SOLAR-DRIVEN DESALINATION SYSTEM (SDDS) FOR SMALL SCALE DECENTRALIZED WATER PRODUCTION

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APPROVAL SHEET

Certified that the contents and form of thesis entitled "Solar-Driven Desalination System (SDDS) for Small Scale Decentralized Water Production" submitted by Furqan Arshad, Muhammad Arslan, Muhammad Waleed Waris and Saud Shahid have been found satisfactory for the requirement of the degree.

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Dedication

We dedicate this endeavor to Almighty Allah,

Our families

&

friends

who encouraged us when needed, raised us when we were down and

ultimately helped make this immense task a reality.

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Most of all we are thankful to Allah who gave us the Will and determination to accomplish this task in this manner.

Also we offer our profound thanks to our families and friends whose unwavering love and unconditional support guided us through ultimately making this a reality.

Sincerely,

Furqan Arshad

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Abstract

Solar-Driven Desalination System (SDDS) for Small Scale Decentralized Water Production

Clean potable water suitable for drinking is a major concern in Pakistan. This problem coupled with energy crises raises the need for a sustainable system, whereby drinking water could be provided to areas which have a water source with high TDS. Moreover, SDDS was designed, keeping in view portability, so that it could be applied in remote areas. This system used the basic science of solar still coupled with photovoltaic panels to clean water with low TDS value. The SDDS relied on solar energy. A photo-voltaic module of 230 watt was connected to a DC coil. Upon the supply of electricity from the PV module the coil heats up. It raises the temperature of water in the tank. The vapors generated by the heating water were condensed in the second compartment. The results of this experiment yields water with TDS values within the WHO limits. The results vary from 12 mg/L to 100 mg/L depending upon the conditions were observed. TDS removal efficiency of range 94% to 98% was observed in SDDS. The average volume collected in 12 tests was 0.482 Liter. As the initial TDS and initial volume increases, volume collection decreases. Hence, through this lab scale study it was shown that a good range of efficiency could be achieved with economical and viable design using this method of solar desalination.

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List of Abbreviations

SDDS	solar-Driven Desalination System
RO	reverse osmosis
HDH	humidification–dehumidification
FO	forward osmosis
PVD	passive vacuum desalination
MSF	multi-stage flash
MD	membrane distillation
MED	multi-effect distillation
FM	freezing–melting
ST	solar still
TVC	thermal vapor compressor
MVC	mechanical vapor compressor
ABHP	absorption heat pump desalination
ADHP	adsorption heat pump desalination
ED	electro-dialysis
IE	ion exchange
CDI	capacitive deionization
SP	solar pond

LCZ	lower convective zone
NCZ	non-convective zone
GOR	gained output ratio
UCZ	upper convective zone
PV	photovoltaic
ETC	evacuated tube solar collectors
HP	Heat Pump
ORC	organic Rankine cycle
CAOW	closed air, open water
CWOA	closed-water open-air
DCMD	direct contact membrane distillation
AGMD	air gap membrane distillation
SGMD	sweeping gas membrane distillation
VMD	vacuum membrane distillation
FPC	flat panel collectors
DEAHP	double absorption heat pump
TES	thermal energy storage
CPC	compound parabolic collector
PTC	parabolic trough collectors
CSP	concentrating solar power
EDR	energy recovery device
Ppm	parts per million
TDS	total dissolved solids

1.1. Background

Excessive use of fossil fuels is threatening to change our way of life as we know it. Rising Temperatures and changing landscapes are threatening wildlife and altering weather patterns all over the world. The electricity generation using fossil fuels accounts for nearly one fourth of all the greenhouse gas emissions.

Without a doubt, climate change has emerged as a serious priority for us all. Hence, the rate at which we develop future cleaner energy technologies will determine to a large extent whether this climate crises will remain manageable or will it become a threat to human life.

The availability of high quality drinking water can be assessed by the press release of UNO Secretary General on world water day 2002. “An estimated 1.1 billion people lack access to safe drinking water, 2.5 billion people have no access to proper sanitation, and more than 5 million people die each year from water-related diseases — 10 times the number killed in wars, on average, each year. Water is treated as an infinite free good. Yet even where supplies are sufficient or plentiful, they are increasingly at risk from pollution and rising demand. By 2025, two thirds of the world's population is likely to live in countries with moderate or severe water shortages”.

Water is a necessity to sustain life. Fresh water comprises 3% of the total water on earth. Only a small percentage (0.01%) of this fresh water is available for human use (Hinrichsen and Tacio, 2002). The downside to this is that even this small proportion of fresh water is under immense stress due to population boom, rapid urbanization and unethical consumption of water in industry and agriculture. According to a United Nations report, the world population is increasing exponentially while the availability of fresh water is declining. Many countries in Africa, Middle East and South Asia will have serious threats of water shortage in the next two decades. In developing countries the problem is further aggravated due to the lack of proper management, unavailability of professionals and financial constraint (PCRWR, 2005).

As is the case with all the developing countries of the world, Pakistan is also facing critical water shortage and pollution. The country has almost exhausted its available water resources (PCRWR, 2005); Pakistan is considered as water stressed and is likely to have a water scarcity in the near future (Hashmi et al., 2009a and WWF, 2007). An important aspect is that the water precipitation rate is lower than the evaporation rate in the country, which further causes a continuous decrease in water quantity in its rivers, lakes and diminishing the groundwater as well. Moreover, this problem is further worsened by factors like long droughts and lack of construction of new water reservoirs (PCRWR, 2005 and Ullah et al., 2009).

This decrease in water quantity along with the increasing demand of water resulted in severe water shortage in almost all sectors of the country. The per capita water availability in the country dropped from 5000 in 1951 to 1100 m^3 per annum (WB-SCEA, 2006). Rapid exponential increase in the population of Pakistan with no development of new water resources may cause per capita water availability of less than 1000 m^3 from the year 2010 onwards. The situation may get worse in areas situated outside the Indus basin where the average per capita water availability per annum is already below 1000 m^3 (PAK-EPA, 2005b).

In some areas, such as the drought-affected areas of Sindh, people already have no fresh water for drinking and are compelled to drink brackish water (Ullah et al., 2009). In Baluchistan, the underground aquifers are dropping at a rate of 3.5 m annually and will be exhausted in the next 15 years (Sajjad et al., 1998). This deadly combination of decreasing quantity and increasing usage in multiple sectors has no doubt, adversely affected the quality of water. It has created a serious problem of water pollution. As is the case that water quality in most of the rivers, lakes and ground aquifers of the country is considered unsafe for human consumption.

Water desalination is now becoming a solution for providing drinking-water in several countries around the world. The desalination of saline water has been recognized as one of the most sustainable and new water resource alternative. This also plays a crucial role in the socio-economic development for many communities and industrial sectors. At the moment there are more than 14,000 desalination plants in operation worldwide producing several billion gallons of water per day. Fifty-seven percent are in the Middle East and Gulf region where large scale conventional heat and power plants are installed.

With the fluctuation in fossil fuel production and prices these power plants, are becoming expensive. With the involvement of fossil fuels, the operation cost and the greenhouse gas emissions they produce have been deemed as harmful to the environment. In remote areas or even near coastal areas where salt water is abundant, such a plant may not be economical. Most of the areas around the world experience fluctuations in fossil fuels and irregular supply of electricity.

Hence, renewable energy coupled with desalination and water purification is now becoming the choice as the cost of conventional systems is increasing. Moreover, as the international community move towards reducing the greenhouse gas emissions and achieving energy targets through the use of renewable energy it is now more important than ever to focus on green technology.

Thus, solar energy could provide a sustainable alternative to drive the desalination plants, especially in countries which lie on the solar belt such as Africa, the Middle East, India, and China.

1.2. Concept of desalination

Desalination is the process in which saline water (high TDS) is converted into water with low TDS. The system is divided into two parts- one of it has a low concentration of dissolved salts and the other has a higher than original concentration of salts. (Buros, 2000) The former could be termed as fresh water while the later could be termed as either brackish water or seawater depending on the salinity and water source.

1.3. Renewable Energy in Desalination

In total about 1% of total desalinated water is being produced from renewable sources. As the usage of renewable energy is gathering more and more attention and technology prices are decreasing, there is a lot of potential for renewable energy powered desalination systems worldwide.

Renewable technologies which are applicable to desalination include solar thermal and PV, wind and geothermal energy. Another aspect to this is that as electricity storage is a challenge, combining power generation and water desalination can also be an effective option for electricity storage when generation exceeds demand.

The following figure shows the integration of renewable energy technologies with desalination:

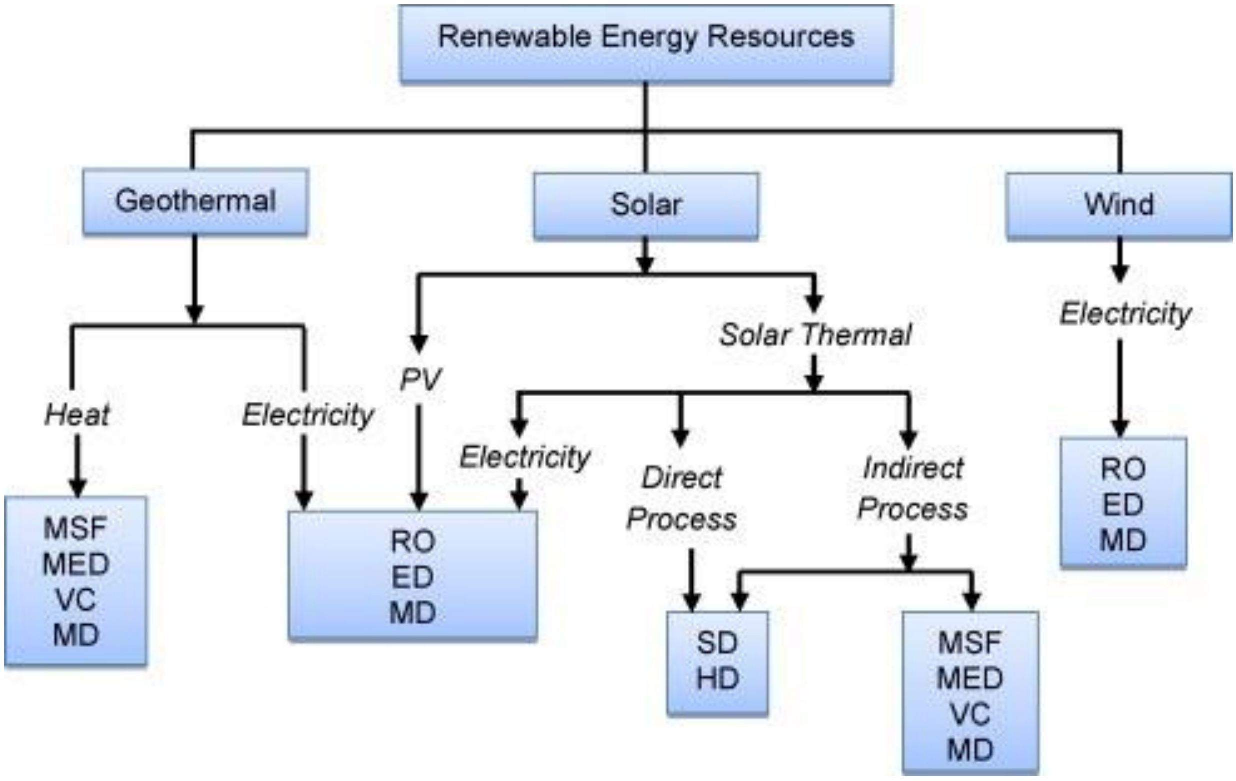

Figure 1.1. Combinations of renewable energy resources with water desalination technologies (Shatat & Riffat, 2012).

