DETERMINATION OF OPTIMUM CONDITIONS FOR AN ENERGY EFFICIENT SOLAR WATER DISINFECTION SYSTEM

By

Haider Ali

NUST201261022MSCEE65112F

A thesis submitted in partial fulfillment of requirements for the degree of

Master of Science

in

Environmental Engineering

Institute of Environmental Sciences and Engineering (IESE)
School of Civil and Environmental Engineering (SCEE)
National University of Sciences and Technology (NUST)
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It is certified that the contents and forms of the thesis entitled

DETERMINATION OF OPTIMUM CONDITIONS FOR AN ENERGY EFFICIENT SOLAR WATER DISINFECTION SYSTEM

Submitted by

Haider Ali

Has been found satisfactory for the requirements of the degree of
Master of Science in Environmental Engineering

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I dedicate this thesis to my parents and my wife for their endless support and encouragement

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HAIDER ALI

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List of Abbreviations

AC	Alternating Current
APHA	American Public Health Association
CFU/mL	Colony Forming Unit Per Milliliter
DC	Direct Current
DNA	Deoxyribonucleic Acid
DO	Dissolved Oxygen
E. *coli*	Escherichia coli
EMB	Eosin Methylene Blue
H_2O_2	Hydrogen Peroxide
Kw/m^2	Kilo watt per metre square
MF	Membrane Filtration
NaCl	Sodium Chloride
NTU	Nephalometric Turbidity Unit
POU	Point Of Use
PVC	Photovoltaic Cell
ROS	Reactive Oxygen Species
S. *Typhi*	Salmonella Typhimurium
SODIS	Solar Water Disinfection
SPC	Spread Plate Count
UNICEF	United Nations Children's Fund
UV	Ultraviolet
WHO	World Health Organization
Wm^{-2}	Watt per metre square

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ABSTRACT

Worldwide about 1 billion people have no access to safe drinking water and the problem is most severe in developing countries. 20 to 50 liters of safe and clean drinking water is needed by each person on this earth per day. Over $150 billion is needed by developing countries to setup a drinking water supply system. However such sum is not easy to generate. Conventional treatment methods like filtration and chemical treatment require facilities and materials that are not economically feasible for such countries. This calls for alternatives like boiling of water. A common perception is that boiling kills all the microorganisms in water. However, it was observed that heating the water to 60^0C for 5 minutes served the purpose equally well. In current research a pasteurization unit was developed that used solar energy to achieve the required temperature. The unit built was cost effective and can disinfect water through solar water pasteurization. Initially a lab scale disinfection unit was established in which pasteurization temperature was achieved through electric current and optimum conditions for the disinfection of two pathogens i.e. *Escherichia coli* and Salmonella *Typhimurium* were determined through lab tests. E. *coli* was inoculated at 10^7 CFU/mL while S. *typhi* was inoculated at 10^5 CFU/mL in the feed tank of lab scale unit. Complete reduction of E. *coli* to 0 CFU/mL was observed by heating water for 3 minutes at 50^o C while S. *Typhi* was observed to reduce to 0 CFU/mL by heating water for 6 minutes at 60^o C. This was followed by design of a full scale solar disinfection unit. 50^o C was achieved by solar water heater in 3 hours while 60^o C was achieved in 4 hours. Turbidity had no effect on thermal disinfection of drinking water.

Chapter 1

INTRODUCTION

1.1. BACKGROUND

Access to safe and clean drinking water is a basic human right. However, water resources are depleting from the world at a much faster rate than they are replenished. It is expected that about 44% of the world population would be living in water stressed areas by 2050 (Bichai *et al*., 2012).

Lack of sufficient availability of drinking water and contamination of available water results in a large population suffering from water borne diseases. One of the many reasons of contamination of water is the anthropogenic activities primarily in remote areas as a result of which local communities depend on untreated surface, ground and waste water which poses a higher risk of diseases to humans (Davies *et al*., 2009).

Rural populations are unable to access centralized piped water system in most of the areas of the world and the faulty drainage system accompanied by poor supply lines result in the supply of unsafe drinking water to households (Mohsin *et al*., 2013).

A multitude of factors effect water quality during its collection, treatment and distribution that deteriorate its quality and the final treated water that reaches the consumers is unfit for drinking purposes. Indicators of drinking water quality are coliform bacteria. Their presence in water indicates fecal contamination which may be either due to inadequate treatment, insufficient disinfectant residual or cross

contamination of lines (LeChevallier *et al*., 1996). WHO requires that coliform bacteria must be zero/100 mL in drinking water when tested with Membrane Filtration method and <1.1/100 mL when tested with Most Probable Number (MPN)Technique.

To disinfect water from coliform bacteria, various physical and chemical methods are employed. Most commonly used water disinfection method is chlorination but it is limited by the formation of disinfection by-products like trihalomethanes by reaction between chlorine and organic matter in water (Sciacca *et al*., 2011). Also, chemical disinfection requires expensive chemicals which have limited shelf life. On the other hand, physical treatment methods such as filtering and UV disinfection require expensive materials (Hindiyeh and Ali, 2010). This, in addition to high maintenance costs that are associated with piped water supply systems and factors like ageing and disinfection call for household disinfection technologies referred to as Point-of-use (POU) disinfection technologies (Howe and Mitchell, 2012; Sobsey, 2007).

Certain criteria need to be fulfilled by a treatment technique to make it acceptable for the users. This includes low cost, easy to use and sustainability (McGuigan *et al*., 2012). Point-of-use disinfection techniques include solar disinfection, sand filters and boiling. One of the most common techniques to make water suitable for drinking at household level is boiling. Among all options, ultraviolet light disinfection is a better option due to its low consumable requirements and its efficiency against all pathogens (Lui *et al*., 2014).

Solar water disinfection (SODIS) is a very useful technique to treat drinking water in households where adequate sunshine is available. It has been in use since 30 years in one way or the other. It is known that more than 5 million people use SODIS to disinfect drinking water. SODIS converts the solar energy into heat which increases the water temperature. It is easy, simple and clean technology and does not require electricity for operation. Basically, it uses a combination of UV and temperature which disinfects water (Vivar *et al*., 2013).

Commonly, SODIS refers to exposing water in transparent bottles for a minimum of 6 hours of sunlight. Exposure time may vary from 6 to 48 hours which depends upon the sunlight intensity that is available and the resistivity of pathogens (McGuigan *et al*., 2012). It is suitable for small scale disinfection of water and is effective against a wide range of pathogens which include *Shigella dysenteriae, Salmonella typhimurium, Vibrio cholera, Escherichia coli* and *Pseudomonas aeuiginos* and this results in reduction of diseases like cholera etc.
(Nalwanga *et al*., 2014).

Much research has been carried out to improve SODIS by developing low cost reactors. However, despite its cost effectiveness and particularly easy for countries that lie between 35°N and 35°S latitude, SODIS has not been used to disinfect household water at a larger scale (McGuigan *et al*., 2012; Marques *et al*., 2013; Hindiyeh and Ali, 2010).

1.2. THE PRESENT STUDY

In the present study, a lab scale disinfection unit was developed in which water inoculated with E. *coli* and S. *typhi* was disinfected by varying the temperature and time. Membrane Filtration (MF) technique was used to enumerate E. *coli* while Salmonella was determined through Spread Plate Count (SPC) technique. Effect of turbidity on disinfection efficiency was also determined. Finally a full scale solar disinfection unit was developed.

1.3. AIMS AND OBJECTIVES

The study was aimed to provide water disinfection solutions to common man at an affordable cost. Objectives of the study were to:

1. Develop lab scale disinfection unit.
2. Find the disinfection conditions with microbiological analysis.
3. Develop full scale solar disinfection unit.

Chapter 2

LITERATURE REVIEW

Potable water that is clean and safe is an essential necessity of life. For this purpose various disinfection techniques are used. However, developing countries fail to give this necessity to its citizens due to non-availability of funds and inadequate treatment systems. One of the most common techniques to make water suitable for drinking is boiling. The common reason of boiling the water is the perception that it kills germs and makes water suitable for drinking. In contrary to this perception, literature supports that it is not necessary to boil water rather heating it at 60-70^{0}C for a couple of minutes makes it microbiologically safe (Skinner and Shaw, 2004). This process is termed as pasteurization. Due to absence of large scale treatment plants, water is often treated for individual households through various disinfection methods which are discussed below.

