Earth, Life & Social Sciences
Utrechtseweg 48
3704 HE Zeist
P.O. Box 360
3700 AJ Zeist
The Netherlands

www.tno.nl

T +31 88 866 60 00
F +31 88 866 87 28

TNO report

2016 R11001 | Final report

Pilot test Solar Driven Membrane Distillation for drinking water production at Robanda Tanzania
NWASH project result 2:
Innovative Fluoride removal technology

Date	30 August 2016
Author(s)	W.G.J.M. van Tongeren, BSc W.J. Assink, MSc W.A.J. Appelman, MSc, MBA with the cooperation of P. Verhagen, TNO (SBA) M. Bongaerts (AAWS/ TU-Delft) M. Nitzsche (AAWS) J. H. Hanemaaijer (i3 Innovative Technologies bv)
Copy no	
No. of copies	
Number of pages	59 (incl. appendices)
Number of appendices	6
Sponsors	Netherlands Ministry of Foreign Affairs TNO Dunea
Project name	Networking WASH projects in Mara Region, Tanzania
Project number	060.02221

Summary

In this report the results are described of a pilot research project (proof-of-concept) aiming at the development of a new Solar driven Membrane Distillation (SdMD) technology to provide a safe and sustainable supply of drinking water at point-of-use level in rural areas. Field work with two prototype systems has been carried out at a small village in Tanzania, Robanda, where the removal of fluoride from drinking water is necessary. The research is part of the Networking WASH projects in Mara region, Tanzania. These projects address the sustainability crisis in rural water supplies, focusing on two inter-related problems: the high non-functionality of water facilities in rural areas of Tanzania and the high fluoride content of the water sources in some areas.

The technology of membrane distillation (MD) has made important improvements the last decade on performance and process design. One of the improvements is internal recycling of the heat for evaporation, making it possible to operate the process directly using solar heat. First SdMD prototypes were developed and built by i3 Innovative Technologies and TNO, tested at TNO and subsequently transported to Tanzania for testing at location, at a household and a hospital. The results of the pilot tests were promising. The pilot was operated and monitored for a period of over 1 month in May 2016 and daily water production was around 10 liters, while salt concentrations were reduced with a factor of 80. The fluoride concentration in the produced water was below the detection limit of 0,02 mg/l. A number of problems in the current design related to the robustness of the system and the occurrence of leakages have led to first ideas towards a new design.

Figure: Solar driven Membrane Distillation: The main parts of the unit are a flexible matrass with membrane of 3 – 4 meters length and 3 vessels; 1 input water (green pipe), 1 clean output water (blue pipe) and 1 dirty warm output water (red pipe)

In general only a small fraction of the success of an innovation can be contributed to the functioning of technology. Success largely depends on user adoption and finding a sustainable business model. Affordability is a main driver for success. Based at the current insight the production costs of the SdMD are estimated to be around 200.000 TSH (95 USD). Given the proof-of-concept stage of the product,

the above calculations can still vary substantially, both up and down. The cost calculations are based on a series of assumptions, that all need to be tested further to improve the accuracy of the calculations.

The calculated costs of clean water are in the range of 25 TSH/liter. Looking at their daily expenditure on water (so water for drinking, cooking, washing, hygiene, cleaning etc.) the SdMD will add 5 TSH/liter to the price of the input water. When input water is free (which it isn't in many cases), this means people will spend 7% of their income on water, which is significantly higher than the 3% that is used as a benchmark by the UN.

Comparing SdMD to current and alternative point-of-use solutions, RO-based water shop and rainwater collection are the most competitive options to the SdMD. Both are able to provide clean drinking water at a 3 times lower price per liter than the SdMD, aligning better with the expressed willingness to pay. However, water kiosks only work when they can service a large enough market, in general starting at 400 individuals. The SdMD is able to service a single household. The benefit of rainwater is that families are more self-reliant and should not be depended on the presence/operation schedule of a water shop or any other way of access to water. Rainwater harvesting obviously has its drawbacks in the dry season.
From the previous analysis we have seen that the SdMD technology at current small scale level of development is still too expensive for the average Tanzanian family and faces significant usability issues. However, we also see that the improved version of SdMD is able to compete with existing products that target single households. It is one of the few products that is able to generate sufficient clean water for a whole family's daily water need, also when fluoride (or similar) contamination is present.

There are a number of strategies how the SdMD could be implemented in developing countries:

- When the mission of a water company is to provide everyone in a large region with clean water, the SdMD can be used to provide some families that live far away from a piping infrastructure, and with only contaminated water available, with the option to clean this water themselves. In the case of Robanda it can be an option as long as central treatment (point-of-entry) is not available.
- The SdMD could be a viable option in very remote regions where the water is heavily contaminated, and no village or neighborhood scale alternative is available. A typical location are small islands that are scattered in archipelagos far from the coast, and have no clean water sources of their own.
- A third scenario is using the SdMD in emergency situations (comparable to the target market of the LifeStraw). Depending on the situation the size of the product could be an issue there, but on the other hand, comparing to the LifeStraw it can produce drinking water from all types of sources, removing not only micro-organism but also physical-chemical pollutants.

Based at the technical and economical evaluation i3 Innovative Technologies and Aqua-Aero Water Systems BV intend to further develop the technology together with TNO. Plans will be discussed and further developed with sponsors and NGO's.

Contents

1 Introduction

1.1 The Networking WASH project

The Networking WASH project addresses the sustainability crisis in Tanzania, focusing on two major problems: the high non-functionality of water facilities in rural areas of Tanzania and the high fluoride content of the water supplied in some areas. The two problems are inter-related as the same factors which cause the falling into disuse of the water facilities also prevent an effective treatment of water.

In this report the third phase of the WASH project - Water Treatment Innovation - is described [1].

In the first phase an inventory of available relevant available water treatment technologies for fluoride removal has been carried out (TNO report 2013 R12119) [2]. Based on the assessment of the available technologies it was concluded that using a low cost adsorption material or a (simplified) reverse osmosis system, will be most suitable for application in the water scheme of Robanda, Tanzania. Also the capacitive deionization technology is considered a promising option.

In the second project phase – the innovation phase - the boundary conditions for the application at the local situation were defined. The most promising technologies were selected by the consortium for further development and tested at laboratory scale (TNO report 2014 R11584) [3]. During the execution of this phase (mini) solar driven Membrane distillation (SdMD unit) has been identified by the consortium as an interesting and promising option and different set-ups have been tested.

After a discussion about the results of the first two project phases and the wish to demonstrate an innovative technology, it was decided in March 2015 to focus in the third phase on a SdMD unit Point-of Use (PoU) system [4]. This means that the purification technology is applied at the side of consumers instead of purifying centrally (Point of Entry system). In the same time also one of the project partners decided not to continue in the project and was replaced by i3 Innovative Technologies and Aqua-Aero Water Systems BV by the end of 2015. These SME's are well experienced and equipped to develop (in collaboration with TNO) and eventually launch SdMD in the African market.

1.2 Pilot test Robanda

In different parts of Tanzania water sources like wells and lakes contain higher concentrations of fluoride than allowed by the World Health Organization. Since many people drink from these water sources people suffer from Fluorosis. Fluorosis is a disease caused by fluoride damaging the teeth and bones. However, more diseases and health effects are related to an excess of fluoride intake [5].

TNO, i3 Innovative Technologies and Aqua-Aero Water Systems BV were responsible for the pilot test and have had support at location of Bomba Ltd., which has the task to supply water to the houses of villages. Many villages in Tanzania such as Robanda have a water supply system built by the government several years ago. In the case of Robanda this supply consists of a pump station, a tank to store water on the hill and distribution pipes from the tank to the houses in the village. In the past people did not pay for the water supply and therefore there was also no money for any maintenance. The goal of Bomba Ltd. is to maintain the already existing water supply systems and expand these supplies where needed. By letting the people pay for the use of water, Bomba Ltd. aims to make this a sustainable business model.

As mentioned the main objective is to reduce the amount of fluoride (and possible other contaminations) from the current water supply sources. TNO, i3 Innovative Technologies and Aqua-Aero Water Systems BV have developed a new water purification system for point of use applications. This water purification system makes use of a purification method called Membrane Distillation and uses solar heat for heating the water (chapter 2).

A number of three different sized pilot systems were designed, built and tested in the Netherlands and transported to Tanzania (chapter 2,3 and 4). Two of the systems have been installed at different locations in the village of Robanda. One system was being demonstrated at a hospital and the other at a household. Both systems have been in operation for more than a month. (chapters 5 and 6)

To investigate the potential for market uptake, also local issues and opportunities for market uptake were identified (chapters 7 and 8). Information has been gathered on how people in Tanzania, Robanda, are dealing with water and their willingness to pay for a clean and safe water supply. This also includes information about expenditures of people on water and information about their monthly income. This information is used to determine what investments are accessible for people.

As the time available for the development of a pilot installation was limited, the tested system should be regarded as a first experimental prototype and the results of the pilot tests could be used for further development of the technology and further testing for longer periods, for example using next generation pre-production prototype systems in larger cohorts.

Figure 1.1 SdMD unit 2 in Robanda. Site: Mama Lucy.

2 Membrane distillation

2.1 Membrane Distillation

Membrane Distillation is a process in which a pure water flow (distillate) may be obtained from a wide variety of feed water qualities. It uses a hydrophobic membrane with air filled pores. The surface tension of the feed water and distillate will prevent the water to enter the pores of the membrane, hence keeping the water out of the membrane. A water vapour pressure difference is accomplished by applying a sufficient temperature difference across the membrane. This is accomplished by heating the feed water and/or cooling the distillate at other side of the membrane. This results in a flow of water vapour through the membrane and results in the distillate after condensation.

Membrane distillation (MD) is a known technology for over 40 years, but only the last decade important improvements have been made on performance and process design, leading to commercial interest in the technology. One of the improvements is internal recycling of the heat for evaporation, as described in the next paragraph.

The integration of heat recovery in MD accomplishes a relatively low heat consumption per m^3 distillate. Values as low as 200 MJ/m^3 have been claimed for specific cases, pointing to a Gained Output Ratio (GOR) of 10 or more. The Gained Output Ratio states how many kilograms of distilled water are produced per kilogram of steam (usually it is assumed that 1 kg steam equals 2326 MJ). More realistic values for commercial MD units vary between less than 1 and more than 8.

2.2 Memstill®

Memstill® is a TNO patented membrane-based distillation concept, which has the potential of reduced heat input requirements and low costs. The technology uses hydrophobic membranes to separate the feed water from pure distillate. Because a Memstill® module houses a continuum of evaporation stages in an almost ideal countercurrent flow process, a very high recovery of evaporation heat is possible.

The feed water is preheated in an impermeable channel by the condensation of water (see figure 2.1). This channel rises the temperature of the water by 40-70 °C, after which an external heat exchanger adds a small additional amount of sensible heat to accomplish a final temperature step of 3–8 °C. This preheated stream is returned to the module as feed water in the membrane channel, where the aforementioned temperature difference drives the distillation process.

Cold feed water thus takes up heat in the condenser channel through condensation of water vapour at the other side of the condenser. After it leaves the module, a small amount of (waste) heat is added, and flows counter currently back via the membrane channel of the module. The cooled brine is disposed, or extra concentrated in a next module.

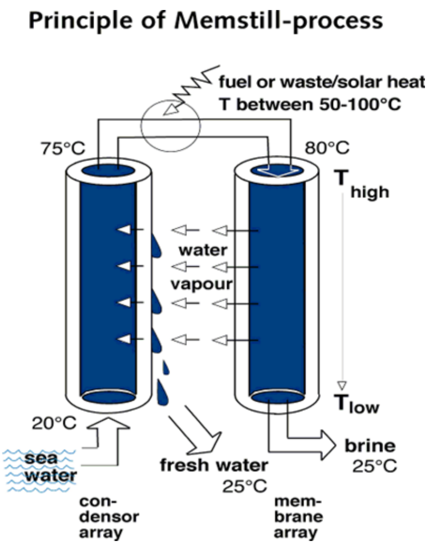


Figure 2.1 Principle of Memstill®.

The process promises to decrease desalination costs to well below 0,50 €/m³ , using low grade waste steam or waste heat as driving force. Pilot tests have demonstrated the excellent product water quality, the need for little water pretreatment and a thermal energy requirement of approx. 500 MJ/m^3 water.

Membrane distillation or Memstill® can be used for producing drinking water out of groundwater. Memstill® removes all (not volatile) components in the feed, so also components like fluoride and arsenic will be removed. The produced water meets international standards for distillate water. Viruses, pathogens and bacteria are also retained.

The tested pilot module is a special designed variant of this Memstill® concept, especially aiming at a low capacity (household scale), low investment costs and effective capture of solar heat to drive the process.

2.3 Modelling

A mathematical model has been built to examine the results of the tested pilots and to estimate the achievable production rates. This model is written in Python and details are provided in the report of M. Bongaerts [6]. It also incorporates relations for heat transfer in spacer filled channels.

To provide an understanding for the main physical MD principles the basic generic relations for membrane distillation for water production are described in this paragraph.

The membrane distillation process can be considered as a water producing heat exchanger, i.e. heat is exchanged between the two main channels because of an existing temperature difference. The heat transfer Q will largely be done by conduction, but in the membrane this changes to predominantly latent heat transfer, i.e. transport of water vapour adds to the total heat transport through the membrane.

The heat transfer in the membrane (Q_m in terms of W/m^2) is thus a combination of conduction (Q_c) and vapour transport (Q_v):

$$Q_m = Q_c + Q_v = -k_m.\frac{dT}{dx} + J.\Delta H \qquad (1)$$

Here is dT/dx the temperature gradient across the membrane, J the vapour flux (kg/m^2.s), ΔH the latent heat of water vapour (J/kg) k_m is the combination of heat conduction via the solid material of the membrane and via the vapour phase:

$$k_m = \frac{(1-\epsilon)}{\tau}.k_p + \epsilon.k_v \qquad (2)$$

In (2) is ε = porosity of the membrane, τ = tortuosity of the pores, k_p = thermal conductivity of the membrane material and k_v = thermal conductivity of the water vapour, actually the vapour saturated air in the pores.