Another advantage of solar water desalination technology is that during the peak demand of water the energy harnessed is also at its peak. Similarly, there has been a considerable development of affordable solar energy technologies which will have a significant impact and long term benefits. Moreover, such a technology will also increase energy security and decrease energy poverty through the use of indigenous, inexhaustible and most importantly a resource which will enhance sustainability, reduce carbon emissions and lower the cost of battling climate change (International Energy Agency, 2011).

1.4. Solar water desalination technologies

Desalination of water through solar energy traces its roots way back to the sixteenth century. The first use of solar stills was in 1872, by the Swedish engineer, Carlos Wilson, who built a large scale solar still to supply drinking water to a community in Chile (Intermediate Technology Development Group, 2007).

Solar energy can be captured for use by either photovoltaic (PV) and solar collectors or through solar ponds as thermal energy (Quteishat & Abu-Arabi, 2012). Such desalination systems are divided into two categories, direct and indirect systems as shown in Figure 1.2.

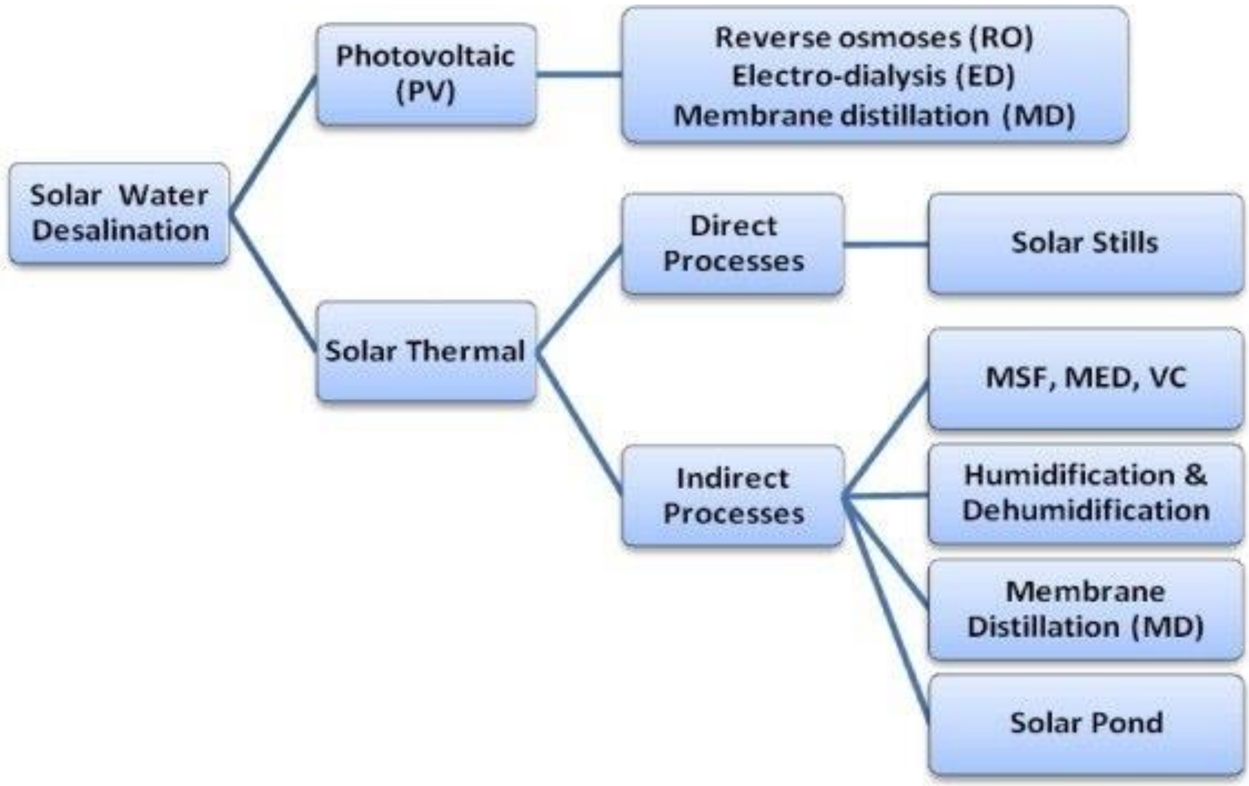

Figure 1.2. Probable configurations of solar energy resources with water desalination technologies.

1.5. Proposed Solution

After taking into account the aforementioned details and discussions, the indirect process of humidification and dehumidification was selected. In this process, water with high TDS is evaporated with the use of thermal energy and the subsequent condensation which is produced produces freshwater. This system is maintained at atmospheric pressure (DESWARE, 2007). Air has the capability to hold extensive quantities of water vapor, this quantity may increase with the increase in temperature as the capacity of air to hold vapor increases with temperature. (Parekh, Farid, Selman, & Al-hallaj, 2004). Many studies on desalination using humidification–de humidification have been conducted with a variety of devices (Orfi, Galanis, & Laplante, 2007). The principle of this process is based on evaporation of water and the subsequent condensation from humid air.

Using high efficiency mono-crystalline photo voltaic panels, the necessary thermal energy was provided to the humidification-dehumidification system. Water samples with varied TDS were tested and efficiency was noted.

1.6. Present Study

The use of humidification-dehumidification process for desalination was used to test the TDS removal efficiency of such a system for saline water of Pakistan. The objective of this study was as follows:

- Designing a lab scale humidification-de humidification system
- Solar energy feasibility- Pakistan
- Testing removal efficiencies for water samples
- Fine tuning the design to achieve high removal efficiency

2.1. Solar Radiation in Pakistan

Pakistan is estimated to possess a 2.9-TW solar energy potential. Photovoltaic units have been installed in mosques and schools and used for solar lanterns, solar home light systems, street and garden lighting and telecommunications.

It further stated that the maximum amount of solar radiation in Pakistan is around Quetta. The breakdown was as follows:

- Sindh and Baluchistan: > 440 cal/cm^2 day
- Punjab and KPK: 400-440 cal/cm^2 day
- Northern areas and Kashmir: < 400 cal/cm^2 day

Daily average global irradiation is estimated to be about 200-250 W/m^2 which amounts to about 6840–8280 MJ/m^2 in a year. (Bhutto et al., 2012)

2.2. Humidification-Dehumidification System

A system with main components are humidifier (evaporator), dehumidifier (condenser), and solar water heater (evacuated tube solar collector). This system was based on an open cycle for water and closed cycle for the air stream. The HDH system consisted of three loops. Two loops were for the water (one for hot brackish water and the other for cold brackish water) and the third one was for the air. In hot water loop, the hot water was delivered from the evacuated tube solar collector through a hot water pump and sprayed by using a hydraulic grid at the top of the humidifier. The hot water was sprayed on the packing material to increase the contact surface area of air and hot water. The packing was supported such that it did not block the air flow path and remained continuously wet. The air was circulated either by natural or forced circulation. Forced circulation is carried out through a pump.

This study concluded with the following results:

- The maximum productivity could be obtained when the ratio of cold water at dehumidifier inlet to hot water humidifier inlet is twice.
- Forced air circulation gives higher performance.
- Wet surface area is the main parameter for HDH desalination system and affects the performance of the unit. (A.E. Kabeel, 2014)

2.3. Desalination through solar stills

These systems are direct as the thermal desalination processes take place in the same device and it is mainly suited to small production systems, such as solar stills, in regions where the freshwater demand is less than 200 m^3/day (Ma & Lu, 2011).

It represents a natural hydrologic cycle on a small scale. The simple solar still is shown in Figure.2.1.

This still is working to trap the solar radiation. The transparent cover lets the radiation pass through and into a basin containing salt water, a pair of glass or plastic panels which may be sloped at an angle above the basin and connecting at the apex. Hence, creating a structure similar to greenhouse. It is generally painted black to maximize the absorption of the long wave radiation falling at the top.

Solar radiation falls on the inclined panels and the greenhouse effect that is produced in the inside. This raises the temperature of the salt water in the basin. Surface water is evaporated, the water vapor rises in the still and reaches the sloping panels, where it condenses to liquid water and finally runs down the side of the panel. The water is collected and drawn off to provide fresh water. Solar stills can produce 3–4 L of fresh water per day per square meter.

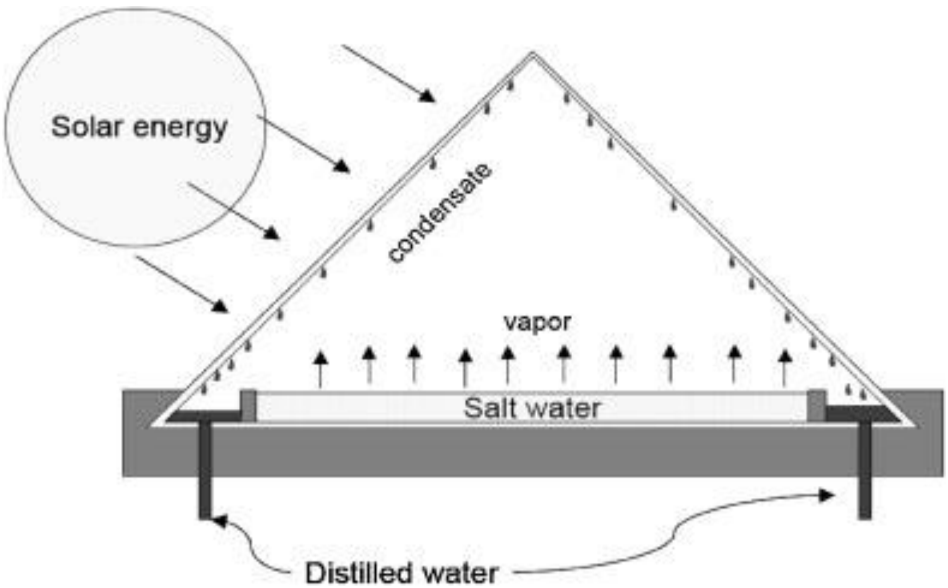

Figure 2.1. Solar still desalination unit (Ali et al., 2011).