2.1. METHODS OF WATER DISINFECTION

Generally, there are two methods used for household water disinfection i.e. chemical and physical disinfection.

2.1.1. Chemical Methods

Two chemicals are basically used for disinfection. These include chlorine and iodine. Chlorine is the most widely used disinfectant due to its low cost and its inactivation efficiency. Chlorine is also beneficial due to its residual effect that prevents issues of recontamination (Burch and Thomas, 1998).

Iodine is also used for disinfection of water mostly by travelers like backpackers and hikers in USA as an easy and portable method for water disinfection. However, iodine is not widely used due to its high cost. Iodine is known to cost 20 times more than chlorine (Ellis, 1991).

However, these options are not viable for low income families due to the cost of chemicals, training required to calculate required dosage and aesthetics such as taste and odor of water. Another disadvantage is the low shelf lives of chemicals due to their chemical oxidation.

2.1.2. Physical Methods

Physical methods for water treatment include boiling and UV treatment. Boiling water is a very conventional and easy method but it has few limitations like availability of resources i.e. gas, wood, electricity etc. As a general perception, it is mandatory to boil the water for few minutes in order to make it microbiologically safe. Boiling water leads to unpleasant taste of water and is a time consuming process (Acra *et al*., 1984). UV treatment refers to a process in which water is exposed to light with wavelength of 250 nm through a UV lamp. This process has its own limitations like purchase of equipment, maintenance cost and availability of an operator. Moreover, high turbidity hampers the UV treatment process as a result of which filtration is required prior to UV treatment. These issues make UV treatment not a practicable option for domestic water treatment (Burch and Thomas, 1998).

2.1.3. Boiling vs Pasteurization

Various research studies have been carried out to evaluate the effectiveness of boiling against pathogens. It is recommended that bringing water to rolling boil for about 1 to 5 or 10 minutes is sufficient to kill microbes (WHO, 2004). Sobsey (2002) reported that observing a rolling boil water is assurance that water temperature is sufficiently high to kill microbes.

Lehloesa and Muyima, (2000) carried out a study on the effect of boiling on the ground water quality of the Victoria district of South Africa. Boiling water for 5 minutes resulted in water quality to improve to the drinking water standard limits. Boiling has its advantages like it can be effective against many pathogens and works equally well in high turbid water and no specific instrument and training is needed for it. However, boiling has problems associated with it like it imparts bad taste and odor to water, long time is required for cooling of water after boiling and large energy consumption. Moreover, it causes scaling (Skinner and Shaw, 2004; Brick et al., 2004; Colwell et al., 2003).

It is reported in literature that heat for boiling water is unnecessary i.e. in excess to what is required to kill microbes. Rather heating it to 60-70^{0}C for a couple of minutes is sufficient to make it microbiologically safe (Siochetti and Metcalf, 1984). This process of heating water to a certain temperature to make it microbiologically safe is termed as pasteurization. Though not widely used, pasteurization has been known to be an effective method in water treatment. 60^{0}C is reported as an effective temperature for disinfecting E. *coli* in water.

A study carried out in Kenya on batch pasteurization of drinking water showed that incidence of diarrhea reduced by approximately 50% due to improved quality of water (Fewtrell et al., 2005).

In a study carried out in Bangladesh, Islam and Johnston (2006) pasteurized water through waste heat generated in clay ovens. Temperature was maintained at 70°C and a complete inactivation of thermotolerant coliforms was observed.

Pasteurization has advantages over boiling like scaling risk is lower in this case as compared to boiling; also it takes less time and energy. However, effectiveness of treatment cannot be determined in the absence of indicator. In case of solar heating, temperatures of around 65 to 70^0C can be reached by using two sided solar reflectors or boxes (Safapour and Metcalf, 1999; Stanfield et al., 2003). This temperature can inactivate most of the pathogens (Skinner and Shaw, 2004).

2.1.4. Solar Water Pasteurization

Solar water pasteurization is the most reliable alternative to physical or chemical disinfection methods as it is cost effective and energy efficient (Burch and Thomas, 1998). Foods and beverages are pasteurized i.e. heated to a certain sufficient temperature to make it free of microbial contamination. Generalized pasteurization temperature conditions to kill microbes in water are 60°C for bacteria *Salmonella typhi Escherichia coli, Vibrio cholerae, Enterotoxigenic* and *Shigella sp.* Thus heating water to about 65°C would potentially make it free of microbial pathogens (Safapour and Metcalf, 1999).

Effectiveness of pasteurization depends upon certain factors which include contact time, temperature and pathogen heat resistance (Islam and Johnston, 2006). Chemicals like sodium carbonate, citric acid, copper plus carbonate or lime juice/pulp have been reported to enhance SODIS (Fisher *et al*., 2012)

2.2. MECHANISM OF SOLAR DISINFECTION

2.2.1. Spectrum of Solar Radiation

Solar radiation is divided into different bands on the basis of the wavelengths. These include ionizing radiations and non-ionizing radiations. Ionizing radiation includes X-rays and gamma rays while non-ionizing radiation includes visible light, ultraviolet radiation and infrared radiation. Part of the radiation between 100 and 400 nm wavelength is referred to as ultraviolet radiation and is used for solar disinfection (Hindiyeh and Ali, 2010).

Inactivation of bacteria by solar radiation is the result of two components i) UV-A (wavelength between 320 and 400 nm) and visible light (wavelength between 400 and 490 nm) ii) temperature (minimum 45° C). (Sommer *et al*., 1997; Wegelin *et al*., 1994). This means that in addition the pasteurization effect, high temperatures may also inhibit DNA (McGuigan *et al*., 1998).

UV-A light results in the formation of reactive oxygen species (ROS) which includes singlet oxygen, hydrogen peroxide, superoxide and hydroxyl radical. These ROS cause damage to the DNA, oxidation of amino acids and fatty acids. Sunlight may also be absorbed by humic acids and chlorophylls which may in turn react with oxygen to produce ROS which causes disinfection (Blough *et al*., 1995)

Rijal and Fujioka (2001) worked to evaluate the synergistic effect of solar radiation and heating on drinking water disinfection. It was concluded that UV radiation and heat both worked together to disinfect fecal bacteria from water and even if the water temperature does not reach 60°C, effective disinfection may result. Through synergistic effect, 3 log reduction of fecal coliform was observed within 2-5 hours exposure to sunlight.

2.3. ADVANTAGES OF SOLAR DISINFECTION

Major advantages of disinfection by solar energy are that it is low cost, requires limited resources and can be carried out by people easily at household level. In a study by Dessie *et al*. (2014) solar disinfection was evaluated as a suitable approach for low cost water treatment. Solar disinfection was carried out at local conditions i.e. pH 7, 2 NTU and temperature ranging from 38 to 51° C. At an irradiance of 3.99 Kw/m^2 complete inactivation of fecal coliform was observed in an exposure time of less than four hours. No regrowth was observed after inactivation.

Solar water heating can disinfect even highly contaminated water. Caslake *et al*. (2004) carried out disinfection of river water and waste water that was partially treated. In midday sunlight, for 1 litre of water, it took less than 30 minutes to achieve 4 log reductions of bacteria.

One advantage of SODIS is that it can be carried out under real conditions and requires no simulation. Boyle *et al*. (2008) worked to determine bactericidal effect of real sunlight. In real sunlight conditions it was determined that for complete

inactivation or removal below detectable limits for E. *coli* 90 minutes were required. Conditions of real sunlight included maximum irradiance of 1050 Wm^{-2}.

There are many ways in which SODIS may contribute to improve the household finances. These include

1. Costs of fuel for boiling water is saved
2. Reduced deaths increase the number of earning hands
3. Illness-associated costs may be reduced which may include costs for medicine, transport to and from hospitals etc (McGuigan *et al*., 2012).

2.4 FACTORS AFFECTING SOLAR INACTIVATION

2.4.1. Turbidity and pH of Water

Turbidity of water plays an important role in solar disinfection. Research has shown that turbid waters at 300 NTU, results in less E. *coli* inactivation as compared to those with lower turbidity. This may due to the fact that higher turbidity results in shielding of microorganisms from sunlight. Joyce et al. (1996) found that only some amount i.e. less than 1 % of UV can penetrate with 200 NTU turbidity. Thus, it is important to filter water of higher turbidities before exposing to sunlight.

