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A method for water disinfection with solar pasteurisation for rural areas of Bangladesh

En metod för vattenrening med hjälp av solenergi för landsbygdsområden i Bangladesh

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Erika Lundgren

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ABSTRACT

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In order to improve the water situation in rural areas of Bangladesh, a research group at the University of Dhaka has been developing low cost domestic methods to remove pathogens from surface water through pasteurisation using free solar energy. Pasteurisation is a process in which water is heated to approximately 60 °C and maintained for about 30 minutes to destroy pathogens. In these methods, the water is also exposed to UV-light from the sunshine, which causes destruction of diarrhoeal pathogens at temperatures somewhat lower than required in normal pasteurisation. However, despite many advantages these devices need to be installed for each time of use.

Recently, a semi-permanent device has been developed which is expected to be more user friendly. The objective of this Master thesis has been to study and optimize the low cost semi-permanent device that can deliver safe drinking water to people in rural areas. Two test devices were constructed to determine the most effective treatment e.g. temperature, time, solar radiation, user-friendliness and cost. To replicate the results from the solar heating tests a model, based on the solar radiation and convective heat loss from the device, was used. The model was also able to determine the time duration at a certain solar radiation level to estimate when the water is safe to drink.

The results revealed that the performance of the device depends on thickness of the insulation and thickness of the air gap. This is because the most important factors to achieve safe drinking water are solar radiation and time. The modelling indicated that the measured water temperature corresponds well with the calculated water temperature and also showed that the lowest required solar radiation is 390 W/m^2 to reach drinking water criteria, at an air temperature of 25 °C. A study of microbiology showed that the semi-permanent low cost device could purify surface water to a safe level.

KEYWORDS: Solar water pasteurisation, surface water, semi-permanent device, solar radiation, Bangladesh.

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REFERAT

En metod för vattenrening med hjälp av solenergi för landsbygdsområden i Bangladesh

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I syfte att förbättra vattensituationen på landsbygden i Bangladesh har en forskargrupp vid universitetet i Dhaka utvecklat billiga inhemska lösningar för att kunna rena ytvatten. Metoden som används för att avlägsna patogener från ytvatten uppnås genom pastörisering av vattnet med hjälp av solenergi. Pastörisering är en process där vatten upphettas till ungefär 60 °C och håller denna temperatur i ca 30 minuter för att möjliggöra desinfektion av patogener. I dessa metoder utsätts vattnet även för UV-strålning från solen, vilket eliminerar patogener redan vid något lägre temperaturer än för normal pastörisering. Trots många fördelar måste dessa behållare installeras var gång vid användning.

Nyligen har en semi-permanent behållare utvecklats, som förhoppningsvis kan bli mer användarvänlig. Syftet med det här examensarbetet har varit att studera och optimera den semi-permanenta behållaren för att uppnå gynnsamma dricksvatten-förhållanden. Till hjälp byggdes först två testanordningar för att bestämma de mest effektiva faktorerna vid optimering av behållaren, med hänsyn till temperatur, tid, solinstrålning, användarvänlighet och kostnad. För att replikera resultaten från sol-uppvärmningstesterna användes en modell, som baseras på solinstrålning och konvektiva värmeförluster från anordningen. Modellen kan även beräkna den uppehållstid som krävs, vid en viss solinstrålning, för att erhålla säkert dricksvatten.

Resultatet påvisade att tjocklek på isolering och luftlager var avgörande för behållarens funktion. De två viktigaste faktorerna för att uppnå rent dricksvatten beror på solinstrålning och tid. Modellen visade att den uppmätta vattentemperaturen överensstämmer väl med den beräknade vattentemperaturen och visar också att den lägsta solstrålningen som fordras är 390 W/m^2, vid en lufttemperatur på 25 °C, för att nå dricksvattenkriterier. Enligt en mikrobiologisk studie uppnår den semi-permanenta lågkostnadsbehållaren kriterierna för dricksvattenkvalitet.

NYCKELORD: Pastörisering, solinstrålning, ytvattenrening, semi-permanent behållare, Bangladesh.

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PREFACE

This Master thesis has been written as the last part of the Masters Programme in Environmental and Water Engineering at Uppsala University. It has been performed as a Minor Field Study (MFS) at the department of Biomedical and Physics at University of Dhaka, Bangladesh. Financed by the Swedish International Development Agency (SIDA) on behalf of International Science Programme (ISP) at Uppsala University. The thesis was supervised and initiated by Siddique Rabbani, professor at Department of Biomedical Physics & Technology at Dhaka University. Subject reviewer, but also the supervisor in Sweden was Roger Herbert, professor at Department of Earth Sciences, Program for Air, Water and Landscape Sciences at Uppsala University.

I would like to begin with thanking my supervisor, Siddique Rabbani, for all guiding and support throughout this study. Without your and the departments warm welcome and hospitality, the time in Bangladesh would not have been the same. This has been a memory for life thanks to each an every one at the department, who also became my family during the study. A special thank you to Yousuf Abu, for being an amazing co-partner spending hours with me in the sun. I would also like to thank Sharmin Zaman for providing the microbiology tests and being supportive along the way.

Further would I like to express my gratitude towards Roger Herbert for your great input and help during this Master thesis. I cannot express the value of your feedback through the last part of the project.

Moreover, I would like to thank the department of Microbiology at Dhaka University for the help in accomplishing the calibration of thermistors and microbiology test. Also great thanks to the department of Renewable Energy at Dhaka University for helping out with the calculations of the LUX-meter and solar insulation data. The thesis would not have been possible without the support from ISP at Uppsala University, thank you for making this project possible.

Finally but not least would I like to express gratitude towards my friends and family for supporting and encourage me throughout the project. Especially, I want to show my warm appreciation to Beatrice, without your support would I not have gone through the last weeks submitting the report.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Rent vatten är en av de mest grundläggande förutsättningarna för att nå hållbar utveckling under detta århundrade. Dock finns det fortfarande länder i världen som idag saknar rent dricksvatten. Bangladesh är ett ut av dem, med en befolkningstäthet på 150 500 invånare, på en yta stor som en tredje del av Sverige. Fler än 25 miljoner människor saknar tillgång till rent vatten och majoriteten av dessa bor på landsbygden i Bangladesh. Den kritiska vattensituationen i Bangladesh drabbar både grund- och ytvatten. Grundvattnet är förorenat med arsenik, vilket leder till hälsoskador samt dödsfall. Ytvattnet innehåller och andra sidan patogener som bland annat orsakar diarré och är en av de mest förekommande orsakerna till dödsfall hos barn. Arsenik förekommer i grundvattnet som en hårt bunden kemisk förening, vilket är svårt att reducera. De tekniker som idag finns tillgängliga för eliminering av arsenik i vatten är avsevärt dyra. Således, skulle det vara mer praktisk att ta bort smittoämnen från ytvatten istället för att rena grundvatten från arsenik.

Vid universitetet i Dhaka har en forskargrupp utvecklat inhemska och billiga lösningar för att kunna rena ytvatten på landsbygden i Bangladesh. De olika metoderna är uppbyggda av material som delvis finns på landsbygden och baseras på en princip där patogener avlägsnas från vatten genom pastörisering med hjälp av solenergi. Pastörisering är en process där vatten upphettas till ca 60 °C och behåller den temperaturen i ungefär 30 minuter för att desinfektion av patogenerna ska fullföljas. I denna process utsätts även vattnet för UV-strålning från solen, vilket möjliggör att patogener kan elimineras redan vid lägre temperaturer än för normal pastörisering. Trots att dessa metoder har många fördelar måste de installeras på nytt var gång innan användning, vilket är en nackdel.

Nyligen har professor Rabbani vid universitetet i Dhaka utvecklat en design av en semi-permanent behållare, som förhoppningsvis kan bli mer användarvänlig. Dock har denna behållare ännu inte testats eller undersökts vidare. Syftet med det här examensarbetet har varit att studera och optimera den semi-permanenta behållaren för att uppnå gynnsamma dricksvattenförhållanden. Till hjälp byggdes först två mindre testanordningar för att bestämma de mest effektiva faktorerna vid optimering av behållaren, t.ex. temperatur, tid, solinstrålning, användarvänlighet och kostnad. Genom att utföra tester både inom- och utomhus med testanordningarna kunde dessa faktorer utvärderas. Designen består till grunden av en behållare i frigolit, samt en polyetenpåse och ett lock gjort av en bambu-ram och polyproperlen. Allt material är tillverkat i Bangladesh och finns tillgängligt på lokala marknader. Testerna genomfördes med varierande tjocklek på behållarens isolering och luftlager närmast vatten-påsen. Detta för att få en uppfattning om hur god förmåga isoleringen har att hålla värme, men även för att se om ett tjockare luftlager kan ha någon temperaturförhöjande effekt på vattnet.

För att evaluera hur tillförlitliga resultaten från soluppvärmnings-testerna är användes en modell, som baseras på solinstrålning och de konvektiva

värmeförlusterna från anordningen. Modellen är framtagen i Excel och kan även beräkna uppehållstiden som behövs för att erhålla säkert dricksvatten vid en viss mängd solinstrålning.

Resultatet visade att en förbättring av behållaren kunde åstadkommas genom att öka tjockleken av isoleringen och tjockleken på luftlagret. De två viktigaste faktorerna för att erhålla rent dricksvatten med hjälp av behållaren beror på solinstrålning och tid. Modellen konstaterar att den uppmätta vattentemperaturen stämmer väl överens med den uträknade vattentemperaturen. Den definierar även att vid en lufttemperatur på 25 °C krävs minst en solinstrålning på 390 W/m^2 för att uppnå dricksvattenkriterierna. Enligt en mikrobiologisk studie uppfyller den semipermanenta lågkostnadsbehållaren kriterierna för dricksvattenkvalitet.

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1 INTRODUCTION

Water is an essential source to make life possible and is of course an important matter. But there are still countries in the world today where large amounts of the population are lacking fresh drinking water (WHO and UNICEF, 2013). Bangladesh is one of these countries with a dense population of 150.5 million inhabitants on a landmass of 147,570 km^2 (World Bank, 2011). More than 25 million people lack access to an improved water resource and the majority live in the rural areas of Bangladesh (WHO/UNICEF (JMP), 2013).

The availability of clean fresh water is one of the most basic conditions for achieving sustainable development in the 21st century (Stikker, 1998). Improvement in health, mortality, food security, access to energy, economic growth and climate change all depend on water. In September 2000, world leaders came together at the United Nations Headquarter to form the Millennium Development Goals (MDGs) (UN, 2013). The goals were created to develop a concrete action plan for the world to address eight of the most important global problems before 2015. This project addresses two of these goals. Goal number 4: *Reduce child mortality* and goal number 7: *Ensure environmental sustainability.* The last mentioned goal is expected to halve the proportion of people without access to improved sources of water.

The critical water situation in Bangladesh involves both the groundwater and the surface water. The groundwater is contaminated with arsenic, which creates health problems that in the end may lead to death (WHO, 2000). On the other hand the surface water contains pathogens, which cause diarrhoeal diseases and are a major cause of child death (WaterAid, 2012). However, arsenic occurs in groundwater as a dissolved chemical compound, which is difficult to remove and such techniques are also expensive. Further on, any arsenic removal technique will eventually result in a waste with high concentrations of arsenic. If this waste is not disposed of properly, unfortunately a very likely scenario in rural Bangladesh, it may contaminate the surface area and vegetation, causing irreparable damage. On the other hand, diarrhoeal pathogens are easy to destroy, just by heating the water to a certain temperature. Thus, from a practical point of view it would be wiser to disinfect surface water rather than removing arsenic from groundwater.

In order to improve the water situation in rural areas of Bangladesh, a research group at the University of Dhaka has been developing low cost domestic methods to remove pathogens from surface water through pasteurisation of water using free solar energy. Pasteurisation, which destroys all diarrhoeal pathogens, is a process in which water is heated to 60 °C and maintained for 30 minutes (Hynes, 1968), or heated to 70 °C and maintained for 15 seconds. Some types of bacteria may still survive, but these are usually harmless (University of Dhaka, 2011). The device involves the use of polyethene sheets or polyethene bags filled with water and other materials available in the rural area in order to set up a simple device that creates 'Greenhouse Effect'-conditions. This is essentially a flat plate solar water heater and provides the user with safe drinking water. In this method, the water is also exposed to UV-light available in the sunshine which causes destruction of diarrhoeal pathogens at temperatures somewhat lower than that required in normal pasteurisation.

The overall goal with this project is to contribute safe drinking water for people living in rural areas in countries such as Bangladesh, but also to provide safe drinking water after flooding or other natural disasters.

1.1 Objective of study

The objective of the present MSc project is to study and optimize a low cost semi-permanent solar pasteurisation device that can deliver safe drinking water to people in rural areas of Bangladesh, as well as being user friendly.

1.1.1 Specific objective

- To examine the factors that needs to be taken into consideration to achieve the most effective treatment e.g. temperature, time, solar insolation, user-friendliness and cost.
- To evaluate the optimum thicknesses of bottom insulation and air layer(s) in order to improve the construction of the device.

1.2 General delimitations

Since solutions of community scale appear to be unsustainable in Bangladesh because of cultural traits, this project targets a solution for domestic scale (University of Dhaka, 2011).

The fieldwork during this project was time-limited to three months in Bangladesh, from end of January until end of April 2013. The political situation in Bangladesh at the time of visit was unstable since general election was coming up and the prosecution of war criminals from the liberation war in 1970 caused demonstrations and riots in the country. This instability made it unsafe and in some case dangerous to pursue a field study. The violence and clashes became especially aggressive in the rural areas. Therefore practical testing of the device was not possible in rural areas of Bangladesh, and testing was performed at the university in Dhaka.

2 BACKGROUND

2.1 Bangladesh

During the late 16th century India, Pakistan and Bangladesh were colonized by Britain (Van Schendel, 2009). In 1947 Britain left their colony and the imperium was divided into two parts, India and Pakistan (NE, 2012). Bangladesh evolved out of what was known as the eastern half of Pakistan. The region suffered from economical, political and cultural oppression and a civil war broke out in 1971, resulting in the independence of Bangladesh (Van Schendel, 2009).

The international media highlighted Bangladesh after the Rana Plaza garment-factory collapse on 24 April 2013 and the whole world became aware of this small country in South Asia (Guardian, 2013). However, this is not the first tragic disaster that has affected Bangladesh during the decades. In 2007 the cyclone Sidr damaged the coastal areas and a quarter of the heritage forest, the Sundarbans, got destroyed (Bhowmik, 2013). Another constantly recurring natural disaster is flooding, which cost the life of 36 million people in June 2004 (EM-DAT, 2013). This demonstrates some of the greatest challenges and vulnerabilities that the country is facing.

The country is placed in South Asia and formed as a low lying flood delta, with rivers coming from India in the west, Nepal and Himalaya from the north and Myanmar in the east (Van Schendel, 2009). The three largest rivers crossing the country are Ganges, Brahmaputra and Meghna, Figure 1, shows how they link together and continues out to the Bay of Bengal (OECD, 2003). The flood delta is both the blessing and curse of the country. Each year monsoon rain falls and overloads the rivers, which are the main reason to the flooding that causes huge damages (Shaw et al, 2013). About 30-70 % of the country is normally flooded each year (OECD, 2003). During the other half of the year almost no rain falls and causes droughts instead (Shaw et al, 2013). This is a huge problem for agriculture, which is one of the major incomes of the country (OECD, 2003).

The landmass of the country is little compared with its population, which is near 152.9 million inhabitants on a land area of 147 570 sq. km (World Bank, 2011), the size of one third of Sweden. The population density is more than 1.209 persons per sq. km and 71 % of the population lives in rural areas (World Bank, 2011). Bangladesh ranks low on all measures of economic development and the Gross Domestic Product (GDP) growth was 6.0 % in 2012, which have maintained the same during 2013 (Hussain, et al. 2013). Though a change in the percentage of population living below the national poverty line can be seen and has declined from 40.0 % in 2005 to 31.5 % in 2010 (World Bank, 2011).

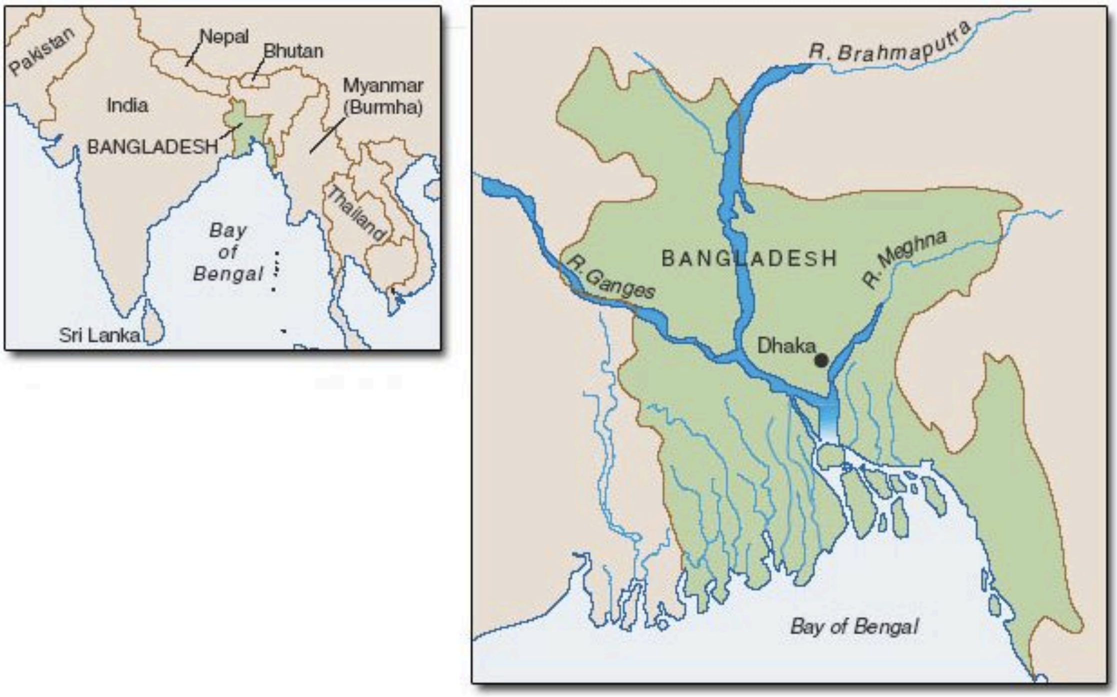

Figure 1 Map of Bangladesh with the neighbouring countries (left) and the three largest rivers (right) (The Open University, 2007).

2.2 Climate in Bangladesh

Bangladesh has a subtropical climate with heavy rainfall, high humidity and warm temperatures (Shaw et al, 2013). The average temperature is about 25 °C (World bank, 2011) and average monthly values can be seen in Figure 2. The climate is influenced primarily by monsoon and partly by pre-monsoon and post-monsoon circulations (OECD, 2003). The southwest monsoon originates over the Indian Ocean and carries warm, moist, and unstable air, which causes rainfall. The monsoon begins the first week of June and ends in the first week of October, but some annual variability in its starting date can appear (Shaw et al, 2013). Besides monsoon, the easterly trade winds provide warm and relatively drier circulation (OECD, 2003). Warmer weather conditions starts during late spring from March to May and during summer the warmest temperatures are reached from end of May to July before the monsoon starts (World bank, 2011). The climate change has affected Bangladesh in different aspects that cause change in season, considering temperature and precipitation change (OECD, 2003). But most critical effects will be caused by sea level change and changes in cyclone or tornado intensity (Shaw et al, 2013).