The water vapour flux J may be described by the pressure difference across the membrane:

$$J = B_0.(T_{m,1} - T_{m,2}) \qquad (3)$$

B_0 refers to the permeation coefficient of the membrane and the second subscripts of the membrane temperature T_m to the place, i.e. the number of the adjacent channel. The permeation coefficient is usually estimated via the 'Dusty gas' model:

$$B_0 = \frac{1}{R.T.\delta}\left[\frac{3\tau}{2.r.\varepsilon}\left\{\frac{\pi M}{8.R.T}\right\}^{0.5} + \frac{\tau.P_a}{\mathbb{D}.P_{tot}\varepsilon}\right]^{-1} \qquad (4)$$

Where r = pore size, ε = porosity of the membrane, τ = tortuosity, $\mathbb{D}$ = diffusion coefficient, M = molecular mass of water and R = gas constant.

The heat transfer in other elements and channels of the module is described by Fick laws for conduction:

$$Q_1 = h_1(T_{1,b} - T_{1,m}) \qquad (5)$$

$$Q_2 = h_2(T_{2,m} - T_{2,c}) \qquad (6)$$

$$Q_c = \frac{k_c}{\delta_c}(T_{c,2} - T_{c,3}) \qquad (7)$$

$$Q_3 = h_3(T_{3,c} - T_{3,b}) \qquad (8)$$

In which temperature differences are taken either:
- Over the total thickness of a layer (cases Q_2 and Q_c). These are more or less stagnant layers, where subscript c refers to the condenser material and subscript 2 refers to the distillate channel, or
- Between the bulk of the flowing liquid and the temperature at its interface (cases Q1 and Q3). Subscript b refers to the bulk temperature and the other subscripts to the adjacent layers (see figure 3.1).

In case the liquid is flowing one can use a Nusselt relation to estimate the heat transfer coefficient, since Nusselt is defined as:

$$Nu = \frac{h.d_h}{k_l} \qquad (9)$$

In which h = heat transfer coefficient (of channel i), d_h = the hydraulic diameter of the channel (or hydraulic diameter of the spacer) and k_l = the specific heat transfer coefficient of water. Empirical relations with dimensionless Reynolds and Prandtl numbers have been established that can be used for estimation of the heat transfer coefficients (h_i). A typical example is:

$$Nu = 0.664.f(x).Re^{0.5}.Pr^{0.33} \qquad (10)$$

Where Re is the Reynolds number (=ρ.v.d/μ), Pr the Prandtl number (= C_p.μ/k) and f(x) a relation depending on the characteristics of the spacer (Phattaranawik et al [7]) provide a complex relation for f(x), with spacer porosity, filament thickness, grid size and angle of the filaments as main input parameters. This is also used in the Python model, but will not be discussed here.

Under steady-state conditions all heat transfers are equal. From this set of equations a temperature profile across the channels can be calculated. For a correct calculation all construction materials and parameters of the unit and the total temperature difference across the channels at the outside should be known. The model will estimate the temperature difference across the membrane iteratively, because a small change in temperature will have an important effect on the transport of latent heat and hence the temperature profile in other parts of the module.

2.4 Limitations of Membrane Distillation

There are a few characteristics that may limit the applicability of Membrane Distillation.

1. Membrane fouling: This entails clogging of small particles and growth of bacteria on the membranes. This clogging results in a decreased production since the effective membrane surface is decreased. The particles may be inorganic as well as organic, e.g. lipids (Kimura [8]). Besides clogging by particles, the membrane may suffer from biofouling. A number of micro-organisms may colonize the membrane and in that way hinder the transfer of water vapour.
2. Membrane wetting: Wetting may occur due to reduction of the surface tension in the feed water or by applying high hydrostatic pressures. In this case pores get wetted by the feed water and this may result in direct transport of the feed water to the permeate side. Now, the membrane is not selective to water vapour only and contamination can enter the other side of the membrane. Therefore, it is important that no surfactants like soap will enter the system since this decreases the surface tension of the feed water. For a PTFE membrane with 0,3 μm pores wetting can occur if pressures above 2,4 bar are applied [9].
3. Membrane rupture: Due to external forces or high pressure differences rapture of the membrane could occur.

4 Evaporation of volatile components in the feed through the membrane, causing odour and taste problems.

3 Current design

In this chapter the design of the membrane module is described that has been used in this project. As explained in chapter 2, the temperature difference across the membrane is the driving force behind the Membrane Distillation technology. The current design of the module is a development by i3 Innovative Technologies with assistance of TNO. A starting point for the design is that the module should be:

1. easy to transport and install
2. easy to maintain
3. robust
4. having low purchasing costs
5. having low maintenance costs
6. having a high endurance

The tested membrane module consists of a few layers or channels. This is schematically shown in figure 3.1. Spacers are used to improve the mass and heat transfer in channel 1 and 4, and to keep the channels at a constant thickness. An light transparent, air-filled ‘bubble’ on top of the unit presses the polymeric sheets underneath together, which should prevent bulging of the water filled channels and short-circuiting of water flows. The feed water (the dirty water) is fed at point 1 into the module. The incoming water flows from point 1 to point 2 and turns around flowing towards point 3. During this trajectory the water will be heated by the black layer on top where heat from the sun is absorbed. This heat is transferred to the water.

The design consists of two parts or compartments: the solar heating area and the membrane area (figure 3.1, left and right respectively). The solar heating area has no membrane and is used only to capture solar heat. When the water flows from point 3 to exit point 4 there is a membrane below the channel. This membrane has small pores where water-vapour can flow through. Since there is a temperature difference between the relatively warm water above and the relatively cold water below the membrane water vapour will flow from above to below through the membrane (indicated with the smaller arrows). After this the water vapour will condensate and turns into liquid water. This water will then be transferred to point 5 where it can be tapped as distillate or clean water.

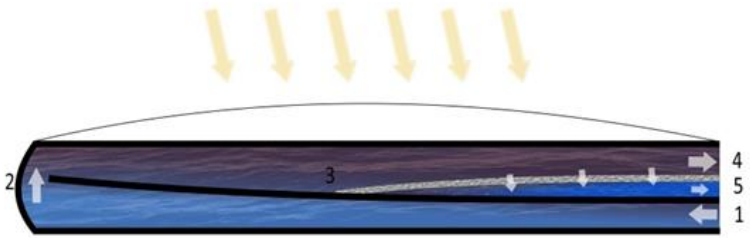


Figure 3.1 Schematic view of the Solar driven Membrane Distillation (SdMD) design.

The flow of the water from point 1 to 4 requires some pressure of the water on the inlet point. This can be done by making use of gravity, since the pressure drop in the unit is low. In practice this can be created by placing a barrel of feed water on a table and a barrel for the outlet of the feed water on the ground. Due to this pressure difference (approx. 1 meter water column) the water will flow through the

SdMD unit at a relatively steady flow rate. This set-up can be seen in figure 3.2. The feed water will flow into the MD module via the green pipe and will exit the SdMD UNIT system via the red pipe. Clean water will exit via the blue pipe. It should be mentioned that there should be an 40-80 μm strainer (filter) placed at the inlet pipe to prevent clogging of the pilot unit by particles.

The layers shown in figure 3.1 are in fact less than 1 mm thick. The layers through which the feed water is flowing do have a spacer. A spacer is a fine meshed grid with enough space to allow fluids to flow through. Spacers are used to increase the turbulence of the flowing media whereby heat transfer is improved. No information can be provided on the type of spacer.

The black layers are made of Polyethylene mixed with carbon to make it black. This latter is for increasing the absorbing properties of solar irradiation. Thus, the black layers form the channels through which the water flows and absorbs most heat at the top.

Figure 3.2 Set-up of Solar Driven Membrane Distillation (SDMD UNIT) as installed in Tanzania.

For a first sizing of the water treatment system the following assumptions were made. The unit may adsorb up to approx. 1000 W/m^2 solar heat at noon, which is enough to heat water by 40 °C at a flow rate of 6 g per second (21,5 litres/h). Assuming furthermore a recovery of 4%[1] , this results in a production rate of 0,85 litres per hour per m^2. Other hours of the day will result in lower production rates, but on average one may assume a production rate of 5 litres distillate per day per m^2 (see also paragraph 5.4). When each household requires 10 to 20 litre distillate per day a total surface of at least 2 m^2 is required. It is noted that larger quantities may be achieved by mixing the fully demineralized water with untreated water containing fluoride up to the required maximal concentrations.

[1] Commercial, optimized units have recoveries between 4 and 8%

The Python model mentioned in chapter 2 was used to estimate the temperature profile in the module with an PTFE membrane. Typical values used in the model are given in table 3.1. The estimated temperature difference across the membrane is approx. 4,6 °C (see figure 3.3).

Table 3.1 Parameters used in the Python model.

Dimensions module	Thickness of channel 1: $\delta_1 = 1000 \cdot 10^{-6}$ [m]
	Thickness of membrane: $\delta_m = 150 \cdot 10^{-6}$ [m]
	Thickness of channel 2: $\delta_2 = 200 \cdot 10^{-6}$ [m]
	Thickness of condenser: $\delta_c = 55 \cdot 10^{-6}$ [m]
	Thickness of channel 3: $\delta_3 = 1000 \cdot 10^{-6}$ [m]
	Length of unit: $L = 2$ [m]
	Width of unit : $W = 0{,}5$ [m]
Specific heat coefficients	$k_1 = 0{,}6$ [W/mK]
	$k_2 = 0{,}6$ [W/mK]
	$k_3 = 0{,}6$ [W/mK]
	$k_m = 0{,}9 \cdot 0{,}3 + 0{,}1 \cdot 260 \cdot 10^{-3}$ [W/mK]
	$k_c = 0{,}4$ [W/mK] (PE)
Other model parameters	r = $0{,}15\ 10^{-6}$ [m]
	ε = 0,9 [-]
	τ = 1,59 [-]
	$\mathbb{D} = 0{,}282 \cdot 10^{-4}$ [m^2/s]

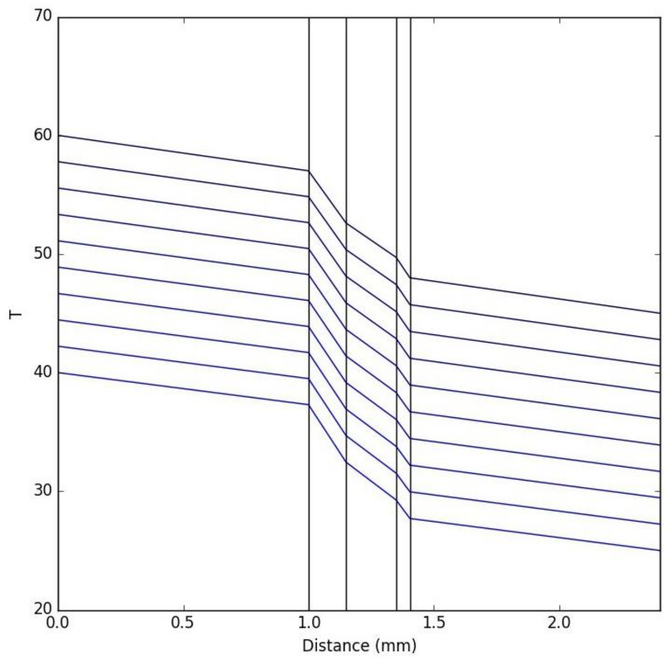


Figure 3.3 Calculated temperature profiles across the membrane for different y-positions, using 1 m^2 PTFE membrane. Lines correspond to position along the length of the membrane. From left to right: warm return channel, membrane, distillate channel, condenser sheet and feed channel.

4 Method

4.1 Introduction

The different pilot systems of SdMD units were tested on location in Robanda, using both the same type of membrane. The pilots differ in properties: length and membrane surface. SdMD unit 1 (Hospital) has the dimensions 300 cm × 50 cm and uses 0,55 m^2 membrane area. Unit 2 (household Mama Lucy) measured 400 cm × 50 cm and utilizes 0,77 m^2 membrane. To evaluate the individual performance and to compare the SdMD units some parameters were followed:
- production rate of the permeate,
- flowrate of the feed water,
- conductivity of the permeate,
- temperature inside the SdMD unit.

4.2 Production rate permeate

The production of the permeate is measured around every 10 minutes. In this manner the production rate characterizes the performance of the SdMD unit at a certain time. An uncertainty of 10 ml in the measuring cup is taken as the reading-error in this measurement.

4.3 Flowrate feed water

The flow of the feed water influences the performances of the SdMD unit in several ways. A part of the feed water flow will evaporate, i.e. it passes the membrane as vapour, condenses and becomes the permeate. This amount is depending on the temperature profile in the unit and the heat transfer through the membrane. The feed flow can influence the temperature profile in two ways. Since higher flows will induce higher Reynolds numbers it will also increase the heat transfer through the membrane. On the other hand, higher flowrates will reduce the temperature increase by the sun. The flowrate of the feed water is therefore an important parameter to investigate the performance of the SdMD unit. It is measured on the exit side of the unit by using a stopwatch and a measuring cup. The flowrate is measured three times in every 10 minutes, the average is used as the flow in 10 minutes. For this measurement we take an uncertainty of 10 ml/min.

4.4 Wetting

When a membrane is wetted (or leaking) we expect ions to pass the membrane. Wetting can therefore easily be detected by measuring the electric conductivity of the permeate. By measuring the permeate conductivity we also obtain knowledge about the integrity and possible leakages in the membrane. These measurements are performed by using a HM Digital EC-3 conductivity meter.