Table salt (NaCl) can be used to lower the turbidity of water. Dawney *et al.* (2014) carried out a study to determine the effectiveness of NaCl to remove the colloidal particles from water. Upto 92% removal efficiency was observed in various jar tests conducted. It was found that the combination of NaCl with 30% bentonite clay can reduce the turbidity to levels suitable for SODIS.

pH is not known to have much effect on SODIS. Rincon (2004) conducted a research to determine the effect of inorganic ions, organic matter, pH and H_2O_2 on solar disinfection of E. *coli*. pH was varied between 4 to 9. However, no significant variation in disinfection rate was observed.

2.4.2. Agitation, Aluminum Foil and Container Volume

In a study by Kehoe et al. (2001), effect of agitation, aluminum foil and container volume were determined by various experiments. Agitation was shown to result in an increased release of dissolved oxygen and subsequent decline in inactivation efficiency while covering the back of the container with aluminum foil actually improved the disinfection efficiency. Foiled container resulted in 1.85 folds higher inactivation as compared to non-foiled ones. Volume of water was varied between 500 to 1500 mL. However, no significant variation in disinfection rates was observed.

2.5. BACTERIAL REGROWTH

Various studies have been carried out to determine the bacterial regrowth after SODIS. Bosshard *et al.* (2009) carried out a study to determine the solar inactivation of bacteria after subsequent storage in dark. Research focused on *Salmonella typhimurium* and *Shigella Flexneri.* No regrowth of bacteria was observed by subsequent storage in dark. It was thus concluded that sunlight leads to irreversible cellular damage.

Adeel *et al.* (2013) carried out a study on the elimination of pathogenic bacteria in lake water by solar disinfection. It was observed that bacteria reduced by 4 log after 6 hours exposure but incubation of the treated waters resulted in regrowth upon

incubation at 37° C for 24 hours. However, after 8 hours disinfection no regrowth was observed in treated samples.

Joyce *et al*., (1996) worked to study fecal bacterial inactivation through solar heating. Complete disinfection of sample was observed after 7 hours exposure and keeping samples for further 12 hours did not lead to any regrowth.

2.6. LIMITATIONS OF SOLAR WATER DISINFECTION

Solar disinfection is effective in case of static volumes of water because it is continuously illuminated till the desired UV dose for bacterial inactivation is achieved in which case complete disinfection occurs. However, when the flow is continuous, as in continuous flow reactors, the disinfection would not be complete (Ubomba-Jaswa *et al*., 2010). Sunlight dependency is a serious short coming of the method as it cannot work in cloudy conditions (Oates *et al*., 2003). Another limitation is that it is not effective when turbidity of water exceeds 30 NTU (Rose *et al*., 2006).

A potential drawback is the length of time required to disinfect water. For this, an awareness campaign is needed to promote use of solar radiation in the communities since it has been observed that lack of knowledge and will to do are the basic hindrances in the area. Alther *et al.* (2008) examined the changes in attitude and other related factors in the use of solar disinfection. It was concluded that intention to use mainly depended upon the realization that neighbors are using the technique but the actual use of it demands real knowledge about the technology. Promotion campaigns are required to incur positive attitude towards the technology in people. Those who

are using solar disinfection reported significantly low incidences of water borne diseases.

2.7. BEHAVIOURAL FACTORS AND ADOPTION OF SODIS

Meierhofer and Landolt (2009) studied the factors related to the sustained use of solar water disinfection. They studied the factors that result in the acceptance of the technology such as education, social pressures, commitment and motivation etc. Solar disinfection needs to be promoted by awareness campaigns, trainings, network activities and public sector advice. Since 2000, solar irradiation has been reported to result in upto 57% reduction in water borne diseases.

Rose et al. (2006) carried out a study in India in which children under 5 years of age were made to drink water disinfected in sunlight. As compared to control it was observed that significant reduction occurred in diarrhea incidences. 40% reduction was observed in diarrhea risk by using solar water disinfection.

Comparing the merits and demerits, it can be concluded that solar is a better technique for low income households than conventional disinfection methods. Other steps may be taken to improve the system but costs associated need to be kept in mind as people who normally use solar disinfection are not economically stable. WHO and UNICEF also recognize solar disinfection as an emergency and short term solution to treat contaminated water since 2005.

Chapter 3

MATERIALS AND METHODS

The campus of the National University of Sciences and Technology, Pakistan was taken as the study site. It is a residential public sector research university established in 1991 while its new campus was established in H-12 sector, Islamabad in 2008. It is spread over 707 acres, has more than 15 schools and institutes as well as hostels for both male and female students including faculty residence.

3.1. PHASE 1- LAB SCALE UNIT

Before designing a solar water pasteurization unit, it was important to identify the temperatures at which bacteria are disinfected. Thus, in phase 1 of this research, a lab scale system was designed to test the effects of water temperature on artificially contaminated water samples.

3.1.1. Experimental Design

In the first phase of research a purpose built disinfection unit was designed and fabricated to conduct the experiments at lab scale. The idea was to have a disinfection unit with a controller such that both the temperature and time of disinfection can be adjusted and that samples can be taken before and after disinfection at different time and temperatures.

Initially, a block diagram of the disinfection unit was drawn. Figure 3.1 shows the working principle of the unit while the details of this disinfection unit are given below. The experimental design included the inoculum of bacteria into distilled water

and then heating it to different temperatures to enumerate viable bacterial counts over time to quantify disinfection by heating.

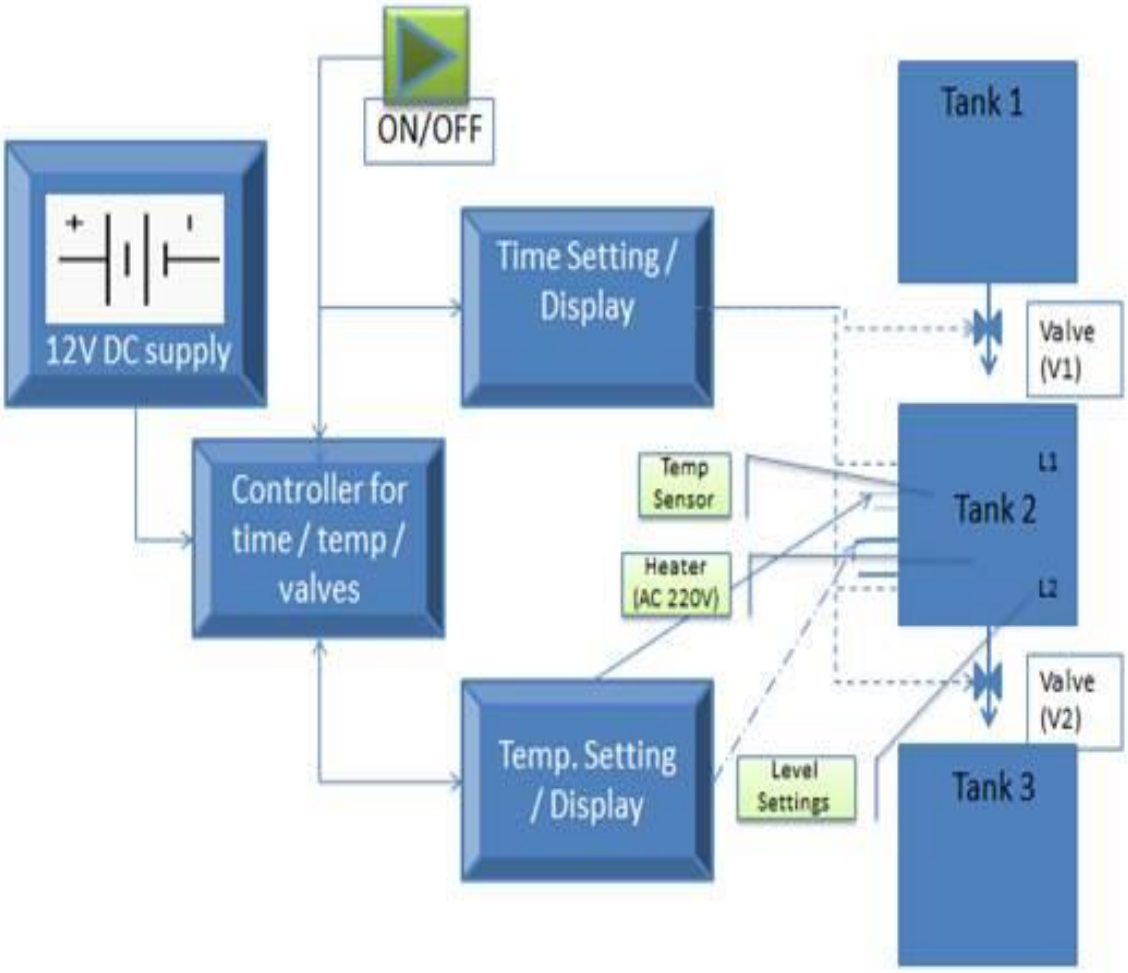

Figure 3.1: Working Principle of the Lab Scale Unit

3.1.1.1. Feed Tank

The tank for the feed water was made of Perspex / acrylic (Figure 3.2). This material can tolerate the heat up to 120^0C without expanding. The dimensions of this tank were 20*20*20 cm, making it 8000 cm^3 or 8 litre.