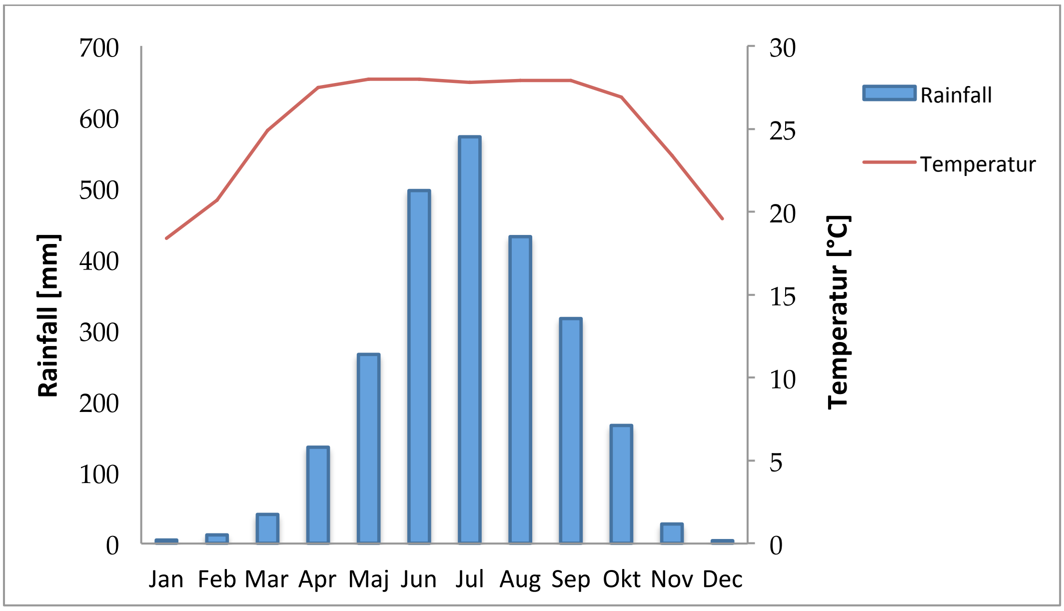

Figure 2 The average monthly temperature (red line) and rainfall (blue bars) for the period 1960-1990 (Data from World bank, 2011).

2.2.1 Solar insolation

The solar insolation is significant for solar water pasteurisation treatment and is one of the factors to examine in this study. Based on solar radiation data collected from the Renewable Energy Research Centre at University of Dhaka and Bangladesh Meteorological Department, the maximum and minimum global radiation in Bangladesh could be defined. The maximum global radiation was recorded in April to May and the minimum in November to December (SWERA, 2007). The geographic location of Bangladesh is 20°34'N to 26°38'N latitude and 88°01'E to 92°41'E longitude (OECD, 2003). This makes the country located near the equator and hence the conditions to obtain sunshine are preferable and the solar radiation is strong 8 months of the year. The Global Horizontal Irradiance (GHI), the total amount of shortwave radiation received from the sun on a horizontal surface, in Dhaka during March and April was measured to 722 W/m^2 and 764 W/m^2 (SWERA, 2007). The total horizontal radiation is usually estimated to $S = 1000\ W/m^2$ on a clear day (Badescu, 1995). The solar radiation test in this study was peformed between March and April 2013 and took place in Dhaka at 23°43'N and 90°24'E (Solargis, 2013). During this time period, the zenith angle was measured to $Z = 20° - 23.5°$ and the diffuse radiation was estimated to $d = 200 - 350\ W/m^2$

The total solar insolation striking the surface can be estimated using the equation (1) (Badescu, 1995):

$$I = S\ cos\ Z + d \qquad (1)$$

The estimated value of the solar insolation in Dhaka during late March, when most outdoors test where made, was calculated to approximately $I = 1139\ W/m^2$. This value should be comparable with the solar radiation tests during this study.

2.3 Drinking water in Bangladesh

2.3.1 Surface water contamination

Surface water sources of drinking water in Bangladesh have historically been contaminated with pathogenic microorganisms, which cause a significant burden of disease and mortality. Diarrhoeal disease is the second leading cause of mortality in children under five years old in the world (Boschi-Pinto et al, 2008). It is both preventable and treatable, but still diarrhoea kills around 760 000 children under five each year (WHO, 2013). In developing countries, like Bangladesh, diarrhoea is also a major cause of malnutrition (Boschi-Pinto et al, 2008).

In the 1970s gastrointestinal diseases was an acute problem; infants and children suffered the most from these grave diseases as the result of pathogenic contamination in pond water, rivers, lakes etc. (WHO, 2000). Hence, rapid actions were necessary and tube wells began to be installed (UNICEF, 2008). The installation of tube wells spread fast and Bangladesh shifted from drinking surface water to drinking groundwater. Unfortunately, the water turned out to be contaminated with arsenic.

2.3.2 Arsenic problem

Tube wells have been used in Bangladesh since the 1940s, but only recently has the problem with arsenic-contaminated water come to light (WHO, 2000). This is due to the increasing installation of tube wells during the past 30 years and the consequential rising number of persons drinking from them.

During the 1970s, the United Nations Children's Fund (UNICEF) and the Department of Public Health Engineering installed tube wells around the country to intentionally provide safe drinking water (UNICEF, 2008). At this time arsenic in water supplies was not known as a problem and hence standard testing of water did not include arsenic tests.

In 1993 the first arsenic contaminated water was detected and further testing was done in the following years, including investigations by the Department of Occupational and Environmental Health of the National Institute of Preventive and Social Medicine. Results from various laboratories were gathered in a World Health Organisation (WHO) country report in 1996. In about half of the measurements, the arsenic concentrations were above 50 μg/l (WHO, 2000). This did not meet the guidelines from WHO where the recommended maximum level is 10 μg/l. Even worse was that cases with concentrations higher than 50 μg/l were identified in Bangladesh.

According to survey data from 2000 to 2010, an estimation of 35 to 77 million people in the country have been chronically exposed to arsenic (UNICEF, 2008). This has been described as the largest mass poisoning in history (WHO, 2000). A map of arsenic contaminated areas in Bangladesh between 2002-2003 is shown in Figure 3 (UNICEF, 2010).

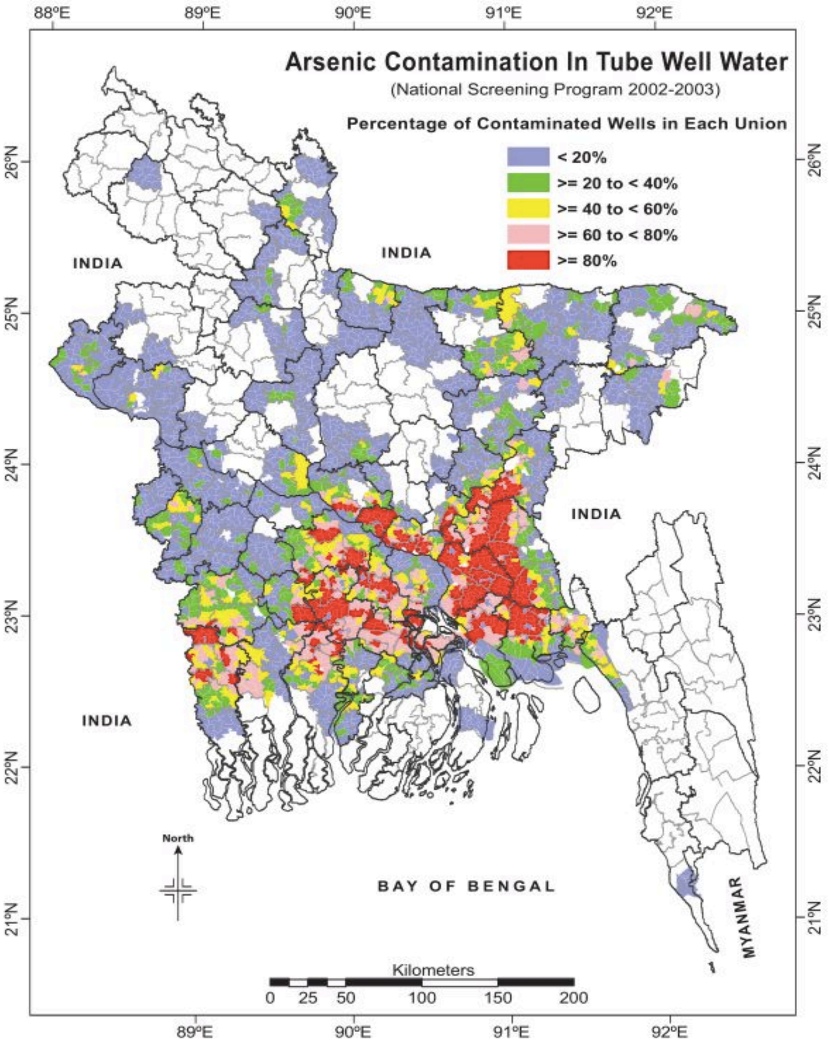

Figure 3 Areas in Bangladesh with arsenic-contaminated tube well water, during the period 2002-2003 (UNICEF, 2010).

2.4 Waterborne pathogens

The surface water, for example rivers, canals, lakes and ponds are free of arsenic. But instead, these may carry different types of pathogenic microorganisms contaminated by human or animal faeces. The most common waterborne diseases are caused by pathogenic bacteria, viruses and parasites (e.g. protozoa and helminths) and are a widespread health risk related to drinking water (WHO, 2011). Not all pathogens are harmful for humans, but many are and the most critical waterborne pathogens detected in contaminated drinking water supplies are *Campylobacter, Shigella, Samonella, toxigenic Escherichia coli (E-coli), Vibrio cholera, Legionella, Enterovirus, Hepatitis A virus, Rotavirus, Entamoeba, Cryptosporidium* and *Giardia*. (Meybeck et al, 1990). Table 1 shows the relevant characteristics for these pathogens in terms of health significance, persistence in water, relative infectivity and important animal source. Waterborne pathogens, such as *Legionella*, may grow in water, however noroviruses and *Cryptosporidium* are host-dependent waterborne pathogens and cannot grow in water but are able to persist there (WHO, 2011).

Waterborne pathogens that are host-dependent gradually lose viability and ability to infect after leaving the host body. The decay rate is normally exponential and after a certain period the pathogen will become undetectable. Hence pathogens with low persistence must immediately find new host bodies are often more liable to spread by person-to-person contact or weak hygiene than by drinking water (The WHO, 2011). Persistence depends on several factors, and the most important is temperature. Higher temperature generates a faster decay and may get amplified by the effects of UV-radiation from sunlight near the water surface area (Livsmedelsverket, 2005).

Although consumption of contaminated drinking water represents the major risk in diarrhoeal diseases, other routes of transmission could also lead to diseases, see Figure 4 (WHO, 2011). In some cases pathogens can transmit by multiple routes, such as inhalation of water drops (aerosols), in which the relevant organisms have multiplied because of warm water and the presence of nutrients (Livsmedelsverket, 2005). Direct contact with contaminated water resources is another vital transmission route, e.g. when collecting water or when using water for bathing or laundry (WHO, 2011). Body resistance can usually protect a person from such casual contacts or intakes of small amount of pathogens, but when a large amount of pathogen is ingested with drinking water, the human body cannot cope up with the invasion, and disease results.

Table 1 Shows the relevant characteristic for waterborne pathogens in Bangladesh, in terms of health significance, persistence in water, relative infectivity and important animal source and size. The table is reproduced from WHO (2011) and Livsmedelsverket (2005).

Pathogen	**Size** [***μm*** = 1/1000 mm] [nm= 1 million parts mm]	**Persistence in water supplies**	**Health significance**	**Resistance to chlorine**	**Important animal source**
Bacteria					
Campylobacter jejuni, C. coli	> 0.2 *μm*	Moderate	High	Low	Yes
Escherichia coli - Pathogenic	> 0.7 *μm*	Moderate	High	Low	Yes
E. coli – Enterohaemorrhagic	> 0.7 *μm*	Moderate	High	Low	Yes
Legionella spp.	-	May multiply	High	Low	No
Salmonella Typhi	> 0.7 *μm*	Moderate	High	Low	No
Other salmonella	> 0.7 *μm*	May multiply	High	Low	Yes
Shigella spp.	> 0.7 *μm*	Short	High	Low	No

Vibrio cholerae	> 0.5 μm	Short to long	High	Low	No
Viruses					
Adenoviruses	80 nm	Long	Moderate	Moderate	No
Astroviruses	28-30 nm	Long	Moderate	Moderate	No
Enteroviruses	25-30 nm	Long	High	Moderate	No
Hepatitis A virus	27 nm	Long	High	Moderate	No
Hepatitis E virus	-	Long	High	Moderate	Potentially
Noroviruses	27-40 nm	Long	High	Moderate	Potentially
Rotaviruses	70 nm	Long	High	Moderate	No
Protozoa					
Cryptosporidium hominis/parvum	4-6 μm	Long	High	High	Yes
Cyclospora cayetanensis	8-10 μm	Long	High	High	No
Entamoeba histolytica	-	Moderate	High	High	No
Giardia intestinalis	8-12 μm	Moderate	High	High	Yes

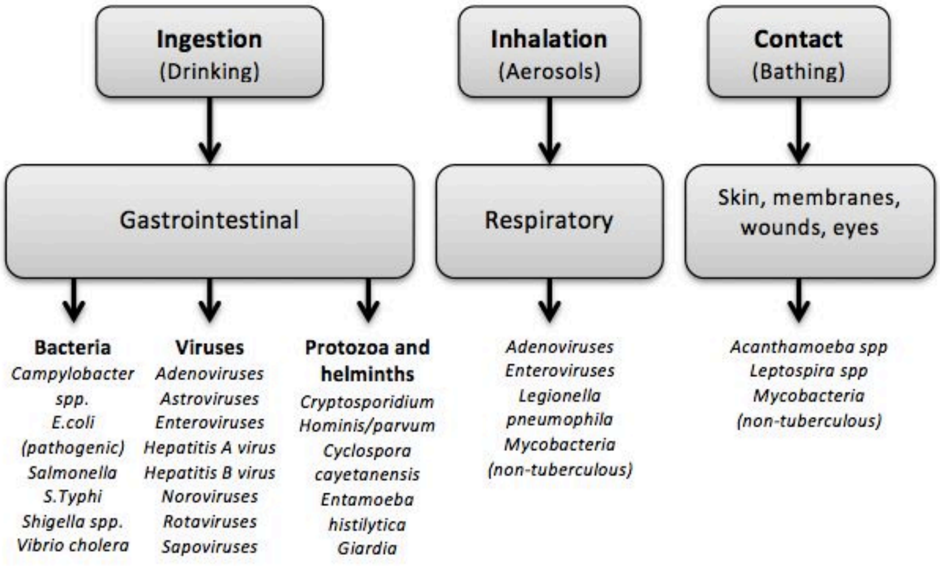

Figure 4 Transmission pathways of the selected water related pathogens (WHO, 2011). The figure is reproduced after approval from WHO.

Each group of pathogen are represented in the following paragraphs.

2.4.1 Bacterial pathogens

Bacteria are the most sensitive group of pathogens towards inactivation by chemical decontamination (WHO, 2011). The size of bacteria varies from > 0,2 to 1 μm, which is larger than viruses but smaller than protozoa and hence are easier to remove with filtration or UV-treatment (Svenskt Vatten AB, 2011). Generally enteric bacteria do not grow in water and have shorter lifetimes than viruses and parasites. However, there are some free-living pathogens, such as *Legionella* and non-tuberculous *Mycobacteria* that can grow in the water and soil environment (WHO, 2011). Most bacterial pathogens transmitted by water will affect the gastrointestinal tract and are excreted in the faeces from infected humans and animals (Svenskt Vatten AB, 2011). The exposure routes to bacteria consist of drinking, inhalation and direct contact with water through bathing.

There are potential waterborne bacterial pathogens detected with known diarrhoea diseases and some of them are *Vibrio cholera*, *Campylobacter*, *E. coli* O157, *Salmonella* and *Shigella* (Livsmedelsverket, 2005).

2.4.2 Viral pathogens

Viruses are the smallest group of pathogen with the size of 0,01-0,3 μm and thus are more difficult to remove through physical processes e.g. with filtration (Svenskt Vatten AB, 2011). They can persist for long periods and may be less sensitive to UV light than bacteria and parasites (The WHO, 2011). Growth of viruses are limited to the host, this implies problem when several species have a typically low infective dose. The temperature is also a significant factor for survival for viruses, where a lower temperature gives a higher viability.

2.4.3 Protozoa

Protozoa are the least sensitive group of pathogens to inactivation by chemical disinfection, e.g. UV-treatment, but they can easily be removed by physical processes due to their moderate size of >4 µm (Svenskt Vatten AB, 2011). UV-light is an effective treatment to remove *Cryptosporidium* (Livsmedelsverket, 2005). Protozoa can survive for long periods in water and infective doses are generally low (WHO, 2011). *Giardia* infections are normally more common than *Cryptosporidium* infections, according to models tested by WHO and symptoms can last longer. Nevertheless, the size of *Cryptosporidium* is smaller than *Giardia* and hence more difficult to remove though physical processes (WHO, 2011).

2.5 Disinfection and solar water pasteurization

The death rate of waterborne diseases can be reduced significantly through treatment of drinking water, improved sanitation and hygiene (WHO, 2013). Frequent diarrhoea, is the most common waterborne disease both for adults and children (WHO, 2011). For adults it takes away working time and the family income are reduced. In some cases death can be the final consequence (University of Dhaka, 2011). Therefore, treatment of drinking water is prime importance.

Since the surface water contains more pathogenic microorganisms than the groundwater it is crucial to disinfect the surface water, but usually the groundwater also gets disinfected as a precaution (Crittenden, 2005). The disinfection should be able to ensure the destruction effect on the microorganisms before it enters the current water mains and reaches the user (WHO, 2002).

Fortunately, there are many solutions of how to disinfect the surface water by using various technologies and methods of water treatment for microbial contamination. Depending on the condition of the water and the surrounding possibilities.

2.5.1 Chemical disinfection

Chemical disinfection of drinking water often uses a chlorine-based technology such as free chlorine, chlorine dioxide, ozone or other oxidants and strong acids and bases (WHO, 2011). The most common chemical disinfection in developing countries for household water is free chlorine. In order for the free chlorine to give desired effect, certain water qualities are required. Different forms free chlorine will be active during the disinfection reliant on the pH level of the water (Svenskt Vatten AB, 2011).

Another important factor except pH is the concentration of organic material in the water (WHO, 2002). If the water contains organic material, this will oxidize with the free chlorine and create a chlorinated organic compound that could be carcinogenic (Crittenden, 2005). Hence the chemical disinfection should take place in the end of the treatment, when the concentration of organic material is low. The recommendation does for free chlorine is approximately 2 mg/l to clear water and the double to turbid water (4 mg/l) (WHO, 2011).

Other useful chemical disinfection is either chlorine gas, which is decreasing pH or hypochlorite that has pH-increasing effects (Svenskt Vatten AB, 2011). Both chemicals have the characteristic that will continue to disinfect the water even after reaching the water pipes.

2.5.2 Filters and membrane

Almost all surface water requires some sort of filtration, since the water often contain particles from suspended solids such as algae, silt, clay and organic or inorganic materials (WHO, 2002). Filtration is also effective to remove microorganisms from surface water but needs to be combined with other treatment processes (Svenskt Vatten AB, 2011). Though the groundwater contains less microorganisms and suspended solids, the groundwater treatment also involves filtration since subsequent processes (as oxidation) requires particles to be removed (Crittenden, 2005).