4.5 Temperature

Since the temperature difference across the membrane is the driving force behind Membrane Distillation, the temperature profile was measured inside the SdMD units. Three types of sensors were considered (see Appendix B) of which a thermistor was ultimately chosen. The thermistors were used in combination with an solar powered logical (Arduino) board.

Also an assessment for error propagation was made (see Appendix B), after which it was concluded that the expected error is usually ± 0,5 °C.

5 Results

5.1 Laboratory testing at TNO

The pilot units were delivered to TNO for testing in the laboratory in week 14 of 2016. The main objective was to examine the correct functioning of the SdMD unit and to establish basic values for production rates with fresh water at different flow rates. Figures 5.1 gives an impression of the used set-up. The first tests were done with an aluminium strip on the sides of the SdMD unit to fixate the module. Heating has been carried out by an IR heater of 1000 W/m^2 but it proofed not to be possible to increase the temperature to above 38 °C. Under these conditions a distillate flux of 0,3 to 0,7 l/h was achieved, what was considered good for low operation temperatures.

The available time for further testing was too limited as some changes had to be made after the first tests. Also a first hint on the importance of sufficient air bubble pressure was found at the last day of experiments (see table 5.1). The permeate stream increased suddenly when the pressure of the air bubble increased a little. Despite the limited data available and some leakages it was concluded that the system was fit for further testing in Tanzania.

a b

Figure 5.1 a) MD water treatment pilot with pressurized air bubble; b) set-up with flat IR radiator (1000 W/m^2), hanging a minimum level (5 cm) above the SdMD unit.

Table 5.1 Test results of SdMD pilot (tested 5 April 2016 at TNO).

Time [min]	Feed flow [L/h]	Flux [L/h]	Temp	Remarks
25	8,4			
30	7,2	0,24		
40	7,2			EC distillate= 18 uS/cm
55	6,8			
60	9,6		35	Temperature assessed with thermocouple, at return-end of module
65	8,4	0,36		
70	13.2	0,12	37	Pressure difference air bubble 4,5 cm -> 8,5 cm. Foil rises by heating.
75	14,4		38	
80	15,6	0,48	35	Pressure difference 8,5 cm -> 10,5 cm.
90	16,8			Pressure difference 10,5 cm -> 9 cm.
93		0,18		Distillate flux on average 0,3 l/h
140	13.9	0,32	28	Distillate flux on average 0,32 l/h. Temperatures with Arduino (4 sensors under, 3 above)
150	24,0	0,72		Pressure difference 9,5 cm. Flow and distillate flux increases suddenly.
155	22,8	0,36		EC distillate = 77 uS/cm
165				Module slipped from Al-strip; gets filled with water. Leakage membrane and into surroundings.
170				EC destillate = 185 uS/cm, leakage ?
175				End experiment

5.2 Pilot test at Robanda Tanzania

5.2.1 Introduction

The pilot equipment was transported by plane followed by off–road trip to Robanda and was installed on location by the end of April 2016. Experiments were conducted till the end of May (see figure 5.2- 5.4). The logbook of the experiments is given in Appendix D. Initially three units were installed for investigation. However, one system showed leakages after installation and repairs did not solve the problem. After one week SdMD unit 1 (Hospital) was also starting to have small leakages at the non-membrane side. Furthermore, for both pilot systems the pressure in the air bubble was not stable. The pressure could be increased by pumping air into bubble. However, the pressure decreased significantly within a number of minutes.

Several measurements were done to investigate the performance of the water systems. Two types of measurements can be distinguished. The first type includes overall measurements where the production was measured over longer periods. This also included conductivity measurements to investigate the degree of purification of the feed water. The second type is a detailed measurement involving the Arduino (microcontroller) to measure real-time temperatures inside the SdMD units. Besides these measurements the production of permeate for each 10 minutes is recorded as well as the average flow during this period.

Figure 5.2 SdMD unit 2 in Robanda. Site: Mama Lucy.

Figure 5.3 SdMD unit 2 in Robanda. Site: Mama Lucy.

Figure 5.4 SdMD unit 2 in Robanda. Site: Mama Lucy.

5.2.2 *Permeate quality*

The conductivity of the permeate over time is shown in figure 5.5. Since most feed water has a conductivity around 800 µS/cm it is clear that the SdMD units are producing permeate containing around 80 times less solutes. The fluoride concentration of the samples analysed were all below the detection limit of 0,02 mg/l. Although the conductivity was low and no fluoride was present, the permeate still tasted not good, since there was a plastic taste in the permeate. The origin of the off-taste may be caused by residues from the glue and the plastic materials where the SdMD unit consists of. This plastic off-taste reduced over time, but not completely.

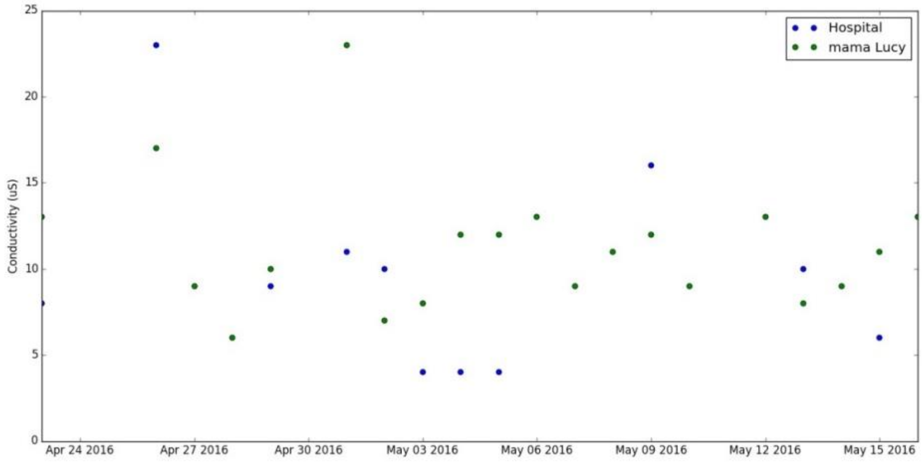


Figure 5.5 Conductivity of permeate over the time. Most feed water had a conductivity around 800 µS.

5.2.3 *Temperature profile and performance*

The temperature measurement was conducted by using thermistors connected to an Arduino microcontroller logical board powered by a solar panel. In this way 9 temperatures inside the SdMD unit were measured real-time. Such a measurement is displayed in figure 5.7 where temperatures above and below the membrane are plotted. By averaging the temperature from these intervals data can be generated for finding relationships between temperatures, flows and production rates. Averaging the temperatures also decreases the uncertainty in the measurements (see appendix B). From figure 5.7 it can been seen that in the fourth graph uncertainties start to overlap. However, this is not considered to be a problem since average temperatures are used in the analysis and uncertainties are reduced with a factor √N (N = number of measurements for averages).

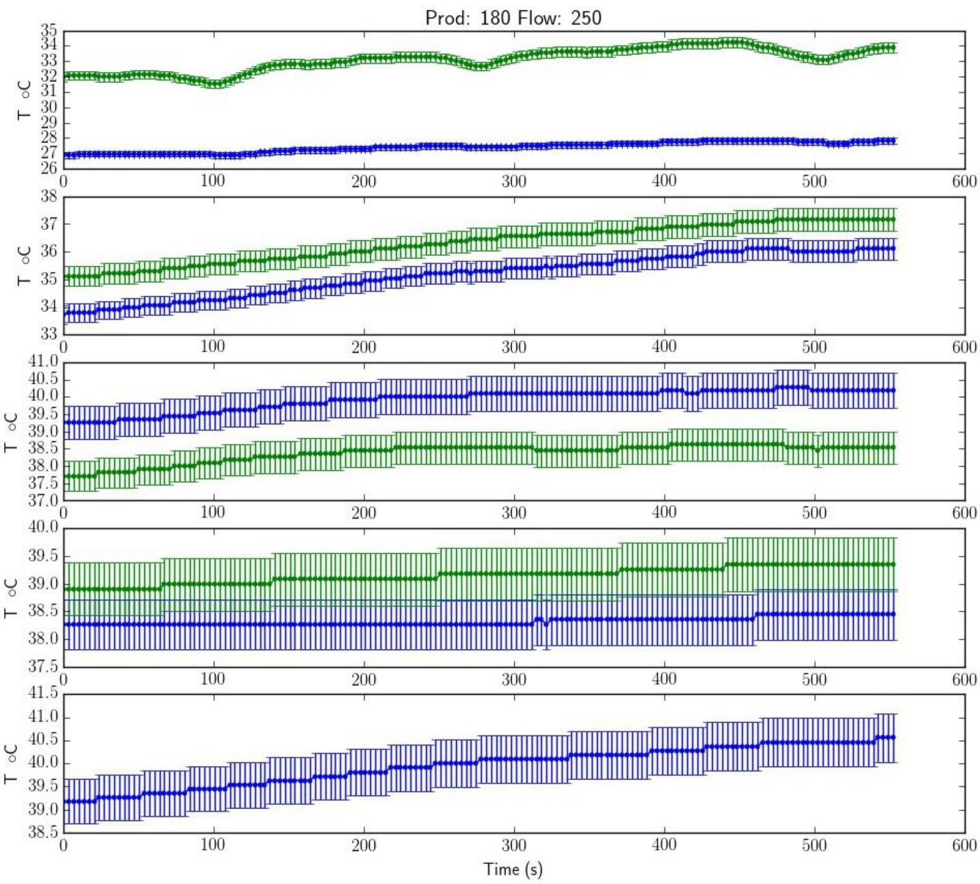
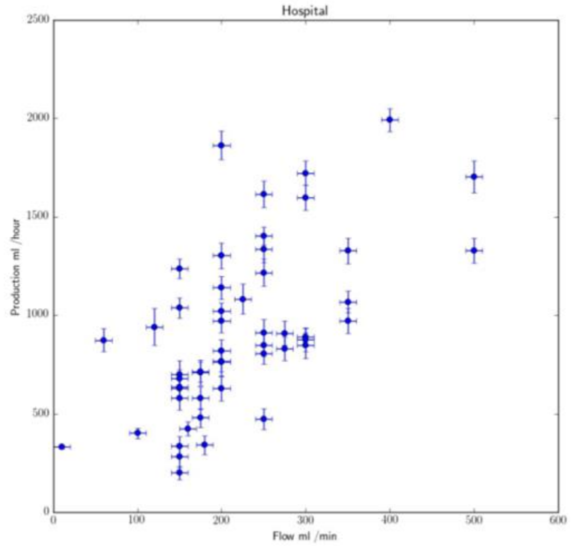


Figure 5.6 Example of measurement at pilot 2 (Mama Lucy). In the first four figures the measured temperatures above (warmest) and below (coolest) the membrane are showed. The last figure is the temperature at sensor 3 (see appendix C).

The production rates are plotted against the feed water flow in figure 5.8. Especially for system 1 (Hospital) in figure 5.8 it is clear that increasing the feed water flow will generally increase the production rate. This is more difficult to see in case of system 2 (Mama Lucy) since the measurements are more scattered. This is probably related to the variable air bubble pressure (see below). The relation for system 1 is more in agreement with the expected relation. The Nusselt number increases because of the increasing Reynolds number, which improves the heat transfer orthogonal to the flow direction. Some variation may occur because of variable temperatures during the measurements.

The second observation which is remarkable is the fact that higher production rates are achieved with SdMD unit 1 than SdMD unit 2. Productions rates found for SdMD unit 1 are above 1000 ml/hour while SdMD unit 2 (Mama Lucy) mostly has production rates below 1000 ml/hour. It is unlikely that this is a results of different sun intensities since most measurements are performed under similar conditions (clear weather). In addition, we would expect unit 2 to have higher production rates since the membrane surface is larger (0,77 m^2) than the area of unit 1 (0,55 m^2). The data displayed in figure 5.9 may give an explanation for this observation. SdMD unit 1 (Hospital) achieves higher temperature differences than unit 2 (Mama Lucy). This could explain the difference in performance, since the temperature difference is the driving force behind membrane distillation (see equation (3)).



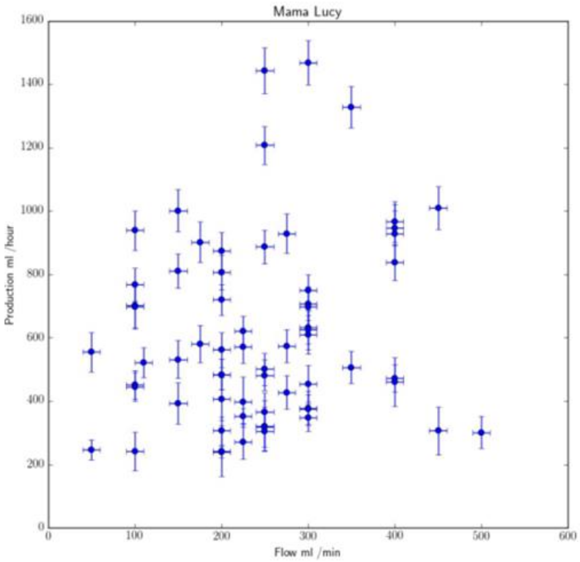


Figure 5.7 Production rates plotted against the feed water flow. The y-scale differs for both figures. First graph SdMD unit 1 at the hospital. Second graph: SdMD unit 2 at Mama Lucy.