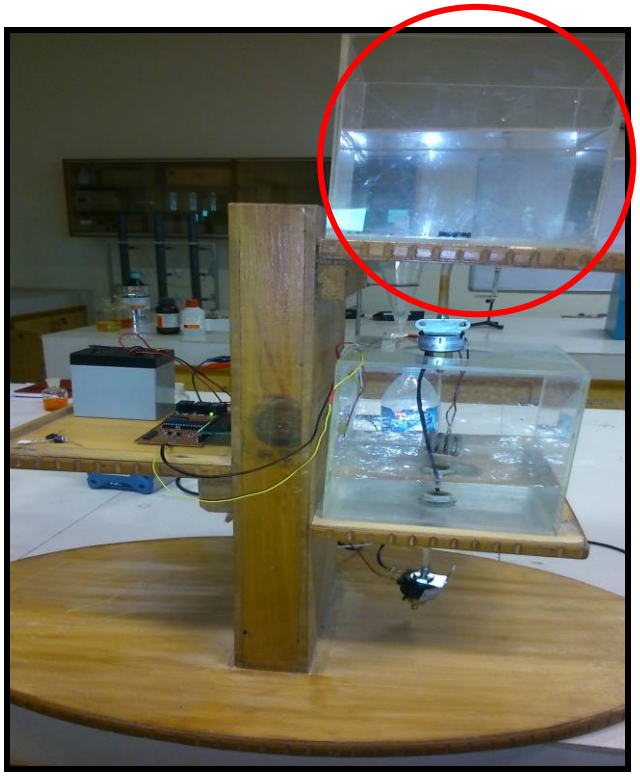

Figure 3.2: Feed Tank of the Lab Scale Unit

3.1.1.2. Disinfection Tank

The disinfection tank was made of the same material and capacity was also the same as that of feed tank but with different components. It primarily consisted of the heating filament, temperature sensor; upper and lower level transmitters and solenoid valves. This was the main tank in which heating and disinfection took place (Figure 3.3)

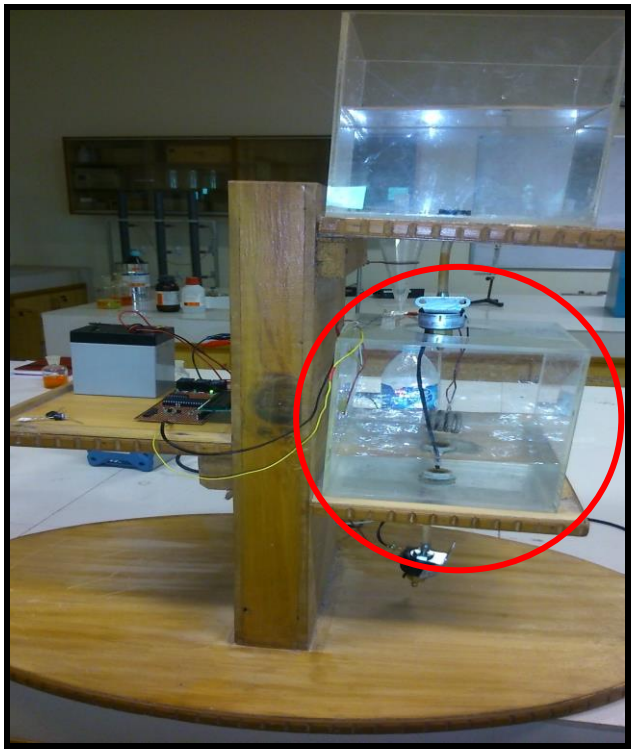

Figure 3.3: Disinfection Tank of the Lab Scale Unit

3.1.1.3. Temperature Sensor

The temperature sensor can sense the temperature from 0-99^{0}C (Figure 3.4). It was made water proof to avoid any damage and short circuiting. The temperature sensor was used to convert the current water temperature into electrical signals and then transmit it to controller.

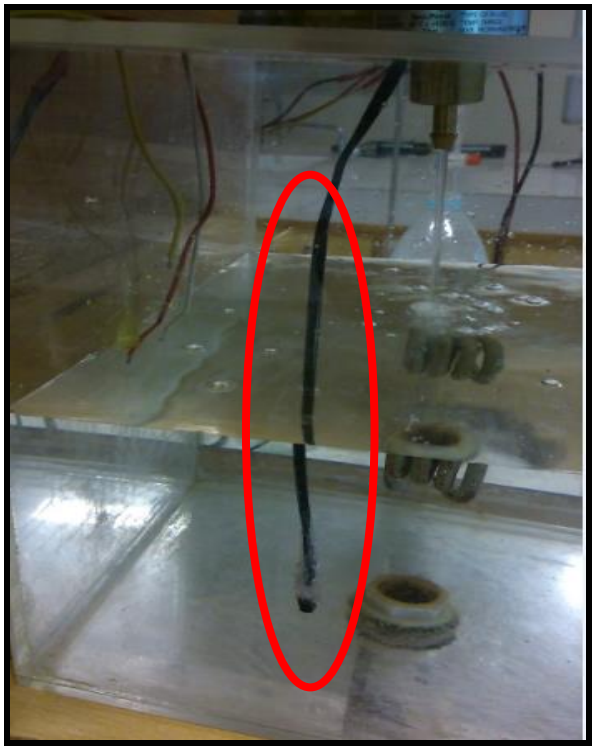

Figure 3.4: Temperature Sensor of the Lab Scale Unit

3.1.1.4. Level Transmitters

Two level transmitters were installed in the disinfection tank for the safety of solenoid valves and heating filament (Figure 3.5).

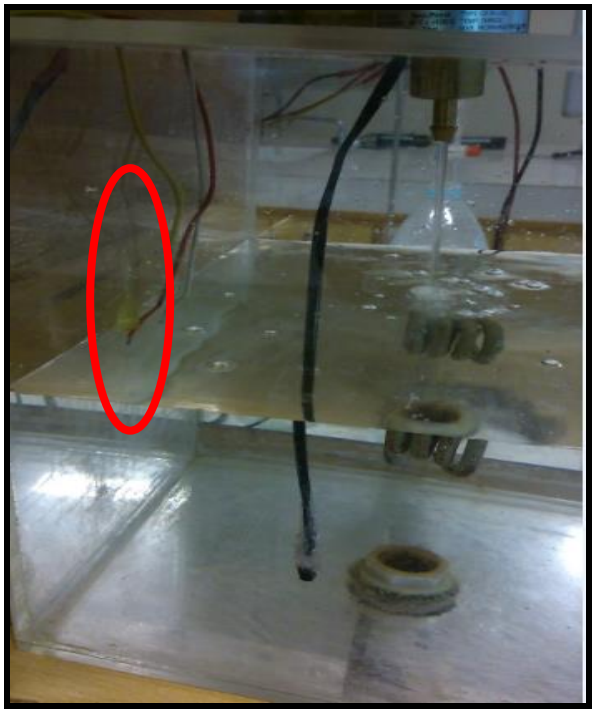

Figure 3.5: Level Transmitters of the Lab Scale Unit

The programming was done such that when the water reaches lower level indicator it switches off the filament so that it would not keep on heating without water causing damage to the filament. Moreover, when the water reached the lower level sensor, it gave signal to solenoid valve to send more water from feed tank (Figure 3.6). The purpose of upper level indicator was to communicate with the upper solenoid valve (from feed tank) to close as the disinfection tank was now full.