There are many different types of filters, which depend on pore size and consist of carbon block filters, porous ceramics containing colloidal silver, reactive membranes and fibre or cloth filters (WHO, 2011). The process is based on physical straining through a single or multiple porous surfaces with structured pores to remove and retain microorganism pathogens by their size. Some of these filters could have surfaces that are treated with chemical antimicrobial or bacteriostatic modifications (Crittenden, 2005).

There is a simpler method to reduce *Vibrio cholera* from the water just by using a cloth filter made from e.g. a sari cloth (fabric often used by a women) (WHO, 2011). Though, these cloths filters only reduce *Vibrio cholera* with copepods or other larger encaryotes and will not retain smaller bacteria since the pores will allow them to pass through.

Other options are filter techniques such as ultra filter, nano filter and reverse osmosis but they require supply of reliable electricity to be operated (WHO, 2011).

2.5.3 Granular media filters

Granular media filters removes suspended solids and oils as the water passes though granular material or filter media (Crittenden, 2005). The filters are often used after gravity separation and removes particles by filter bed or surface layers of sand, coal, diatomaceous earth or other minerals which water passes though or over (WHO, 2002). To retain microorganism pathogens the filters use a combination of physical and chemical processes, including sedimentation and adsorption (WHO, 2011). The most common filter processes are rapid filtration, slow sand filtration and precoat filtration. In rapid filtration, pre-treated water flows down and passes through a filter bed with a depth of 0.6-1.8 m (or with an even deeper depth of 4 m) (Crittenden, 2005). The particles get removed during the downward flow throughout the bed. Slow sand filtration operates similar as the rapid filter but with a rate about 100 times lower than rapid filtration (WHO, 2002). The precoat filtration involves a thin filter layer or cake of 2-5 mm, where the particles mainly get removed on the surface of the cake (Crittenden, 2005). These technologies often have a two stages process, one incorporating mode and one regeneration or backwash mode, in order to rinse the filtration and restore the capacity of the filters (Svenskt Vatten AB, 2011).

The granular media filter could also be biologically active since they develop layers of microorganisms, which are common in slow sand filters (WHO, 2011).

2.5.4 UV light technologies (using lamps)

UV light is an electromagnetic radiation, which causes an inactivation effect on microorganism pathogens, mainly bacteria but also most viruses and protozoa. The light generates a photochemical reaction in the DNA-molecule of the microorganism and thus prevents cell division and absorption of nutrients (Svenskt Vatten AB, 2011). In this process water leads trough a vessel or inside a flow-through reactor where it will be exposed to UV radiation from UV lamps with a sufficient does that can destroy microorganism pathogens (Crittenden, 2005). This technique becomes limited in low-income countries, since the application requires maintenance equipment with reliable electricity supply (WHO, 2011).

2.5.5 Thermal technologies

The thermal technologies are mainly using heat from burning fuel as the mechanism to disinfect water from microorganisms (WHO, 2011). Boiling or heating water through pasteurization to a certain temperature is the recommendations for water treatment (Svenskt Vatten AB, 2011). Then the water should cool naturally after treatment and kept storage afar from additional risk of contamination (WHO, 2011).

Most people living in rural areas, in counties such as Bangladesh, often treat the water by boiling it using fuel from e.g. firewood, charcoal and kerosene (University of Dhaka, 2011). This fossil fuel could cause coughing and serious lung problems (WHO, 2011). This especially affects women and children since they usually are involved with the cooking and thus also water collection (University of Dhaka, 2011). If there is a possibility to reduce the amount time by the fire, that is sustainable from a health, environmental and economical perspective, not only to prevent lung diseases but also to save money by buying less wood and last but not least to reduce environmental impact (WHO, 2011). In many rural situations burning fuel is also scarce, so an alternative is necessary (WHO, 2002).

2.5.6 Coagulation, precipitation and sedimentation

Coagulation or precipitation often includes a coagulant of natural or chemical kind, or suspended particles to enhance sedimentation (WHO, 2011). The process for sedimentation involves methods using settling of suspended particles to separate microorganism from the water (Svenskt Vatten AB, 2011). In order to remove the formed floc, which are the coagulated or precipitated particles, from the water a fibre media or cloth filter could be used as straining. This step could contain a simple sedimentation, without any chemical coagulants. The water should be kept stored for at least 2 days to reduce microorganisms after these processes (WHO, 2011).

2.5.7 Combination treatments

All previous mentioned technologies, in this paragraph, could be used combined together simultaneously or sequentially to treat water. The combinations are coagulation and disinfection, media filtration and disinfection or media filtration and membrane filtration (WHO, 2011).

2.5.8 Solar disinfection

Water can also be disinfected from pathogens only by using the sun as a source of energy. The sun destroys pathogens both by heating up the water though pasteurisation and also using UV-light as disinfection; this is the meaning of solar water pasteurisation (WHO, 2002). The basis of pasteurisation is that it takes 30 minutes at 60 °C or 15 seconds at 70 °C to eliminate the pathogens in water (Hynes, 1968). With solar water pasteurisation both heating and UV-light will be contributing to the disinfection of the water (WHO, 2002). Which factor that is contributing most depends on the weather and on the time of the year. During days when the solar insolation (sunlight intensity) is high, the water will be heated faster, since both these factors are combined. On a cloudy day the water might not reach the same high temperature as on a sunny day, but the UV-light will still destroys the pathogens even with a lower water temperature (Rabbani, 2002). When UV-light enters the cells walls, it reacts with the proteins in the DNA-molecule (WHO, 2002). The reproduction of the DNA-cell will then stop working and the microorganisms will not be able to continue reproducing (Svenskt Vatten AB, 2011). Extensive microbiological studies have been carried out by the Dhaka University group and they found that diarrhoeal pathogens can be destroyed even at 50 °C, for a 1 hour exposure in the sun (University of Dhaka, 2011). The measured temperature of destroying different microorganisms pathogens is represented in Table 2.

Table 2 The minimum temperature and duration needed to destroy pathogens (Hynes, 1968; Chowdhury, 1988).

Pathogens	Diseases	Destruction temp [°C]	Destruction time [min]
Salmonella	Typhoid, Paratyphoid	60	20
Vibrio cholera	Cholera	55	30
E.coli	Diarrhoea	60	20
Shigella	Dysentery	55	60
Rotavirus	Child diarrhoea	60	30

Some of the pathogens that are transmitted by contaminated drinking water can produce severe and sometimes life-threatening disease. Examples of these diseases involve typhoid, cholera, infectious hepatitis (caused by hepatitis A virus or hepatitis E virus) and disease caused by *Shigella* spp. and *E. coli* O157.

2.6 Method of University of Dhaka

In 1982 professor Rabbani, at the department of Physics at Dhaka University, started to invent and test different methods that could treat contaminated water in rural areas of Bangladesh by using solar energy. The design of the methods has taken the following points in consideration: a) The unit must cost as little as possible. b) Most of the materials should be available in rural areas. c) Technology should be simple use. d) The unit should be usable in situations of emergency, e.g.

during natural disasters as floods and after cyclones. e) It should be able to raise the temperature of at least a few litres of water to more than 60 °C (Rabbani, 1985).

The methods are based on solar water pasteurisation and materials that could be found in rural areas such as hay, bamboo, bricks and mud. In order to treat the water with solar pasteurisation the contaminated water first needs to be filtered to remove particles from the water. A cloth filter can be made using multiple folds of a sari (dress worn by women in Bangladesh) or any sort of close-knit cloth tied over a bucket. Water can then be poured over this cloth filter and it could be filtered again if needed. The following sections present a description of which processes that are operating and how they work during application of these methods.

2.6.1 Trapping solar energy

The methods from Dhaka University are constructed in a way that capture solar insulation and can thus use the process of green house effect to increase the water temperature. Greenhouse effect is a natural process, which appears when solar insolation reaches earth (Likhtenshtein, 2012). The solar insolation has the form of electromagnetic waves with a large range of wavelength that includes all spectrums from ultraviolet, visible, short infrared and long infrared radiation (Nersesian, 2010). When they reach earth some of the radiations filters though the atmospheric layer of gases. Some of the radiation gets absorbed on earth and their energy contributes to heat up the temperature that makes this earth habitable for animals and plants to live (Likhtenshtein, 2012). These warm objects then radiate long infrared radiation some of which passes through the atmospheric gas layers back to space again, otherwise the temperature would be unbearable to live on earth. The problem during the last decade is that too much anthropogenic greenhouse gases have been produced, mainly from fossil fuel (Bodlund-Ringström, 1990). This is causing harmful consequences on the earth climate, because these gases do not allow the long infrared radiation to pass. Therefore, the energy radiated by heated up objects on the earth remain trapped within the earth’s atmosphere, resulting in global warming.

2.6.2 Ability to heat up a thick water layer

In the Dhaka University methods, water can utilise both trapping solar energy and UV-light simultaneously, which is a big advantage (Rabbani, 1992). Their deigns usually have a base of thick thermal insulation made of either straw, expanded polystyrene foam, or any other material (Appendix A). This is mainly to block heat loss through conduction underneath. On the top of the insulation is a tray placed, with structure made of bamboo. In case of the foam plastic it self can be made into a tray. The top surface of this bamboo tray is painted black. Alternatively a black cloth or a black plastic sheet is spread on the tray. A transparent polyethene sheet is now spread over the tray into which water is poured to make a depth of about 2 cm (University of Dhaka, 2011). As the polyethene sheet is thin, the water is effectively in intimate contact with the black surface below. The black surface absorbs solar energy, heats up, and warms the lowest layer of water through conduction (Figure

5). The whole water layer is then heated through convection. A second transparent polyethene sheet is placed on the water surface in order to prevent evaporation of water which otherwise would condense on the transparent covers above. Two transparent PVC sheets are spread on top leaving air gaps in-between. Separating items, such as hay straws, could be used to prevent the plastic sheets from touching each other. The air gaps provide insulation to prevent heat loss towards the top. The transparent covers and water allow visible and short infrared solar radiation to reach the black surface below. The long infrared solar radiation is emitted by the heated water and gets trapped by the transparent PVC sheet above (Rabbani, 2002). It needs to be mentioned that the PVC and polyethene sheet can get affected after some time of use, therefore be aware to exchange then while turning gloomy so that the infrared radiation can reach the water. In this device UV-light also passes on to the water layer.

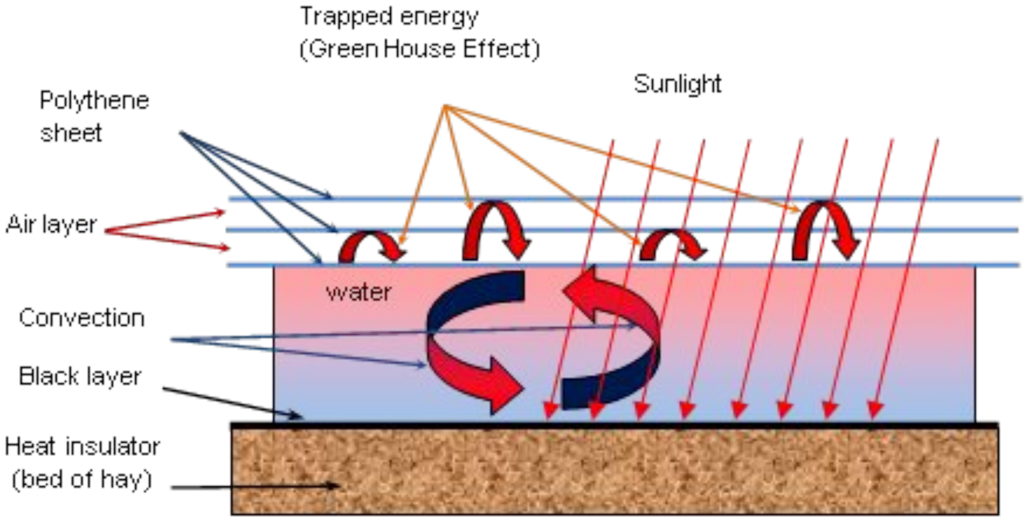

Figure 5 Schematic picture of how solar water pasteurisation and trapping solar radiation works. Solar energy in the visible and near infrared gets absorbed in the black bottom surface and heats the water (University of Dhaka, 2011). Note that polythene is the same as polyethene, which is the International Union of Pure and Applied Chemistry (IUPAC) name of polythene.

2.7 Alternative methods for solar pasteurisation

In this chapter, two other methods will be presented and compared with the Dhaka University method. All methods are using the sun as the source for the water treatment, but each method has their own type of device that provides individual functions. The key properties of the different methods are presented in Table 3.

2.7.1 SODIS

SODIS EAWAG is an initiative from The Swiss Federal Institute of Aquatic Science and Technology. The Institute works with aquatic research and has developed a method of how to disinfect water by using sunlight and a PET bottle filled with water. The method is called SODIS and uses solar water pasteurisation to disinfect water in a PET-bottle. The user takes a transparent PET-bottle or glass bottle and fills it with contaminated water and places it out in the sun for six hours (Figure 6)

(SODIS, 2013). The water in the bottle is exposed to the UV-light from the sun and gets heated. The same technique that is described in Section 2.5 and after six hours the water is free from harmful pathogens and is now drinkable (SODIS, 2013). Paraffin wax can be used as an indicator, place a small piece on a corner of the bottle and when the wax melts the water has reached the desired temperature (WHO, 2002).

Figure 6 Picture of the SODIS method, when the transparent PET bottles are exposed in the sun (SODIS, 2013).

This method of pasteurising water is an easy and simple method for the user to apply (SODIS, 2013). The disadvantage is that it takes six hour to disinfect the water and if the bottle is thicker than a normal PET-bottle the UV light may not be able to enter (WHO, 2002). The turbidity has a huge impact on the disinfection effect; if the water contains a high turbidity the UV light might not reach down to the bottom of the bottle (SODIS, 2013). This could cause a reduced disinfection effect on water quality (WHO, 2002).

If the bottles are exposed for too long in the sun or if there is a crack in the bottle, small plastic particles could start to leak out that will migrate into the water and may generate free radicals (SODIS, 2013). These free radicals are harmful compounds for human beings. In some villages PET-bottles are not as common and since the bottle are limited to 1 or 1.5 liter the user would need several bottles to get enough water for one household per day (WHO, 2002).

During partially cloudy conditions, disinfection of water with SODIS, could be achieved if the PET bottles maintains exposed in the sun for about two days (SODIS, 2013). Important to mention is when the team at Dhaka University were testing the SODIS method, they used pond-water and found that the 6 hour-treatment method under clear sun works, it destroyed all the diarrhoeal pathogens. However, when they tried it for partial cloudy days, in which they left the water bottle out for two days, the contamination of bacteria had increased (Rabbani, Personal communication). The reason for this could be that the SODIS method was not tested on water containing nutrients, which the pond-water is expected to have (WHO, 2002).

2.7.2 SOLVATTEN

SOLVATTEN is a Swedish invention by Petra Wadström from 2006. Today it is a used and well-known method in many places in the world. It is a portable black container, which is using the sun to treat and heat water at a household level. The container is specially designed to treat the water with heat and UV-light from the sun but also a built-in filter to clean the contaminated water (SOLVATTEN, 2012). Containers with black cover or opaque will achieve higher temperatures that directly can inactivate pathogens and are therefore less affected by turbidity or suspended solids (WHO, 2002).

SOLVATTEN can clean 11 liter of water by opening the container and exposing it in the sun for 2-6 hours (SOLVATTEN, 2012). The construction is made out of a black plastic container with four caps, two of them to pour the contaminated water in and two of them to pour the treated water out. The user pours water into the container and then opens the container so that the plastic cover of the two sections is facing the sun, see Figure 7. After exposing it in the sun, an indicator will show the user when the water treatment process is complete.

Figure 7 The open purchase from SOLVATTEN, ready to gain heat from the sun (SOLVATTEN, 2012).

Another positive aspect with SOLVATTEN is that this invention has been tested and used for more then 7 years which shows that the method is well established (SOLVATTEN, 2012). The containers reach the user through distributers, such as an NGO or other organizations since it only can be order in units of 72 containers at a time (SOLVATTEN, 2012). This means that the user could not construct the container it self, in this way the sustainability of the water treatment method is deficient and it could be difficult to find spare parts if something in the device breaks.

Table 3 A comparison of the three water treatment methods: SODIS, SOLVATTEN and Dhaka University. The table presents the difference in time of treatment, water volume, advantages, disadvantages, material and costs.

Method	**Time of treating and volume of water**	**Advantages**	**Disadvantages**	**Material**	**Cost**
SODIS (SODIS, 2013)	6 hours 1 liter /1.5 liter water per bottle	Simply and easy to use and safe to store the water after treatment.	Free radicals could be found in water from the PET-bottle and water with high turbidity can affect the water quality.	PET-bottle, industrial made.	0-1 dollar (3 dollar /year) (WHO, 2002)
SOLVATTEN (SOLVATTEN, 2012)	2-6 hours 6.3 liter/hour or 11 liter/105 min	Simple and easy to use and safe to store the water after treatment. Indicates when the water is clean.	The container needs to be received from a distributer and is not available to construct on your own.	Black PVC-container, industrial made.	Sponsored
Dhaka University (University of Dhaka, 2011)	1-2 hours 5-8 liter	Made of material that you partly can find in the rural areas. Can make it your self and adapt to your own needs.	Needs to be installed each time of use. Storage of water is not provided.	Polyethene or poly-propylene, bamboo hay and has a black painted bottom, hand made.	1-2 dollar (2.5 dollar)

3 METHOD AND MATERIAL

The study in this MSc project involves optimizing a semi-permanent solar water device based on the earlier Dhaka University designs. The earlier devices had to be installed daily for each treatment cycle of water. To make the device user-friendly, this semi-permanent device was conceived with a slightly higher cost.

At the beginning of the project, an initial prototype of a semi-permanent solar pasteurisation device was made according to Professor Rabbani's design based on previous experience and intuition, see Figure 8. The motivation was to improve the design of the semi-permanent device through an understanding of the associated dynamics of heat and solar radiation in this design. A series of tests will be determined: cooling test, solar heating test and tests with the improved device is described in the upcoming sections. Following tests have been performed together with my colleague Yousuf Abu.

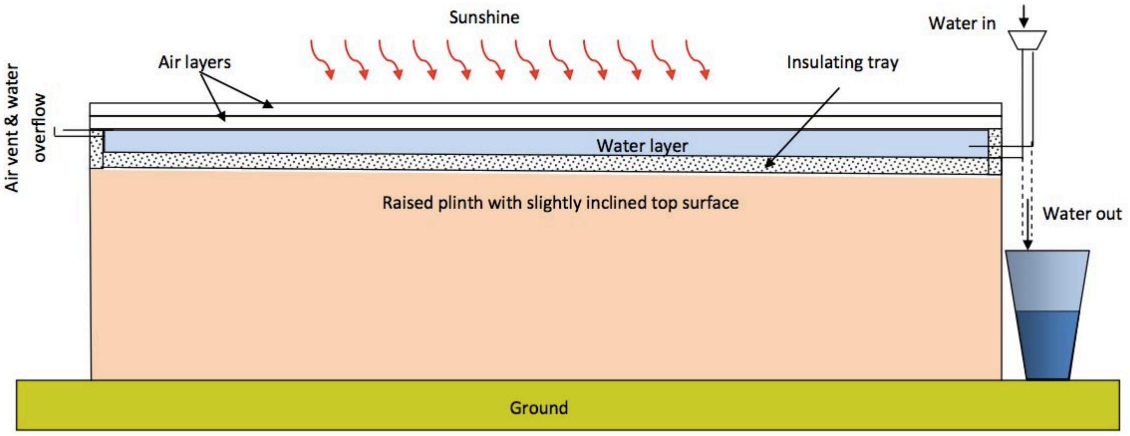

Figure 8 A semi-permanent solar pasteurisation device, as designed by Professor Rabbani.

