energy-prin-page.cfm
[Accessed 30 October 2012].

Kalogirou, S. A., 2004. Solar thermal collectors and applications. *Progress in Energy and Combustion Science,* 3(30), pp. 231-295.

Kumar, R. & Kalam, M., 1991. Laminar thermal convection between vertical coaxial isothermal cylinders. *International Journal of Heat and Mass Transfer,* Volume 34, pp. 513-524.

Kumar, S. & Tiwari, G., 1996. Estimation of convective mass transfer in solar distillation systems. *Solar Energy,* Issue 57, pp. 459-464.

Lazenby, H., 2012. *Energy intesive users prepared to reduce demand.* [Online]
Available at: http://www.engineeringnews.co.za/print-version/energy-intensive-users-prepared-to-reduce-electricity-demand-2012-01-10-1
[Accessed 11 January 2012].

Prasad, V., 1986. Numerical study of natural convection in a vertical, porous annulus with constant heat flux on the inner wall. *International Journal of Heat and Mass Transfer,* 29(6), pp. 841-853.

Thomas, R. & de Vahl Davis, G., 1970. Natural convection in annular and rectangular cavities–a numerical study. *Proceedings of the Fourth International Heat Transfer Conference,* Volume 4.

Tsilingiris, P., 2007. The influence of binary mixture thermophysical properties in the analysis of heat and mass transfer processes in solar distillation systems. *Solar Energy,* Issue 81, p. 1482–1491.

Venkata Reddy, P. & Narasimham, G., 2008. Natural convection in a vertical annulus driven by a central heat generating rod. *International Journal of Heat and Mass Transfer,* Issue 51, pp. 5024-5032.

Weng, L. & Chu, H., 1996. Combined Natural Convection and Radiation in a verticalannulus. *Heat and Mass Transfer,* Issue 31, pp. 371-379.

Zheng, H., Zhang, X., Zhang, J. & Wu, Y., 2002. A group of improved heat and mass transfer correlations in solar stills. *Energy Conversion and Management,* Issue 43, pp. 2469-2478.