Desalination of the brackish water using a passive solar still (Omar Ansari, 2013) with a heat energy storage system put under the basin liner of the still is analyzed. From this study, the following conclusions can be drawn:

- Excess energy produced during sunshine times is stored in the PCM for use later during the night or even to provide energy during cloudy days.

- The heat energy storage enhances significantly both the productivity of the fresh water and the efficiency of the distillation system.

- We expect that the cost of one liter of fresh water will be weakly affected by the implementation of the storage system in the solar still device. This could be proved by an economical study of the entire system.

Another new design of solar still was proposed (Figure.2.2.) which significantly increased the water output without neglecting the key advantages of the still. Based on the experimental study and the cost analysis conducted, the following conclusions were deduced:

- The introduced rotating cylinder significantly accelerated the evaporation process and results in a 200–300% enhancement in productivity compared to the control. The enhancement in productivity due to this low-cost amendment exceeded that of many of the complex modifications introduced to the solar still before.

- An economic assessment of the proposed system revealed that the cost per unit water produced is comparable to that reported in the literature for other renewable-based desalination methods.

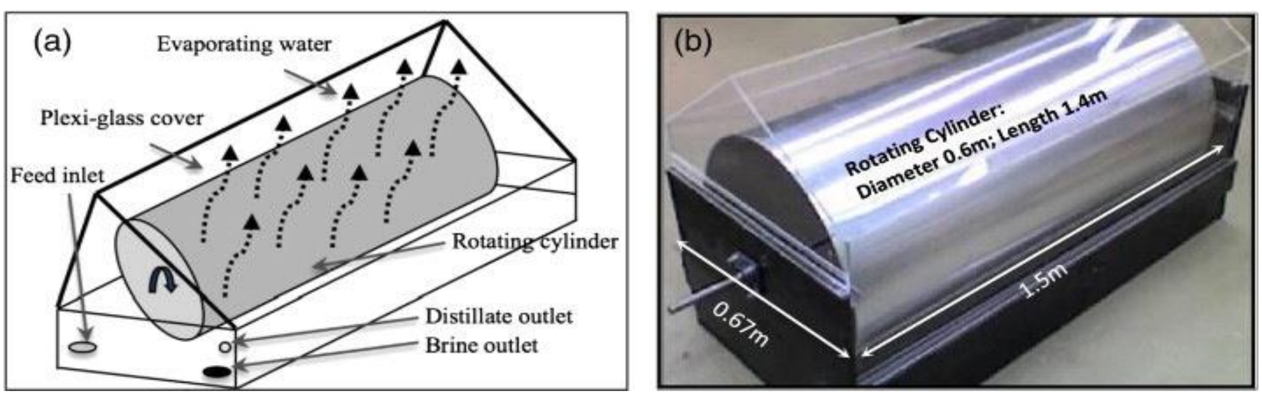

Figure 2.2. a) Modified solar still with introduced drum; (b) Photo of the system during construction.

2.4. Multi-effect solar desalination system

The main objective of this work was to determine the operational and performance characteristics of the system with use of packed porous plastic balls and finned heat exchangers. The effect of operating parameters such as the heating temperature, the seawater flow rate (Mw) and the air flow rate (Va) on the system performance was studied.

The aforementioned experiment study was performed to investigate the influence of the operating conditions on the performance of this desalination system. The experimental results indicated that this unit had a good productivity performance due to re-utilization of the latent heat of condensation of vapor between the two desalination loops. Use of the heat exchangers with corrugated fins in the dehumidifiers and also porous plastic balls humidifiers had enhanced the condensation and evaporation process by increasing the contact surface area. (Zehui Chang, 2014)

2.5. Two-stage solar humidification–de humidification desalination process

The paper experimentally evaluated a two-stage technique to improve the humidification–dehumidification process in fresh water production from brackish water. According to the modelling results of multi-stage process and on the basis of construction cost estimation, using a two-stage process is the most suitable choice that can improve important parameters such as specific energy consumption, productivity and daily production per solar collector area and thus, investment cost.

This unit was tested on hot and cold days. The production varied from 580 l/day in summers which was twice that of winter. Moreover, fresh water production could reach by 7.23 ($l/day\cdot m^2$) (M. Zamen, 2014).

2.6. Improvement techniques to increase solar still efficiency

In order to improve the efficiency of the solar still (V. Sivakumar, 2013) several techniques were tested. The results were: Any heat storing method in solar desalination process is effective as compared to that without heat storage. The sun tracking system is more effective than fixed system and it is capable of enhancing the productivity of the still. The solar still coupled with solar collector, solar pond, cooling tower and additional condensation on sidewalls of the basin shows better performance.

In 2000 a study was conducted to observe the efficiency of single basin and multi effect solar water desalination was critically reviewed with special emphasis on the humidification and dehumidification water desalination systems. The multi effect solar desalination units are found to be more efficient but they are not economical. On the other hand, single basin desalination systems are less efficient but economical. However the humidification and dehumidification systems are not much efficient as well as not much economical but if they are modified (like utilization of waste heat of condensation for external usage), they can be used for beneficial purposes. In the case of humidification-dehumidification systems, the energy costs associated with the condensers and pump operation as well as the energy saving associated with coupling the system to waste heat energy sources may end up being crucial in developing a commercially viable system (Goosen et al). The most interesting aspect of humidification dehumidification process is the use of this technology to create greenhouse effect for plant growth under controlled conditions as described by Paton and Davis

It has been demonstrated (by Caruso et al.) that it is possible to separate salts from seawater by using full-titanium made desalinator along with a small solar pond. Solar pond is used as a source to run the desalination unit. The development of thermal processes of desalination as multi-effect distillation (MEF) and multi-stage flash desalination (MSF) permit operation with a temperature range around 60-70°C. In this case it is possible to use solar pond technology as a heat source where seawater or brackish water is available to produce fresh water (G.Caruso et al.). From technical perspective the above mentioned technology was found out to be satisfactory but there are several interesting commercial perspectives for this technology, with the possibility of economic profitability in remote areas.

World is consuming a large amount of fossil fuels for the desalination process. Solar desalination is emerged recently as renewable energy powered technology for the generation of fresh water. According to Parekh et al., solar desalination based on the humidification dehumidification cycle presents the best method of solar desalination due to overall high-energy efficiency. The effect of water flow rate on the performance of the unit is important but the effect of air flow rate on productivity is termed insignificant by most of the researchers. They concluded that surface area of condenser and evaporator is one of the most important controlling factors in the productivity of humidification and dehumidification process. Although solar desalination units based on the HD principle have been in existence for a while, more work needs to be performed to increase the productivity and decrease the cost of water produced from these units (Parekh et al.).

A closed circulation desalination unit based on humidification dehumidification principle is much preferred as compared to open circulation desalination unit. It can operate 24 hours a day according to Yuan and Zhang. There are several factors that can affect the productivity of fresh water. For a fixed solar area an increase in the feed water flow rate will decrease the fresh water production. The proportion of cooling water flow rate with solar area is very important. Weather can affect the production of fresh water. The year-round study shows that in Xi'an, China, 5.2 $kg/m^2/d$ of fresh water can be obtained in June and in December, 2.7 $kg/m^2/d$ can be reached (Yuan and Zhang).

In a study conducted in 2006, a mini solar pond assisted solar still is studied and in the mini solar pond, experiments were performed for different salinity. It was observed that the heat storing capacity of the solar pond increases by increasing the salt concentration in the pond but the optimum value of salinity is 80 g/kg of water. Different types of solar stills were studies like ordinary still, still with sponge, still integrated with a pond, and still with sponge integrated with mini solar pond. The average production of distilled water has been increased while using sponged solar still integrated with a mini solar pond. The average distillate productivity of a mini solar pond integrated with sponged still is 57.8% more than productivity of ordinary still. (Velmurugan and Srithar).

The experimental setup unit was consisting of a solar parabolic trough with focal pipe and simple heat exchanger. Oil was the working fluid and was forced flowing as cycle through the focal pipe and serpentine. The oil in the heat exchanger is heated during the sunlight by two sources, direct solar radiation and solar energy concentrator (solar parabolic trough). The saline water is heated directly by solar radiation and also, by the oil in the heat exchanger as the oil cycle. The experiment yields that this modified system has more productivity. The fresh water productivity is increased by an average percentage of 18%, according to the modification design (Abdel-Rehim and Lasheen). Moreover, the productivity also declines before sunset due to variation of solar radiations.

Realia and Modica used the tubes for sea water desalination. The evaporation section was made up of horizontal transparent thin-walled plastic or glass tubes that were half-filled with sea water which absorbs solar radiation. The condensation section is physically isolated from the evaporation section in a shaded place, and comprised of horizontal plastic or metal tubes of relatively smaller diameter. Water vapors formed in the evaporation tubes got condensed by transferring their latent heat to the atmosphere. Enhanced fresh water productivity is achieved with respect to conventional solar stills in which sea water evaporation and water vapor condensation occur in one confined space (Realia and Modica).

In 2006 Qiblawey and Banat compiled different methods of solar desalination. According to the authors, solar desalination can either be direct i.e. use of solar energy to produce distillate directly, or indirect i.e. combining conventional desalination techniques, such as multistage flash desalination (MSF) with solar collectors for heat generation. The direct solar energy methods were more appropriate for very small water demands and where large land is available. However, they are preferred to the indirect systems due to their simplicity and low cost. In indirect solar desalination two sub system were applied one for desalination and other for solar energy collection. Solar thermal desalination plants utilizing indirect collection of solar energy can be classified into the following categories: atmospheric humidification/dehumidification, multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC) and membrane distillation (MD) (Qiblawey and Banat).

A closed circulation humidification dehumidification process was studied. The hot water was used to heat and humidify the circulated air and that hot water is obtained from the solar collector or from electric heater. Latent heat of condensation was recovered in the condensation chamber and used to pre-heat saline water. The designed unit has greater efficiency than conventional solar stills. The unit production first increases upon increasing the flow rate to an optimum value but beyond that value the unit production decreases with increasing water flow rate (Farid et al.). This is because increasing the water flow rate increases both heat and mass transfer coefficients as well as the solar collector efficiency. On the other hand, it lowers the water temperature and hence lowers the evaporation and condensation efficiency. The effect of air velocity is quite ignorable at high temperatures. This suggests that this setup can be operated with natural air circulation at high temperatures, and with forced circulation at low temperatures.