3.1 Step 1: Test devices

In order to optimize the initial device, smaller test devices were made to determine the following: i) optimum thicknesses of bottom insulation, made of polystyrene foam; ii) thickness of air layer(s) at the top if using a) single transparent cover and b) double transparent cover.

3.1.1 Constructing the test devices

Two similar devices were constructed of 30x30 cm polystyrene foam trays, with a foam thickness of 2.5 cm. For studying the effect of insulation thickness, another 2.5 cm foam block was placed underneath. Each had a transparent polyethene water bag, carrying water to a depth of 1 cm, with transparent PVC covers at top to make devices with single air gap and double air gap. Temperature probes were inserted at all interfaces and underneath the foam insulation below. The whole assembly was placed on a 2.5 cm thick particleboard table. Ambient temperature was also measured under shaded conditions and the different tests that were that were carried out are shown in Table 4.

Table 4 The Step 1 tests that were performed with the test devices, showing the different thicknesses of insulation and air gap.

Type of test	Bottom insulation	Insulation thickness [cm]	Air gap	Air gap thickness [mm]
Cooling	Single	2.5	Single	5, 15, 24
Cooling	Double	5	Single	5, 24
Cooling	Double	5	Double	5/24 and 24/5
Solar heating	Single	2.5	Single	5, 24
Solar heating	Double	5	Double	5, 24
Solar heating	Double	5	Double	5/24 and 24/5

3.1.2 Cooling test

To attain a high temperature in a solar water heater, the heat loss to the surroundings should be a minimum. This was done through this cooling test where hot water was introduced simultaneously to two test devices, which differed, by one parameter at a time. This allowed an understanding of the effect of each parameter.

The following studies were made to understand the heat dynamics of the different changes in the design of the devices.

1. The two test devices were used with two different air gaps (air layers) of height 5 mm and 24 mm respectively, see Figure 9. Both had a single air layer. Many small rings of polyethene (about 10 to 15 cm diameter) of the same height were made and spread in the air layer to maintain the air gap between the water bag and the PVC cover at top. This arrangement was also expected to reduce convection in the air layer.

2. A new test device with an air gap of size 15 mm was constructed, to find out what the optimum air layer for the initial device would be considering heat loss due to convection.

3. Investigation of the impact of the thickness of insulation on the heat dynamics was studied adding another thickness of insulation (2.5 cm polystyrene foam) at the bottom and surrounding the two test devices, with the air gap of height 5 mm and 24 mm.

4. The tests were continued adding another air layer (i.e., two air layers) to find out if the convection or heat loss would decrease.

5. To study the impact of the rings that helps sustain the air gap a test without rings for single air layer of 24 mm was made, mainly to see if it affects the convection.

The cooling tests were made indoors, at room temperature with an initial water temperature of 75-70 °C. For these tests tap water was heated in a water heater and 1 liter water was poured into each of the two devices. The temperatures were measured as the water was cooling down. The measurement interval for reading data was 5 min and readings were taken up to 30 min.

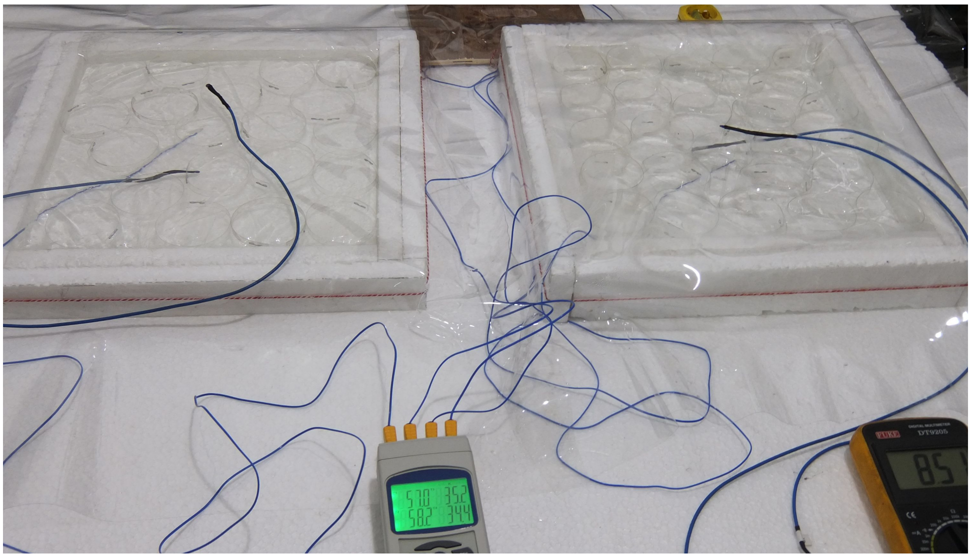

Figure 9 The two test devices with air layer of 5 mm (left) and 24 mm (right), which were used during the cooling tests indoors.

3.1.3 Solar heating test

To study the solar heating effect, tests were made outdoors in clear sun using the same test devices with an initial water temperature of 28-30 °C. There was no device to measure solar radiation in the laboratory. Hence, to measure the solar radiation, a digital light meter (Brand: Instek, model GLX-301) was modified by covering the sensor using a 3 mm white acrylic sheet. Otherwise the meter would become overloaded. With this arrangement, the value given by the meter (quoted in LUX, but obviously not the right value because of the extra cover) was used to represent the relative solar radiation. Thus the relative solar radiation was measured at periodic intervals in apparent LUX units at time intervals of 10 min, continued for 120 min. The light meter was calibrated with a solar pyranometer available at a different institute in Dhaka University at two occasions. However, the calibration varies with solar spectrum since the light meter and the pyranometer did not have the same spectral response. Therefore, the calibration figures were only approximate.

For these tests the top surface of the insulated base (made of polystyrene foam) of the test devices were painted black for absorption of energy from sunlight. Since the solar radiation changes with time and the ambient conditions may also change, two devices were tested at the same time to be able to compare their performances (picture can be seen in Figure 10). Room temperate tap water was used for these tests, and each device was filled with 1 liter of water. In this way the following studies were undertaken for heating test with solar radiation.

1. ***Test for air gap for single air layer:*** Two test devices with air gaps of 5 mm and 24 mm were tested simultaneously. It needs to be noted that the 24 mm air gap showed best result on the previous cooling test.
2. ***Test for air gap for single air layer and double air layer:*** One test device had a single air layer 24 mm thick and the other device had double air layer of thicknesses 24mm and 5 mm. Both the devices had double insulation (2 cm + 2 cm). This was again tested for the following two variations for the device with double air layer:
    a. 24 mm gap at the bottom, and 5 mm gap at the top
    b. 5 mm gap at the bottom, and 24 mm gap at the top
3. ***Tests for rings in the air gap:*** To see how the rings in the air layer affect the heat loss through convection, one device had many small rings made of polyethene sheets within the air gap while the other had no rings. In both the devices the air gap was 24 mm.

The temperature needed to be measured at six points of the test device. However, the laboratory had only a 4-channel digital thermometer (model: TM-947SD), which used thermocouples as sensors. For the two remaining, two thermistors were used as sensors and measured their resistances using a digital multimeter (Brand: ALDA, model: DT-830D). The digital multimeter measured resistances of the thermistors in ohm, which was converted to degrees using a calibration chart, made for each thermistor earlier. In order to convert the solar radiation measured in LUX to w/m^2 a calibration was made. (The first calibration was made in 2012, performed by my colleagues Yousuf Abu and Sharmin Zaman. The second and most recent calibration was performed on 1st of April 2013).

Figure 10 The performance of solar heating test with double insulation and single air gap compared with double air gap. Here the two test devices are set with thermometers and polyethene sheets on top ready for measurement.

3.2 Step 2: Improving the semi-permanent device

The observations from the Step 1 studies are now applied to modify the semi-permanent device described earlier. This will improve the semi-permanent device as far as practicable. Continued study of the water temperature under various sunshine conditions and microbiological studies of treated water (Table 5) were made to see if the device fulfills its purpose. During the Step 2 tests, microbiological analyses were performed as well.

Table 5 Device configuration used with the improved device in the Step 2 tests.

Type of test	Bottom insulation	Size	Air gap	Size	Weather
Solar heating	Double	5 cm	Single	24 mm	Sunshine and cloudiness
Microbiology	Double	5 cm	Single	24 mm	Sunshine

3.2.1 Water collection

Water used for microbiology testing was collected according to regulations from the department of Microbiology and performed with help from Sharmin Zaman in the microbiology lab. The contaminated water, which was used for this microbiology testing, was taken from a pond in the nearby area. To collect the water a bucket were filled with approximately 20 liter of pond water. The water was collected 15 cm below the surface to avoid the top layer of the pond. Since the surface of the pond had been exposed to the sun for a longer time it could have less bacteria. Besides, the top water also could contain particles of dirt, leafs and branches, etc. From this collected pond water, a reference sample of 50 ml was collected, to be able to compare the treated water with after testing. The reference sample was kept indoors and the rest of the pond water was placed in the shade while filling the water bag of the device.

3.2.2 Microbiology testing

All the samples were tested for bacteria following standard methods of the microbiology laboratory, see Appendix B. The reference sample was tested in the lab 1.5 hours after collection. After filling the water bag of the solar device with 11 liter of pond water, the thermometers, bamboo frame and top polyethene sheet were placed in position and the measurement could begin. A water sample was taken after 1 hour treatment in the sun and got tested after 30 min in the laboratory. Another water sample was taken after 2 hours treatment and was tested after 40 min in the laboratory. To obtain reliable results, the water samples should be tested within 1 hour of sampling (Zaman, Personal communication). All the water samples were cultured in medias of TSA (Tryptic Soy Agar) and S.Mac to study the quantity (counts/ml) of total aerobic bacteria and *E.coli*, respectively. The total aerobic bacteria and *E.coli* is only used as an indicator to determine the survival of microorganisms in the water.

Indicator organisms are often used to assess the drinking water quality of water (Svenskt Vatten AB, 2011). In this case total aerobic bacteria signifies the presence of any active microorganisms including *Coliforms* (WHO, 2001). Which is useful to indicate the efficiency of the treatment or process such as disinfection and will confirm if there still are microorganisms remaining in the water. Though this does not identify the spices of the pathogenic microorganisms or their source. Hence *E.coli,* the most appropriate group of coliforms due to its thermophile ability, is used to indicate microorganisms derived from faecal contamination (WHO, 2001). *E.coli* is not harmful by itself, but have similar behaviour to that of pathogenic bacteria such as *Salmonella* and *Shigella* (Livsmedelsverket, 2012).

3.2.3 Investigation of user-friendliness of device

The user friendliness of the initial device was investigated to accomplish a more convenient way for the user to use the device.

A criterion, which was taken in account, was that the device should be simple to use, especially while filling and emptying it with water. The device should be easy to store while not used, therefore not to heavy. It should be cost effective to make and easy to produce. Mostly it should fulfil the quality level of safe drinking water and be able to deliver water for a whole family. The construction of the device should be made from material that is cheap and convenient to get in the rural areas.

3.2.4 The pouring technique

One of the known problems with the initial device was that air bubbles were formed in the water bag as the water was poured into the device. Therefore it was necessary to find a way to pour water into the device that would minimize the air bubbles in the water bag. In order to avoid bubbles in the water bag, the following factors were evaluated as possibly effecting bubble entrapment:

1. Combining inlet/outlet or one inlet and one outlet
2. The pouring technique

   During these tests, water was poured into the water bag in two different ways:

   a. The first way was with a simple measuring cup and holding the tip of the water bag folded so that the water would enter little by little.
   b. The other way of pouring water was with a funnel and a silicone tube, which were placed at the opposite end of the device.
3. Adjusting the slope of the device while pouring in and out water
4. Shake the device while pouring water in and while taking water out

3.3 Comparing measured temperature with calculated temperature

It is crucial that drinking water is heated to at least 60 °C for a minimum of 30 minutes to obtain disinfection, see Section 2.5. Hence, it would be useful to be able to calculate the time needed to heat a specific water volume in the semi-permanent device, based on ambient air temperature and incoming solar radiation.

The change in water temperature in the semi-permanent device can be calculated from the laws of thermodynamics, considering both the energy transferred to the water volume from solar radiation and the energy loss by convective transfer of heat from the device surface into the surrounding air (Atkins. et al., 2010). Based on these facts a model can be developed that makes it possible to calculate the needed time duration of the water in the device.

To enable such a model, the measured values from the improved semi-permanent device in Step 2 were used as basis for the calibration. To facilitate the calibration, the following calculations are based on the assumption that the air gap above the water bag and the water bag itself can be considered as one closed system. Thus, the air gap is assumed have the same temperature and the same physical properties of the water bag. From here on, this enclosed system will be referred to as "the functional layer".

The energy needed, E_{tot}, to heat the water in the semi-permanent device depends on the relation between the energy generated by the absorbed incoming solar radiation, $E_{incoming}$, and the energy loss, E_{loss} due to flaws in construction of the device (Demïrel, 1995), see equation (2).

$$E_{tot} = E_{incoming} - E_{loss} \tag{2}$$

The incoming energy, equation (3), is based on the solar radiation, S, that is not reflected of the surface the top polyethene sheet, R, multiplied by the size of the exposed area of the device, $A = 0.558\, m^2$. The reflection is specific for the polyether material, and is approximately 5 % which gives $R = 0.05$ (Demïrel, 1995).

$$E_{incoming} = SA(1 - R) \tag{3}$$

The size of the energy loss depends partially on the upward energy loss from the exposed non-insulated area of the device, called convection, q_{conv}, but also by the vertical and downward losses due to flaws in the insulation, called conduction, q_{cond}, see equation (4).

$$E_{loss} = q_{conv} + q_{cond} \tag{4}$$

To simplify the calculation the loss due to conduction is neglected, where q_{cond} is considered to be zero.

The convective heat transfer, q_{conv}, is heat going from the device towards the surrounding air and can be estimated with equation (5). That is, a part of the absorbed energy stored as heat in the functional layer will be transferred to the surrounding air, thus heating it. The size of this loss depends on the exposed area of the device and the heat transfer coefficient for air, h_c, which signifies the ability of to absorb heat. This coefficient range from 5 to 25 w/m^2 °C for air, and is initially chosen as $h_c = 5w/m^2$ °C (Demïrel, 1995). Also, the difference in temperature between the functional layer and the surrounding air, ΔT_q, has to be taken into account.

$$q_{conv} = h_c A \Delta T_q \tag{5}$$

ΔT_q is calculated using the calculated temperature for a totally insulated system, T_{ins}, and the temperature of the surrounding air, T_{air}, see equation (6).

$$\Delta T_q = T_{ins} - T_{air} \tag{6}$$

T_{ins} is based on the initial measured temperature of the functional layer, T_m, and the increase in temperature of the functional layer as a result of incoming energy, ΔT, see equation (7).

$$T_{ins} = T_m + \Delta T \tag{7}$$

The energy needed to increase the temperature of the functional layer, that is ΔT, can be estimated by using equation (8). Since $E_{incoming}$ is assumed be all the incoming solar radiation, which is required to heat the water, $E_{incoming}$ could also be used to calculate ΔT as follows:

$$E_{incoming} = mC_p \Delta T \tag{8}$$

Where $E_{incoming}$ is the energy needed to heat up the water in the bag and thereby the functional layer to a specific temperature. The required energy is proportional to the mass, $m = 11408\ g$, of the water inside the device, multiplied by the specific heat capacity of the water, $C_{p(water)}$. The heat capacity for water has a specific value of $C_{p(water)} = 4.186$ J/g °C and signifies the ability for water to retain heat (Atkins. et al., 2010).

Equation (8) can be rewritten so that an expression for ΔT can be obtained. Hence, equation (6) can be calculated by using the expression for ΔT and equation (7).

$$\Delta T_q = T_{ins} - T_{air} = (T_m + E_{incoming}/mC_p) - T_{air} \tag{9}$$

Thus, the total estimation of E_{tot} from equation (2), can be achieved by using equation (3) and (4). To estimate E_{losses} in equation (4), ΔT_q from equation (9) were inserted which is shown in equation (10).

$$E_{tot} = E_{incoming} - E_{losses} = SA(1-R) - h_c A((T_m + Q/mC_p) - T_{air}) \tag{10}$$

The equations above forms the model and makes it achievable to predict the duration time needed to heat up the water in the device to 60 ºC, only by knowing the incoming solar radiation. To maintain these graphs of duration time, the model first needs to be calibrated using the measured values. This also made it possible to see how representative the measured temperatures, from the solar radiation test using the improved device, are by comparing them with the theoretical temperature achieved from the model in Excel. The graphs showing the required duration time are presented in Section 4.4.

4 RESULTS

In this part, the results from the tests are presented in the same order as they are mentioned in Section 3. Table 4 and 5 shows the tests that were actually performed, both with the test devices and the improved device. The results that are shown in the following graphs represents a mean value of the water temperature measured under the water bag of the device. Regarding the solar heating tests, are the most representative test is shown in this section, the rest can be seen in Appendix C.

4.1 Cooling tests with test devices

The measured water temperatures from cooling tests with test devices are shown below. In Figure 11, results from test with single insulation and air gap of 5, 15 and 24 mm are presented. The air gap of 24 mm maintains a higher temperature for both single and double insulation, which can be seen in Figures 11 and 12.

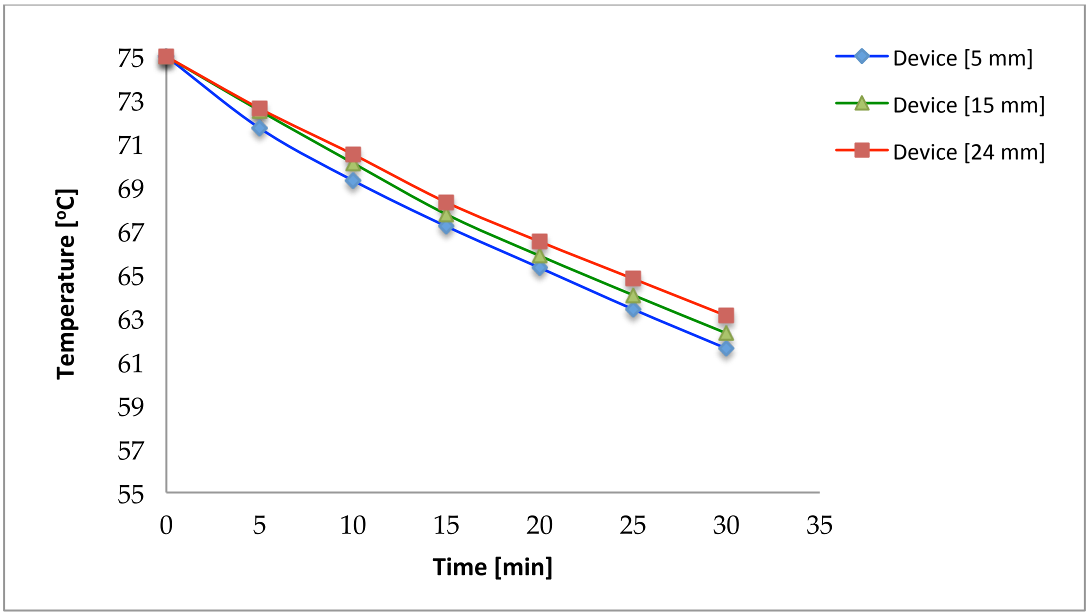

Figure 11 Water temperature from cooling tests with single insulation and single air gap of thicknesses 24 mm, 15 mm and 5 mm.