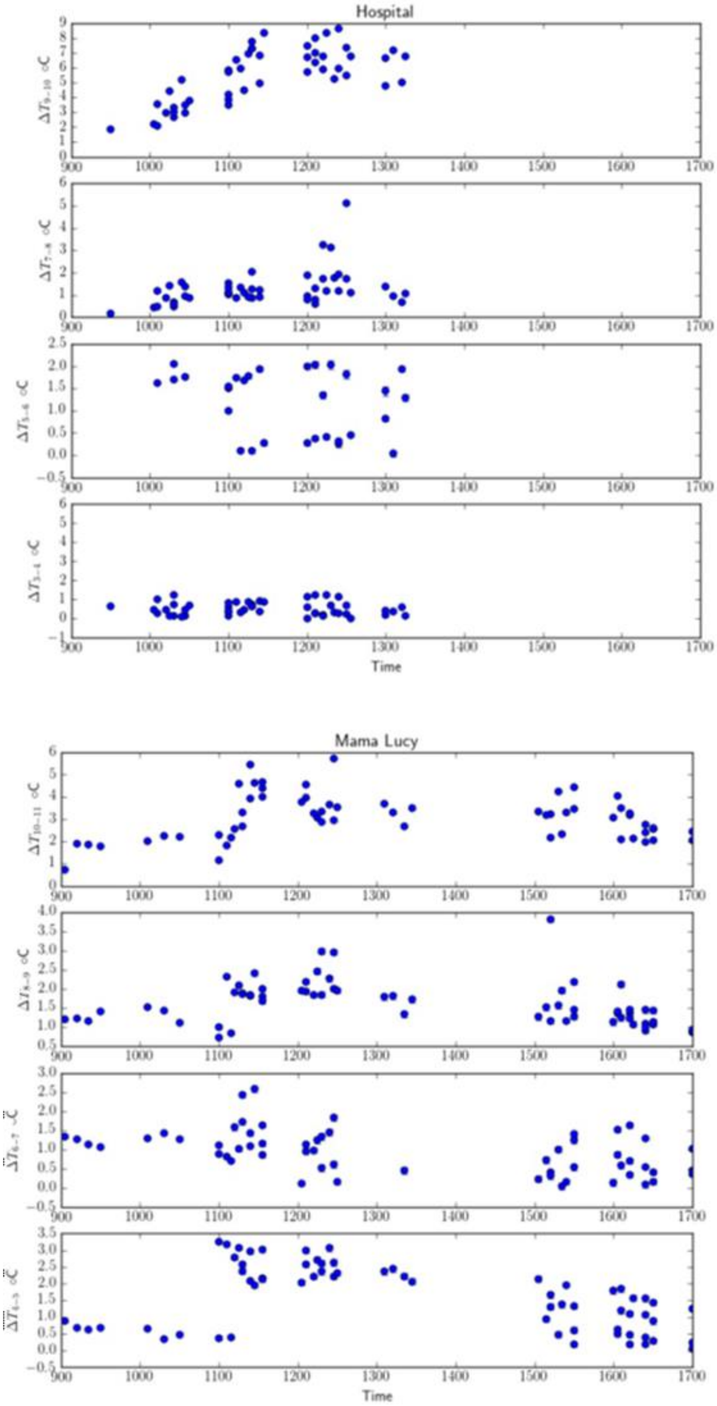


Figure 5.8 The temperature differences across the membrane are plotted in each figure. The upper figure is the temperature difference for in inflowing and outflowing water. The lower figures are the other temperature differences in spatial order. Uncertainties are displayed but not visible since they are smaller than the dot icon. First graph: Pilot 1 at the hospital. Second graph: Pilot 2 at Mama Lucy.

These temperature differences may be systematically larger for unit 1 than for unit 2. However, Appendix E shows that the measured temperatures do not differ a lot for both systems.

Another explanation may be found in an unstable pressure of the air bubble. It proved that the pressure inside the air bubble of unit 1 was more stable than the air bubble pressure of unit 2. Within minutes the pressure dropped significantly in the air bubble of SdMD unit 2. Since the air bubble pushes down the different layers it is expected that a low pressure inside the air bubble allows water channels to expand. In this case the distribution of water will be less homogeneous and this will also adversely affect the heat transfer across the spacer layers. Some channel formation was also visually observed in unit 2 which contributes to this idea.

5.3 Modelling results

The Python model (chapter 2) was used to estimate the production rates for the current design. Having 1 m^2 of PTFE membrane, the model predicted above 4,4 L h^{-1} m^{-2} with $\Delta T_m \approx 4{,}6$ °C for temperature ranges $T_{1,b}$ = 60 − 40°C and $T_{3,b}$ = 45 − 25°C. The measurements performed during the pilot tests and the corresponding temperature ranges, flows and other properties were used in the model to check the validity of the model. The dimensions of the membrane in unit 1 (Hospital) are 1,39 m × 0,4 m giving around 0,55 m^2 of membrane surface. Production rates calculated by the model and measured data can be found in table 5.2.

The modelled values are around a factor 2-3 lower than the measured value. This can be explained due to simplifications of the model itself as well as unknown average pore sizes (r1,2). Also, there are reasons to believe that the temperature measurements differ from the real bulk temperatures. This was for example showed by analogue temperature measurements which differed from the bulk temperatures measured by the NTC thermistors.

Still, the order of magnitude of the production rates which are calculated by the model correspond with the measured data. Therefore, the model was considered a useful tool to explore possible improvements of the current design.

Table 5.2 The bulk temperature ranges (in y-direction) with the corresponding measured data for the SdMD unit system 1 (hospital) and the modelled values.

Feed water flow (mL/min)	T 1 (°C)	T 3 (°C)	Model production rate (L/hour)	Measured production rate (L/hour)
275 ±10	49-40	49-34	0,42	0,91 ± 0,06
275 ±10	48-40	48-34	0,42	0,83 ± 0,06
300 ±10	49-42	49-35	0,53	1,6 ± 0,06
300 ±10	44-38	43-31	0,51	0,88 ± 0,06
300 ±10	42-37	41-30	0,48	0,97 ± 0,06
350 ±10	42-37	41-30	0,49	0,97 ± 0,06
350 ±10	60-44	59-37	0,77	1,07 ± 0,05
350 ±10	39-37	38-30	0,47	1,33 ± 0,07

5.4 Expectations on water production of current design

Since the pressure inside the air bubble was decreasing within a number of minutes it was not possible to measure long-term productions. Furthermore, there were many rainy afternoons in the period the pilot was tested. Therefore, less data are gathered during the afternoons. However, it was tried to estimate the production of the current design when all the conditions are optimal. This includes a stable pressure in the air bubble, flow of the feed water above 15 litre per hour and a clear and sunny day. The production is estimated by approximating the production rates with a Gaussian curve. In figure 5.10 the fit is shown with some data points used to estimate the parameters of the Gaussian fit. This fit is not determined by error minimization of the data points since it is supposed that the current amount of data is not sufficient for such an analysis. Still, this curve gives us an first estimation for possible production of SdMD unit 1 under ideal conditions. A production rate of circa 10 litres per day is obtained.

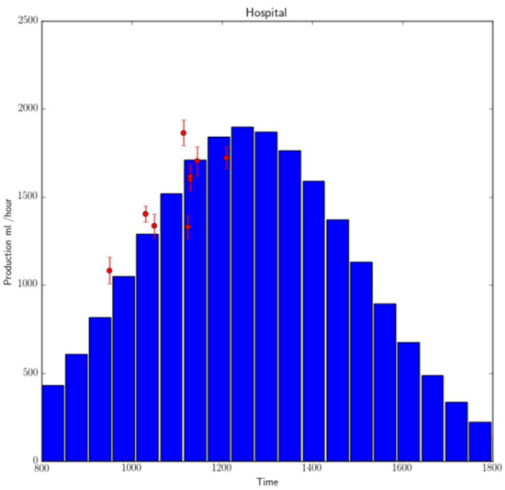


Figure 5.9 Estimation of production rates over the time for unit 1 (Hospital). Fitted with a Gaussian curve with μ = 1230 and σ = 250, with maximum production 1900 ml per hour.

6 Adaptation and re-design

6.1 Introduction

During the pilot experiments a few problems where observed concerning the current design. The main problem was the leaking air bubble which decreased the performance of the SdMD units, since the heat transfer across the membrane was reduced. Also the distribution of the feed water is decreased due to channel formation. Therefore, adjustments to the current design are necessary to solve the mentioned problems. These adjustments were established during intensive discussions between i3 Innovative Technologies, Aqua-Aero WaterSystems BV and M. Bongaerts. In this chapter some adjustments are presented together with calculations to support the choices. i3 Innovative Technologies and Aqua-Aero WaterSystems BV are planning to develop this new design for further investigation.

6.2 Adjustments to the solar collector surface

As explained in chapter 5 the pressure of the air bubble seems to be important since it pushes down the layers improving the overall heat transfer in the SdMD unit. Another function of this air bubble is the isolation by which radiation is more probable to get adsorbed in the water channels. The air bubble prevents the heat absorbing black layer (see figure 3.1) to be easily cooled by convection. However, it turned out that the air bubbles are far from sustainable because the air bubbles did not maintain their pressure. Also one can doubt the life-expectation of a thin sheet of polymer under UV irradiation. Searching for alternative solutions is therefore preferred.

A structure was searched that is inexpensive, sustainable, rigid, transmitting solar radiation and preventing convective cooling at the heat absorbing surface. A material with these properties is possibly a double walled polycarbonate sheet; it transmits more than 80% of the solar radiation depending on the angle of incidence (δ = 1,58 mm) [9]. The Young's modulus of polycarbonate is Y = 2,0 − 2,4 GPa. The question how thick the polycarbonate sheet has to be to prevent bending is addressed in Appendix E.

The current design consists of two separate parts: the solar heating area and the membrane area (see figure 3.1 left and right respectively). The solar heating area is the area without membrane where feed water is only heated. As described in chapter 5 the performance of pilot 2 (Mama Lucy) was less than pilot 1 (Hospital) although the solar heating area of water pilot 2 was bigger (and also the membrane surface). An explanation for this difference was provided. Simple calculations show why increasing the solar heating area is favourable. From a steady-state condition and choosing the solar heating area as the control volume we can calculate the expected increase in temperature of the feed water:

$$\Delta T_{Solar} = \frac{\eta . P_{Sun} . W . L_{Solar}}{\phi . C_p} \qquad (11)$$

Where ΔT_{Solar} is the temperature increase of the water, P_{Sun} the power irradiation of the sun in [W/m^2], η the percentage of heat absorbed by the water, W the width of the SdMD unit, L_{solar} the length of the solar heating area and ϕ the flow of water in [m^3/s]. On average the sun irradiation in Tanzania is 550 W/m^2 [1]. With L_{solar} = 2 m, W = 0.5 m, ϕ = 5 ml/s and η = 0.5 [9] we get ΔT_{solar} = 13°C. Increasing the unit length by 1 m results in ΔTsolar = 19,5°C, which is a difference of 6,5°C. When we assume the water will enter the solar heating area at 40°C this increase in L_{solar} will translate in a vapour pressure difference of around 0,05 bar. This is significant, since the total vapour pressure difference across the membrane is in the order of 0,01 bar [11]. Therefore, we expect a major increase in production rates by this adjustment. Note that increasing the length of the SdMD unit will increase the pressure needed for the same feed water flow . In this case higher barrels for the feed water are recommended. Furthermore, this calculation confirms the idea that unit 2 (Mama Lucy) was not working properly since this SdMD unit did not show higher temperatures than water unit 1 (Hospital).

6.3 Other adjustments

It is found that the production rate increases with the flow of the feed water. Further increases in the flow rate may be beneficial. However, it is expected that the production rate will reach a maximum and even decrease at very high flow rates, because the feed water is heated for shorter times resulting in lower temperatures (see relation 11). Higher flows can be obtained by steady water column height, forced by the place of the feed barrel. This may also entail a larger barrel such that water level drop is small over time or a refilling of the barrel during the day.

One other proposal is the reduction of the thickness of the spacer, reducing $\delta_{1,3}$ from 1 to0,5 mm. This effect is modelled while keeping the feed water flow of 5 ml/s constant. The production rates are calculated for different bulk temperature ranges for both $\delta_{1,3}$ = 0,5 and 1 mm. The model predicts an production rate increase of above 10%. Therefore, this adjustment could be favourable. However, thinner spacers could also entail other problems like blockages by dirt.

Currently, the absorbing surface is made of polyethylene added with carbon. These plastics have in general high absorbance of solar energy but also high emittance which means that these materials radiate energy according to the Stefan-Boltzmann law. So attempting to replace the polyethylene with another material with increased absorbance and lowered emittance could improve the production rates of the SdMD unit. However, major improvements can only be made by replacing the polyethylene by much more expensive materials such as nickel or copper [9]. This option is therefore considered unsuitable.

6.4 Impression re-design

The new design consists of three basic parts: the polycarbonate sheet, the core of the module with the spacers and membrane, all supported by a wooden sheet. The air bubble is replaced by a sheet of polycarbonate which presses down the different layers making it a more sustainable and reliable water system. The idea is to fix all layers on the wooden sheet at the bottom with wooden girders. Ideally, the space between the girders have to be less than 0,5 m to prevent bulging of the water channels. Note that these girders reduce the amount of solar collector surface and thus the thickness of these girders is important. Using wood in the design is favourable for a two reasons: it is a material which is easily available and it is a sustainable material.

The thickness of the spacer-layer is decreased improving the production rates (above 10 % according to the model). If the solar heating area is expanded, higher temperatures can be reached which increases the vapour pressure difference significantly. The glue can be replaced by a plastic welding method were plastic materials are melted to each other. This can also increase the sustainability of the SdMD unit.

Figure 6.1 Impression of redesign.

7 Viability of the concept from a user perspective

Only a small fraction of the success of an innovation can be contributed to the functioning of technology. Success largely depends on user adoption and finding a sustainable business model. Although the project is mainly about a proof-of-principle of the technology, a first exploration of the user and business perspective is performed. This analysis yields results that help set design criteria for further improving the technology into a direction that has the highest chance of adoption.