There are several techniques that are being used for the desalination of seawater. Among them the multiple-effect boiling (MEB) system and, in particular, the multiple-effect stack (MES) type evaporator, is the most appropriate for solar energy utilization since it can be used under varying energy supplies without upset (Kalogirou). In multiple-effect boiling (MEB), the steam from one effect is used as heating fluid to heat fluid of another effect which, while condensing, causes evaporation of the saline water. In multiple-effect stack (MES), sea water is sprayed into the top of the evaporator and descends as a thin film over the horizontally arranged tube bundle in each effect. Among all other desalination techniques these two methods (MES and MEB) are most preferred because they are simple, has a low specific energy requirement and low equipment cost. There are two basic types of solar assisted technologies first is thermal process, and second one is membrane processes. Solar assisted thermal processes include multi-flash (MSF), multiple effect desalination (MED) and mechanical vapor compression (MVC) while membrane technologies mainly include reverse osmosis and electro dialysis. Thermal processes have advantages over membrane processes as they produce higher quality product water, less capital cost and less rigid monitoring than for membrane replacement. A study conducted by Al-Mutawa et al. in 2003 demonstrated a lab-scale unit for solar-assisted single stage/effect evaporation desalination process. The study has provided validation of concepts related to full-scale solar-assisted desalination plant for commercial purposes. Hot air is used for desalination purposed. The outlet temperature of the flowing air increases with the increase of the collector length and breadth as well as with collector tilt angle. The temperature of outlet air deceases with mass flow rate. The result from the simulation indicated that this system would be able to produce the required hot air with temperature in the range of 40° to 50°C in order to dry the drying product chosen (Al-Mutawa et al.).

One of the most important driving factors of any technology is the economics related to that project. A study conducted by Banat and Jwaied shows the economics of a solar desalination unit. Large autonomous solar powered membrane desalination systems were economically examined for the supply of potable water in the arid areas. It is found that solar powered membrane desalination technology still expensive compared to other desalination processes, although the desalinated water was produced using solar energy (free energy). The water production cost was calculated to be \$15/m^3 to \$18/m^3 from the given system (Banat and Jwaied). It was found that increasing the reliability of the membrane distillation technology and plant lifetime could reduce the cost of the produced water significantly.

Budihardjo and Morrison studied the performance of water-in-glass evacuated tube solar water heaters using experimental measurements of optical and heat loss characteristics. The water-in-glass evacuated tubes solar water heater was found to be the most commonly used type of evacuated tube collector because of its higher thermal efficiency, simpler construction requirements and lower manufacturing costs. A water-in-glass evacuated tube solar water heater comprised of 15–40 flooded single ended tubes, connected to a horizontal tank. The solar absorber tube consists of two concentric glass tubes sealed at one end with a vacuum space and a selective surface absorber on the outer surface (vacuum side) of the inner tube. Natural circulation of water through tubes cause the heat transfer in this collector. Water in the tubes is heated by solar radiation, moves up to the storage tank and is replaced by colder water from the storage. The performance of evacuated tube collector system was found to be less sensitive to tank size than flat plate collector systems. Comparison between water-in-glass evacuated tube solar water heaters and flat plate systems operating in Sydney shows that an evacuated tube system with 30 tubes has slightly lower energy savings than a two panel (3.7 m^2) flat plate system (Budihardjo and Morrison).

Solar ponds are a source of renewable heat energy and are used for desalination purposes. A solar pond is a shallow water body which behaves like a solar collector with integral heat storage for providing thermal energy. There are two basic types of solar ponds: Convective and Non-Convective. The deep salt-less pond and the shallow solar pond are the types of convective ponds while salinity gradient solar pond (SGSP), membrane solar pond and polymer gel layers solar pond are types of non-convective solar ponds. Incident solar radiations are collected and stored which may be delivered as thermal energy i.e. temperature near 100 ^oC. The salinity gradient solar pond is the most environment-friendly among all the solar energy systems and has wide range of applications like hot water applications in agriculture, electricity generation, desalination, green house heating, domestic hot water production and cooling of buildings (Saifullah et al.).

According to Samee et al., southern and south-western regions of Pakistan have serious issues regarding the availability of potable water and it poses a big problem for health of general public. The underground water resources, where exists, are usually brackish and water is unfit for drinking purposes. The most economical and easy way to accomplish this objective is using solar still as Pakistan has vast solar potential that can be exploited to convert saline water to potable water. A single basin solar still was fabricated and tested for treatment of desalinated water in Islamabad. The bottom area of the still was 0.54 m^2 and was made by using galvanized iron sheet of 18 gauge thickness. The side and bottom of the basin were insulated by 3 cm thick thermo pore sheet surrounded by a wooden frame of 2 cm thickness. The surface of the basin was painted black to absorb maximum solar radiations as black colored surfaces are the best absorber. The optimized glass cover angle was 33.31^{o} for PIEAS, Islamabad (33.31 ^{o} N latitude) and the efficiency was calculated as 30.56% (Samee et al.). This efficiency is same as that of conventional stills and hence this technology can be adopted to provide fresh water to rural population.

Seawater reverse osmosis technology is adopted at industrial scale in various coastal areas around the globe with limited natural hydrological resources. There are many technological innovations which are trying to improve the reverse osmosis desalination process. Lowest water cost can be achieved by the adaptation of improved research technologies on desalination plants which will entail a decrease in energy consumption. The energy consumption has been reduced dramatically these days. According to Baltasar and Rodríguez there are even cases that has lowered the cost to 2.00 kWh/m^3 and this has been possible because of the development of more efficient membranes, the use of energy recovery systems, new materials with less friction and variable speed engines.

3.1. Materials:

Following materials were used for the construction and fabrication of desalination chamber lab equipment used in the study are also listed.

3.1.1. Desalination Unit

- **Acrylic Sheets** of following thickness were used:
- 2mm for roof top
- 6mm for chamber construction
- **Heating element** with rating of 1000 W. The element was made up of silver metal. The element takes input current as DC.

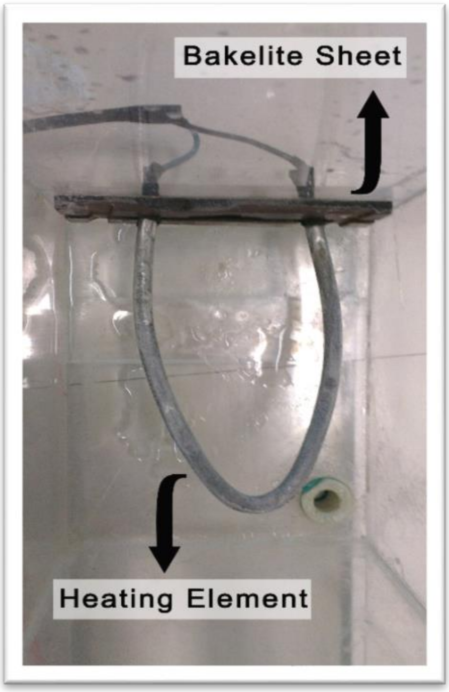

Figure 3.1. Heating Element and Bakelite Sheet

- **Bakelite sheet** of $50cm^2$ and 0.6cm thickness was used as an insulating material where the coil's terminal subjected out of the acrylic sheet. It was also used to protect acrylic sheet from melting down. It is heat resistant and non-conductor of electricity.

- **Roof Top Sliders** were used in order to make the roof slide able. This was done in order to clean, pour water and to provide other maintenance of the chamber.

Figure 3.2. Moveable Sliders

- **GMSA Elfy** was used in order to bind the acrylic sheet to build up the desalination unit.
- **Silicon** was used as a sealing material. It was used to stop leakages.
- **Chloroform mixed with acrylic powder solution** was used to stop any further leakages and isolate the box completely at intersections.
- **Acrylic cutter** was used in cutting the acrylic sheets properly and according designed dimensions
- **Black matte paper** was pasted outside the operating chamber of desalination unit. This was done to entrap maximum heat energy in open atmosphere.
- **Black insulation tape** was used to paste the black matte paper.
- **Thermometer** of range -10 ^oC to 110 ^oC was hung inside the operating chamber with the coil in order to note timely temperature of feed water.

- **Plastic Stoppers** were used on the bottom of both operating chamber and water receiving chamber. This was done in order to remove water completely from both chambers.

3.1.2. Wiring and Solar panel

- Two **Solar Panels of 150 Watt and 80 Watts** were used manufactured by MINGLY Germany.

Figure 3.3. Solar Panel (150W)

- A series module was made of both the panels to get a collective power. The real time outputs were measured as follows:

- Voltage: 19.5 Volt
- Current: 10.75 Ampere
- Power: 211 Watt

- **Fuse** was used of 13 Ampere rating. This was used in order to save the solar panels if any unwanted event takes place.
- **Insulation tape** was used to bind the joints made in wiring.

- **6 meters long copper wire** was used to connect the coil terminals and the Solar panel directly.

3.1.3. Lab equipment and Sample preparation

- **Sample preparation** was done in the lab. The water was taken from IESE water treatment lab's tap. The required concentration of TDS was made by adding salt.
- **Sodium Chloride (Nacl) salt** was used to bring up the required concentration of TDS in the tap water. It was well stirred in order to get the correct conductivity reading.
- **0.5 Liter measuring cylinder** was used to measure the required volume of water and added inside the operating chamber of Desalination Unit.
- **Conductivity meter** was used to measure the conductivity of the prepared sample. From the measured conductivity by inserting the probe, TDS was measured.
  TDS is measured by multiplying conductivity (µS/cm) by the factor of 0.49.

Figure 3.4. Conductivity Meter

3.2. Methods

3.2.1. Design of Desalination Unit

3.2.1.1. Fabrication

Under the following design the unit was fabricated. The 6mm and 2mm sheets were cut by acrylic cutters according to proper dimensions. Their edges were feathered by filing. The heating element was then placed at its designated place and holes were drilled inside the sheet for termination subjection of element, two holes were drilled at the bottom of each chamber. GMSA Elfy was used for tacking and constructing of whole unit. Chloroform and Acrylic Powder mixture solution was used to seal the intersections.