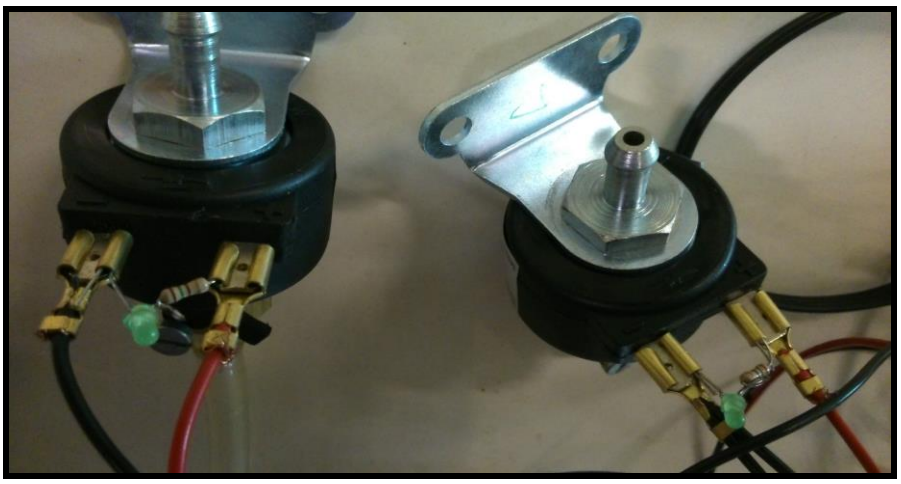

Figure 3.6: Solenoid Valves of the Lab Scale Unit

3.1.1.5. Controller

Controller, which was the brain of the whole disinfection system, was programmed in the following way (Figure 3.7):

- By switching the main power ON of the controller, the feed water started coming from feed tank to disinfection tank up to the point when the water reached high level indicator.
- The display screen on the controller asked for the required heating temperature in Celsius and required heating time in minutes (Figure 3.8)
- With the help of 2 buttons each for temperature and time, the set point could be adjusted.

- After entering the temperature and time of heating the filament started heating.
- Meanwhile the screen displayed the current temperature of water and the set point along with the set point of time.
- When the water reached the temperature of set point, the timer started and maintained the temperature till the time that was set.

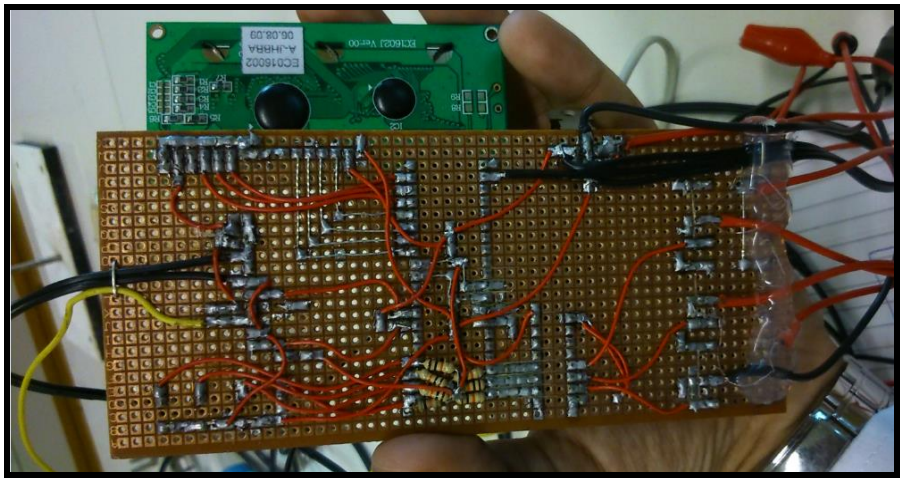

Figure 3.7: Controller of the Lab Scale Unit

- As an example let us say that we wanted to see the effect of heating on bacteria at a temperature of 60^0C for 7 minutes. We entered the temperature of 60 and time 7. The heating filament started heating up to the temperature of 60 and as soon as the temperature reached 60, it switched off the filament and started the timer of 7 minutes. During this 7 minutes time, the controller maintained the temperature of 60 by switching the filament ON and OFF where required. After 7 minutes, the bottom valve opened automatically and discharged the disinfected water.

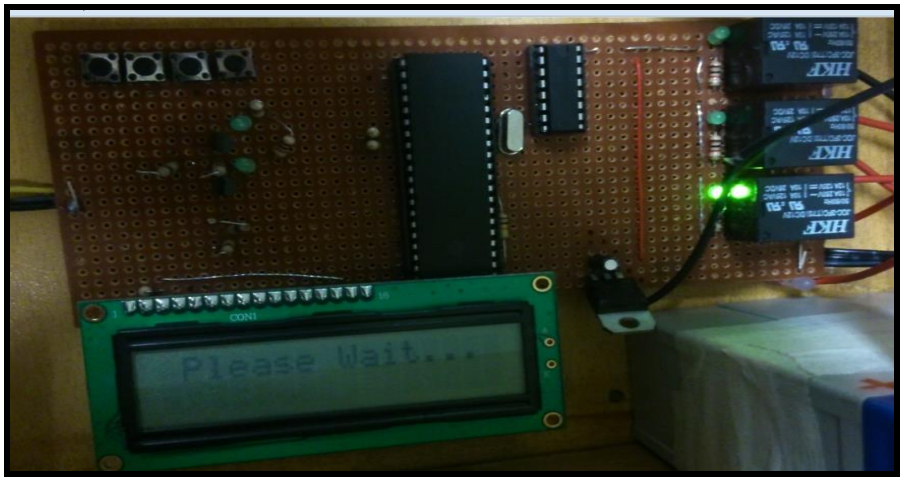

Figure 3.8: Display Screen of the Lab Scale Unit

3.1.1.6. Power Source

The power required in this system was provided from the lab as it was a lab scale unit to obtain results of heating with respect to time. Heating filament used 220V AC supply for heating and the controller used 12V DC supply for operation of solenoid valves and controller itself. This 12V DC supply was provided using a Voltage regulator in lab that used to convert 220V AC supply into 12V DC supply (Figure 3.9).

Figure 3.9: Power Source of the Lab Scale Unit

3.1.2. Physicochemical Analyses

pH, temperature, turbidity and dissolved oxygen were measured using HACH 156 pH meter, HACH 2100N turbidimeter and Crison Oxi 45 DO meter respectively. All the analysis were performed as per the Standard Methods for the Examination of Water and Waste Water (APHA, 2012).

3.1.3. Optimization of Disinfection Conditions

In order to optimize the disinfection conditions for the established disinfection unit, microbiological testing of water was carried out which is explained below.

3.1.3.1. Selected Microorganisms

Selected enteric microorganisms include *Escherichia coli* and *Salmonella typhi* both of which cause infection and diseases in humans. Common sources of these pathogens in water bodies include contamination of water with human urine and faeces.

3.1.3.2. Preparation of Glassware

Sterile leak proof 250 mL Schott (glass) bottles were used for sampling. All bottles were washed with detergent, rinsed with distilled water and autoclaved at 121°C, 15 psi for 15 minutes and then oven dried at 105°C for one hour. Following this treatment bottles were tightly capped and wrapped.

3.1.3.3. Preparation of Media

For preparing bacterial inoculum, nutrient agar plates were prepared by dissolving 20 g of agar in 1 litre distilled water and autoclaving at 12°C and 15 lb/cm^2 for 15 minutes. Agar was then poured in sterile autoclaved and oven dried petri plates and

incubated for 24 hours at 37°C to check sterility of plates. EMB agar plates were also prepared by similar method by dissolving 37.5 g of agar in 1 l distilled water.

3.1.3.4. Preparation of Inoculum

For preparing S. *typhi* inoculum, S. *typhi* was grown on SS agar plates (Figure 3.10). Fresh culture after grown for 24 hours was washed with phosphate buffer solution and inoculated at 10^5 CFU/mL in the feed tank.

Similarly for preparing E. *coli* inoculum, E. *coli* was grown on EMB agar plates for 24 hours and fresh culture was washed with phosphate buffer solution and inoculated at 10^7 CFU/mL in feed tank.