7.1 Village of Robanda, people and income

In Robanda, a small village in Tanzania, the number of inhabitants is between 3.000 and 4.000 people. Most families in Robanda generate income by having a small cattle farm, herding sheep or working on small plantations on which crops such as corn are grown. Larger sized farms are not found in this area because of the presence of elephants in the bush. These animals pose a serious problem to the farmers because they tend to destroy plantation in search for food. Apart from farmers, there are tradesmen around trading goods such as milk, alcoholic drinks, food, fuel and water. Cattle is being sold in the nearby city of Mugumu, about 40 km from Robanda.

Most transportation in Robanda is done by foot, bicycle or by using a cart. Carts are sometimes pushed by animals, sometimes just by people. Some people own a motorcycle and cars are only scarcely found. Most houses in Robanda are built by the owners themselves, using hand-made bricks from the soil and the roofing is made from cheap corrugated plates.

In Robanda not too many regular paid jobs are found. Some people are involved in the tourist sector doing all kinds of work, but most of these jobs are only seasonal. Thus most people do not earn a regular fixed income per month. According to the Robanda Municipality Office, the average family income in town is 3.240.000 TSH a year, or 270.000 a month. This is 1.480 USD per year, or 123 USD per month (1 USD=2.190 TSH). We have no information on the distribution of the income.

To get a better understanding of income, we looked at 2 different professions, school teacher (civil servant) and sheep herder. Primary school teacher at Mugumu is considered to be a well-paid job and delivers around 460.000 TSH, or 210 USD, per month. Since shepherds are common in Robanda it is also interesting to have some insight in their income. Having cows can generate relatively a lot of income since milk and meat can be sold. In Robanda milk is sold for 1.000 TSH per 1,5 liter. If we estimate the sale of milk at 6 liters a day, this activity will generate up to 180.000 TSH per month. From a Robanda shepherd it is known that he sells on average 9 cows per year. Most of these cows are sold in Mugumu, a larger city 40 km from Robanda. On the market in Mugumu cows are sold for 200.000 - 600.000 TSH depending on the size. In general adult cows are sold for over the 400.000 TSH. So a rough estimation will tell us that another 300.000 TSH per month is earned by selling cows. All together will this result in an income of 480.000 TSH per month or about 220 USD per month. We see that shepherds can earn above the average income of Robanda.

As a civil servant, the school teacher will receive his salary on a regular basis (weekly/monthly), while a sheep herder has to deal with strong fluctuations in salary. Most months of the year, the sheep herder will have very little income, while once he sells off some of his cattle, he will at once have a large amount of cash. People are generally very cautious how to spend this large amount of cash, because it will have to sustain them for a long period of very low income.

In our further analysis we shall use the average family income of 270.000 TSH per month as a benchmark.

7.2 Access to water

Robanda has its own water supply built several years ago by the Government. The source of this water is a 40 m deep ground well located just outside the village. From here the water is pumped by a diesel engine to a tank located uphill. From the tank the water is distributed to the houses through a pipeline. Normally tap water is available once a week for a couple of hours.

Before 2016 people did not have to pay for the water. The fuel needed to power the diesel-powered pump was provided by the owners of nearby safari camps who were also in need for water.

With the installation of a new piped system by the newly set enterprise Bomba water Ltd. the situation has changed: people now have to pay to become connected to the pipeline as well as to pay for the water consumed. Generating income with that, Bomba takes care of the water operation, the maintenance of the system and takes care of extending the pipeline to build more taps at different locations in the village. Bomba also operates stand-alone taps that are connected to a tank. This tank is filled by a Bomba water truck on a regular basis. Still many people are not using the Bomba service. People are resourceful, and sometimes retrieve water from the small lakes around the village, that are also used by cattle herders. Some villagers have rainwater harvesting systems. The hospital has a large rainwater collection system that is free to use for anyone, but empty in the dry season. When the Bomba water temporarily wasn’t available, a grass roots water trade system emerged where people paid up to 500 TSH for 40 liters of water (mostly rainwater).

For rich Tanzanians and tourists also bottled water is available in Robanda. Some shops in the center are selling these bottles at a pricing of 1.000-1.500 TSH per 1,5 liter. The cost of the bottled water make it far too expensive for average families in Robanda to convey to this source of water. Given a daily average income of about 9.000 TSH it would take about 17% of the daily income of a family to buy only one bottle of 1,5 liter water.

In Appendix F an overview is given of the other water systems available.

7.3 Need of Water Purification

According to Bomba Ltd. people in Robanda are aware of the need to treat the water, but only for bacteria. People know that the water is contaminated with bacteria causing sickness, but they do not have another option than to take the water as it is. People are used to the quality of the water, their bodies are accustomed to the bacterial load present in the water. Very little people in Robanda are aware that the water they perceive as clean is in fact not clean, but contains amounts of fluoride that pose long term health risks.

In a meeting of 27/04/2016 between Bomba and the villagers, people expressed their hope that the upcoming generation will not suffer from the brown teeth problem. People feel ashamed of themselves or their children having brown teeth, but are unaware that the actual cause of this problem is the fluoride in their drinking water. The local doctor explained that a lot of children are suffering from dental fluorosis, a clear indication that fluoride concentrations in the water are too high at present. Some cases of skeletal fluorosis are also present in the village. Since the tap water is having a good taste, there is no direct indication for people that the brown teeth are caused by the tap water. This links to the knowledge of people about the implications of drinking contaminated water which, is only sparsely present.

Although consuming rainwater would be a healthier option (more clean: conductivity of the rainwater is circa 50 µS/cm, whereas tap water is having a conductivity of about 800 µS/cm) most people do not drink or like drinking rainwater. Reason for that is they believe that you get sick from rainwater. People from the Hospital confirm this viewpoint of the villagers in Robanda. Another reason for people not shifting to rainwater harvesting is the fact that upfront a relative high investments is needed to start rainwater collection. Gutters have to be installed on the roof, piping has to be bought and installed and a collection tank has to be set in place before rainwater harvesting can be started on permanent basis.

7.4 Value proposition and target groups

Considering the current water supply of the Bomba piped or delivered tap water, the main value is access, availability and convenience. Customers do not have to manually carry large amount of water to their homes, but can get it straight from the tap in their yard, or within a close distance from their home. The water is considered to be clean and healthy, but in reality the high amount of fluoride poses a long-term health risk.

The SdMD does not change anything in terms of access and availability of first drinking water needs. It offers another value proposition. It offers consumers a more safe and sustainable water supply by providing really clean and healthy water, without any fluoride contamination and bacteria, allowing them to live without brown teeth, and without long term health issues. In theory, people could have both a Bomba connection for easy access, and a SdMD to provide for really clean water for drinking water purpose.

Depending on the way the system is designed, the dirty exhaust water of the SdMD is warm. This could have some added benefits, such as a more comfort when washing with it. However, just leaving a black bucket of water outside in the sun for a couple of hours would lead to the same result, so in general we do not consider this to be of major value. But as the people in Robanda see this as an advantage in combination with the clean water production it has added value.

Given the economic activity in the Robanda village, we can identify four different target groups who could be interested in clean water without fluoride contamination:

- Local families wanting to have clean water for drinking as well as for cooking. In their 2014 Maji Mazuri report, students from TU Delft concluded that within a family, it usually is the female who is in charge when it comes to purchasing decisions regarding health and water, and who gathers the families daily water needs.
- Small business owners, who could either sell clean water, or use clean water in a small scale production process (for making and selling of tea, coffee, self-made soft drinks, or even ice-cream (the latter requires strong hygiene, a cooling device and sufficient electrical power). However, very few businesses are present in Robanda, and the small daily production of a SdMD seems limited for small business use.
- Safari camp owners, who want to offer really clean water to tourists. However, most safari tourists can easily afford and are accustomed to the bottled water.
- Small scale cattle farmers, who want clean water for their animals. Fluorosis does not only affect humans, it can also have negative effects on cattle. Healthier cattle means a better income. However, the daily production of one SdMD is not sufficient for a flock of animals, and many farmers are herders, not being bound to one location.

Each group will have a different view on the benefits of the system, and each group will make a different price comparison. Based on the above, the main target group for the SdMD are local families, with a focus on women as decision makers, Small business owners are a possible second, but very small, target group.

7.5 Usability of the SdMD

The SdMD is designed as a (relatively) low cost desalination device, to be used at point-of-use, without any need for electricity. For proper working, the device poses a series of requirements on its environment. The basic working principle of the device requires a combination of 1) a temperature difference between input water and output water, and 2) a hydraulic pressure from the input water to create clean output water. This leads to the following list of requirements associated with to the technology:

- The top of the device needs to be heated by the sun. The device does work less in cloudy or rainy weather and not at night.
- The input water needs to be of a low temperature. The higher the input temperature, the less the efficiency of the device.
- The input water needs to have a certain pressure for the system to work. The easiest way to obtain this is by placing the input water in a vessel at some height above the SdMD.

- When water flows through the device, a small fraction of the water (~4%) is desalinated, and flows out. The rest of the dirty water also flows out of the system, through another tap. This means that for the generation of 24 liters of clean drinking water, a total of 600 liters of input water needs to flow through the device. By recycling the remaining water this input volume can be reduced to 100 l/ day. The remaining water can also be used for other purposes like washing and cleaning. Furthermore the device requires 3 vessels (1 untreated input source water, 1 clean output, 1 output of untreated water).
- The dirty output water can be fed back into the system, to again create 4% of clean water from it. However, dirty output water will have a higher temperature than the original dirty input water, so when the water is fed back into the system, the temperature difference will be lower than in the original cycle, and the efficiency will be lower.
- As no water can be wasted, the dirty output water needs to flow into a vessel. This vessel needs to stand beneath the SdMD. So the generator needs to be on an elevated surface.
- The device needs to be placed on a flat surface of about 3 meters long, for the right flow through the device.

These conditions create 2 serious implications, one in terms of usability, and one in terms of cost.

Regarding usability; for 24 liters of clean water output a day, the top vessel of the systems needs to be filled with either one load of 600 liters of dirty input water, or dirty output water from the bottom vessel needs to be fed back into the dirty input water vessel. This means a user has to lift 600 kilos of water once a day, or lift e.g. 100 liter of water 6 times a day. Previously we concluded women as the main target group both for purchasing the device, but also for operating it. In that aspect, this requirements seems even more blocking.

Adding a solar panel powered water pump would allow the system to recirculate without user intervention. Because the water is recirculated, smaller vessels would suffice. We recommend a 120 liter dirty water input, and 5-6 times recirculation a day, to reach a total output of 24 liters of clean water, and 96 liters of dirty water, in line with a family's daily use. This solution would deviate significantly from the original design principle of having no complex moving parts or electricity required.

When the device is developed further, from proof-of-principle into a prototype, we strongly suggest to look for other low-cost/low maintenance solutions that are able to take away some of the usability weaknesses of the system.

8 Viability of the concept from a business perspective

8.1 Economic analysis and affordability of water delivered by Bomba Pvt Ltd.

In the meeting of Bomba Ltd. (27/04/2016) with Robanda villagers the pricing of the tap water was discussed. Many people complained about the price setting: a connection to the pipeline costs between 130.000 TSH and 180.000 TSH depending on the distance to the main pipe. Further Bomba demands also another 5.000 TSH per month to take care of the operations and on top of that people have to pay 3 THS per liter for the water consumed.

According to most villagers these prices are too high and the water should cost not more than 2 TSH per liter. This discussion gives us another insight in what people are willing and able to pay for water.

In Table 8.1 the true cost of the Bomba water services are calculated and compared to what people can pay for water. The latter being investigated by the UN in various publications. Please note that we estimate that people on average use 20 liters a day (the average water consumption for sub-Saharan Africa), and not the 50 liters a day target as set forth by the WHO.

Table 8.1 Cost elements of Bomda water for villagers Robanda.

Cost elements of Bomda water		
Family income	270.000	TSH per month
Bomba connection	155.000	TSH connection costs
Bomba maintenance fee	5.000	TSH per month
Water price	3	TSH per liter
Consumption per family member	20	liter
Number of family members	6	persons
Volume of water per day needed	120	liter
Volume of water per month	3.600	liter
Tap water cost	10.800	TSH per month
Average cost of water in Robanda	17.645	TSH per month
Allocation of family income for water	6,5%	
Max affordability of water according to UN	3,0%	
Affordable water price	2,3	TSH per liter

Table 8.1 indicates that the pricing of the Bomba tap water is higher than what UN mentions for an affordable family (3%). Bomba demands more than double. In this calculation we have depreciated the initial cost of installing the pipe connection over a 7 year period, to come to the average price. In reality, people have to pay this amount (half a monthly salary) at once, which is another barrier to start using the tap water. Based on this calculation it can be concluded that the services of Bomba Ltd. will not reach the majority of Robanda families simply because they cannot afford it.

8.2 Cost price of the SdMD

Table 8.2 gives a detailed cost analysis of the SdMD, one analysis with cost as it is produced at present and the second for a future situation after a redesign and at a scale of 1000 units. These costs include material, manufacturing, distribution, awareness, marketing, and maintenance. From this table it can be learned that the cost of the SdMD in its current design and scale of production is almost 900.000 TSH (408 USD) per unit. And once all testing and prototyping is done and the first series of 1.000 new SdMD units is produced, we expect the price to come down to about 208.000 TSH (95 USD) per unit, with the effective surface of the membrane of 1 m^2.

The successful operation of the SdMD requires a specific environment. Firstly, the unit has to be placed on a horizontal flat surface and, secondly, the hydraulic pressure between the input water and output water has be created in order to push the water though the system. This means that the investment costs of a family are not limited to the cost of the system itself, but should also take into account the costs of an elevated, flat surface of almost 3 meter long to support the generator and two barrels for the input and output brine water, assuming that no extra costs are needed for the vessel collecting the clean water. The calculation of the cost of the full system, assuming that the input water is free, are given in Table 8.2 below, for both the current and future improved system.

Table 8.2 Calculation of the cost of a full SdMD system.