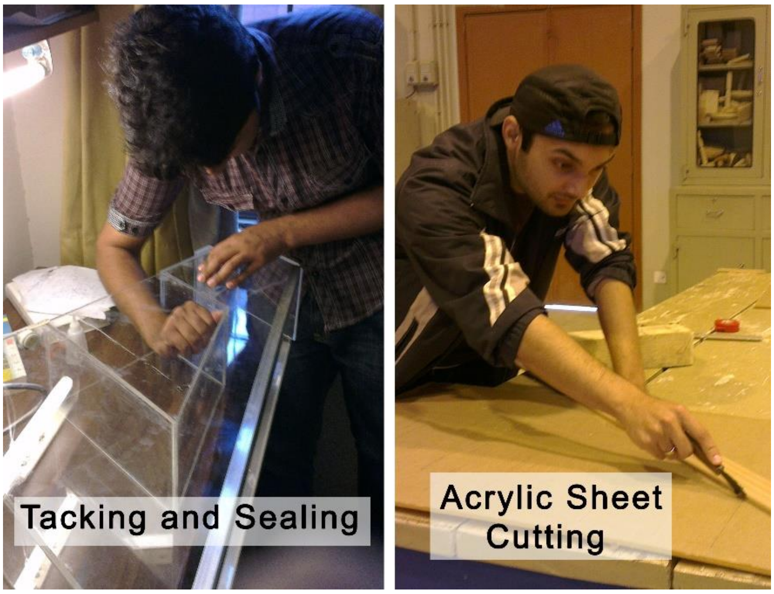

Figure 3.5. Fabrication

3.2.1.2. Design

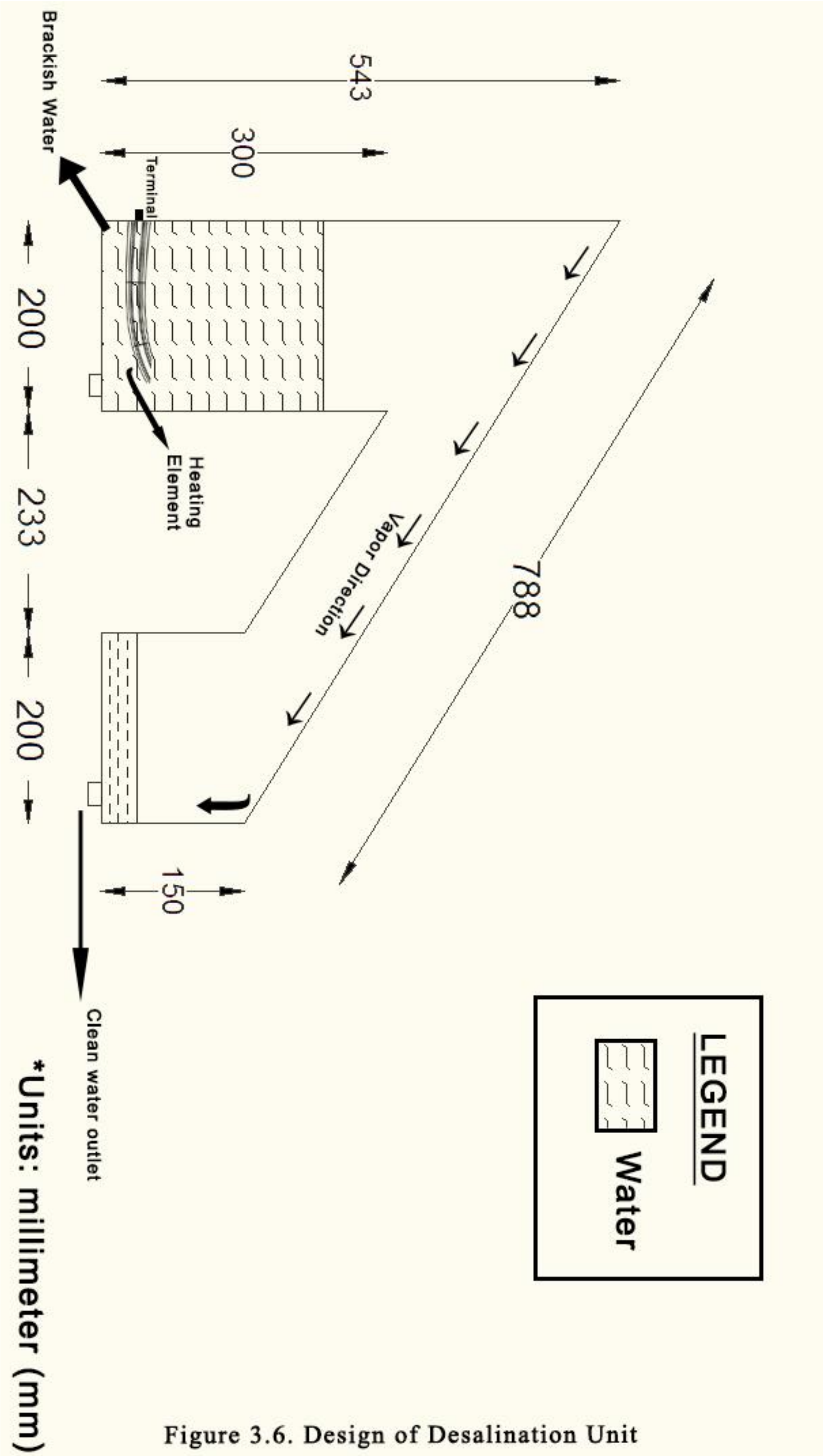

Figure 3.6. Design of Desalination Unit

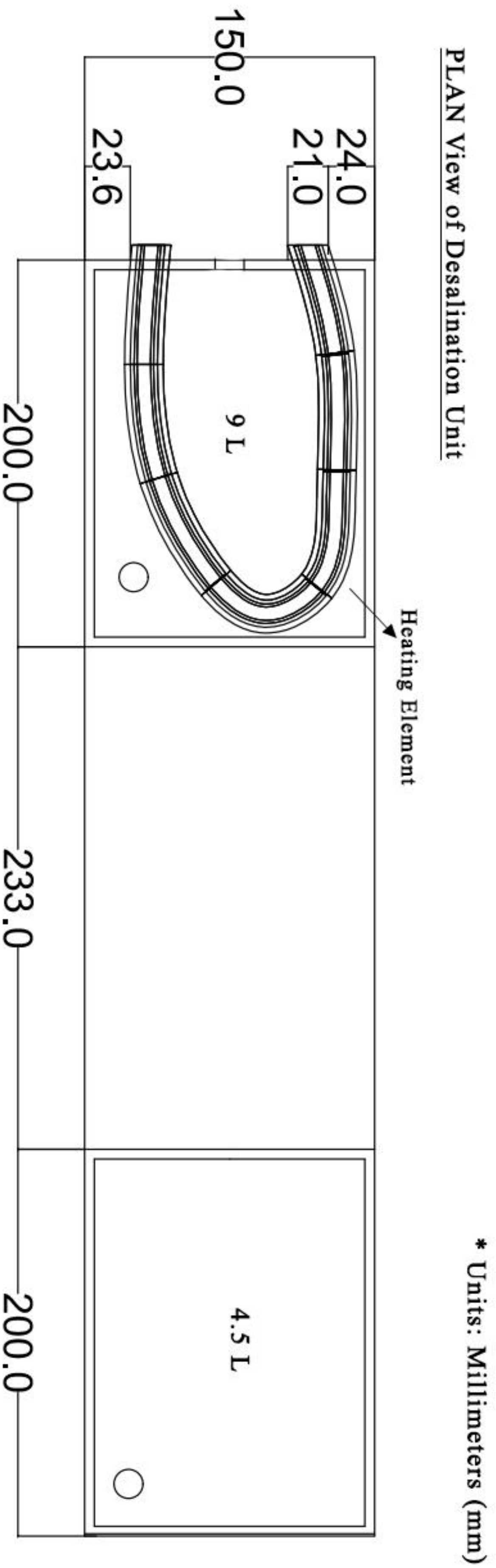

Figure 3.7 PLAN View of Design

The operating chamber with brackish has maximum capacity of 9 liter. It has dimensions of 300 x 200 x 150 mm. it is made up of 6mm acrylic sheet which is bonded with GMSA Elfy and Chloroform. There is a small outlet provided at the base of this chamber to effectively remove the water. The heating element is also installed in this chamber. It is made up of silver and has a rating of 1000 W. Bakelite sheet is attached to the inside surface of acrylic sheet from which the element's terminals are coming out. Bakelite sheet helps providing thermal insulation for acrylic and prevents it from melting down. It also is used for removing any contact of element with the acrylic sheet.

A thermometer is of range -10 ^{o}C to 110 ^{o}C is hung from top of the chamber till it is submerged inside brackish water to note the timely readings. This chamber is well pasted with black matte paper from outside which provides maximum heat trapping. As the water evaporates it goes inside the duct which is tilted at 33.7 (Latitude of Islamabad). The duct has total length of 788mm. The inside length of the duct is 290mm. The upper surface (rooftop) is made up of 2mm thick acrylic sheet. The roof sheet is made sliding for maintenance and water addition purposes. Aluminum sliders are attached to the rooftop.

As the droplets hit the top surface, they lose energy. After sometime humid environment is created inside the chamber. The droplets start to condense and through the duct they reach the receiving chamber. Receiving chamber is total of 4.5 liter in volume with dimensions of 200 x 150 x 150 mm. It is too made up of 6mm acrylic sheet and have a water outlet at the bottom for effective removal of water. It is bonded with GMSA elfy and Chloroform acrylic Powder solution to avoid and account for any leakages. This chamber is not protected any black paper or sheet.

The desalination unit must be well insulated and should have minimum vapor loss through any open joints. The terminal of heating element are subjected out through 50 cm^2 Bakelite sheet placed on inside of acrylic sheet to avoid any thermal damage.

Copper wire is connected to each terminal which is well insulated. The wire directly connects the element to solar module. The two solar photovoltaic panels are used with the rating of 150 W and 80 W respectively with collective ideal output power of 230 W. The panels are connected in series and 13 Ampere fuse on the live wire to avoid any damage to the panels. A male female switch is connected to the wires to break and maintain the connections

3.2.2. Methodology and Experimentation

Water samples were prepared inside the laboratory. Water treatment lab at IESE-NUST was used to prepare the samples. Tap water was used from the lab. To vary the TDS concentration Sodium Chloride salt was added to measured amount of water until desired TDS concentration was reached. Conductivity of samples were measured in µS/cm and multiplied by factor of 0.49 for TDS measurement. Measuring cylinder of 0.5 liter was used to have desired quantity of water.

The palatability of drinking water has been rated by panels of tasters in relation to its TDS level as follows: excellent, less than 300 mg/L; good, between 300 and 600 mg/L; fair, between 600 and 900 mg/L; poor, between 900 and 1200 mg/L; and unacceptable, greater than 1200 mg/L.

