AN EXPERIMENTAL STUDY OF FLOATING WICK BASIN TYPE VERTICAL MULTIPLE EFFECT DIFFUSION SOLAR STILL WITH WASTE HEAT RECOVERY

A thesis submitted by

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in fulfillment of the requirement for the

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in

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CERTIFICATE

I, **Arvind Kumar Kaushal** hereby certify that the work presented in this thesis report titled "**An experimental study of floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery**" in fulfillment of requirement for the award of degree of **DOCTOR OF PHILOSOPHY,** submitted in Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of my research work carried out under the supervision of **Dr. Madhup Kumar Mittal** (Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala) from August 2011 to July 2017. The results embodied in the thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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Abstract

The present research work aims at reducing the unit cost of distillate produced in a solar still by incorporating suitable improvements in the existing basin type vertical multiple effect diffusion (VMED) solar still. Extensive literature survey was done to study the design innovations done by various researchers to enhance the distillate productivity of solar stills, particularly the basin stills. An improved and modified version of basin type VMED solar still, having multiple floating wicks in basin, and heat exchanger for waste heat recovery for feed water pre-heating (FW-BVMED-HR), has been developed. This floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR) has double glass covers in its basin section. The partition plates had divided wick structure for uniform wetting, in which each of the wicks were fed by feed water from gravity flow, by individual feed tubes. Longitudinal rubber spacers were used to divide the cotton cloth wicks and maintain partition plate gaps, and also to effectively seal the partition cells on the border of partition plates. The basin section had internal stainless steel reflectors. The first partition plate was of copper and rest partition plates were of stainless steel. Another still identical in dimensions and features, to FW-BVMED-HR still, was fabricated. Without floating wick and heat exchanger, this still served as a reference still, for comparison experiments. The complete experiments were done in an order and hence the experimental set-up was also fabricated in stages. Initially, a basin still was fabricated, with copper plate as back wall, which was well insulated on the outer side. Few experiments were conducted on basin still to find out its productivity. The conventional basin still is then converted into basin type vertical single distillation cell (VSDC) solar still. In other words the conventional basin still is converted into basin type VMED still with two effects. Experiments were done on the basin type vertical single distillation cell (VSDC) solar still alone, for performance testing of the divided wick structure and individual wick feed water arrangement, at varying feed water rates. Its productivity was compared with the basin still. The productivity of the basin type VSDC still was found 15-20% higher than the basin still. Subsequently, the effect of heat recovery from waste feed water, on the performance of basin type vertical multiple effect diffusion solar still with heat recovery (BVMED-HR) was investigated. BVMED-HR still with four effects was made after adding, two more partition plates to the basin type VSDC still (two effect VMED still), and a heat exchanger for feed water pre-heating by heat recovery from waste feed water. The partition plate gap and basin water depth both were kept 10 mm, for both BVMED-HR and reference stills. The experiments were done at varying feed water rates. The experimental