	Current SdMD system	Improved SdMD system	Comments
Unit cost of SdMD (TSH)	895.000	208.000	
Generation capacity per day (l)	15	20	
Number of units per family	1,6	1,2	Scale up factor for capacity of 24 l/day
Cost of two 600 l barrels (TSH)	96.000	96.000	
Total investment per family incl. barrel and flat surface (TSH)	1.528.000	346.000	
Volume of water produced over lifetime (l)	13.920	13.920	Generation capacity by 290 operational days by 2 years
Cost per liter of clean water (TSH/l)	137	53	
Average cost of water if clean water is used only for drinking and cooking	27	11	Weighted average of cost drinking water and free dirty water
Share of income going to water	29%	7%	

Given the proof-of-concept stage of the product, the above calculations can still vary substantially, both up and down. The cost calculations are based on a series of assumptions, that all need to be tested further to improve the accuracy of the calculations.

We estimate that a person requires 3-5 (so 4 on average) liters of clean water per day for drinking and cooking needs. For washing, cleaning etc. people can and will use water with high amounts of fluoride which does not pose any risks. With the average family size of 6 people it adds up to 24 liters of clean water per day per family. The output of the current prototype with a 1 m^2 membrane is insufficient to produce 24 liters of clean water a day, so a next version should have an increased capacity. In our calculations we assumed the cost of the device rises proportionally to its increase in size, while in reality the cost increase is probably lower.

The size of the barrels is dictated by the 4% efficiency of the water generator, (600 l = 24 l / 4%). When the water is recirculated, smaller barrels will suffice. However, in the previous chapter this recirculation of water was seen as a major usability issue. We have estimated the cost of foldable plastic barrels, to limit transportation cost. In further experimentation it has to be proven that these barrels are sturdy enough to last for at least the lifetime of the device (preferably longer). We have not included any cost for a flat surface, although we are aware that a table or other raised surface might be required. Again, this is to be determined in further research. The total generation capacity is based on the 2 year depreciation period and the fact that the SdMD can only operate during sunny periods, so with a maximum of 290 days per year, (see Appendices).

The stated goal of this project was to produce a family size water production unit for ~100 USD. The current direction is not far off that target, but we do estimate that such a device would be 150 USD instead of 100. Given the fact that people will probably not be able to pay for the device at once, some financial engineering will probably take place to pay for the product over a longer period of use. In that case, it is more appropriate to look at the monthly expenses in comparison to people's monthly incomes, or the willingness to pay for clean water. Conversations with employees from Bomba Ltd., the counsellor of Serengeti and villagers indicate that treated water could be sold at a pricing of 10-20 TSH per liter. The calculated costs per liter of clean water from the water are in the range of 150 TSH for the current prototype to 25 TSH for the next version. Another way to look at the average cost of water for a family is to look at their daily expenditure on water (so water for drinking, cooking, washing, hygiene, cleaning etc.). The SdMD will add 5 TSH/liter to the price of the input water. When input water is free (which it isn't in many cases), this means people will spend 7% of their income on water, which is significantly higher than the 3% that is used as a benchmark by the UN.

In conclusion, the price point of the SdMD is coming within range of the desired price, although much effort will have to be placed in further getting the cost down to decrease both the initial investment as well as the cost per liter. That can be done by either lowering the production and distribution/sales cost of the product, increasing the efficiency, or by increasing the life span. Financial engineering, such as borrowing or leasing mechanisms would help to lower the initial investment for a family, but would in the end increase monthly cost if the cost of money is taken into account.

8.3 Comparing the SdMD to current and alternative water solutions

In Table 8.3 we compare the SdMD to other water supply options potentially available for the villagers of Robanda. The parameters that we consider are the amount of initial investments, price of water per liter and minimal applicable scale for the technology. We used the cost price calculations for the next version of the SdMD, at a scale of 1000 units produced.

Table 8.3 Comparison of SdMD costs to current and other water supply options.

Option	Solves fluoride problem	Initial investment (as share of monthly income)	Clean water cost (TSH/l)	Cost per average liter of water (weight clean and dirty)	Scale and infrastructure
Tap water	No	57%	N/A	5	Village of at least 200 families all connected to a central water grid
Tap water and SdMD	Yes	185%	58	15	
Tap water and central RO plant	Yes	57%	7	7	
Shop with clean water from small RO plant	Yes	0%	13	3	Neighborhood, no central water grid
SdMD with no tap connection	Yes	128%	25	5	Family, no central water grid
Rainwater	Yes	315%	7	3	
Water cones (24 per family)	Yes	389%	24	5	Individual, no central water grid
Life Straw	No	15%	39	8	
Bottled water	Yes	0%	1000	200	

The first three options with tap water are not applicable to the current situation in Robanda, because few people actually have a connection to the pipe yet.

Out of the other options RO-based water shop and rainwater collection are the most competitive options to the SdMD. Both are able to provide with clean drinking water at a 3 times lower price per liter than the SdMD, aligning better with the expressed willingness to pay. The benefit of the water shop is that it doesn't require any investment from the individuals, meaning no risk. However, Water kiosks only work when they can service a large enough market, in general starting at 400 individuals. The SdMD is able to service a single household. The benefit of rainwater is that families are more self-reliant and should not be depended on the presence/operation schedule of a water shop or any other way of access to water. Rainwater harvesting obviously has its drawbacks in the dry season.

However, the SdMD is able to compete with solutions for individual use. The Water Generator beats a (hypothetical) setup of 24 Water Cones based on investment cost, and beats the daily use of Life Straws for a whole family based on price per liter. Water cones only provide 1 liter of clean water a day, so we calculated with 24 water cones, not really a viable scenario. The life straw is more seen as a tool for emergency situations, and it is not able to filter the fluoride out of the water, so also not a viable option. We concluded these options in the chart in order to see that the Water Generator is competitive to those solutions, much more so than to any solution that operates on a village or neighbourhood scale.

8.4 So, what is the market opportunity for the SdMD?

From the previous analysis we have seen that the SdMD technology at current small scale level of development is still too expensive for the average Tanzanian family and faces significant usability issues. However, we also see that the SdMD is able to compete with existing products that target individuals. It is one of the few products that is able to generate sufficient clean water for a whole family's daily water needs when fluoride (or similar) contamination is present.

Despite these drawbacks, we see a number of strategies how the SdMD could be implemented in developing countries:

Providing a 100% clean water policy/strategy
When the mission of a water company is to provide everyone in a large region with clean water, the SdMD can be used to provide some families that live far away from a piping infrastructure, and with only contaminated water available, with the option to clean this water themselves. In this scenario, water companies should make a detailed analysis of a region, and come up with a mix of products to ensure everyone has access to really clean water for the lowest price of the whole system, instead of looking for one standard option for access, and one standard option for purification. When the cost of building a pipe, or the cost of a truck transportation service, from a clean source to this location is very expensive, or an area is to sparsely populated for RO-shops, a SdMD could be a serious alternative. In that case, the added cost of the SdMD could be cross-subsidized by asking the other 99% of customers a small premium. This model moves into the direction of a public service, where societal costs are shared by the whole population, instead of by only those families who have the bad luck of living in a heavily polluted region. This scenario would also work in regions where government demands and actively enforces health regulation that stipulate that no-one is to suffer from fluoride related diseases, and water companies have a legal responsibility to provide all people in their service area with really clean water. Also in the situation that the piping infrastructure is available, but no additional treatment of the water is available, individual families or other users can decide for the SdMD.

Niche strategy
The SdMD could be a viable option in very remote regions where the water is heavily contaminated, and no village or neighborhood scale alternative is available. The process of the SdMD takes out virtually all types of contamination, so it could be used to not only remove fluoride, but also bacterial -, viral - and heavy metal pollution. A typical location are small islands that are scattered in archipelagos far from the coast, and have no clean water sources of their own. Some of these islands will have boat services that transport clean water from the mainland. Usually, that water is subsidized by local government, because otherwise life on those islands would be almost impossible to sustain. In those cases, we could image those families using the SdMD to generate clean water from seawater, making the use of the expensive boat-delivery unnecessary. Further study into those locations, the habits of its inhabitants, and the cost compared to alternatives need to be investigated.

A second scenario is using the SdMD in emergency situations (comparable to the target market of the LifeStraw). Depending on the situation the size of the product could be an issue there, but on the other hand, comparing to the LifeStraw it can produce drinking water from all types of sources, removing not only micro-organism but also physical-chemical pollutants.

In both cases, some of the financial burden could be paid for by charities, NGO's, buy-one give-one programs or impact investors (who fund the whole scheme, and take into account that profitability is lowered somewhat, but all people in a certain region have access to really clean water). In the end, clean water is a basic human need, and investment in clean water greatly improves people's ability to lead a dignified life, and lead to an overall increase in the economy of a region.

Picture: water.org

9 Conclusions and recommendations

Technical feasibility
The pilot test in Tanzania with the SdMD units produced encouraging results.
An acceptable quality of drinking water can be produced having a low conductivity of around 10 µS/cm (starting from 800 µS/cm) and the fluoride concentration is below detection level. Only the taste of the water was not optimal, but this problem is expected to be overcome in a new design. Besides production rates were obtained above 1 l / hour for a membrane surface of approximately 0,55 m^2, what was good under the given condition. The daily production of the tested SdMD unit is estimated to be approximately 10 litres a day operating in Tanzania, Robanda, during the month May.

The system has been operated for about 4 weeks without real big problems. Main problems were related to leaking and air bubbles which restrain heat transfer across the membrane and increases bulging of feed water inside the water channels. To solve these problems and to increase the robustness of the system a re-design of the SdMD unit is needed. This will also increase the production rate. Furthermore the possible recirculation of the water needs attention.

System costs
Based at the current insight the costs of the SdMD is estimated to be around 200.000 TSH. Additional costs for vessels and a table are estimated between 50.000 and 100.000 TSH. Given the proof-of-concept stage of the product, the above calculations can still vary substantially, both up and down. The cost calculations are based on a series of assumptions, that all need to be tested further to improve the accuracy of the calculations.

The calculated costs per liter of clean water from the water are in the range of 25 TSH/l. Another way to look at the average cost of water for a family is to their daily expenditure on water (so water for drinking, cooking, washing, hygiene, cleaning etc.). The SdMD will add 5 TSH/liter to the price of the input water. When input water is free (which it isn’t in many cases), this means people will spend 7% of their income on water, which is significantly higher than the 3% that is used as a benchmark by the UN.

Concluding: the price point of the SdMD is coming within range of the desired price, although much effort will have to be placed in further getting the cost down to decrease both the initial investment as well as the cost per liter. That can be done by either lowering the production and distribution/sales cost of the product, increasing the efficiency, or by increasing the life span. Financial engineering would help to lower the initial investment for a family, but would in the end increase monthly cost.

Comparison SdMD to current and alternative solutions
For point-of-use systems RO-based water shop and rainwater collection are the most competitive options to the SdMD. Both are able to provide with clean drinking water at a 3 times lower price per liter than the SdMD, aligning better with the expressed willingness to pay. However, water kiosks only work when they can service a large enough market, in general starting at 400 individuals. The SdMD is

able to service a single household. The benefit of rainwater is that families are more self-reliant and should not be depended on the presence/operation schedule of a water shop or any other way of access to water. Rainwater harvesting obviously has its drawbacks in the dry season.

Considering small scale technologies the following can be mentioned; water cones only provide 1 liter of clean water a day, so we calculated with 24 water cones, not really a viable scenario. The life straw is more seen as a tool for emergency situations, and it is not able to filter the fluoride out of the water, so also not a viable option.

Market opportunity

Based on the previous analysis we can conclude that the SdMD technology at current level of development is still too expensive for the average Tanzanian family and faces significant usability issues. However, we also see that the SdMD is able to compete with existing products that target individuals. It is one of the few products that is able to generate sufficient clean water for a whole family's daily water needs when fluoride (or similar) contamination is present.
Despite these drawbacks, we see a number of strategies how the SdMD could be implemented in developing countries:

- When the mission of a water company is to provide everyone in a large region with clean water, the SdMD can be used to provide some families that live far away from a piping infrastructure, and with only contaminated water available, with the option to clean this water themselves.
- The SdMD could be a viable option in very remote regions where the water is heavily contaminated, and no village or neighborhood scale alternative is available. The process of the SdMD takes out virtually all types of contamination, so it could be used to not only remove fluoride, but also bacterial -, viral - and heavy metal pollution. A typical location are small islands that are scattered in archipelagos far from the coast, and have no clean water sources of their own.
- A third scenario is using the SdMD in emergency situations (comparable to the target market of the LifeStraw). Depending on the situation the size of the product could be an issue there, but on the other hand, comparing to the LifeStraw it can produce drinking water from all types of sources, removing not only micro-organism but also physical-chemical pollutants.

Follow-up

Based at the technical and economical evaluation i3 Innovative Technologies and Aqua-Aero Water Systems BV intend to further develop the technology together with TNO. Plans will be discussed and further developed with sponsors and NGO's.