Three of the TDS concentrations were in unacceptable region and tested for this system.

Following TDS concentrations were used to perform experiments.

Sr. No	**Conductivity (µS/cm)**	**TDS Concentration (mg/L)**
1	2040.82	1000
2	2551.02	1250
3	3061.22	1500
4	4081.63	2000

Table.3.1. TDS Concentration Used

Initial volume was also varied over constant TDS concentrations. Following volumes were used for testing each TDS concentration mentioned above.

Sr. No.	**Initial Volume Used (Liters)**
1	4
2	5
3	6

Table. 3.2. Initial Volume Used

4.1. Constants and Variables

Constants and variables are very important whenever undertaking any study. In this study following parameters were constants:

- Maximum constant Temperature (72 ^{o}C)
- Time for each experiment (6 Hours)
- Initial volume (in case of varying TDS)
- Initial TDS (in case of varying volume)

4.2. Results for varying initial Volume at a constant TDS concentration

Following final TDS concentrations were measured in laboratory when initial volume was varied at a single constant TDS reading.

4.2.1. Initial constant TDS: 1000 mg/L

Exp. No	Initial Volume (Liter)	Initial Conductivity (μS/cm)	Initial TDS (mg/L)	Final Conductivity (μS/cm)	Final TDS (mg/L)	TDS Removal Efficiency (%)
1	4	2040	1000	26.0	12.7	98.73
2	5	2040	1000	44.1	21.6	97.84
3	6	2040	1000	53.3	26.1	97.38

Table 4.1. Initial constant TDS: 1000 mg/L at varying initial volume

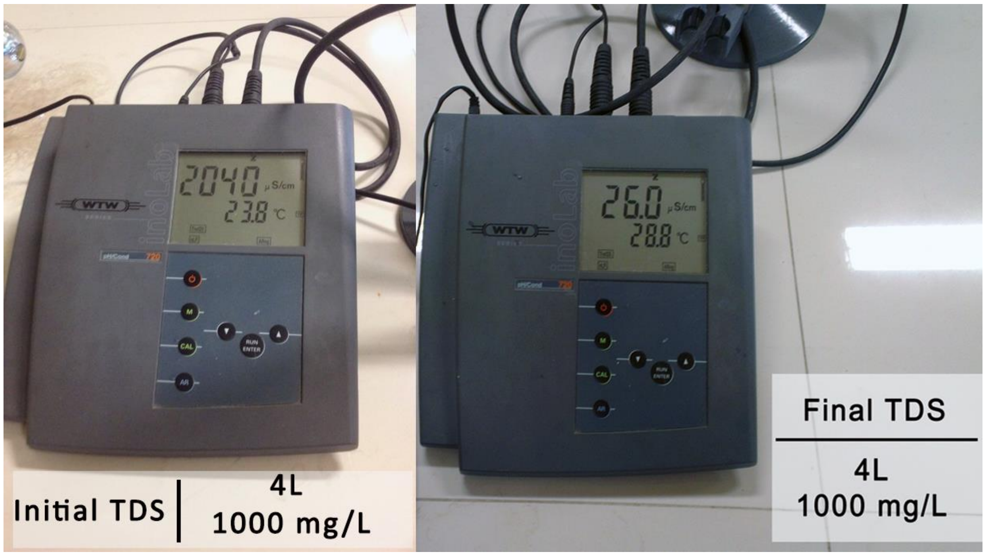

Figure 4.1. Initial and final conductivity readings by conductivity meter at 4 L

Removal Efficiency (%) = $\frac{Initial\ TDS - Final\ TDS}{Initial\ TDS}\ X\ 100$

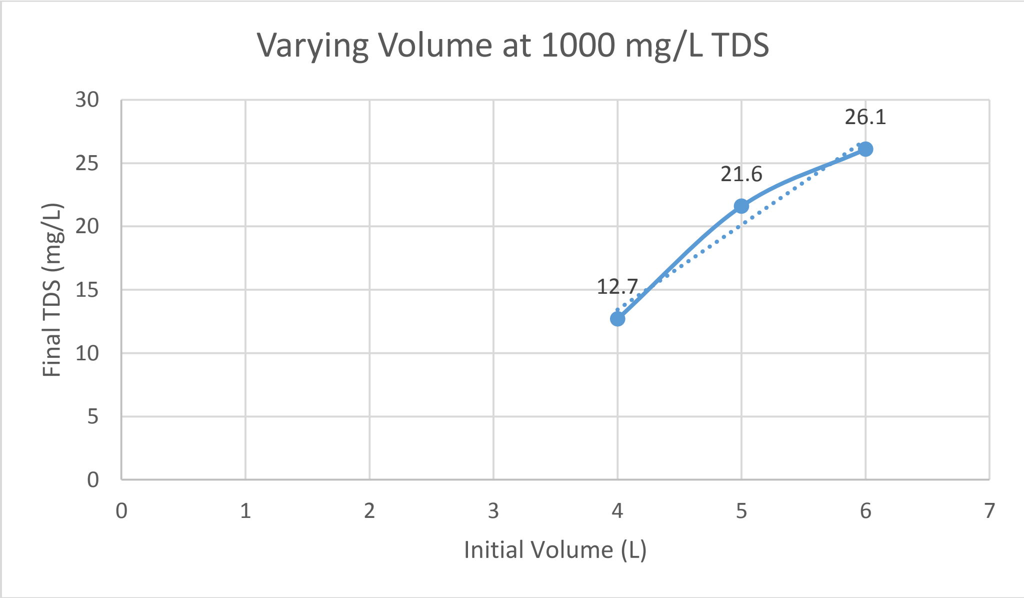

Figure 4.2. Graph of varying volume at 1000 mg/L initial TDS

From the following results TDS removal efficiency at 1000 mg/l (initial TDS) was about 97-98%. As we increase the volume, Final TDS for respective reading also increases as illustrated in the graph.

4.2.2. Initial constant TDS: 1250 mg/L

Exp. No	Initial Volume (Liter)	Initial Conductivity (µS/cm)	Initial TDS (mg/L)	Final Conductivity (µS/cm)	Final TDS (mg/L)	TDS Removal Efficiency (%)
4	4	2551	1250	38.5	18.9	98.48
5	5	2551	1250	53.6	26.3	97.89
6	6	2551	1250	72.6	35.6	97.15

Table 4.2. Initial constant TDS: 1250 mg/L at varying initial volume

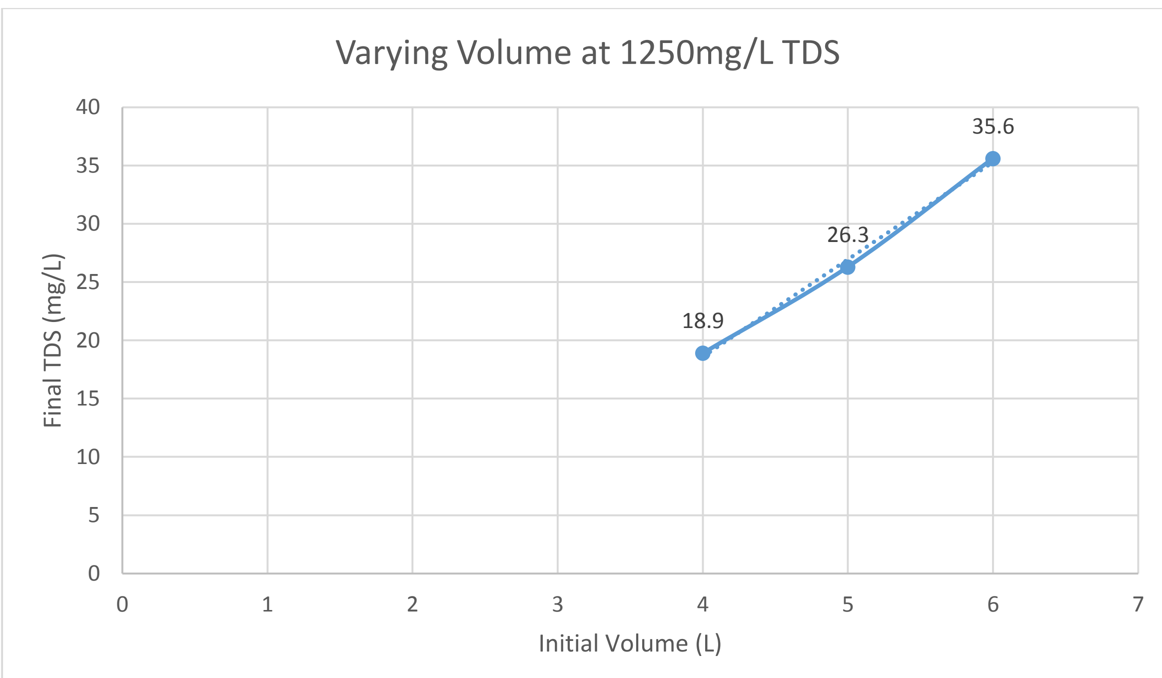

Figure 4.3. Graph of varying volume at 1250 mg/L initial TDS

From the following results TDS removal efficiency at 1250 mg/l (initial TDS) was about 97-98%. As we increase the volume, Final TDS for respective reading also increases as illustrated in the graph.