Considering the insulation, Figure 11 (single insulation) and Figure 12 (double insulation) indicate that the reduction in water temperature decreases with thicker insulation. A comparison with the same figures shows that the reduction rate of the water temperature, between the different thicknesses of single air gap, is less for 24 mm than with 5 or 15 mm. This means that the single air gap with a thickness of 24 mm, maintains the highest water temperature.

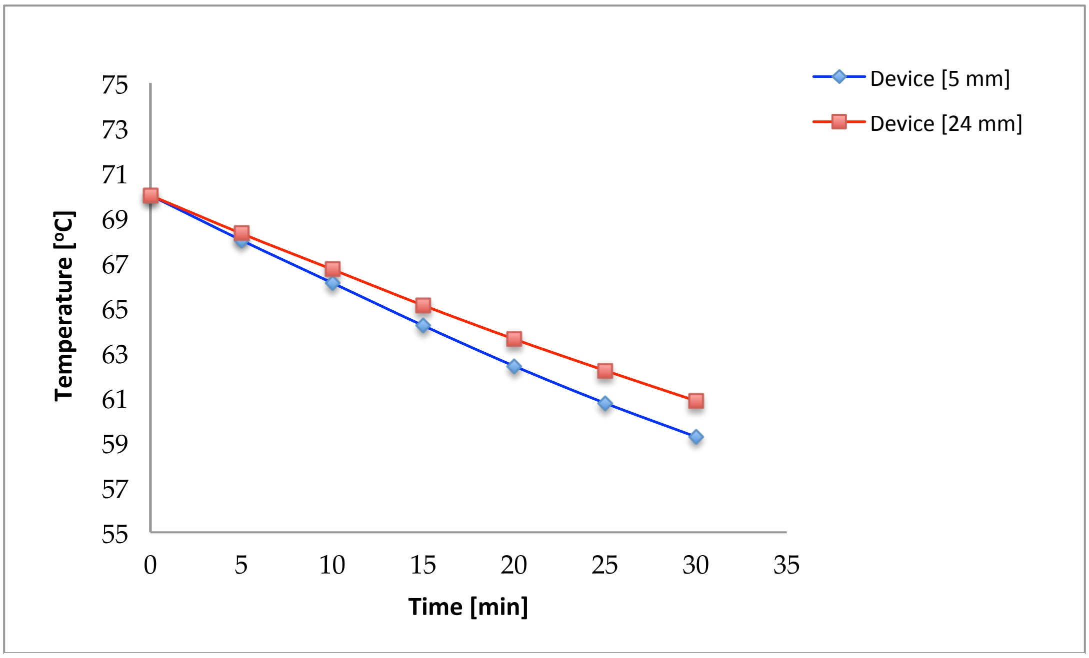

Figure 12 Water temperature from cooling tests for double insulation, single air gap with thicknesses 5 mm (blue line) and 24 mm (red line).

The difference between the tests in Figures 12 and 13, is that a single air gap is used in the test presented in Figure 12. In the test shown in Figure 13 two different types of double air gaps were used. However, both figures have double thickness of insulation.

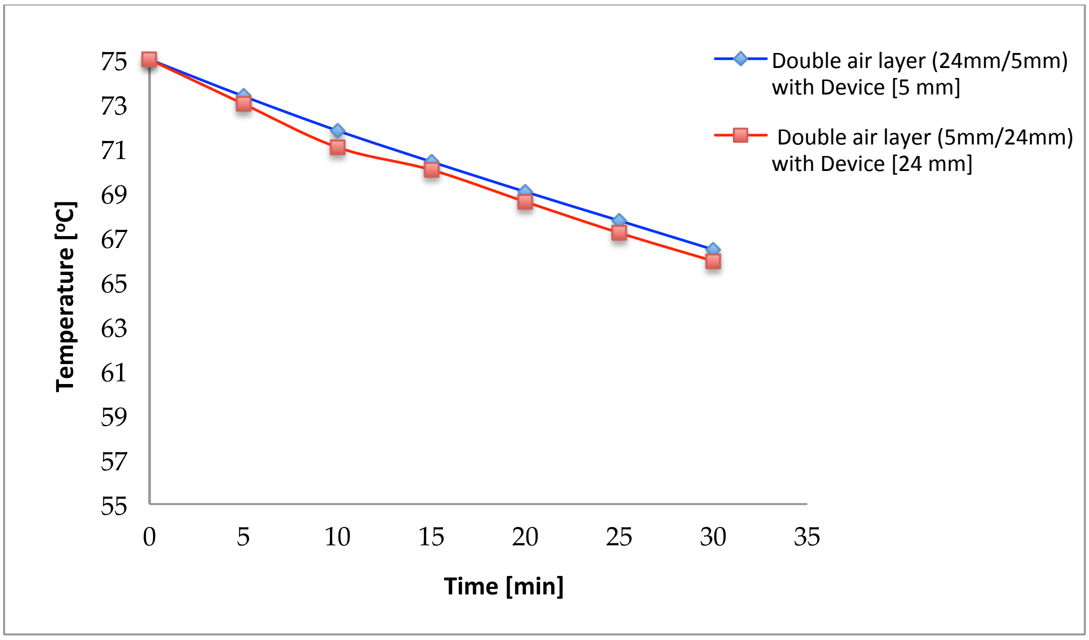

Figure 13 Water temperature from cooling tests for double insulation, double air gap with thickness 24/5mm (blue line) and 5/24 mm (red line). Where the first mention thickness of air gap is above and the other is under.

4.2 Solar heating tests with test devices

Measured water temperature for solar heating tests, using the test devices, are shown below for single insulation with single air gaps of 5 mm and 24 mm (Figure 14). As can be seen a 24 mm layer retains heat better for solar heating treatment. Using double air gap with 5/24mm and 24/5 mm did not give higher temperatures than the single air gap of 24 mm (Figures 15 and 16). A clear correlation between water temperature and solar radiation is observed: when the solar irradiation is strong the water temperature increases.

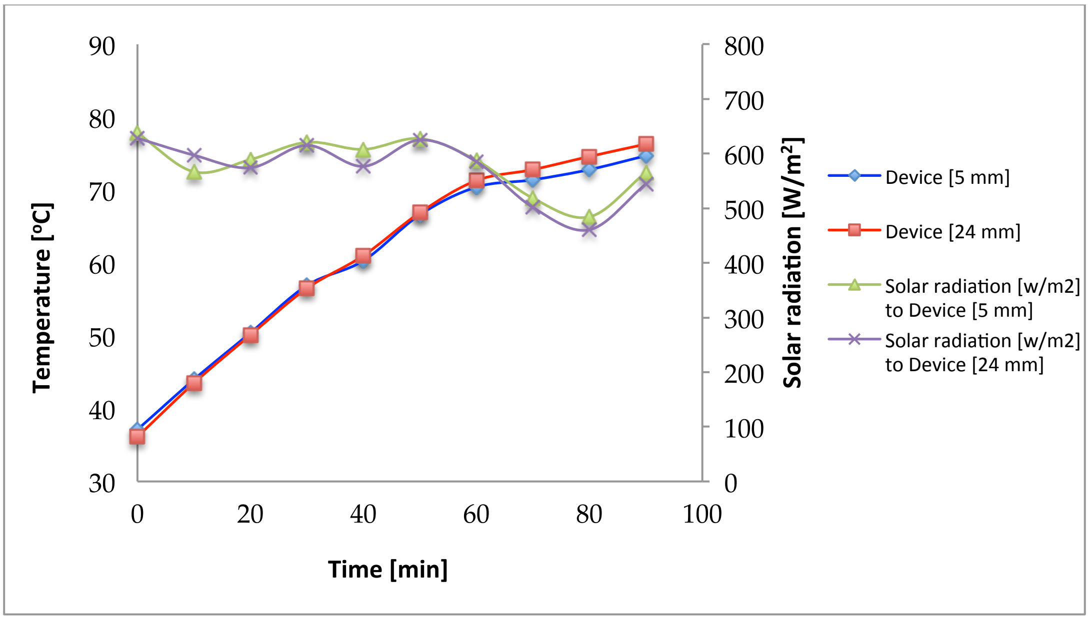

Figure 14 Water temperature and solar radiation from solar heating tests for single air gap with thicknesses 24 mm and 5 mm, using single insulation.

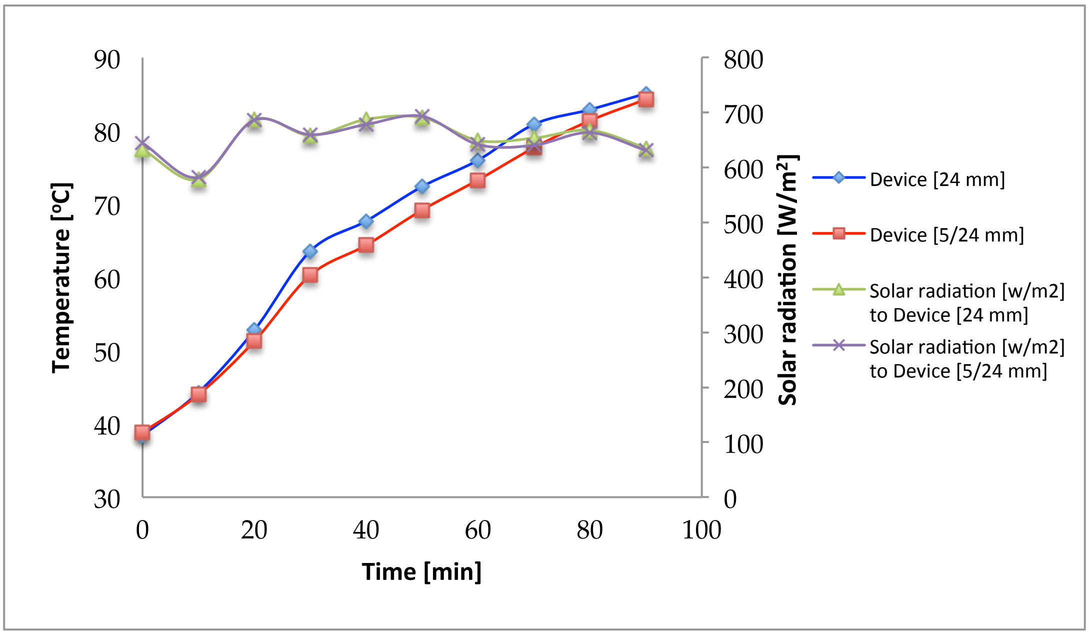

Figure 15 Water temperature and solar radiation from solar heating tests for single air gap with thickness 24 mm compared with double air gap with layers of 5/24 mm, using double insulation.

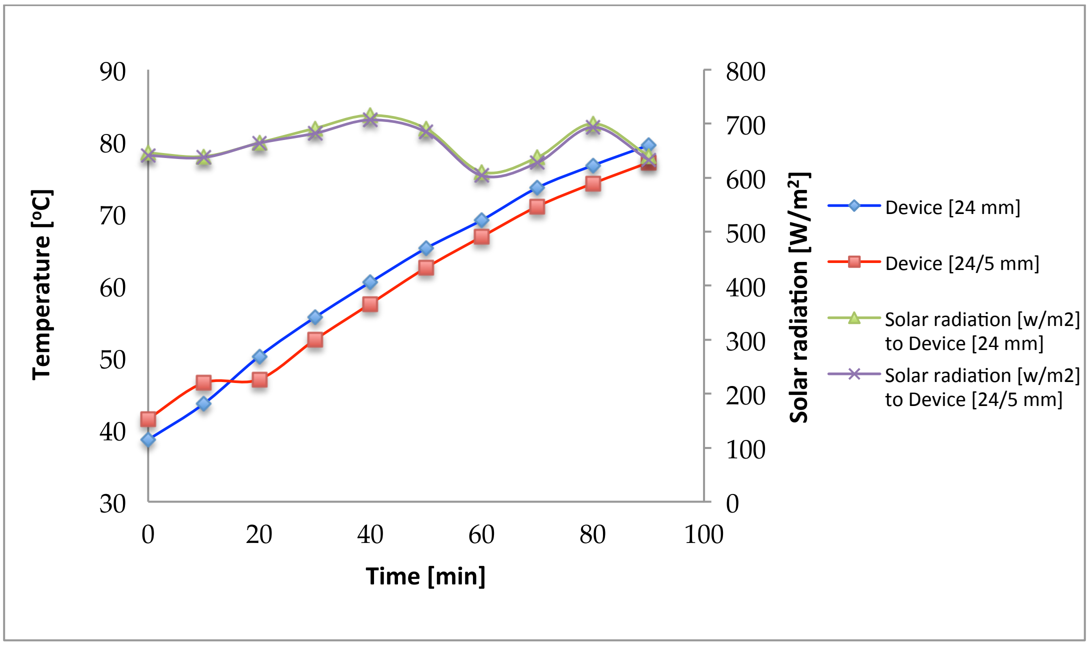

Figure 16 Water temperature and solar radiation from solar heating tests for single air gap with thickness 24 mm compared with double air gap with layers of 24/5 mm using double insulation.

4.3 Improved device

Improvement of the device involved the thickness of the insulation and the thickness of the air gap. The thickness of insulation at the base was enhanced to 5 cm instead of 2.5 cm, see Figure 17. Regarding the air gap, a double air gap is used, even if the results from the test devices did not directly indicate a higher temperature. The results of the solar heating tests with varied weather are shown in Figures 18 to 22. The temperature at various positions in the device during the solar heating tests can be seen in Figures 18 and 19, where the main difference is observed in the water temperature and above the rings (see Figure 20). During cloudiness the temperature fluctuates and does not reach the high temperatures as during sunshine.

Figure 17 Shows the improved device of the solar water pasteuriser, here on a bamboo frame placed on a table.

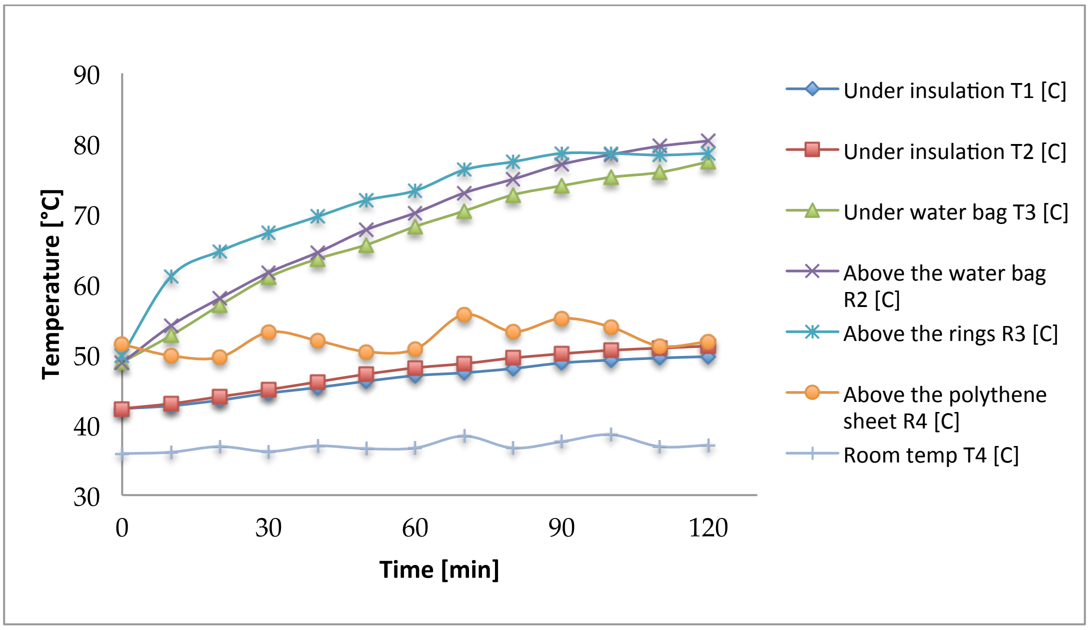

Figure 18 Solar heating test using the improved device during clear sunshine.

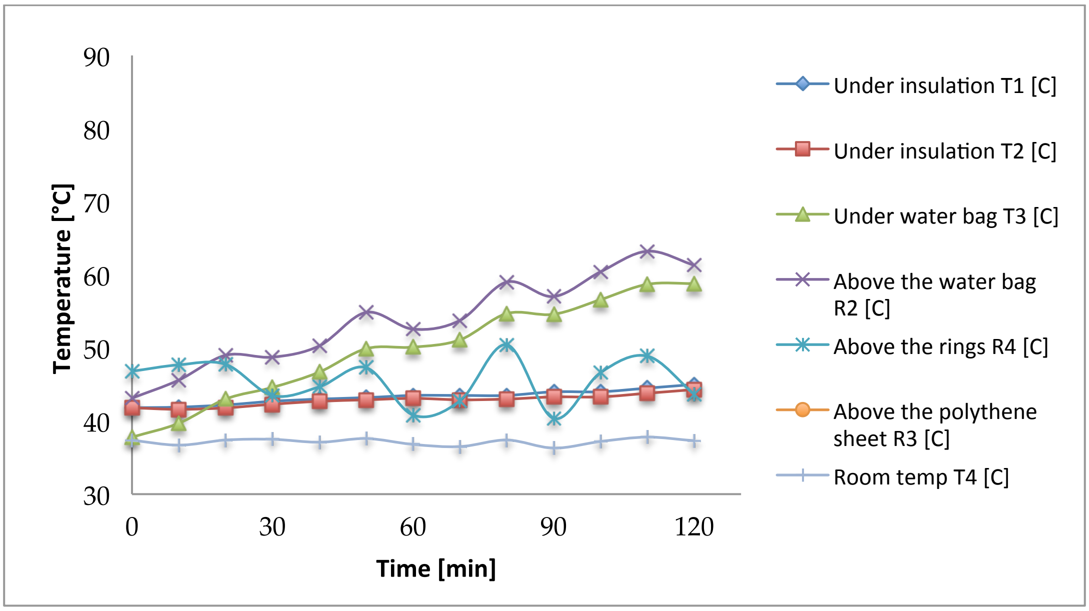

Figure 19 Solar heating test using the improved device during periodic cloudiness.

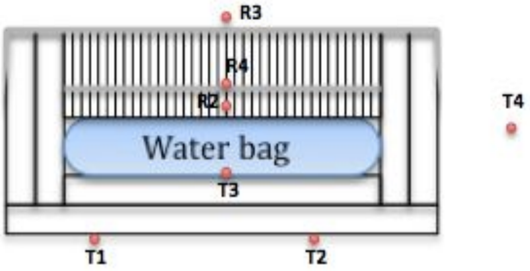

Figure 20 The different sections in the improved device, the red dots shows where the thermometers and thermistors were placed according to figure 18 and 19.

A comparison between the measured water temperature and the calculated temperature, see Section 3.3, is presented in Figures 21 and 22. The calculated temperature (red line) appears to correspond well with the measured temperature (purple dots). The temperature without heat loss (blue line) can be seen in the same figures and increases almost linearly compared with the measured temperature. Solar radiation is presented (light green curve) on its own axis in [W/m^2].