10 Bibliography

1. Project Plan: Networking WASH projects in Mara Region, Tanzania. NL Agency, Ministry of Foreign Affairs, 15 October 2012
2. Lourens Feenstra:: Inventory of relevant available treatment technologies for fluoride removal, TNO report 2013 R12119, December 2013
3. Lourens Feenstra, Result R 2.3.1 Report on Innovation research fluoride removal TNO, December 2014 TNO report 2014 R11584:
4. Lourens Feenstra, Proposal: Plan for pilot program fluoride removal drinking water, March 2015
5. Sananda Dey, Biplab Giri, 2016, Fluoride Fact on Human Health and Health Problems: A Review. iMedPub Journals
6. Michiel Bongaerts, Desalination of water using Membrane distillation with sun heating, July 2016 (Internship report Aqua-Aero WaterSystems BV)
7. J. Phattaranawik, R. Jiraratananon, A.G. Fane, C. Halim, 2001, Mass flux enhancement using spacer filled channels in direct contact membrane distillation. Department of Chemical Engineering, King Mongkuts University of Technology Thonburi, Toongkru, Bangkok, Thailand
8. Kimura, Microfiltration of different surface waters with/without coagulation: Clear correlations between membrane fouling and hydrophilic biopolymers, Water research, 2014, 434-443
9. Leonard D. Tijing etal Fouling and its control in membrane distillation—A review, J. Membr Sc. 475, 2015, 215–244
10. R. Saffarini, H. Araf, R. Thomas, Influence of pore structure on membrane wettability in membrane distillation, Madar Institute of Science and Technology, 2012
11. Eykens et al, Influence of membrane thickness and process conditions on direct contact membrane distillation at different salinities, J. Membrane Science 498 (2016), 353–364
12. J. Phattaranawik, R. Jiraratananon, A.G. Fane, Heat transport and membrane distillation coefficients in direct contact membrane distillation, Department of Chemical Engineering, King Mongkuts University of Technology Thonburi, Bangkok, Thailand, 2003

11 Authentication

Name and address of the principal customer:
SNV Netherlands Development Organisation

Names and function of the co-operators:
W.G.J.M. van Tongeren, BSc
W.J. Assink, MSc
W.A.J. Appelman, MSc, MBA

Names and establishments to which part of the research was put out to contact:
n.a.

Date upon which, or period in which, the research took place:
September 2015 – August 2016

Signature:

W.G.J.M. van Tongeren, BSc
Author

Approved by:

J.M. Jetten, PhD
Research manager Functional Ingredients

A Nomenclature

Symbol	Description	Units
ρ	Density	[kg/m^3]
C_p	Heat capacity	[$J/kg.K$]
μ	Viscosity	[$Pa \cdot s$]
δ_i	Thickness of layer i	
ΔL	Latent heat	[J/kg]
M	mol massMol mass	[kg/kmol]
P	Pressure	[Pa]
V	Volume	[m^3]
T	Temperature	[K]
v	Velocity	[m/s]
J	Vapour flux	[kg/m^2s]
B_0	Permeance	[$kg/m^2.s.K$
Q_i	Heat flux through layer i	[J/m^2s]
L	Length	[m]
W	Width	[m]
k_i	Heat transfer coefficient of layer i	[W/m^2K]
Nu_i	Nusselt Number of layer i	
d_h	Hydraulic diameter	[m]
c	Porosity of membrane	
τ	Tortuosity of membrane	
$\mathbb{D}$	Diffusion coefficient of water	[m^2/s]
(r)	Average membrane pore radius	[m]

B Thermal sensoring

Sensor selection
There are a few sensor types available to measure temperatures. To decide which sensor is applicable for the measurements we have to determine what properties are preferred. By comparing the properties of each type of sensor we can conclude which one fits the best. The following sensors are available:

- Silicon bandgap temperature sensor: There are many different commercial sensors available based on transistor technology. These sensors have a linear relation between resistance and temperature. There are analogue and digital series of these sensors available. The advantages of using the digital variants is that they have a digital output signal giving you the direct temperature. However, these sensors consists of many pins which makes it harder to implement them since more wires are needed. The analogue variants can have 2 or 3 pins (examples KTY sensors or LM sensors). The slope of the linear characteristics are approximate 10 mV/°C [8].
- Thermistor: There are two types of Thermistors: NTC's and PTC's. The difference is the sign of the temperature- resistance relation. Most PTC's (for example PT-series) have linear characteristics. If it is favoured to measure a wide range of temperatures these sensors are applicable. A disadvantage is that their sensitivity is in order of a few Ohms per 10°C. In contrast the NTC's are much more sensitive to temperature changes. However, their characteristics are not linear but exponential according to:

  $$R = R_{25}.exp\left(\beta\left(\frac{1}{T} - \frac{1}{T_{25}}\right)\right) \qquad \text{(B.1)}$$

  There is a certain operational range in which these sensors are really sensitive to changes in temperature due to their exponential characteristics. This can be an advantage since the operational range is known. Their response time turns out to be low.
- Thermocouples: These sensor can be used in a very wide range of temperatures. However, their sensitivity is in the order of a few mV/°C.

Microcontrollers can be used to measure multiple sensors real-time. The microcontroller used in this research is an Arduino an ADC (Analog to Digital Converter) with 1024 points. Therefore the microcontroller operating at 5 V can read analog signals with a accuracy of 5000/1024 ≈ 5 mV/step. Since we have limited accuracy it is important to choose a temperature sensor which is sensitive for temperature changes. From the above analyses it is clear that the NTC Thermistor is the most sensitive. Therefore these sensors are used to measure temperature difference. The NTC Thermistors can differ in β-value and the resistance R25. To determine which NTC Thermistor is preferred some further analyses have been done.

The Arduino will be powered by a small solar panel (2,5 W) and batteries to cover fluctuating power supply from the solar panel. The higher the resistance of the NTC Thermistor the lower the current passing through the circuit which results in less power consumption. Therefore a relative high resistance is preferred. Furthermore, we want to have highly fluctuating resistance of the NTC Thermistor in the range of 20-100°C. Its characteristics is described by equation B.1, therefore we investigate which NTC thermistor fits our purposes best. A simple temperature circuit is constructed by placing a NTC thermistor in series with a constant resistance R2. The voltage drop over the NTC thermistor can be measured and determines the temperature measured. The read-out voltage range should be optimal in the 20-100°C range.

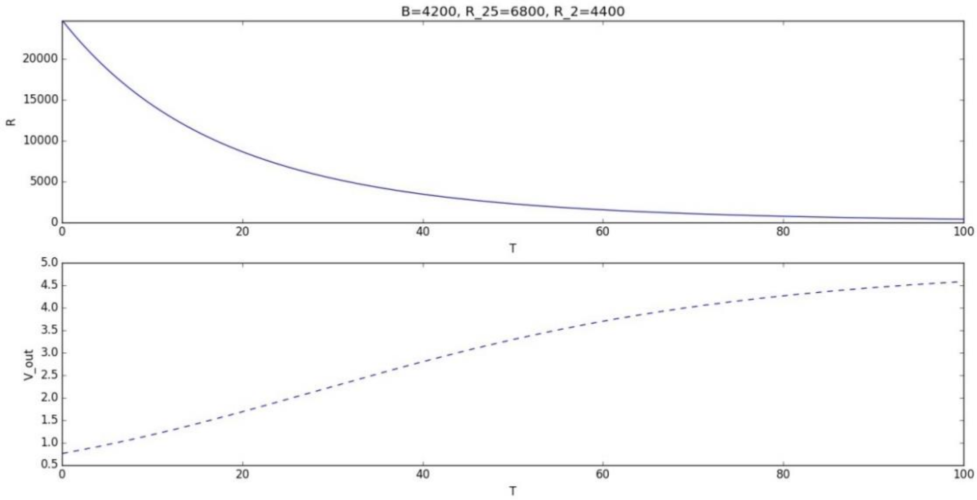


Figure B.1 Read-out of NTC thermistor.

Figure B.1 shows the predicted read-out voltage of the NTC thermistor. The voltage differs from circa 0,75 V to 4,75 V in the temperature range 0-100°C. This result is obtained from a thermistor with β = 4200, R25 = 6800 Ohm and a resistor of R2 = 4400 Ohm. By comparing many different NTC thermistor and R2 resistances, it turned out that this configuration is one of the better configurations, as the Arduino has to run on a battery supply. Circuits with high resistances are preferred because high resistance means less power consumption (P = I·V and higher resistance will decrease the overall current I). With this configuration we achieve sensitivities around 40 mV/°C.

Sensor positioning & testing

In the previous section the choice for the 6,8 kOhm NTC thermistor with an additional R2 of 4,4 kOhm was discussed. These sensors are placed in SdMD unit 1 and 2 while they were constructed. Unit 1 contains 10 sensors while SdMD unit 2 has 11 sensors. The positioning of the sensors can be found in appendix C. From the known characteristic equation B.1 we can without calibration read of the temperature by invoking this equation and calculating the resistance of the thermistor from basic electrical laws.

$$T = \left(\ln(\left(\frac{R_{NTC}}{R_{25}}\right)\frac{1}{\beta} + \frac{1}{T_{25}}\right)^{-1} \qquad \text{(B.2)}$$

Figure B.2 shows that the thermistor indicate the right temperature and fluctuations are in order of a few 0,1°C. Another measurement in shown in figure B.3.

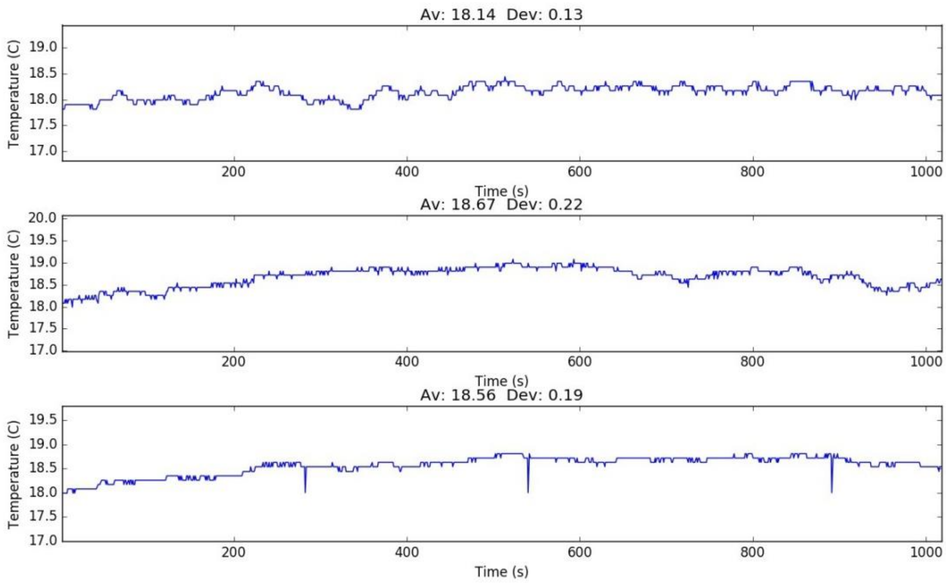


Figure B.2 Registration of three different thermistors at circa 18°C (reference temperature is obtained from an analogue thermometer).

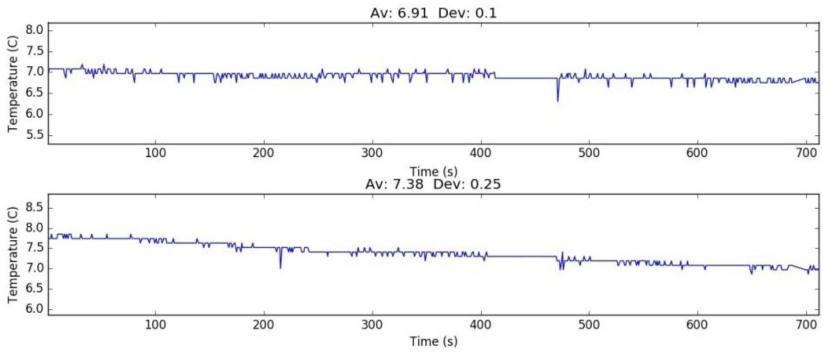


Figure B.3 Temperature-time graphs from two different thermistors in a non-conditioned room of around 7 °C. The reference temperature is measured by an analog thermometer.

Uncertainty temperature measurement

There are different uncertainties which determine the total uncertainty in the measured temperature. First the uncertainty caused by using copper wiring to connect the sensors to the measuring equipment is discussed. Two resistors of 2200 Ohm in series making R_2 = 4400 Ohm are used. The resistance of 4 m wires is however low, approx. 9. 10^{-4} Ohm.

$$\frac{R_{wire}}{R_{NTC}+R_2+R_{wire}} X\ 100\% \approx 1.87.10^{-5}\% \qquad (B.3)$$

This is negligible. Secondly we study the propagation of uncertainty. For instance, the error in resistance R_2 can be deduced from the manufacturer error, which is 1%. Two resistances of 2200 Ohm in series give the following uncertainty:

$$\Delta R_2 = \sqrt{2(\Delta R)^2} \approx 31.1\, Ohm \tag{B.4}$$

This is less than 1%. Also the discrete levels of the ADC may contribute to small errors in the resolution.

$$\Delta V_{NTC} = \frac{V_0}{1024} \tag{B.5}$$

$$\Delta R_{NTC} = \sqrt{\left(-R_2 \frac{V_0}{V_{NTC}^2} \Delta V_{NTC}\right)^2 + \left(\frac{V_0 - V_{NTC}}{V_{NTC}} \Delta R_2\right)^2} \tag{B.6}$$

Furthermore, the uncertainty of Δβ has to be included. The manufacturer provides a value of 3% of β=4200, hence Δβ= 126 which is a relatively important source for errors. The relation now becomes:

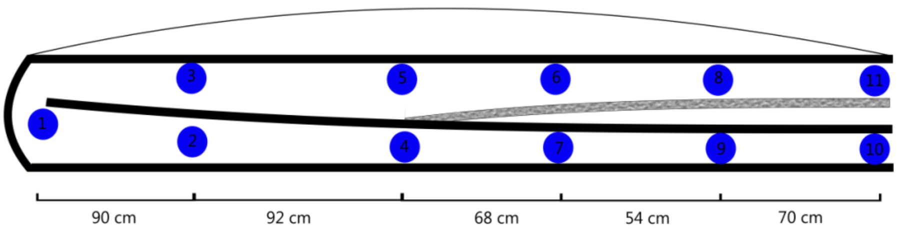
$$\Delta T = \sqrt{\left(\frac{ln\left(\frac{R_{NTC}}{R_{25}}\right)}{\left(ln\left(\frac{R_{NTC}}{R_{25}}\right)\cdot\frac{1}{\beta}+\frac{1}{T_{25}}\right)^2 \beta^2} \Delta\beta\right)^2 + \left(\frac{-1}{\left(ln\left(\frac{R_{NTC}}{R_{25}}\right)\cdot\frac{1}{\beta}+\frac{1}{T_{25}}\right)^2}\left(\frac{1}{\beta . R_{NTC}}\right) \Delta R_{NTC}\right)^2} \tag{B.7}$$

Finally, it is remarked that the uncertainty is reduced when a number of measurements is used to calculate an average:

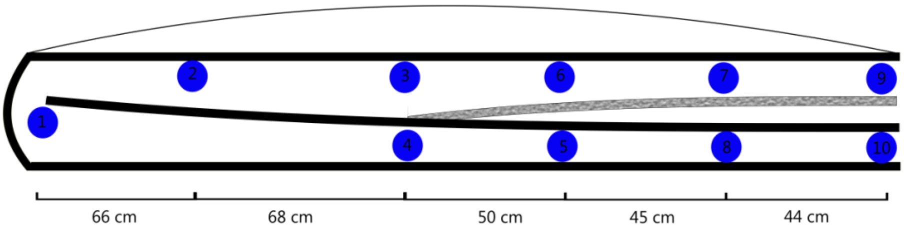
$$\Delta T_{av} = \sqrt{\sum_{i=1}^{N} \left(\frac{\Delta T_i}{N}\right)^2} \tag{B.8}$$

Liability measured temperatures
Besides the measuring equipment and the involved uncertainties it is important to make some remarks about other factors that could influence the measurements as well. First, it has been observed that by measuring the temperature of the water directly at the end of the SdMD unit deviations were observed compared with the nearest sensor. This suggests that the measured temperatures differ from the bulk temperatures. This could be due to several factors such as inhomogeneous flow of the water through the SdMD unit or stagnant water near the sensor. Furthermore, the sensors are placed in an interface between the water flow and glue. In this way a temperature is measured at the edge of the water channels.