Figure 3.10: Spread Plate Technique for growth of S. *typhi* culture on SS agar plates

3.1.3.5. Heating and Sample Collection

After inoculation of culture, water was heated to 35, 40, 45, 50, 55, 60, 65 and 70°C and sample collected at 1, 2, 3, 6 and 9 minutes. Samples were analyzed within one hour of their collection or stored in refrigerator at 4°C and analyses within 4 hours. All the collection and storage procedures were carried out as prescribed in the Standard Methods for the Examination of Water and Waste Water (APHA, 2012).

Triplicates were collected for each sample to validate the results.

3.1.3.6. Enumeration of S. *Typhi*

For the enumeration of S. *Typhi* Spread Plate Count (SPC) technique was used as per standard procedures (APHA, 2012). 0.5 mL of the sample was spread plated onto sterile nutrient agar plates (Figure 3.11). The plates were incubated at 37°C for 24 hours and counted with colony counter (560 Suntax Colony Counter).

Figure 3.11: Picking up sample for spreading using a micro pipette

3.1.3.7. Enumeration of E. *coli*

Membrane filtration technique was used as per standard procedures (APHA, 2012). 100 mL of the sample was filtered through 0.45 microns filter paper (Figure 3.12). The filter paper was placed on EMB agar plates. The plates were then incubated at 37° C for 24 hours and colonies were counted using a colony counter (560 Suntax Colony Counter).

Figure 3.12: Filtering of sample through 0.45 microns filter paper

3.1.4. Effect of turbidity

In order to determine the effect of turbidity on the pasteurization of water, clay was collected from NUST construction site, added to water and stirred for 30 minutes. This clay was then allowed to settle for 1.5 hours (Figure 3.13). Supernatant was collected and turbidity was adjusted to 100 NTU. This turbid water was then added to the feed tank till the desired turbidity of 5-10 NTU was achieved. Water was heated to 40. 45 and 50° C and samples collected at 1,2,3,6 and 9 minutes to evaluate the effect of turbidity on disinfection of S. *typhi* and E. *coli*.

Figure 3.13: Settling of clay

Chapter 4

Results and Discussion

Considering the water situation in the world, the research work was focused on developing low cost domestic methods for water disinfection. The unit thus established, runs on the principle of water pasteurization using solar energy.

4.1. Lab Scale Disinfection Unit

One of the key deliverables of the research work was to develop an engineered disinfection unit in which we introduce microbiologically contaminated water and can get the disinfected water as an output. As described in Chapter 3 in detail, this objective was achieved and the next step was to run it to see the trends of bacterial count against the temperature rise. For that purpose, there was a need to work on microbiological grounds and introduce the bacteria in the disinfection unit.

4.2. Validation of Disinfection Conditions

In order to test the disinfection efficiency of the lab scale unit, two indicator organisms were used i.e. E. *coli* and Salmonella *Typhi.*

4.2.1. Disinfection of E. coli

After inoculation of E. *coli,* water was heated to different temperatures (35, 40, 45, 50, 55 and 60°C) and sample was collected at varying time intervals i.e. 0.5, 1, 2, 3, 6 and 9 minutes. E. *coli* counts as CFU/mL increased from 44 to 92 with increase in heating time at 35°C while at 40°C counts increased from 47 to 77°C. This was surprising and lead to the repeated experimentation. At this stage literature review

was again required and the study concluded that this is because 37°C is optimum temperature for E. *coli* growth. Alam and Zafar (2013) also reported positive correlation ($p<0.001$) of E. *coli* with temperature. Highest E. *coli* growth was observed at temperature 35 to 37 °C.

However, when water was heated at 45°C, E. *coli* decreased from 45 to 21 CFU/mL. Since WHO has set limit of 0 CFU/mL for E. *coli* in drinking water (WHO, 1997). Water was further heated to 50°C. It was observed that counts decreased from 41 at 0.5 minutes to 5 at 2 minutes. Complete removal of E. *coli* was observed after heating for 3 minutes at 50^0C

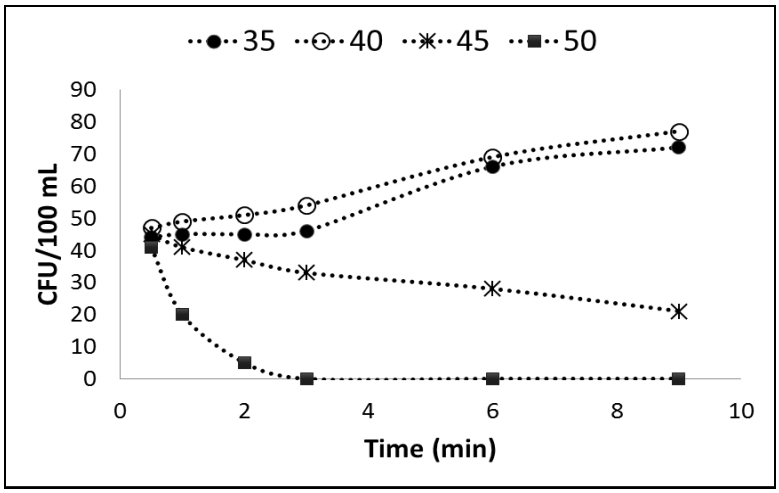

Fig 4.1: E. *coli* inactivation by heating water at different temperatures and for different time intervals

4.2.2. Disinfection of Salmonella *Typhi*

Similar procedure was repeated to determine optimum conditions for disinfection of Salmonella *Typhi*. Salmonella counts were observed to increase from 110000 at 0.5 minutes to 176000 at 9 minutes when water was heated at 35°C. Heating water at

40°C also resulted in counts increasing from 110000 at 0.5 minutes to 181000 CFU/mL at 9 minutes. When water was heated at 45°C it was observed that counts reduced from 106000 to 102000 CFU/mL upto 2 minutes. Further heating to 9 minutes resulted in reduction to 76000 CFU/mL. Heating water at 50°C resulted in counts to reduce from 102000 to 66000 CFU/mL at 0.5 and 9 minutes respectively. Temperature was further increased to 55°C and it was observed that counts reduced from 81000 to 400 CFU/mL by increasing time from 0.5 to 9 minutes. Complete reduction i.e. 0 CFU/mL was observed by heating water at 60°C for 6 minutes.

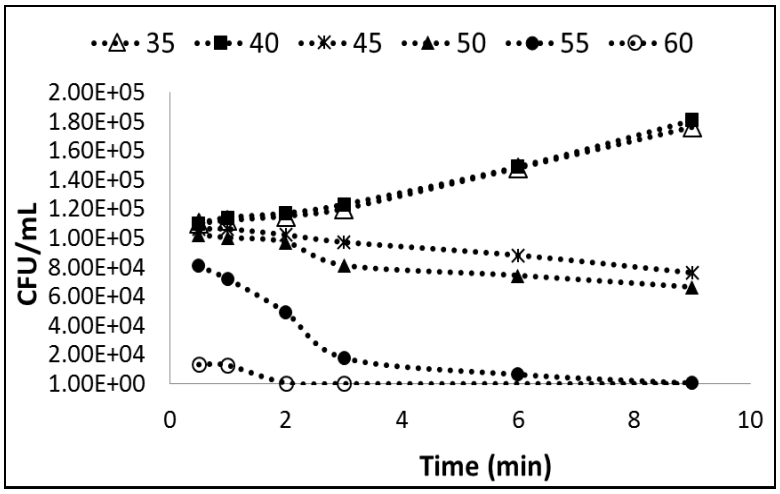

Fig 4.2: Salmonella *Typhi* inactivation by heating water at different temperatures and for different time intervals

4.3. Effect of Turbidity on Bacterial Disinfection

Effect of turbidity on bacterial disinfection was determined by adding a turbid clay solution to water to increase the water turbidity to 5 and 10 NTU. Turbidity did not seem to interfere in disinfection of E. *coli* and Salmonella *Typhi.* Complete disinfection of E. *coli* was found after heating water for 3 minutes at 50°C (Figure 4.3 a and b)