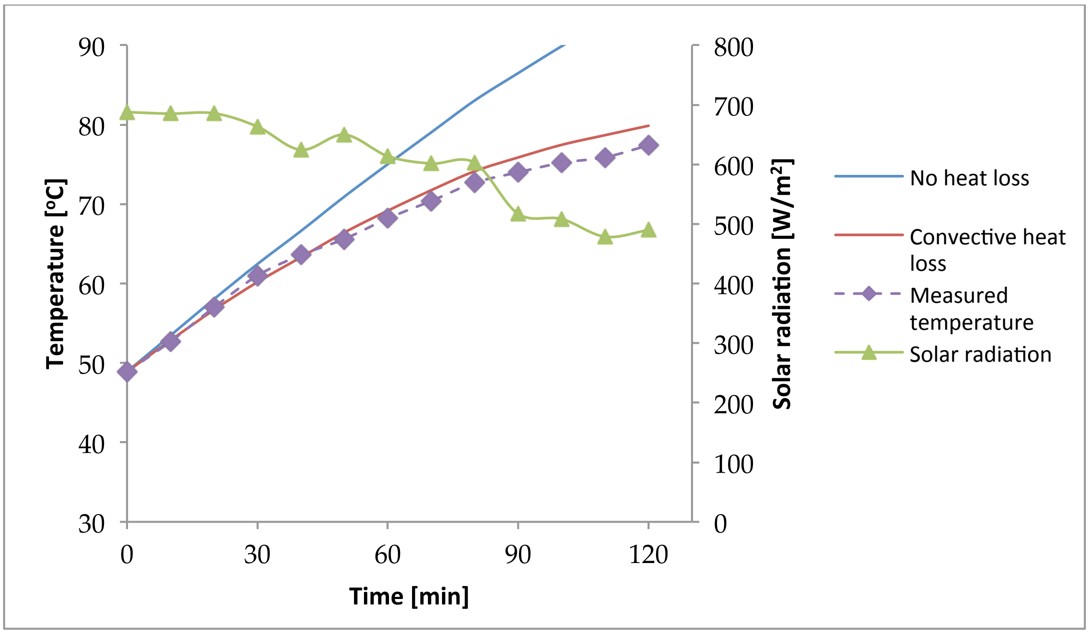

Figure 21 Comparison of water temperature under water bag with theoretical temperature, using $\boldsymbol{h_c} = \mathbf{5}\ \boldsymbol{w/m^2\ °C}$, according to solar radiation on a clear sunny day.

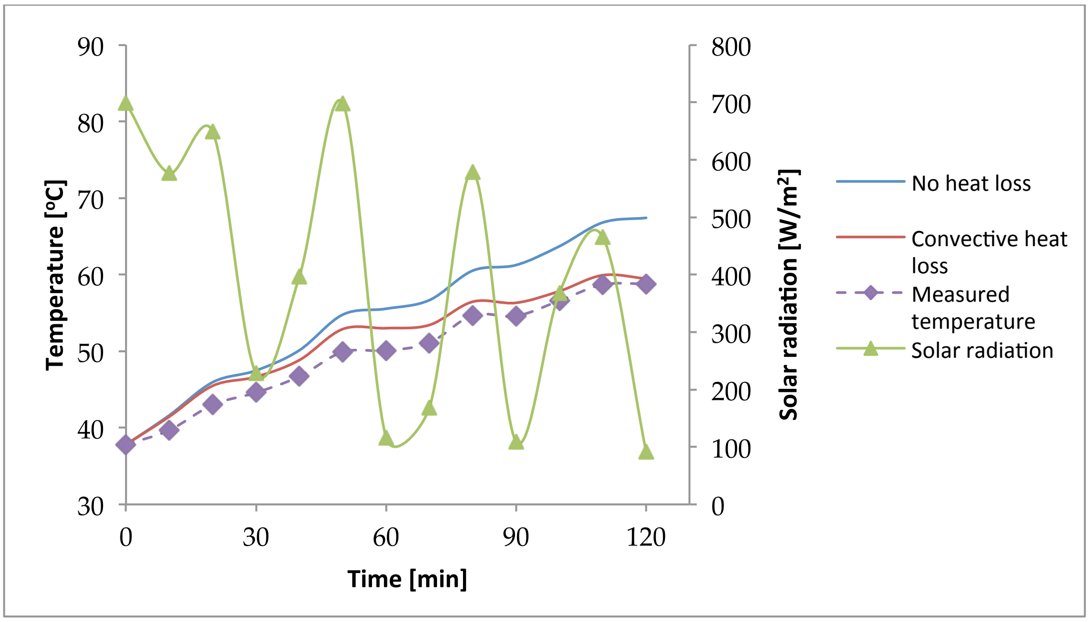

Figure 22 Comparison of water temperature under water bag with theoretical temperature, using $\boldsymbol{h_c} = \mathbf{5}\ \boldsymbol{w/m^2\ °C}$, according to solar radiation on a cloudy day.

4.3.1 Microbiology studies

The result of using the semi permanent device to treat water taken from a pond in the nearby area of the institute is shown in Figure 23, where the measured water temperature also has been compared with the theoretical temperature. After 1 hour the temperature of about 61.4 °C was obtained, and the temperature of 75.4 °C was achieved after 2 hours. The microbiological studies on samples taken at the two intervals above showed total destruction of E-coli after 1 hour, while all forms of bacteria were destroyed after 2 hours treatment in the sun, which can be seen in Table 6.

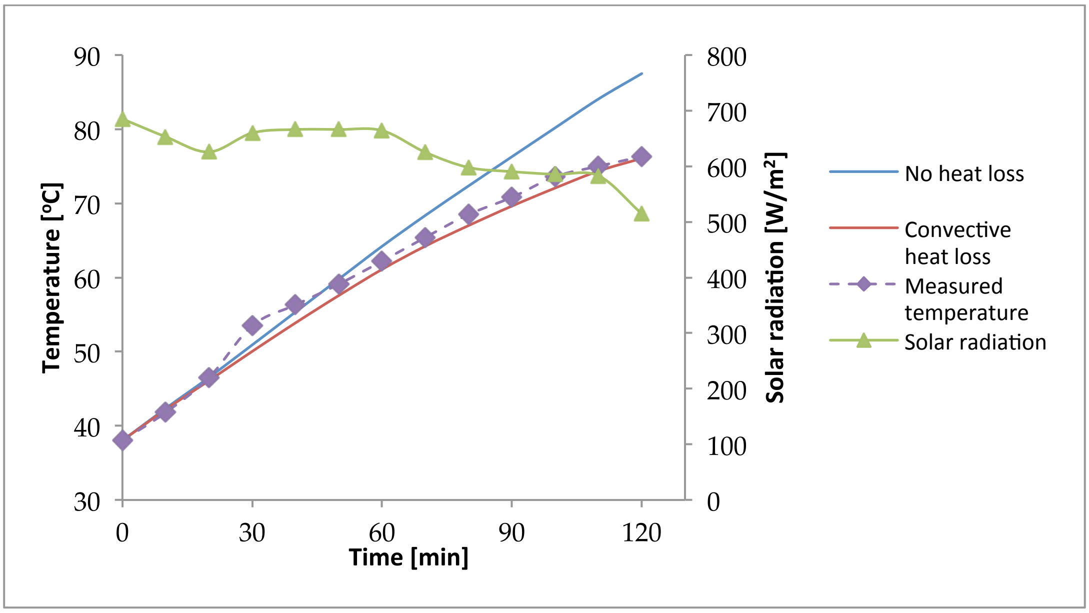

Figure 23 Comparison of water temperature under water bag with theoretical temperature, using $\boldsymbol{h_c} = 5\ \boldsymbol{w/m^2\ °C}$, according to solar radiation using contaminated water. To see how well they comply each other.

Table 6 The results of microbiological test showing the number of detected microorganism, average water temperature and pH in the reference test, and the water samples after 1 and 2 hours compared with drinking water criteria for safe drinking water (WHO, 2011).

Media	**Reference [ml]**	**After 1 hr [ml]**	**After 2 hrs [ml]**	**Drinking water criteria (WHO, 2011)**
TSA (*Tot. aerobic*) [counts/100 ml]	1060	50	0	0
S.Mac (*E.coli*) [counts/100 ml]	210	0	0	0
Average water temp, °C	30.80	61.40	75.35	25.00
pH	8.52	8.59	8.60	8-9

4.3.2 The usage and cost of the device

The semi-permanent device can hold about 11 liter of water and according to WHO guidelines for drinking water quality the amount of drinking water needed for one person is 2 liter/day (WHO, 2011). This will provide 2.2 liter per person, for a family with 5 members.

When estimating the cost for the device the total cost would be 390 taka, Bangladesh currency and about 5 US dollar. The separate cost for each material can be found in Table 7.

Table 7 Shows the cost estimation of the raw material for achieving the improved semi-permanent device. This is only an estimation and displays the cost in taka, Bangladesh currency and the total cost in US dollar (Rabbani, Personal communication).

Item	Material	Quantity	Cost [Tk]	Cost [US dollar]
1	Polystyrene foam (PF)	1.50x1.10 m	170	
2	Adhesive tape		10	
3	Black cloth	1	20	
4	Polyethene bag	1	45	
5	Clear PVC sheet	1	65	
6	Bamboo (Muli) frame	1	20	
7	Glue, picks, manual		10	
8	Carton, for package	1	50	
	Total cost		**390**	**5**

4.3.3 The pouring technique

Previous knowledge, from the Dhaka University group, showed that the construction of the device with one inlet and one outlet was more difficult to fill and empty. Hence, the water bag for the improved device received a water bag with combined in- and outlet.

The test showed that the easiest way to fill and empty the water bag with water, for a combined in- and outlet, was by using a simple measuring cup and holding the tip of the water bag folded. Then the water pours into the device little by little and the amount of air bubbles in the water was reduced. When emptying the water the devices was tilted and water could flow out rapidly into a bucket. Filling and emptying the device could be made on your own.

The other way of pouring water was with a funnel and a silicone tube, which were places in the opposite end of the device. This technique increased the air bubbles and it was more difficult to poor water into the bag. This was also problematic to manage on your own, needed to be two persons.

Shaking the device at the same time as pouring in water to the water bag was most difficult and it also increased the formation of air bubbles. This definitely needs to be done by two persons or more.

4.3.4 Fabrication of the improved device

The improved device was made out of Polystyrene foam (PF) with a base of the size 0.90×0.62 m with raised edges. The surface of the base was painted black and the insulation thickness was 5 cm. A transparent polyethene water bag was made to fill the entire black area to give a water layer depth of about 20 mm, holding about 11 litres of water. Two enclosed air layers (a top air layer of 20 mm and the one below had an air gap of 24 mm) were created above using transparent PVC sheets, stretched in a bamboo frame, shown in Figure 24.

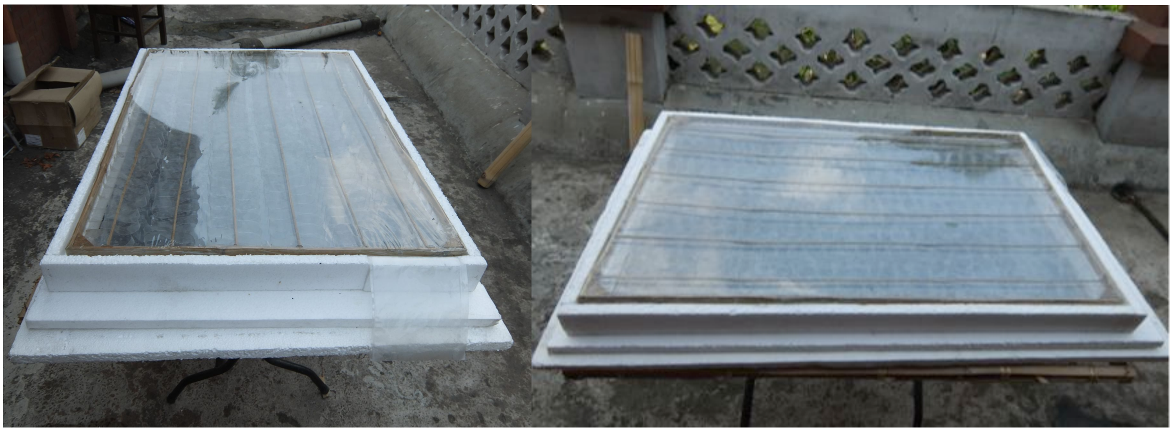

Figure 24 The new improved device on the rooftop of the department where the solar heating tests took place.

4.4 Comparing measured temperature with calculated temperature

The model shows that solar radiation between 100-200 W/m^2 will not reach a water temperature of 60ºC when the air temperature and initial water temperature of 25-40ºC. In Figures 25 and 26 the graphs for predicting the time needed to maintain safe drinking water, with the initial water temperature and air temperature of 25ºC and 35ºC. When the air temperature is 25ºC the least solar radiation needed, to reach a water temperature of 60ºC, is 390 W/m^2.

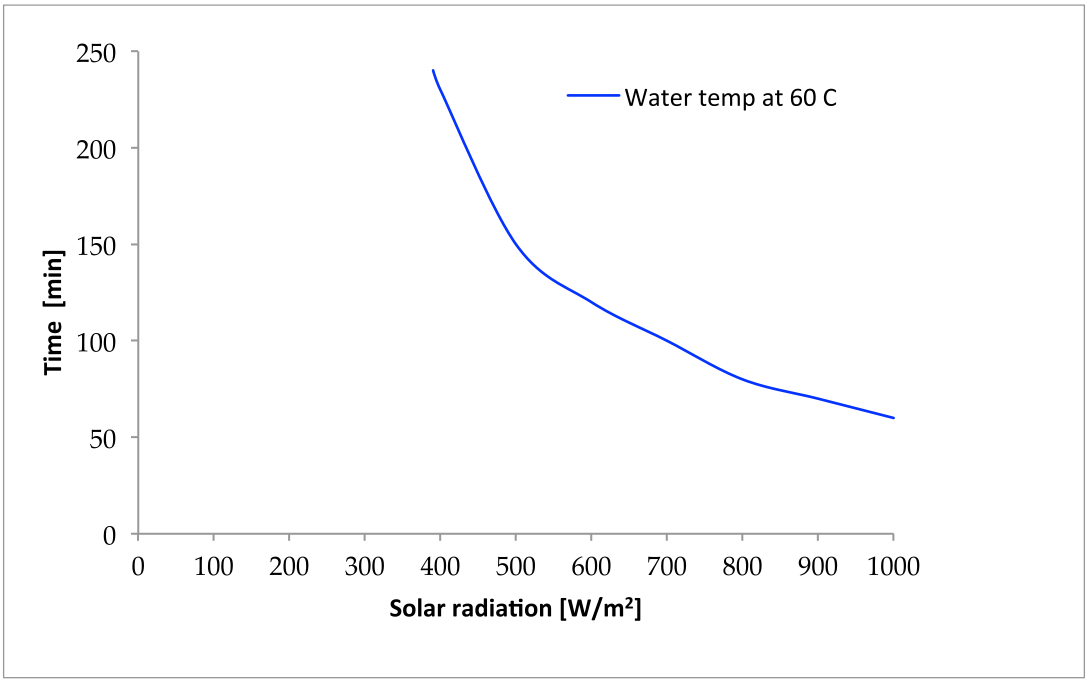

Figure 25 Graph shows the required solar radiation and time to reach the water temperature of 60 °C, when the air temperature and initial water temperature is 25 °C.

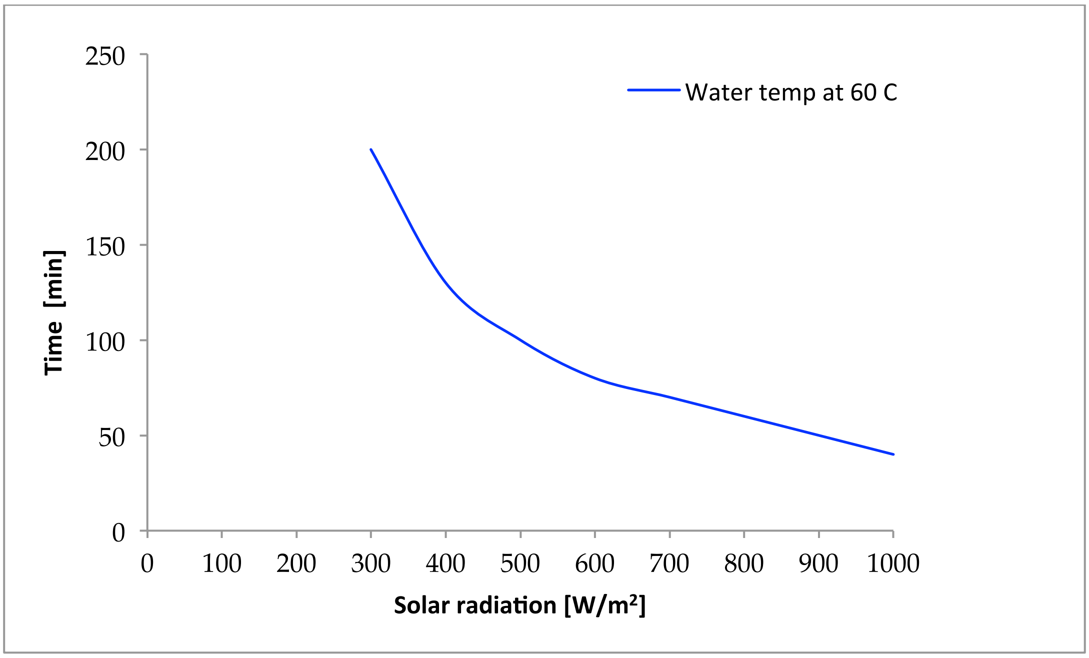

Figure 26 Graph shows the required solar radiation and time to reach the water temperature of 60 °C, when the air temperature and initial water temperature is 35 °C.

5 DISCUSSION

In this study two different test devices for solar water pasteurisation were used to determine the factors needed to improve the semi-permanent device made earlier. The results from the experiments with test devices indicated which factors are important to consider when constructing the new improved device: the factors considered in this study were temperature, time, solar radiation, user-friendliness and cost. Two of the most significant factors are the solar radiation and time to obtain a safe water quality. Since insulation and air gap thickness, as well as duration of time in the sun, have a major impact on temperature, these have been the main focus during the study. Solar radiation is the general source of heat, and is necessary to achieve an adequate water treatment, but if the insulation of the device is lacking, the heat loss would be considerable and the rate of temperature increase will be reduced significantly. The discussion is divided in the same order as the results were presented. Further study, improvement, remaining challenges and possibilities for continued work will also be discussed in this section.

5.1 Cooling tests with test devices

The air gap of 24 mm retained heat better during the cooling tests, which can be seen in Figures 11 and 12. The difference in temperature between the air gaps (5 mm and 24 mm) became even more noticeable with double insulation, where a larger air gap maintained a higher water temperature. Regarding insulation, double thickness of 5 cm appeared to be an optimum value since thicker insulation kept heat better. Another layer of polystyrene foam was not tested, because it would not have been economical regarding the cost for manufacturing the device, especially when the double insulation maintained the required water temperature to achieve safe drinking water.

5.2 Solar heating tests with test devices

The result from the solar heating test also indicated that an air gap of 24 mm gains higher water temperature. Double thickness of insulation showed capacity of retaining the solar energy longer and thus higher water temperature was carried out. As well as for the cooling test another layer of polystyrene foam would not have been beneficial since the necessary water temperature was maintained during each test.