C Sensor positioning



(a) Pilot 2 at Mama Lucy



(b) Pilot 1 at the hospital

D Logbook M. Bongaerts

Mama lucy s2W4

Data 2016	Weather	Time	Measurements D	I	O	S	Remarks
23 april	clear	9:00-14:00	13 µS	912 µS	970 µS		
					40 C	65C	
			1700 ml				25 and 26 it was cloudy in the morning and than rain. And tried to repair unit at Nyambula
26 april	cloudy	8:45-14:00	17 µS	870 µS	920 µS		
						63C	
			1200 ml				
27 april	sunny	9:15-14:30	9 µS	825 µS	980 µS		
					43 C	68 C	
			2825 ml				
28 april	cloudy whole day	9:20-15:30	6 µS	856 µS	930 µS		
					39 C	63 C	
			2000ml				
29 april	clear and sunny. afternoon partly cloudy	9:05-17:30	10 µS	860 µS	940 µS		Thermometre empty
			4150 ml				
30 april	storm plus mgumu						
1 may	partly clouded. 12.00 rain	8:45-11:00	23 µS	870 µS	925 µS		I used the measure cup also for bomba water so this could explain the higher conductivities
					29 C		Taste is improving but whakulu still did not liked and probably did not finished her cup.
			400 ml				
		11:00-16:30	17 µS	870 µS	930 µS		
					27 C		
			450 ml				
2 may	very cloudy later little sun. 13.30 Rain	9:30-13:05	7 µS	890 µS	950 µS		
					34 C		
			1250 ml				
3 may	very sunny	8:50-12:35	8 µS	905 µS	990 µS		
					41 C		
			2000 ml				
4 may	sunny clear afternoon	15:15-15:55	12 µS				in the morning no water due to disconnected pipe.No bomba water
			600 ml				
		15:55-17:10	490 ml				
5 may	very sunny	8:50-14:00	12µS				again low flow due to low pressure in airbubble
			2050ml				
6 may	sunny sometimes cloud, after 12:00 to much clouds and afternoon rain	9:05-11:40	13 µS				very low production compared with similar weather at hospital
			860 ml				
7 may	cloudy	8:50-11:30	9 µS				
			600 ml				
	very sunny	11:30-12:55					due to recycling of water warm water as inlet.
			940 ml				
	very sunny sometimes cloud	12:55-14:50	7 µS				due to recycling of water warm water as inlet.
			1420 ml				
	warm afternoon with some clouds. Later many clouds so I quite	15:05-16:00	7 µS		46 C	62 C	due to recycling of water warm water as inlet.
			300 ml				

Data 2016	Weather	Time	Measurements				Remarks
			D	I	O	S	
8 may	very sunny. At 14:15 very cloudy and then rain	13:15-14:45	11 µS				I went to the hospital for a talk and stayed there the whole morning
			650 ml				PH of Bomba water is around 9
9 may	very sunny	11:00-14:00	12 µS				
			2160 ml				
		14:00-15:55	10 µS				
			1050 ml				
	warm afternoon sun but many clouds shadowing sun	16:10-17:10					very low production due to warm water inlet and many clouds
			200 ml				
10 may	very cloudy but if there was no cloud good sun. Rain afternoon 15:00	9:50-16:20	9 µS	810 µS	860 µS		
			2030 ml		35.6 C		
12 may	very sunny with a few clouds	11:40-15:20	13 µS				
			2000 ml				
		14:40-15:20	12 µS				
			410 ml				
		15:23-16:55					
			640 ml				
13 May	very sunny	8:40-13:40	8 µS				
			2100 ml				
	clouds which later dissappear and good sun	13:50-16:15	8 µS				
			1250 ml				
	very sunny very few clouds	16:48-17:10	110 ml				
14 may	very sunny then some clouds then sun again	9:10-14:50	9 µS				
			1750 ml				
	very sunny sometimes cloud	15:18-16:50	630 ml				
15 may	very sunny	9:20-15:55	11 µS		45 C		water was still flowing at 15:55 but very low pesssure in airbubble
			2700 ml				
16 may	very sunny	10:50-11:10	13 µS				
			300 ml				
	very sunny later very cloudy	11:10-12:46	13 µS				
			1510 ml				
	later sunny again	12: 46-17:10	13 µS				
			1900 ml				

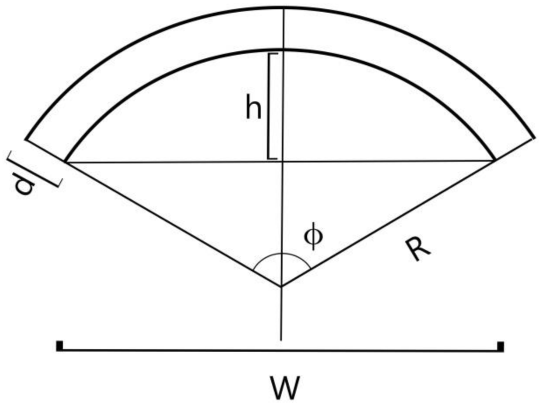
Hospital

Data 2016	Weather	Time	Measurements D	I	O	S	Remarks
23 april	clear	11.15-14:50	8 µS	780 µS	850 µS		
					41 C	45 C	
			1750 ml				
26 april	cloudy. 14.00 storm	9:30-16:10	23 µS	790 µS	820 µS		
					31 C		
			1050 ml				
27 april	Bomba meeting						
28 april	cloudy	12:10-16:00	90 µS				unit not functioning well since water could not flow properly. After highering the table a little the problem was solved.
			550 ml				also I put some extra water in the inlet a few times so no conductivities
29 april	morning sunny. some clouds afternoon	10:00-16:50	9 µS				and trying to measure with arduino temperatures
			2830 ml				
30 april	mgumu						
1 may	partly cloudy. sometimes good sun. 12.00 rain	10:00-10:20	11 µS				high flows 300-500 ml per minute
			210 ml				
2 may	very cloudy later little sun. 13.30 rain	10:25-12:30	10 µS	730 µS	850 µS		
					32 C		
			760 ml				
3 may	very sunny	10:10-11:50	4 µS		720 µS		
			780 ml				
		12:10-15:20	6 µS				Airbubble was almost empty therefore less water went trough. low flow
			1050 ml				
4 may	sunny but thin layer of clouds	9:50-13:10	4 µS				High flows only when airbubble is on pressure.
		9 may	1880 ml				
5 may	very sunny	10:30-11:20	4 µS				
			970 ml				
	sometimes cloud for sun	12:20-13:25	4 µS				
			840 ml				
6 may							measurements at mama lucy and rain in afternoon
7 may							removing unit Nyambula plus measurements mama lucy
8 may							cloudy morning than talk with hospital people and stayed there the whole morning
9 may	very sunny day with some clouds in the wfternoon	9:40-17:40	16 µS				very low production because the airbubble was empty therefore hardly any water went through. water will accumulate in the unit and water will stop flowing
			700 ml				Furthermore there are leakages in the unit just before membrane. This will probably not influence the measurenement much since I measure flow at the outlet
10 may							Unit to damaged to work stand-alone. No measurement possible due to low power from solar panel

Data 2016	Weather	Time	Measurements D	I	O	S	Remarks
13 May	very sunny	10:10-12:28	10 µS 1690 ml				Last period low production because water wat almost empty. strange because flows were high (see measurements). Interestly, it looks like this unit is achieving higher productionrates than the one at mama lucy.
		12:28-13:10	6 µS 540 ml				
15 may	very sunny	10:55-13:30	6 µS later 4 µS 2790 ml				These high production is only possible since I am measuring so always high pressure in airbubble
16 may							A took a barrel from Nyambulu to the hospital so they can use it. Then we talked a lot and I didnt do any measurements anymore.

E Bending of polycarbonate sheet

A (solid) polycarbonate sheet should bridges W = 0,5 m, which is the standard width of the SdMD unit. The sheet is only fixed along its sides.



The energy contained a bending deformation can be determined as follow:

$$U = \int_{R}^{R+d} \frac{YL(\Phi z - W)^2}{2W} = \frac{Y.L}{2.W}\left[\frac{\Phi^2}{3}z^3 - \Phi.W.z^2 + W^2.z\right]_R^{R+d} \qquad \text{(E.1)}$$

With L is length of the surface of interest, Φ the bending angle, R is the bending radius and d is the thickness of the sheet. h Is the maximum deformation of the sheet.

The pressure under the sheet due to water pushing the sheet upwards will be determined by the column heights of the water in the tank connected to the SdMD-unit (see figure 3.2). A maximum height of H = 1 m is assumed, creating a pressure-difference of circa ∆P = 0,1 bar. Let us assume that on average the sheet is lifted 3.h/4. The energy needed to make this deformation is:

$$U_{water} = \Delta P.(R\Phi).L.\left(\frac{3h}{4}\right) \qquad \text{(E.2)}$$

By setting equation (E.1) and (E.2) equal we find the height h. For a polycarbonate sheet of d = 2 cm the maximum deformation will be h ≈ 2-2,5 mm for Y = 2,2 GPa. If we reduce the sheet to d = 1,5 cm the maximum deformation will be around h ≈ 4-5 mm. And for a sheet of d = 1 cm the maximum deformation will be around h ≈ 8-10 mm. There are also hollow, double walled sheet modules available at the market made from polycarbonate. In this case, the thickness of the polycarbonate is less since the sheet consists of a structure made of hollow rectangular tubes. However, since the stiffness of these structures are not known the bending is difficult to predict at this stage.

F Water systems potentially interesting for the people in Robanda

Based on the report of M. Bongaerts [6].

Bottled water
In Robanda small shops sell bottled water produced by different manufacturers. The most common brand is Kilimanjaro water which is sold for 1500 TSH per 1,5 liter. There are other brands available in Tanzania which are sold for 1000 TSH per 1,5 liter. Most people in Robanda do not drink this water since it is much too expensive.

Rainwater harvesting
In general is rainwater harvesting a good source for drinking water [17]. In Tanzania the dry season is from June till October. The rain season is from March till May. There are thus five month with hardly any rain. Therefore, to have enough drinking water during this period one household has to store 5 months × 30 days × 5 people × 2 liter ≈ 2.300 liter of rainwater. A 5.000 liter tank costs around 850.000 TSH or around 390 USD . The advantage of such an investment is that these tank can be robust and provide free and clean drinking water for a long period of time.

Central Reverse Osmosis treatment plant
Another solution to provide drinking water would be a local Reverse Osmosis treatment. In this case people would buy locally treated water. People would not have to invest in this treatment system since this plant is owned by investors which can get some revenues from selling the water to people. The costs per liter differ from manufacturer to manufacturer. Aqua-Aero Water Systems BV builds RO water shops selling water for 0,005 EUR per liter or 13 TSH per liter. Manufacturer Hatenboer can produce with a 7 m^3/hr RO treatment plant water for 0,00053 EUR per liter or about 1,3 TSH per liter (excluding energy costs and profit margins) [14]. However, the investments for the latter are 80.000 EUR and the size is too large for the Robanda context.

WaterCone
WaterCone is a solar still product which can be bought for 20 USD. According to the company the life-expectation of this product is about 5 years. Since it can produce 1 liter a day the price per liter will be around 0,01 USD which is around 22 TSH per liter. So we can see that this really simple product meets the desires of the people in Robanda. However, an average household would have to use 24 of these solar stills for their daily drinking and cooking needs. This again would entail an investment of 300 USD.

LifeStraw
LifeStraw is a company producing several products to treat water. One of their products is a straw which can be directly used for drinking water from a variety of water sources. The company claims the straw will filter the water to particles down to 0,2 µm. It removes bacteria and protozoan parasites from the water. The product can be bought for around 18 USD. However, the disadvantage of this straw is that it

can only filter 1.000 litre of water and thus the price would be around 40 TSH per litre. Furthermore, since it only filters up to 0,2 µm is will allow most ions to pass the filter so no fluoride reduction is expected from this product. So this product can only compete in areas where only removal of bacteria and filtration of water is needed.