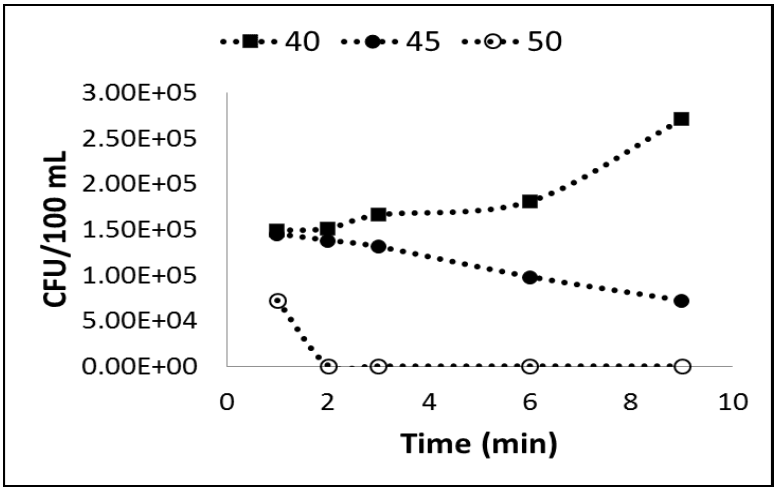

Fig 4.3(a): Disinfection of E. *coli* at various temperatures in water with turbidity of 5 NTU

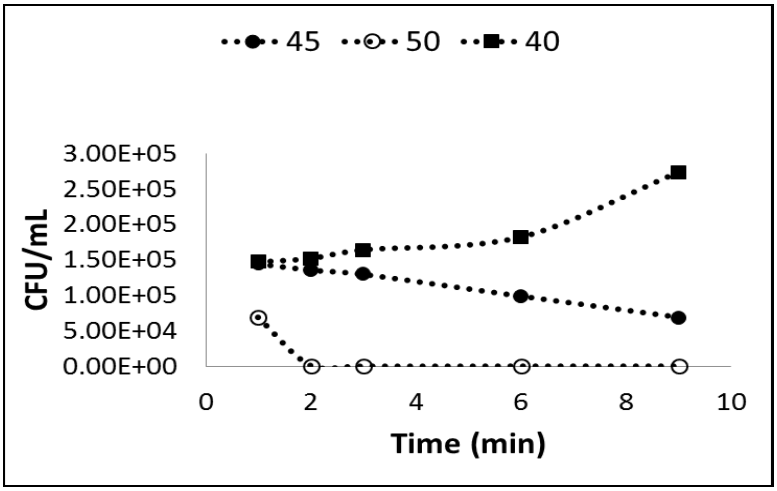

Fig 4.3 (b): Disinfection of E. *coli* at various temperatures and time intervals in water with turbidity of 10 NTU

Heating water for 6 minutes at 60°C resulted in Salmonella *Typhi* (Figure 4.4 a and b) disinfection even in the presence of 5 and 10 NTU turbidity. Hence it was proved that low level of turbidity does not hinder the disinfection process of E. *coli* and Salmonella *Typhi.*

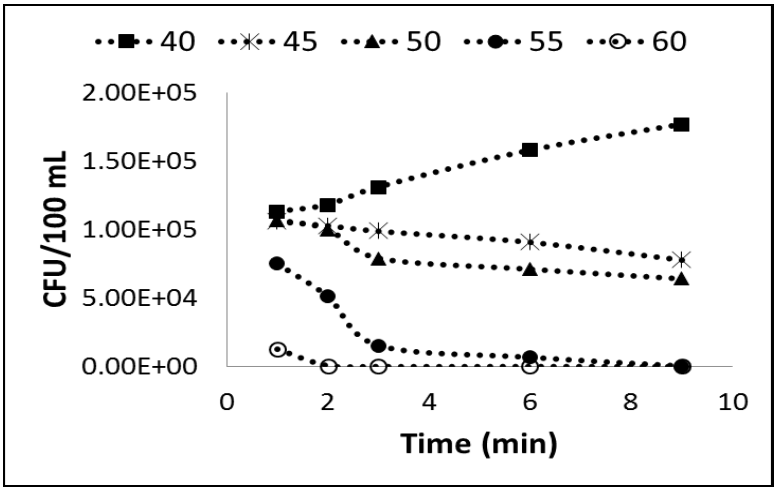

Fig 4.4 (a): Disinfection of Salmonella *Typhi* at various temperatures and time intervals in water with turbidity of 5 NTU

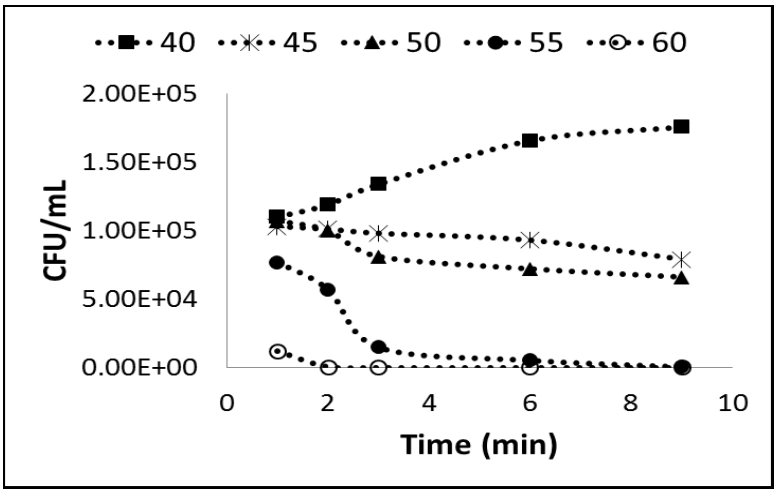

Fig 4.4 (b): Disinfection of Salmonella *Typhi* at various temperatures and time intervals in water with turbidity of 10 NTU

4.4. Ready to Use Pasteurization Unit:

Next step of the research was to bring these efforts and results into a practical and useable pasteurization unit that can help in providing microbiologically safe drinking water at a larger scale. As we know that the purpose of lab scale disinfection unit was to find the optimum conditions that are required to pasteurize the water. Electricity was used as a source of heating in the lab scale disinfection unit but the challenge was

to find a source of energy that can be feasible in remote areas. Several ideas were considered and evaluated financially and environmentally.

After detailed comparison it was decided to use solar water heater as the heating unit for pasteurization as this is the only way in which we can use the natural energy that is abundantly available in Pakistan including the remote areas and is free of cost.

Full scale disinfection unit was designed in a way that time of pasteurization and temperature of pasteurization can be controlled simultaneously along with the utilization of solar water heater.

4.5. Design of Solar Water Heater and Control Unit:

Following components were required to build the required system:

1. Solar water heater
2. Temperature sensor
3. Temperature indicator and controller (with set point adjustment)
4. Time indicator and controller (with set point adjustment)
5. Integration between timer and temperature control
6. Power source of control unit

4.5.1. Solar Water Heater

The solar water heater was placed in an industrial area I-10/3, Islamabad on a roof top in a direction where it can get maximum direct exposure to sunlight. The target was to achieve 60^0C temperature that was found to be the most effective temperature for pasteurization (Figure 4.5)

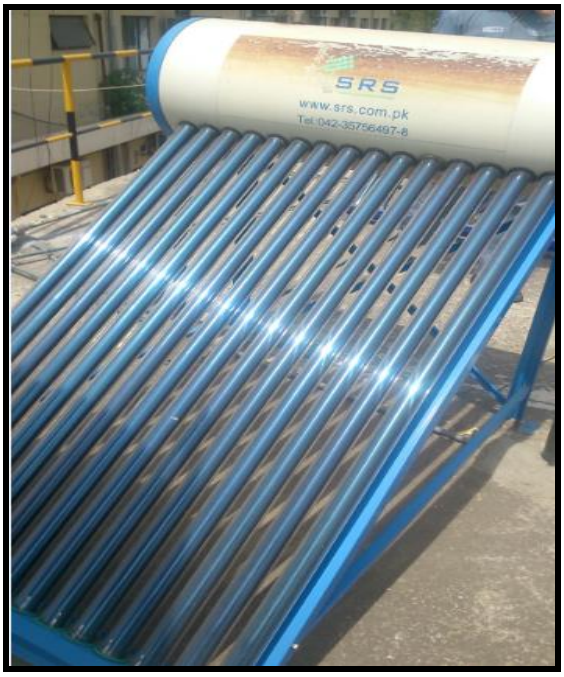

Figure 4.5: Solar Water Heater

4.5.1.1. Specifications of the Solar Water Heater:

1) Inner Tank: 0.4~0.5mm stainless steel
2) Outer Water Tank: Rust Free Color steel
3) Insulation: Polyurethane foam (thickness: 50~55mm)
4) Evacuated Tube: High-quality borosilicate glass
5) Brackets: Imported zinc-coated steel with spraying (thickness: 1.2mm)
6) Reflecting Angle: 38 – 45 degrees
7) Temperature (Sunny Day): 40-96 °C/day
8) Life Of System: 15 years plus

4.5.2. Temperature Sensor

LM35 Precision Centigrade Temperature Sensor was used. Its features are as follows:

1) Calibrated Directly in Celsius (Centigrade)

2) Linear + 10-mV/°C Scale Factor

3) 0.5°C Ensured Accuracy

4) Rated for Full −55°C to 150°C Range

4.5.3. Temperature Indicator

Temperature indicator was used of "KINGBRIGHT" brand of model SA56-11SRDB (Figure 4.6)

Features:

- 0.56 inch digit height
- Low current operation
- Excellent character appearance
- Easy mounting on P.C. boards or sockets
- Mechanically rugged

Figure 4.6: Temperature Indicator

The temperature that was required for pasteurization was set with the 2 (up and down) buttons on the board. The unit saved this temperature in the memory and once the

temperature of water in the solar heater reached the set point, the controller passed the signal to the timer.