4.2.3 Initial constant TDS: 1500 mg/L

Exp. No	Initial Volume (Liter)	Initial Conductivity (µS/cm)	Initial TDS (mg/L)	Final Conductivity (µS/cm)	Final TDS (mg/L)	TDS Removal Efficiency (%)
7	4	3061	1500	74.4	36.5	97.57
8	5	3061	1500	92.2	45.2	96.98
9	6	3061	1500	104.8	51.3	96.57

Table 4.3. Initial constant TDS: 1500 mg/L at varying initial volume

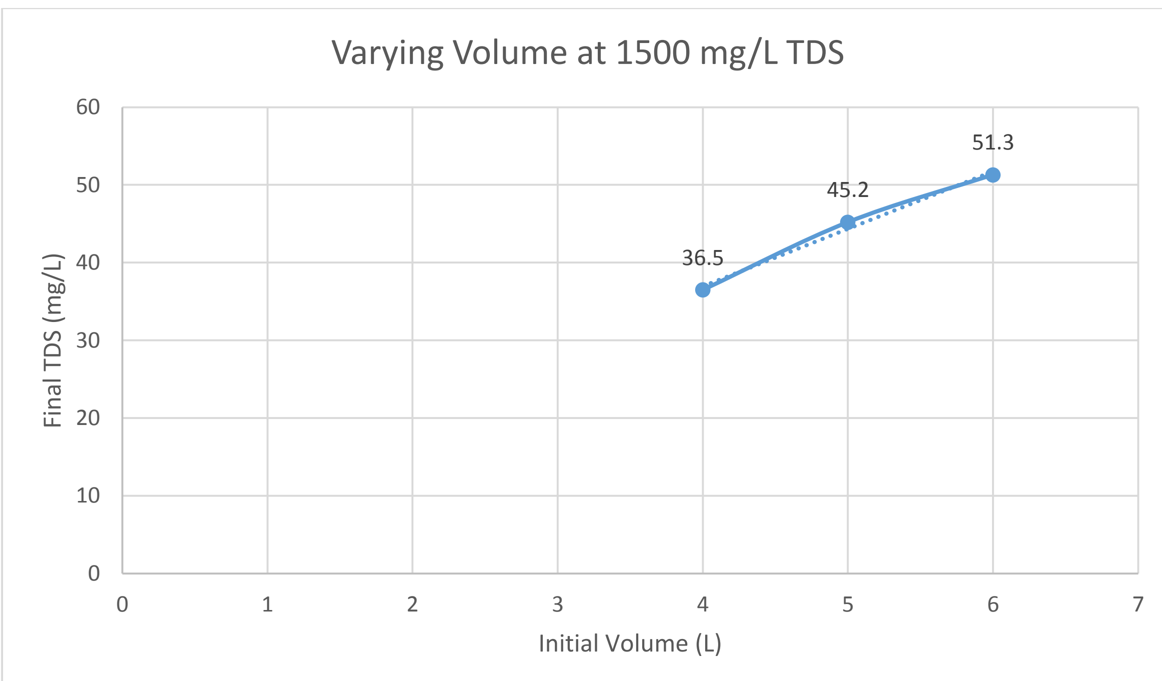

Figure 4.4. Graph of varying volume at 1500 mg/L initial TDS

From the following results TDS removal efficiency at 1500 mg/l (initial TDS) was about 96-97%. As we increase the volume, final TDS for respective reading also increases as illustrated in the graph.

4.2.4. Initial constant TDS: 2000 mg/L

Exp. No	Initial Volume (Liter)	Initial Conductivity (µS/cm)	Initial TDS (mg/L)	Final Conductivity (µS/cm)	Final TDS (mg/L)	TDS Removal Efficiency (%)
10	4	4081	2000	133.1	65.2	96.73
11	5	4081	2000	159.6	78.2	96.09
12	6	4081	2000	205.3	100.6	94.97

Table 4.4. Initial constant TDS: 2000 mg/L at varying initial volume

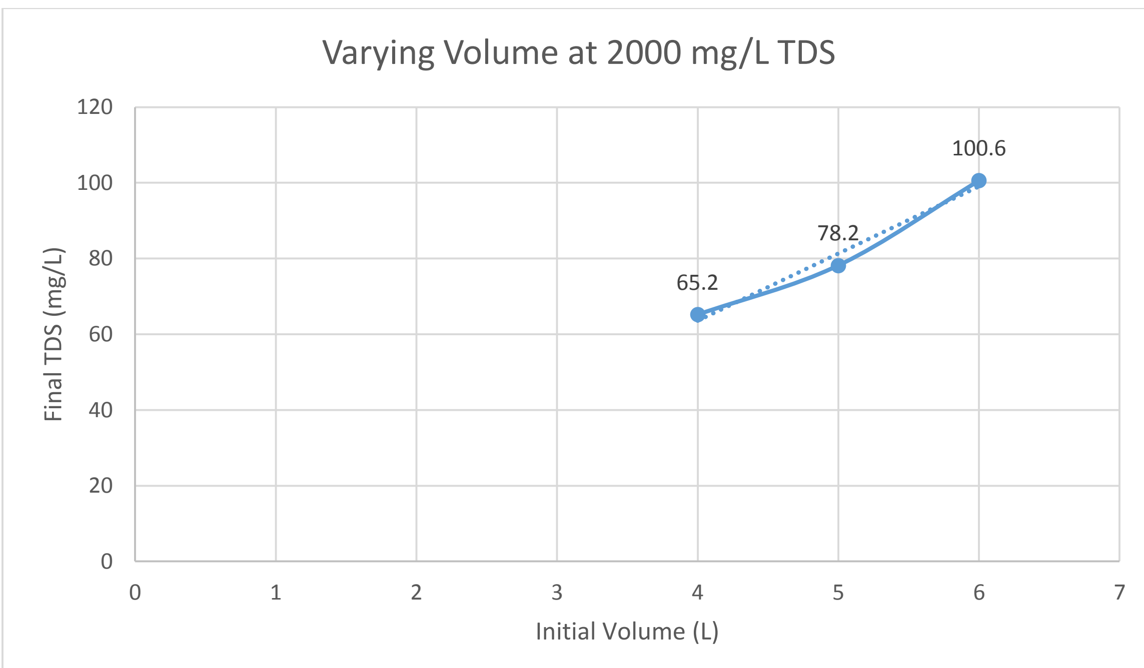

Figure 4.5. Graph of varying volume at 2000 mg/L initial TDS

From the following results TDS removal efficiency at 2000 mg/l (initial TDS) was about 94-96%. As we increase the volume, final TDS for respective reading also increases as illustrated in the graph.

4.3. Results for varying TDS at constant initial volumes:

Following final TDS concentrations were measured in laboratory when initial TDS concentrations were varied at constant initial volumes.

4.3.1. Initial constant volume: 4L

Exp. No	Initial Volume (Liter)	Initial Conductivity (µS/cm)	Initial TDS (mg/L)	Final Conductivity (µS/cm)	Final TDS (mg/L)	TDS Removal Efficiency (%)
1	4	2040	1000	26.0	12.7	98.73
4	4	2551	1250	38.5	18.9	98.49
7	4	3061	1500	74.4	36.5	97.57
10	4	4081	2000	133.1	65.2	96.73

Table 4.5. Initial constant volume: 4L at varying initial TDS

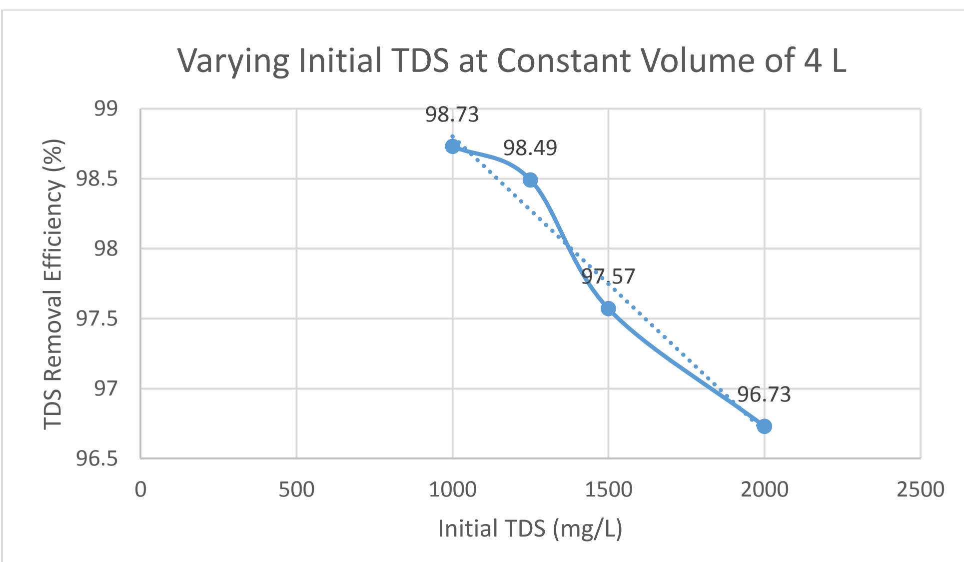

Figure 4.6. Graph of varying initial TDS at Constant Volume of 4 L

4.3.2. Initial constant volume: 5L

Sr. No	Initial Volume (Liter)	Initial Conductivity (µS/cm)	Initial TDS (mg/L)	Final Conductivity (µS/cm)	Final TDS (mg/L)	TDS Removal Efficiency (%)
2	5	2040	1000	44.1	21.6	97.84
5	5	2551	1250	53.8	26.3	97.89
8	5	3061	1500	92.2	45.2	96.98
11	5	4081	2000	159.6	78.2	96.09

Table 4.6. Initial constant volume: 5L at varying initial TDS

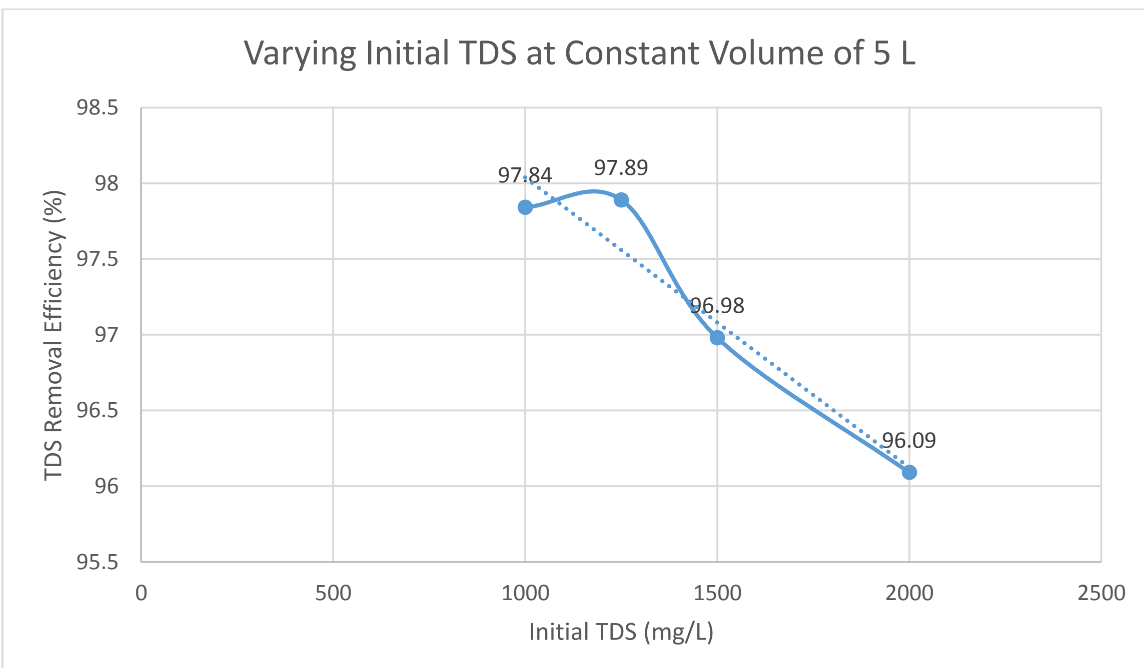

Figure 4.7. Graph of varying initial TDS at Constant Volume of 5 L

4.3.3. Initial constant volume: 6L

Sr. No	Initial Volume (Liter)	Initial Conductivity (µS/cm)	Initial TDS (mg/L)	Final Conductivity (µS/cm)	Final TDS (mg/L)	TDS Removal Efficiency (%)
3	6	2040	1000	53.3	26.1	97.38
6	6	2551	1250	72.6	35.6	97.15
9	6	3061	1500	104.8	51.3	96.57
12	6	4081	2000	205.3	100.6	94.97