Regarding the result from the tests comparing single and double air gap, using double insulation, showed that the single air gap of 24 mm obtained a higher water temperature but the difference was insignificant. Theoretically the temperature would increase with a double air gap due to convection, which is why the test result could seem unreliable. In this respect, a majority of the tests showed the same as for Figures 15 and 16, but a few of them showed the opposite see Appendix C. When estimating the source of errors several factors could be the reason. One of the greatest difficulties while performing the solar radiation test was to maintain the same initial temperature among all tests, since the outdoor temperature was not as constant as the indoor temperature. The preparation time in the sun before starting the tests varied slightly each time, which also affected the starting temperature of the water. Besides the variation in time for preparation, other impacts such as the initial temperature of the table, where the device was placed during the test, fluctuated due to the solar radiation. These issues could explain why the results differed and to make the solar heating tests comparable the most representative result considering solar radiation and initial water temperature, was therefore shown. Calculating a significant middle value of the tests taken during such various weather conditions would have given an uncertain result.

Further solar radiation tests should be done to investigate if theory is consistent with the new tests.

5.3 Improved device

The improved device was developed based on the results from the test devices. The same design was used as the original device but the thickness of insulation was increased at the bottom and around the sides of the device. Double insulation was applied to minimize the heat loss, in order to maintain the required temperature for optimal treatment. Considering the air gap, a double air gap was inserted since the result from the solar heating tests only showed an insignificant difference. As the time were limited for further testing, double air gap of 20/24 mm were applied to the improve device.

The results from the solar heating tests with the improved device have been replicated in a model, which is based on the solar radiation and convective heat loss from the device. The model indicates that the measured water temperature corresponds well with the calculated water temperature. That is, good fit of the model to the measured data suggests that the consideration of solar radiation and convective losses is sufficient to simulate the heating process. The model was also used to calculate useful graphs for determine the time of duration at a certain solar radiation level to know when the water is safe to drink.

5.3.1 Microbiology studies

The microbiology studies show that the improved semi-permanent low cost device can purify pond water to safe drinking water levels. To extend the study further, more microbiology samples should be taken from rivers and other ponds in rural areas. The pond near the institute is not entirely representative of the rural areas and the day when the test was made the sun had pre-heated the water in the pond. This might have affected the water and reduced pathogens already before treatment with the semi permanent device. This could be the reason for the low value of pathogens in the reference samples.

5.3.2 The usage and cost of the device

On a typical day of clear sunshine in Bangladesh (during March to July), when the solar radiation is the strongest, the device could be able to disinfect three water volumes per day. This will give 33 liter of water in late spring and during summer. In the winter (December to February) when the solar radiation is less strong two water volumes per day will be possible to obtain, which provides 22 liter of water. To achieve safe drinking water during the months with less sunshine, a rainwater collector could be used to complement the device. This is another method from the Dhaka University group that collects the daily rainwater by using bamboo sticks, polyethene sheet or cloth and a bucket. The polyethene sheet or cloth is attached in the shape of a funnel on four bamboo sticks that are plugged into the ground, see Figure 27. This will enable collection of clean rainwater, which is suitable to drinking directly or can be stored and is a suitable complement to the solar water pasteuriser.

The costs per liter water using the solar water pasteuriser would be 35.50 taka or 0.45 US dollar. By comparing the price per liter with the other methods in Table 3, the semi-permanent device has the lowest price regarding the time of treatment and how much drinking water you can achieve. The comparison was made with SODIS since SOLVATTEN needs to be distributed and cannot be bought or built on your own. However SOLVATTEN has the most effective time treatment of 11 liter water on 105 min, compared with 11 liter treated water on 120 min with the Dhaka University method, see Table 3.

Figure 27 The construction of the rainwater collector with polyethene sheet, bamboo sticks and a bucket.

5.3.3 The pouring technique

Investigation of the pouring technique was made to find out the easiest way to fill and empty the water bag in the device. The best option occurred to be a combined in- and outlet, which also were most sufficiently to avoid formation of air bubbles. None of the other options of pouring technique did fulfil these goals; hence I recommend using a combined in- and outlet.

5.3.4 Alternative methods for solar pasteurisation

Considering the comparison between the different solar pasteurisation methods that was presented in Table 3, the use of each one of these methods depends on where in the world you are, the cultural aspects and conditions that occurs in this specific area. But it also depends on the quality of the water from the beginning, in some cases high amount of microorganisms and turbidity could present a huge risk by using the methods for a longer time than intended or differently than the instructions. Thus these aspects should be taken into account when deciding which method to use for a specific area. All methods are helpful and generate drinkable water, but in certain case some methods suites better than others.

5.4 Further study and improvement

The study intended to develop a device, which can be used in the rural areas of Bangladesh. Since the test in this study was performed in Dhaka and not in the rural areas, using a table as the base of the device, more tests in rural areas of Bangladesh must be made in order to fulfil the objective of the study. Further tests, especially regarding microbiology, should be implemented, taken from various watercourses such as rivers, ponds and lakes in rural areas. This since the solar radiation probably is stronger in rural areas due to less traffic pollution and could therefore obtain a higher water temperature faster and for longer time. To complete the study more tests should also be performed with the device using a base constructed of materials that exist in the rural areas, for instance on a bed of mud, straw and grass to provide required insulation. The user-friendliness of the device would be interesting to monitor, when families actually are using it. Paraffin wax could also be used as an indicator for the device, in the same way as SODIS are instructing, but needs to be tested to assure safe drinking water quality.

Taste and turbidity of the water have not been investigated in this study, which are two other important aspects to take in consideration. Since turbidity have a major impact on the water quality and could impair the efficacy of the treatment process this needs to be examine. High turbidity restrains the solar radiation from heating up the water and obstructs the disinfecting UV-light. By using a cloth or local seeds, called Moringa (“Sajna” in Bangla), the turbidity and larger microorganisms such as protozoa could be filtered. The seeds will help suspended solids of any type to settle as sediment. The taste of the treated water should also be tested, to see if the water taste different after treatment with the device.

5.5 Remaining challenges and possibilities for continues work

The major challenge is to reach out and promote this solution of water pasteurisation treatment in rural areas. An attempt has been to inform about the device and other solutions from the Dhaka University group through television. The regional TV-channel, Somoy Television, made a program about the different solutions that the Dhaka University group has developed and presented how they can be arranged at home. After the TV-program was broadcasted, several people contacted Professor Rabbani and showed interest in learning how to construct the device.

Another important challenge is to make these solutions available on a larger scale for people in rural areas within short time. To see weather NGO's could be interested in funding local entrepreneurs in rural villages, to start manufacturing the devices and distributing them in the surrounding area, BRAC was contacted. BRAC, Bangladesh Rural Advancement Committee, is one of the most widespread NGO's in Bangladesh. So far this is only a suggestion and Professor Rabbani has sent a proposal to BRAC for an entrepreneurial model of the manufacturing and distribution of a product package with both the solar water pasteuriser and the rainwater collector. The local entrepreneurs could also help install and repair the solar water pasteuriser or rainwater collector if needed. At the moment pilot tests of the device is on-going in nearby villages outside of Dhaka and it will be interesting to see the outcome of these tests. The Dhaka University group has also started to make an instruction video of how to use the device, so the project is still moving forward.

Crucial to keep in mind regarding the surface water is that chemicals cannot be removed through solar water pasteurisation. Rivers or lakes nearby industrial areas could be polluted with pesticides and water collected in lowlands could contain pesticide contamination from farmlands nearby. Thus, before using surface water from watercourses close to farmlands or industries, chemical tests should be performed to ensure that the water is free of chemicals such as pesticides.

6 CONCLUSION

The objective of this study was to investigate and optimize a low cost semi-permanent device based on solar water pasteurisation that can deliver safe drinking water to people in rural areas of Bangladesh. Even though, further testing of the semi-permanent device in the rural areas is required to complete the study, this project reveals some interesting results.

The investigations showed that the most important factors to enable disinfection, that is, obtaining 60 °C temperature for 30 minutes, were incoming solar radiation and time. During the project period, this goal was achieved for each day. However, other methods might be necessary to complement the semi-permanent device during cloudy and cold conditions, for example throughout the monsoon period.

Since the water temperature is crucial to achieve safe drinking water, it was concluded that improved insulation to a cost-beneficial level is of high importance. However, the most significant result was that the larger thickness of air gap was more efficient than the smaller to maintain heat.

This is a solution for rural areas; subsequently the user friendliness is of high importance. A combined in- and outlet turned out to be the easiest way to fill and empty the water bag in the device. This method was also the most efficient way to avoid formation of air bubbles.

The results from the microbiology tests in this study indicated that the semi-permanent device is capable of terminating water-borne diarrheal pathogens. Thus, the objective of this project was fulfilled. It was found that the semi-permanent device can achieve safe drinking water at a low cost and has user-friendliness at level that can be used in rural areas.

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APPENDIX A

MANUAL: How to construct a basic method (Rabbani, 2002)

1. Spread out around 1 1/2 kg hay (paddy straw or grass straw) on the ground, the thickness of hay should at least be 10 cm (Figure 28). The hay bed will prevent heat from escaping below.

2. Take a bamboo tray (about 75 cm in diameter) and place it on the bed of hay. This type of tray is cheap and is widely used in Bangladesh villages for drying food items in the sun. Paint the inside of the tray black using any common paint. Alternatively lay a blackened paper or cloth on the bottom of the tray.

3. Use four transparent and thick polyethene sheets each at least a bit larger than the diameter of the tray. Spread the first polyethene sheet over the tray and pour water to a depth not more than 2 cm. The water will heat up faster if the depth is less and ensure that the water depth is the same on all sides by adjusting the hay below.

4. Spread the second polyethene sheet so that it touches the water surface everywhere. If there is any air bubble, remove it to the sides with the fingers. Otherwise water vapour will condense at the bubble and will block the sunshine.

5. Place a few straws of hay on top of the second sheet and spread the third polyethene sheet on top. Now there is a layer of air between these two sheets to prevent the escape of heat upwards, and the strands of straw are used to ensure that the air gap will proceed. Do not put too many straws, as these will block the sunshine.

6. Place some straws of hay on top of the third polyethene sheet, same as previous step. Place the fourth and the final sheet on top. Again place some straw on top to prevent the third and the forth sheets from touching.

7. Keep all the sheets stretched by putting some weights (e.g. bricks) on the polyethene sheets outside of the tray. If more weight is necessary, make a ring out of a thick rope (of straw) or jute and use as weight to press down the sheets.

8. After being exposed in the sun for 1 ½ to 2 hours during the day, the water will reach a temperature above 60 °C and the pathogens is destroyed. For collecting the clean water remove the top three polyethene sheets and gather the edges together of the first sheet. Now pour the treated water carefully to a storage pitcher or water tank. Make sure that your hands do not touch the water, nor the fourth sheet that holds the water, particularly in the area through which water will be poured out. Our hands always contain some germs and could easily contaminate the treated water. The treated water will be about 5 liters.

The destruction of diarrhoeal pathogens for this method was confirmed through microbiological tests.

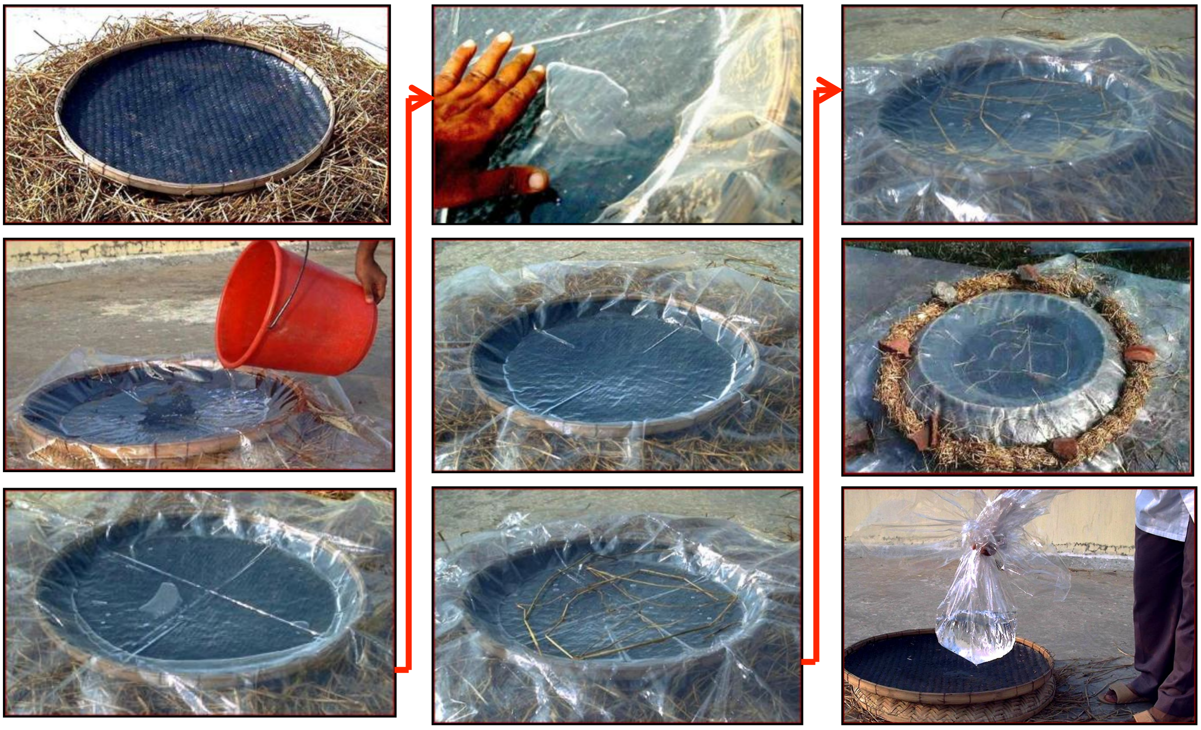

Figure 28 Shows the steps 1-8 of how to construct a basic method to treat water through solar water pasteurisation.

Complement to the basic method

A complement to the basic method is to use large transparent plastic bags, this facilitates the process and makes it easier to preform. Just fill one third of the bag with water and place it on the black painted tray with the open end placed over the raised edge of the tray as shown in Figure 29. Then use two polyethene sheets as before and to create the two enclosed air layers on the top, place a few straws in between (Figure 30).

Figure 29 A Complement for the basic methods is to use a transparent plastic bags bag with water and lay it down on the black painted tray with the open end placed over the raised edge of the tray.

Figure 30 Place two polyethene sheets on top, as before and to create the two enclosed air layers on the top, place a few straws in between the sheets. Then expose it in the sun for about 1 ½ to 2 hours.

If bamboo tray is not available, anything, which is flat and rigid, can be used. Or a black sweater could be used, as in Figure 31. Polypropylene (PP) is more transparent than polyethene and does not become soft when heated, so is better than polyethene if it is possible to get (Rabbani, 1992).

Figure 31 An alternative method, using a black sweater and a polyethene bag where the water is exposed in the sunlight.

APPENDIX B

Microbiology test

The water that is used in the microbiology test was taken from a pond nearby the institution and then solar pasteurisation treatment with the improved device was performed in Dhaka, Bangladesh in April on a clear and sunny day. The following steps describes how the microbiology test was accomplished, this applies to both the reference and the two water samples:

- Take 100 μ liter water from each test with a pipette (volume 20~200 μ liter).
- Spread it over the media, in total 4 medias of each sort of test, 2 of TSA (Total arobic) and 2 of S.Mac (E.coli) (Figure 32).
- Incubate the medias for 18-24 h in a Friocell at 37 °C. (It takes at least 18 hours to get full bacteria growth).
- Analyse the medias after incubation by counting the bacteria, see Figure 33.

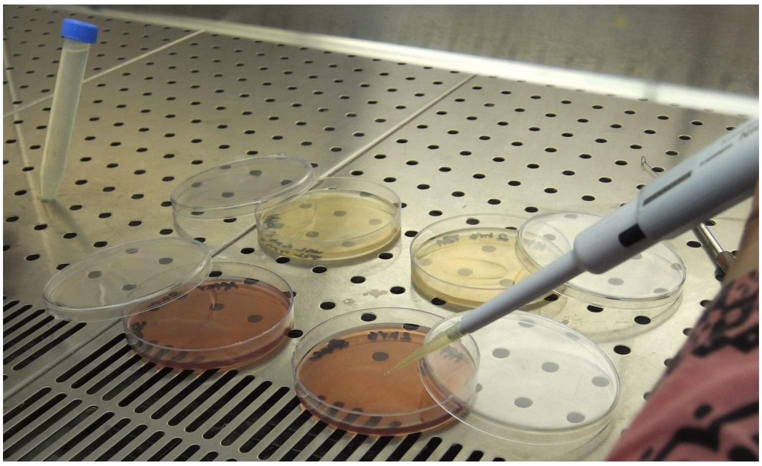

Figure 32 Shows the pipette with 100 μ liter water and how it is spread out over the 4 medias.

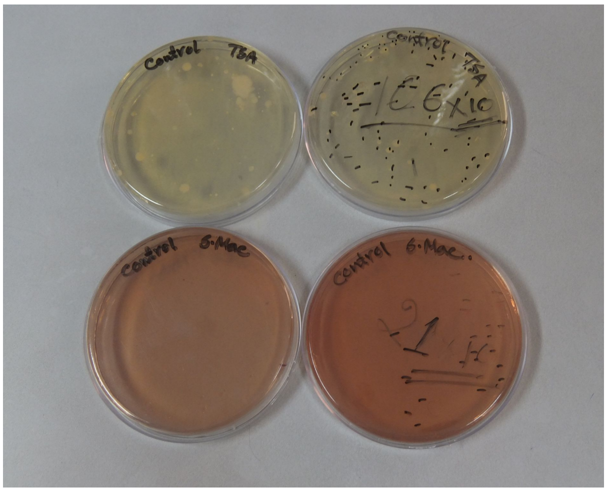

Figure 33 The medias after incubation in the Friocell and the bacteria is now visible for counting.

APPENDIX C

Solar heating tests with test devices

The result from all solar heating tests with single air layer of 24 mm and double air layer of 24/5 mm. Both test devices has double insulation and the temperature from different sections (which can be seen in Figure 20, Section 3.3) was measured. The result can be seen in Figures 34 to 41.

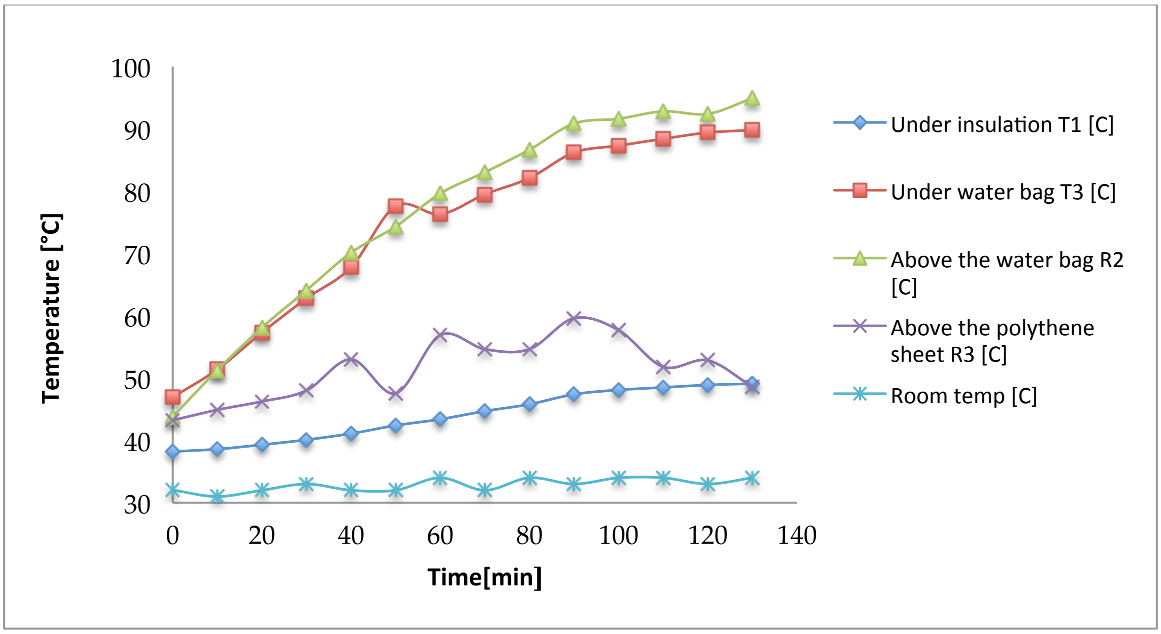

Figure 34 Solar radiation test 1: Shows the temperature in different positions of the test device with single air gap, thickness 24 mm using double insulation.