4.5.4. Time Indicator and Controller

To control the time of pasteurization, there were 2 buttons (up and down) by which we could adjust the set point. Once the set point temperature was achieved, controller passed the signal to time controller, took the set point time into memory and started the timer (Figure 4.7). Once the set point time was completed, the timer passed the signal to orange big LED light which indicated that the pasteurization process is completed and the valve can now be opened.

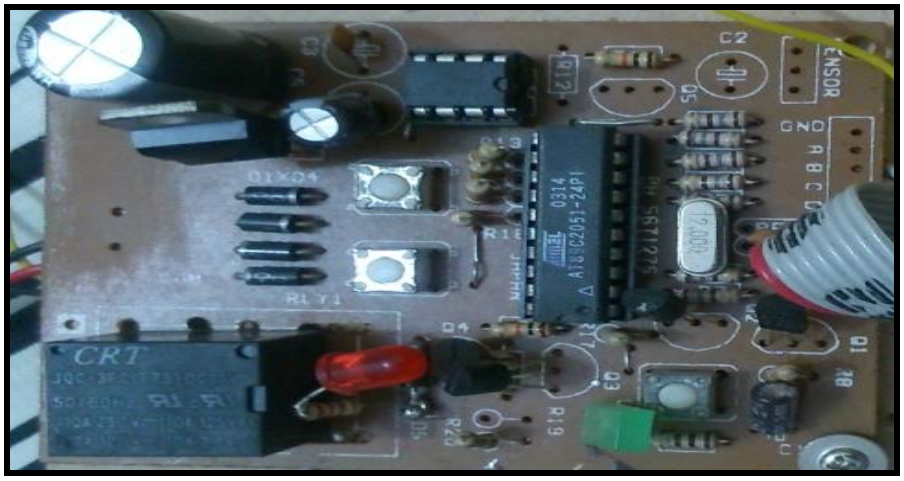

Figure 4.7: Time Controller

We had the option to make the system fully automatic in which the timer directly gave the signal to solenoid valves to open it but this would have required an extra cost and instantaneous requirement of the energy which was not feasible in case of power from solar panel.

As the initial idea was to make the unit to economically provide microbiologically safe drinking water so it was not feasible to increase the cost due to automation.

4.5.5. Integration between Timer and Temperature Control

The temperature sensor was dipped in the solar water heater to sense the current temperature of water. The set point was given to both time and temperature controllers. Once the set point temperature was achieved in the solar water heater, a signal was communicated to time controller to start the timer. When the set point time was also achieved a signal was communicated to LED light that started glowing and indicating that the heating process at a certain temperature is completed for a certain time that was provided (Figure 4.8)

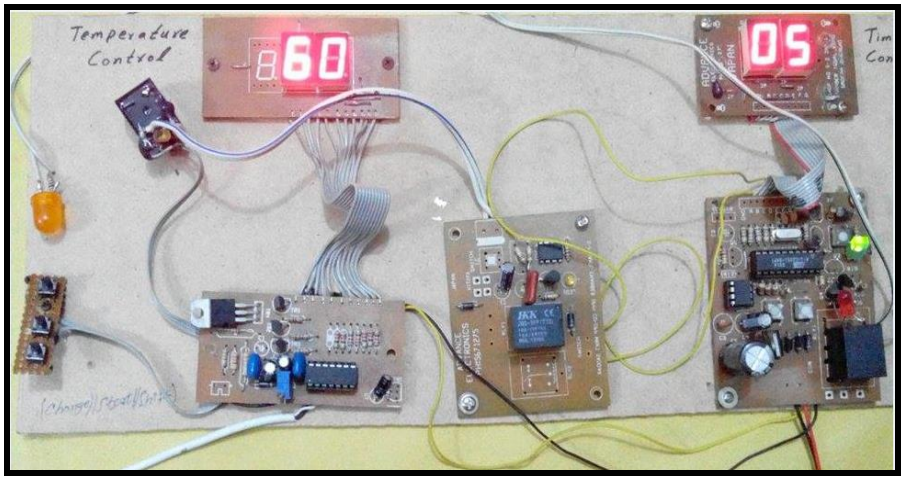

Figure 4.8: Integration between temperature and timer control

4.5.6. Power Source of Control Unit

As the idea was to provide the solar water pasteurization unit in those areas where we have microbiologically unsafe drinking water and there is lack of resources so the effort was in a direction to make this unit totally independent of electricity. The heating was done using the solar energy through the solar water heater but a big challenge was to provide energy to the control unit that contained temperature sensor, temperature set point and timer.

To address this challenge, the control unit was designed in such a way that it could be operated using the output of solar panel. A solar panel was used to charge the battery and the battery was used to supply power to the control unit (Figure 4.9). The purpose of using the battery was to regulate the power and to supply the backup time in night as well as on cloudy days. As the power requirement of control unit is very less so a very small battery was required that was low in cost.

Figure 4.9: Solar Panel

Chapter 6

Conclusion and Recommendations

Conclusion

A pasteurization unit was designed taking into account five key factors i.e. temperature, time, cost, user- friendliness and renewable energy utilization. Following conclusions were drawn from the research work

- Heating water at 50°C for 3 minutes resulted in complete disinfection of E. *coli*
- Heating water at 60°C for 6 minutes resulted in complete disinfection of Salmonella *Typhi*
- Salmonella *Typhi* was observed to be more heat resistant that E. *coli*
- No effect of turbidity was found in case of thermal disinfection of water up to 10 NTU
- It was concluded that boiling of water is not necessary to disinfect it. Heating for few minutes at low temperatures i.e. pasteurization is enough to disinfect it.
- Microbiologically safe drinking water can be obtained using the unit that was developed which is fully dependent on solar energy rather than electricity or any chemical treatment.

Recommendations

- Manual valves may be replaced by solenoid valves.
- Unit may be modified in which a parallel physical water treatment system may be added so that turbid waters may be cleaned prior to microbiological treatment

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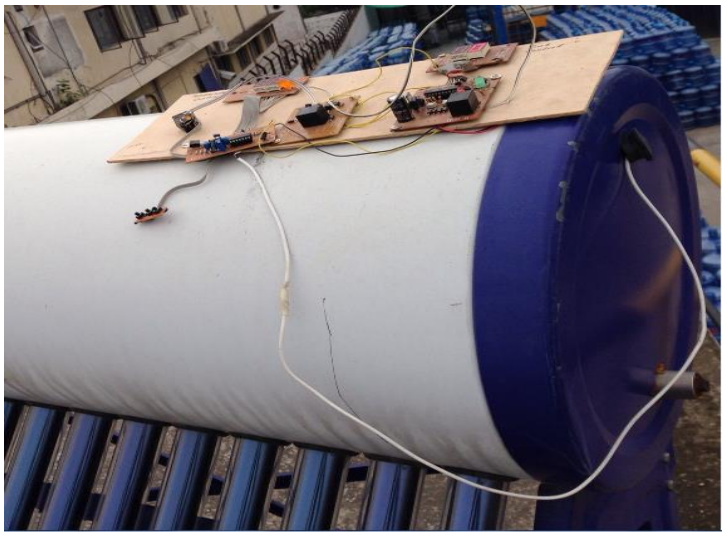
APPENDIX-A



Solar Water Heater and Control Unit

Integration of Solar Water Heater with Control Unit