Table 4.7. Initial constant volume: 6L at varying initial TDS

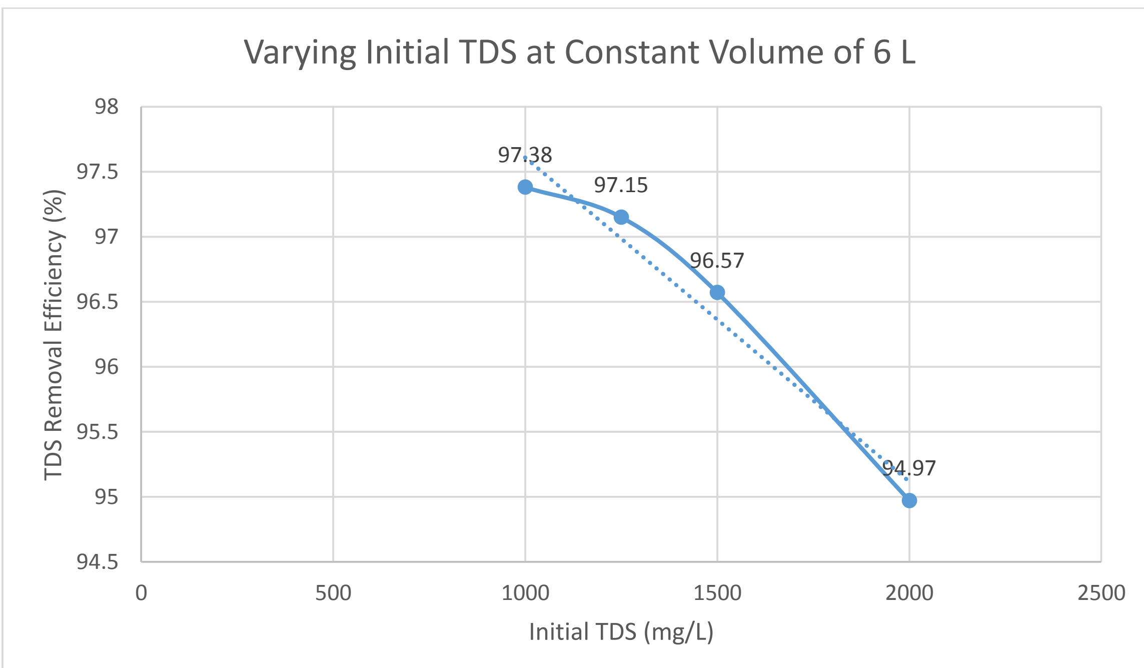

Figure 4.8. Graph of varying initial TDS at Constant Volume of 6 L

4.4. Volume Collection Analysis

For six hour experiment time, the volume collected was measured. This was clean water free of TDS. 12 tests were performed in total. The volume collected was analyzed for each day. Table 4.7 shows the volume collected for six hour time period for each experiment.

Exp No.	Initial Input Volume (L)	Initial TDS (mg/L)	Final TDS (mg/L)	Final Output Volume (L)
1	4	1000	12.7	0.640
2	5	1000	21.6	0.525
3	6	1000	26.1	0.480
4	4	1250	18.9	0.615
5	5	1250	26.3	0.465
6	6	1250	35.6	0.410
7	4	1500	36.5	0.520
8	5	1500	45.2	0.440
9	6	1500	51.3	0.390
10	4	2000	65.2	0.475
11	5	2000	78.2	0.430
12	6	2000	100.6	0.395

Table 4.8. Volume collection results

Average Volume Collected = 0.482 Liters

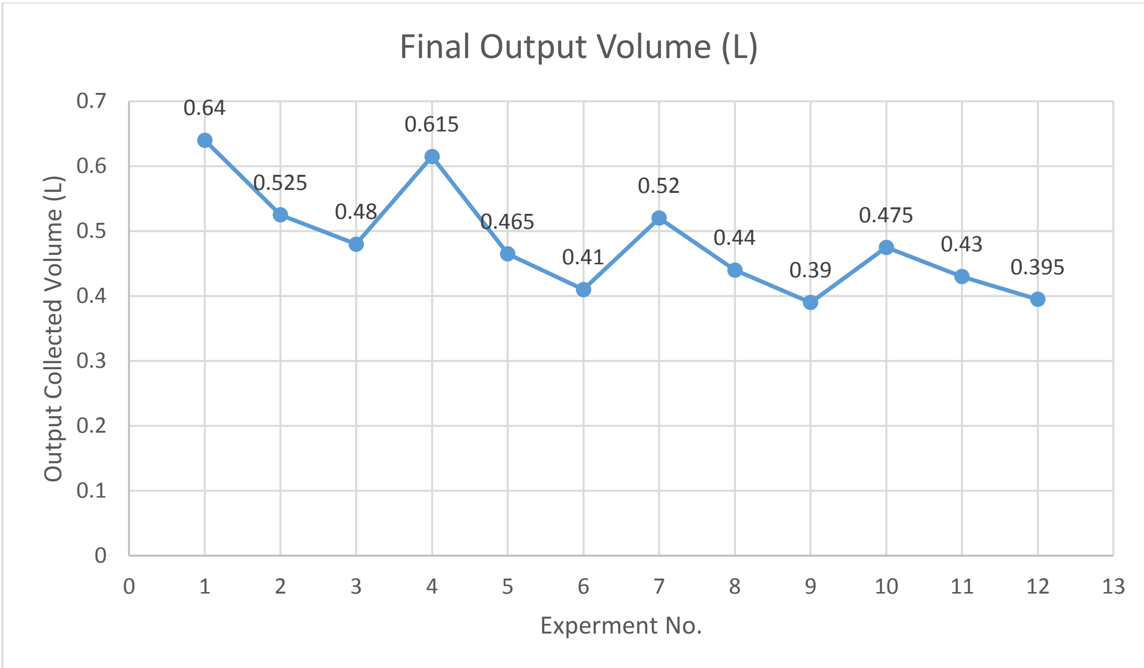

Figure 4.9. Graph of volume collection analysis

5.1. Conclusion

In the study the TDS is removed quite effectively. We are able to remove TDS to a range of 94% to 98%. Moreover, the design is cost effective and decentralized system that can be used for providing water on small scale, in comparatively dry areas of our country. This not only reduces the drinking water problem in those areas but also helps with the economy of our country. This system also eliminated the potential risk caused by the immediate scarcity of drinking water in case of droughts or other natural calamities, as it is portable system that can be installed any time without requiring any technical expertise. The most important prospect of this study is its less land requirement. We achieved a complete sustainable system that requires nothing but solar energy for its operation, which will be a useful option for a developing country like Pakistan, because it not only reduces the carbon footprint but also helps to counter the energy problem of our country.

5.2. Performance Evaluation

In this study excellent TDS removal was achieved with this design. The TDS removal efficiency range was from 94% to 98%. At maximum initial volume (6 L) and maximum initial TDS (2000 mg/L) the TDS removal efficiency was minimum i.e. 94.97%. At lowest initial TDS concentration and lowest initial volume the TDS removal efficiency was maximum i.e. 98.73%.

(Ali Samee, Mirza et al. 2007) reported a TDS removal efficiency of 90% to 96% in a simple single solar still. The solar still efficiency was reported as 30.56% which is comparable worldwide. Our design has shown a TDS removal efficiency of maximum 98% which is better than results reported by (Ali Samee, Mirza et al. 2007).

(Adhikary, Tipnis et al. 1989) have also reported the same pattern of TDS removal as this study's result show. Their TDS removal efficiency was about 60% to 65%. Our results are far better and design is also improved.

As the solar radiation decreases in the day, the temperature began to decrease and we have a low yield of clean water as compared to peak hours of 1200 to 1500 hrs.

Volume collection varies inversely as we increase the initial TDS and initial volume. As the salt concentration increases at constant volume the evaporation rate slows down and less water is collected for each day. The initial volume is increased from 4L to 6L, the clean water volume collection also slightly decreases. The maximum volume of 0.640 L was collected on 1^{st} test which was 4L (initial volume), 1000 mg/L (initial TDS) $72^{o}C$ constant temperature within 6 hours of operation.

5.3. Economics

In this study the design of solar still used is altered with heating coil and solar panels. Due to photovoltaic panels attached, the initial cost was slightly higher than a conventional solar still. Still it has about zero operating and maintenance cost for TDS removal. The designed unit is smaller for rural areas where clean water is not readily available so prime objective was to keep the cost as low as possible. Cost estimation for various components is provided in Table 5.1.

Sr. No	*Component*	*Cost in Pakistan (PKR)*
1	Acrylic Sheet (2mm)	800
2	Acrylic Sheet (6mm)	2500
3	Heating Element	1200
4	GMSA ELFY	150
5	Chloroform	200
6	Sliders	50
7	Solar Panel 150 W	10500
8	Solar Panel 80 W	5000
9	Bottom Stoppers	100
10	Black matte Paper	40
11	Insulated Copper Wire	300
12	Fuse (13 A)	80
13	Thermometer	1200
		TOTAL: 22,120 PKR

Table 5.1. Cost of Components in PKR

5.4. Applications

For this system certain important applications are present especially in Pakistan. Some of them are listed below.

- Installation of this unit in area like Cholistan Desert where high TDS rainwater in collected in ponds. Population is less and excellent sunlight hours are available throughout the day

- It could be coupled with traffic warden stands where they can have clean water whenever they want.
- This system could be installed in far flung check posts where potable water availability is an issue.
- Areas with high TDS concentration in ground water can also be a target for this system. It could provide potable water for rural areas near Faisalabad and Kasoor.

5.5. Future Prospective

There is a need for further research in this project. Volume collection analysis for 24 hour period could be studied. In Night time batteries could be used to take the output. Moreover another design with same components may also increase the output.

This project with the use of helio-tracker would give more promising results. This research could also be done in a positive way to increase Volume collection.

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