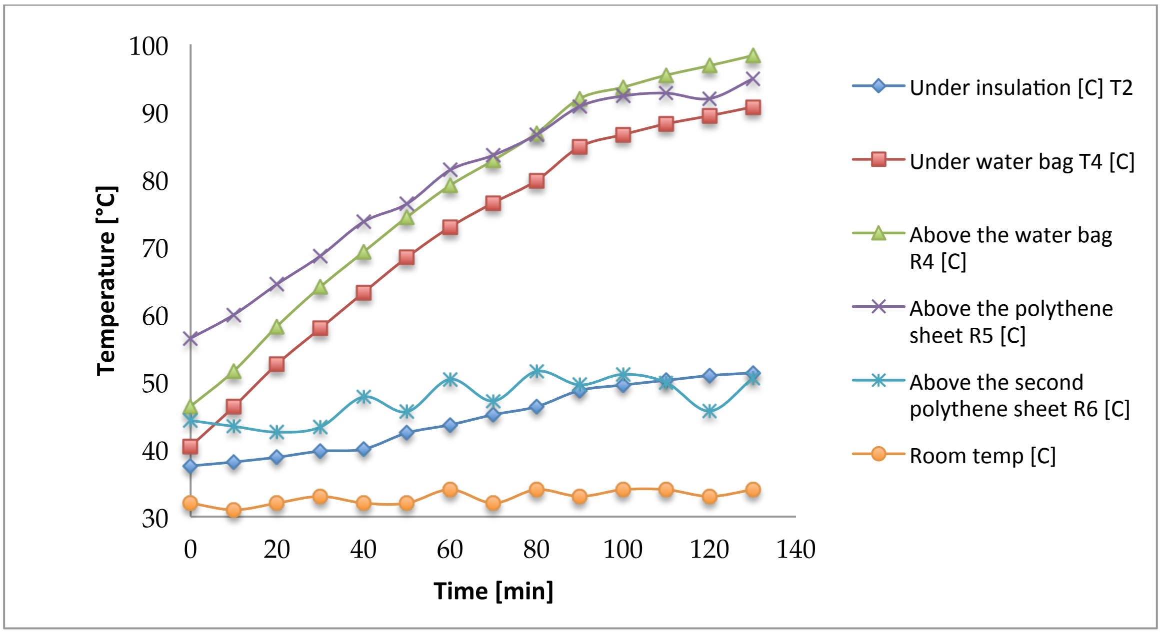

Figure 35 Solar radiation test 1: Shows the temperature in different positions of the test device with double air gap, thickness 24/5 mm using double insulation.

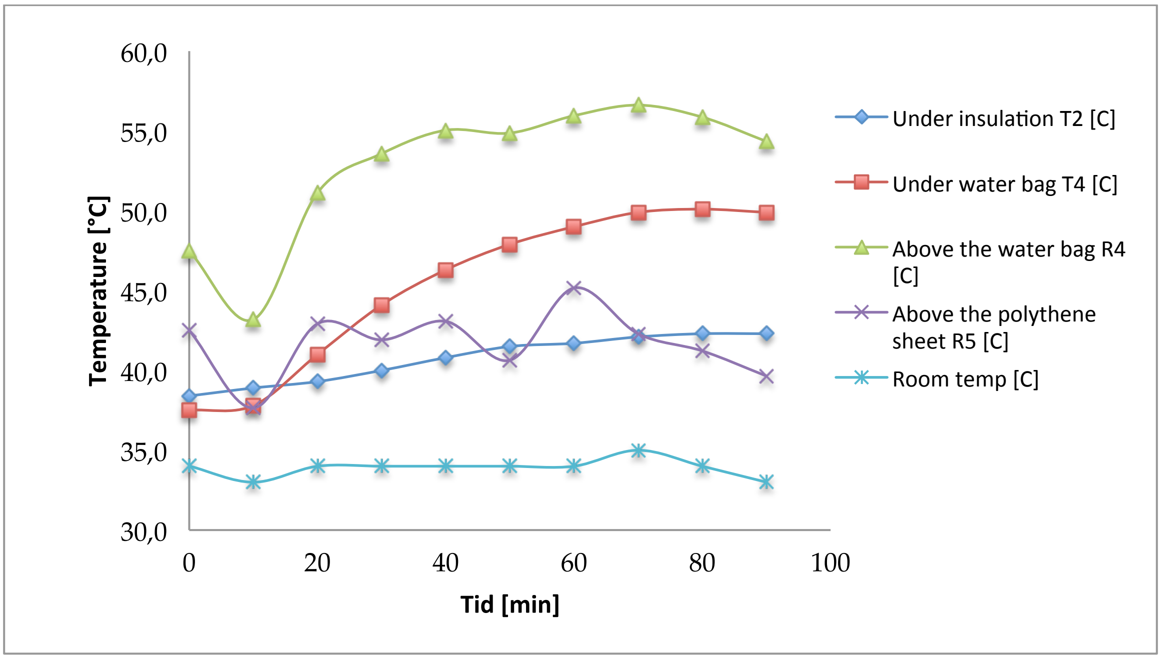

Figure 36 Solar radiation test 2: Shows the temperature in different positions of the test device with single air gap, thickness 24 mm using double insulation.

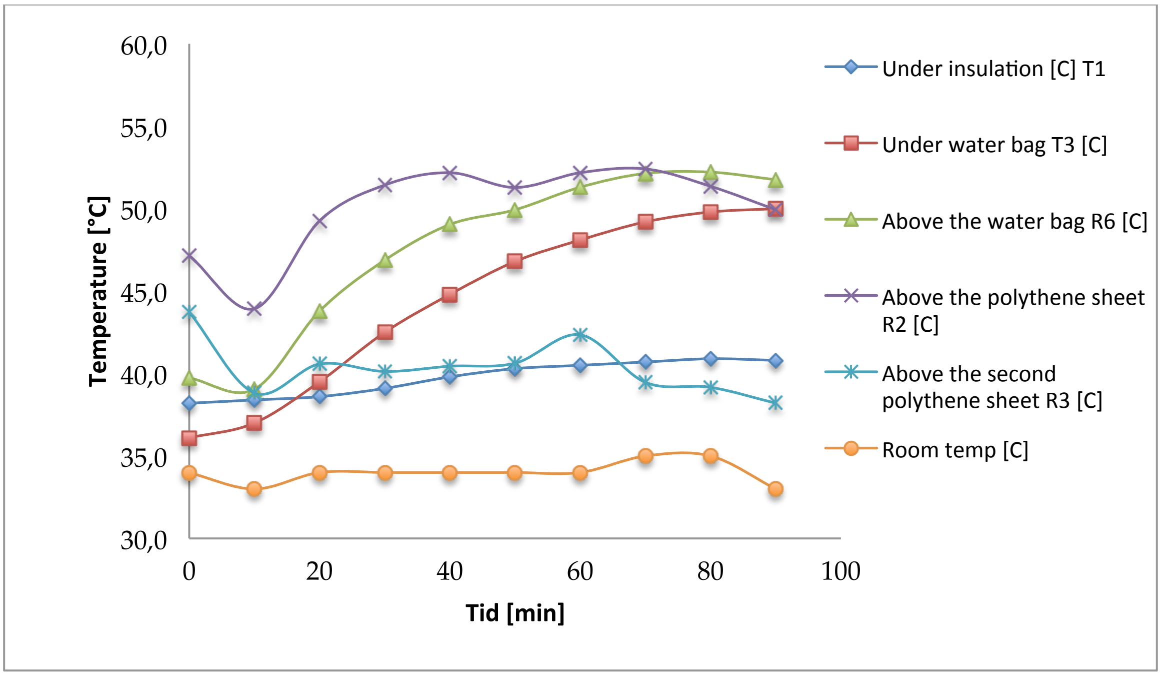

Figure 37 Solar radiation test 2: Shows the temperature in different positions of the test device with double air gap, thickness 24/5 mm using double insulation.

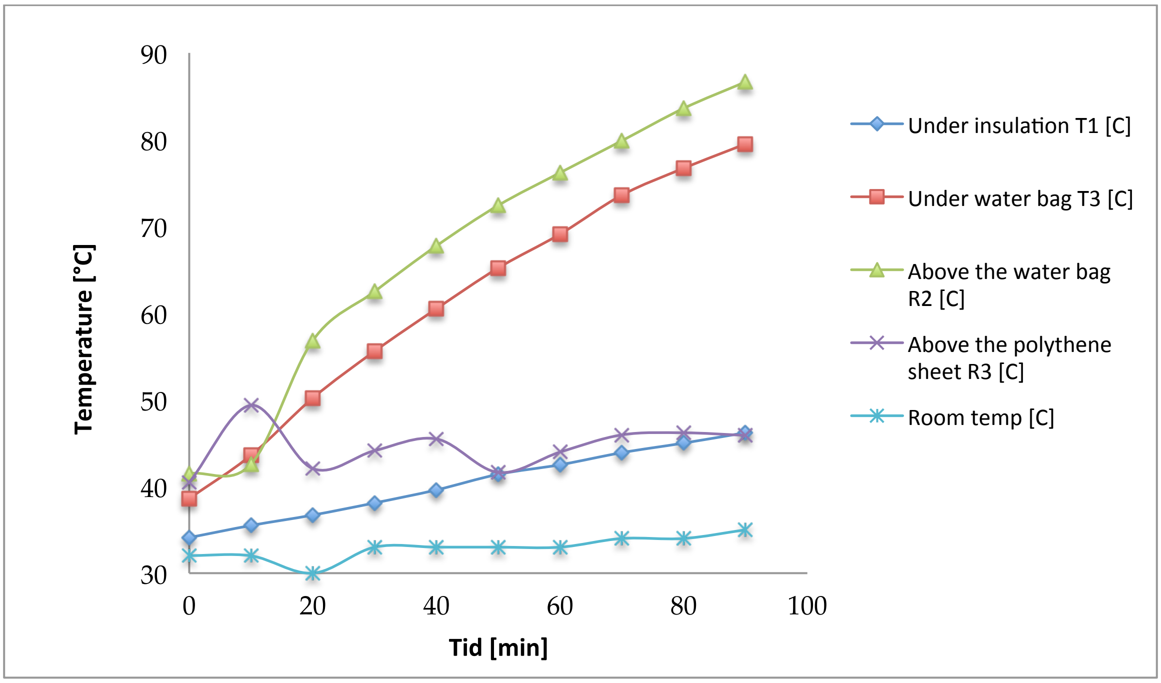

Figure 38 Solar radiation test 3: Shows the temperature in different positions of the test device with single air gap, thickness 24 mm using double insulation.

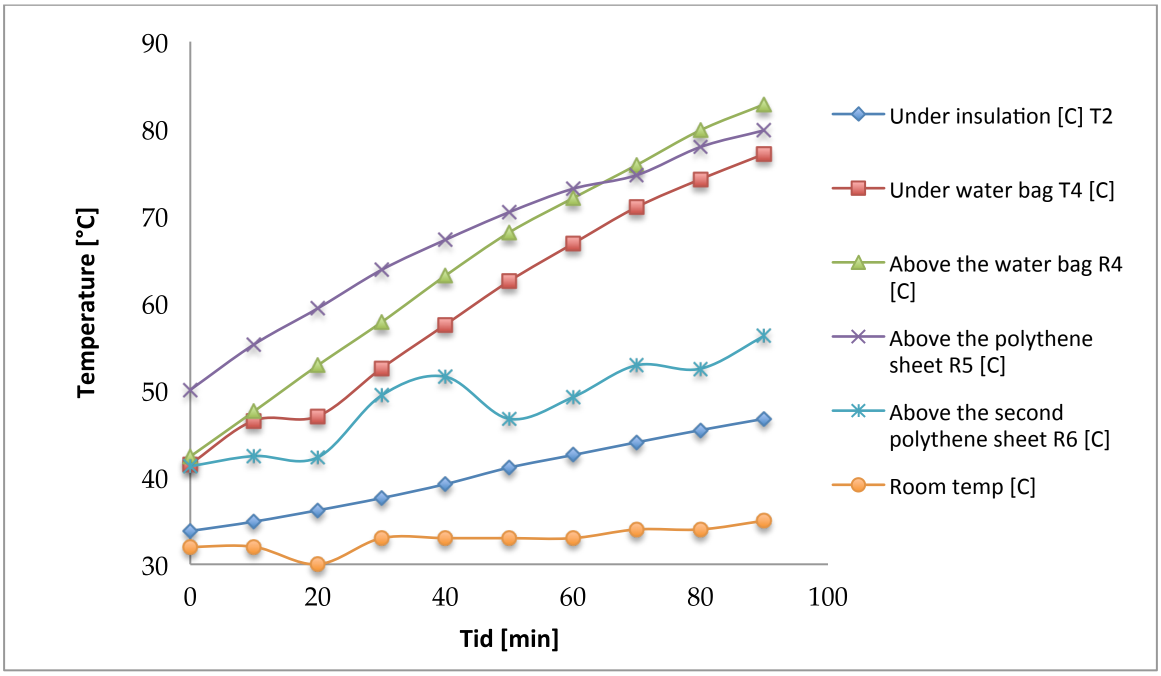

Figure 39 Solar radiation test 3: Shows the temperature in different positions of the test device with double air gap, thickness 24/5 mm using double insulation.

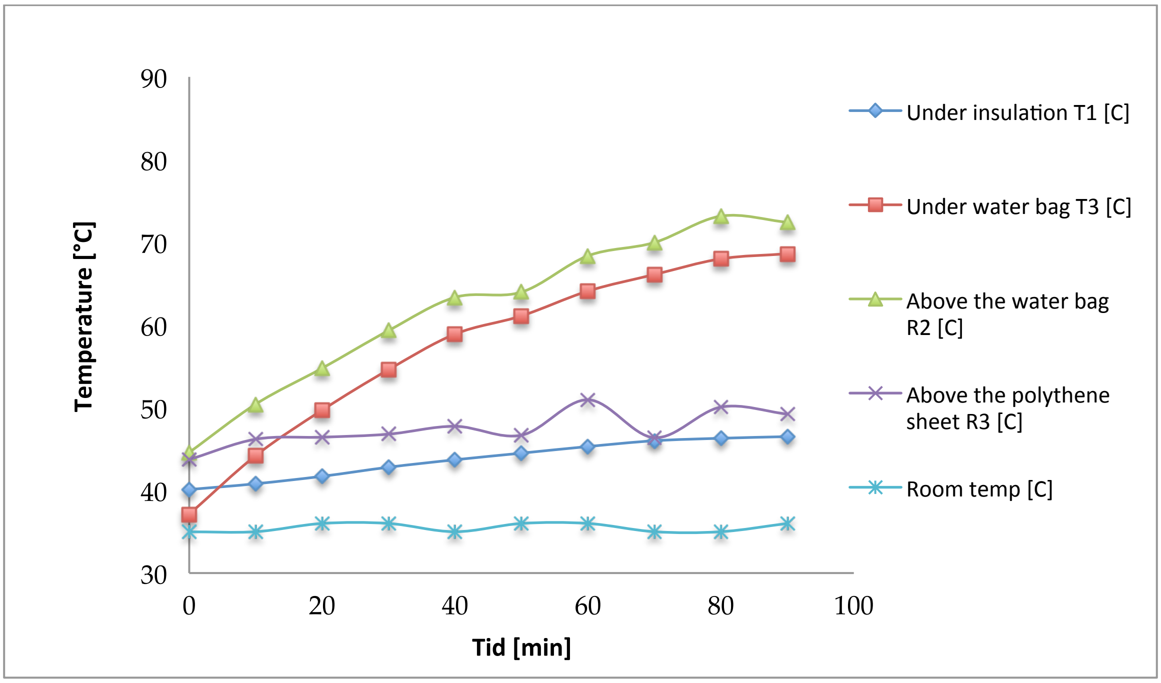

Figure 40 Solar radiation test 4: Shows the temperature in different positions of the test device with single air gap, thickness 24 mm using double insulation.

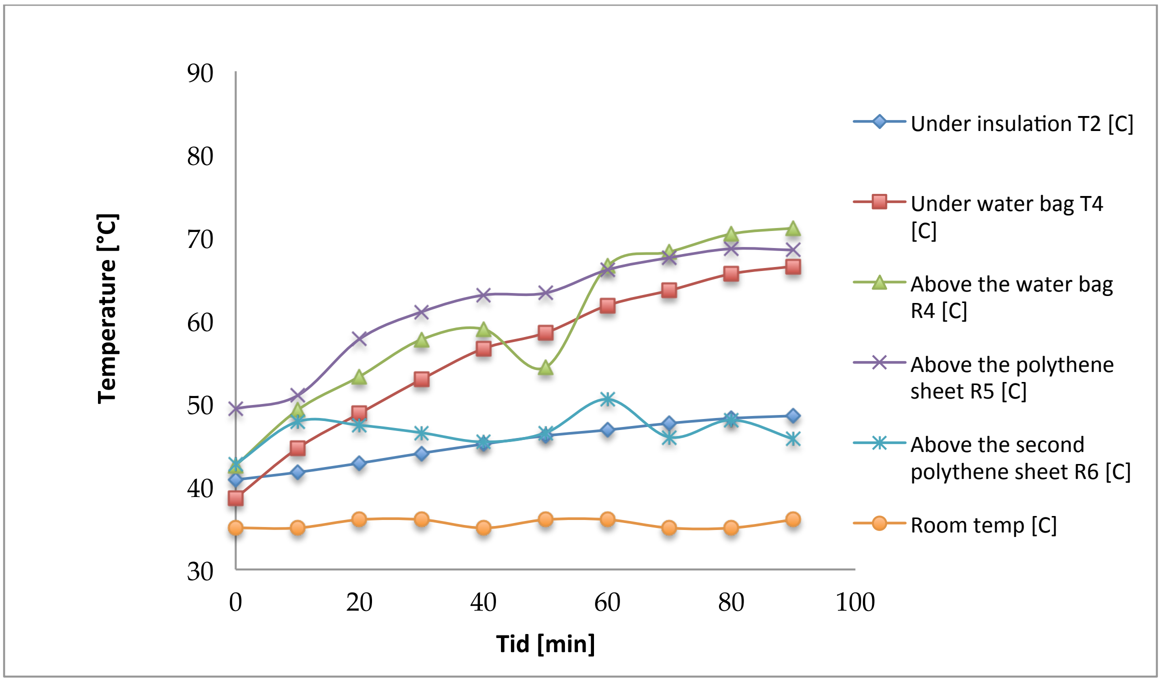

Figure 41 Solar radiation test 4: Shows the temperature in different positions of the test device with double air gap, thickness 24/5 mm using double insulation.