results showed that the distillate productivity of BVMED-HR increased by 10.6% as compared to that of reference still, under the same ambient and operating conditions. An empirical correlation was developed to predict the productivity of BVMED-HR still using the experimental database of the study. The principle weather parameters such as daily total insolation, daily average ambient temperature, daily average wind velocity and daily average relative humidity, along with feed rate and feed water temperature as an important operational parameter are taken into consideration for the development of correlation. A floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR) was fabricated by adding multiple floating wicks in the basin of BVMED-HR still. In the next set of experiments, the performance of the FW-BVMED-HR still was compared with reference still under identical weather and operational conditions, by running them side by side simultaneously. Both the stills consisted of four effects and partition plate gap of 10 mm. The experiments were done at varying basin water depths and feed water rates. On a clear sunny day, the distillate productivity of FW-BVMED-HR still was found to be 21% higher than the reference still. High distillate productivity resulted, due to high convective heat transfer by humid basin air from high temperature float wick surface to first partition plate, feed water pre-heating from waste heat recovery, reduced basin bottom and side losses, and high night distillate productivity as a result of additional heat stored in multiple floating wicks. The higher temperature of first partition plate, due to the higher heat transfer from the high temperature float wick surface, as well as the pre-heated feed water from heat recovery, in case of FW-BVMED-HR still, increased the evaporation heat flux from the first partition plate towards the second partition plate and external environment through partition plates. Subsequently, parametric study on FW-BVMED-HR still alone, was done experimentally, under outdoor conditions. The effect of design parameters of number of effects (n) and gap between partition plates (δ_p) and operational parameters of feed water rate (f) and basin water depth (d), on the cumulative efficiency of the still, within a narrow band variation of solar radiation and other parameters, was studied. Optimum feed water rate for the still was found to be 0.27 g/m^2/s, when the total solar radiation was in the range of 21-23 MJ/m^2/day. The cumulative efficiency increased by a maximum of 33% when gap between partition plates was decreased from 16 mm to 10 mm, at constant feed rate of 0.27 g/m^2/s. The cumulative efficiency decreases by a maximum of 25% as the feed rate increases from 0.27 g/m^2/s to 0.38 g/m^2/s, at a mean basin water depth of 2.25 cm. The maximum decrease of cumulative efficiency was observed to be 8.5%, when the basin water depth was increased from 1 cm to 3 cm, at constant feed rate of 0.21 g/m^2/s. The cumulative efficiency showed a maximum rise of 58% when the number of effects were increased from 2 to 7, at constant feed rate of 0.27 g/m^2/s. The data analysis of experimental results of FW-BVMED-HR still showed that the night productivity has almost linear dependence on day productivity. A productivity correlation has been proposed which can predict the productivity of FW-BVMED-HR still with reasonable accuracy. The proposed correlation predicts the experimental data within the deviation range of -17% to +14% with a mean deviation of 6.6%.The principle weather parameters such as daily total insolation and daily average ambient temperature, along with important operational and design parameters such as feed water rate, feed water temperature, number of effects and gap between partition plates, are taken into consideration for the development of correlation. Economic analysis of FW-BVMED-HR still, based on life cycle costing of the system, has been carried out. The capital cost of this still with increasing number of effects, from 2 to 7, is computed. The annual cost of operating this still based on a life cycle of 10 and 25 years is estimated. The average annual distillate and minimum unit cost of distillate, for increasing number of effects is determined. The minimum cost of distillate obtained for the 7 effect FW-BVMED-HR solar still is estimated to be Rs. 5.45/kg, for a life cycle of 25 years and for interest rate 0.16. With lower interest rate of 0.12, the cost of distillate reduces significantly to Rs. 4.52/kg. The still is found to be economically viable with low payback period. At large number of effects, the reduction in unit cost of distillate with further addition of an effect diminishes. It happens because the distillate gain becomes smaller in magnitude with the addition of each effect and hence addition of an effect beyond a reasonable number does not contribute much in reducing the unit cost of distillate. The unit cost of distillate reduces significantly with decrease in interest rate and/or increase in life cycle of the still, due to reduction in total annual cost resulting from reduced value of capital recovery factor.

Contents

List of publications from present work

(i) A.K. Kaushal, M.K. Mittal, D. Gangacharyulu, **Development and experimental study of an improved basin type vertical single distillation cell solar still**, Desalination. 398 (2016) 121–132. doi:10.1016/j.desal.2016.07.017

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Nomenclature

A	Area, m^2
C	Capital cost per unit glass area, Rs./m^2
C_{dt}	Cost discount, %
CF	Annual cash flow, Rs.
C_{ts}	Total capital cost per unit glass area of FW-BVMED-HR still, Rs./m^2
C_T	Total annual cost per unit glass area, Rs./m^2
C_u	Cost of unit mass of distillate, Rs./kg
d	Depth of basin water, cms
d_m	Mean depth of basin water, cms
D	Total annual distillate per unit glass area, kg/m^2/year
f	Feed water flow rate, g/m^2/s
f_c	Capital recovery factor
F	Sinking fund factor
G_g	Global solar radiation on glass surface, W/m^2
G_T	Cumulative daily solar radiation on glass cover for experimental period, MJ/m^2/day
H_{fg}	Latent heat of water, J/kg
i	Annual interest rate, %
m_d	Mass of distillate, kg
$\dot{m}_e$	Mass flux of water vapor, kg/m^2/s
M	Annual maintenance cost factors, %
M_i	Number of clear days of i^{th} month

n	Number of effects
n_p	Payback period in years
N	Expected life cycle of still in years
P	Daily distillate productivity per unit glass area, kg/m^2/day
P_i	Average daily distillate output of ith month, kg/m^2/day
R_H	Average daily relative humidity, %
S	Salvage value factor, %
S_p	Selling price of distillate, Rs./kg
T	Temperature, °C
T_a	Average daily ambient temperature, °C
V_W	Average daily wind speed, m/s

Greek letters

ε	Effectiveness
ΔT	Rise of water temperature, °C
δ_p	Gap between partition plates, mm
η_c	Cumulative efficiency

Subscripts

b	Basin section
d	Distillation section
f	Feed water
g	Glass cover
m	Miscellaneous components

Abbreviations

BVMED-HR	Basin type vertical multiple effect diffusion solar still with heat recovery
FW-BVMED-HR	Floating wick basin type vertical multiple effect diffusion solar still with heat recovery
HDPE	High density polythene
PVC	Polyvinyl chloride
TDS	Total dissolved solids
VMED	Vertical multiple effect diffusion
VSDC	Vertical single distillation cell

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Chapter 1

Introduction

1.1 GENERAL

Clean and pure water is a necessity for healthy human habitation in any part of the world. Around 97% of the water in the world is in the ocean, approximately 2% of the water in the world is at present stored as ice in polar region and 1% is fresh water available for the need of the plants, animals and human life [1]. In many parts of the world, water is available but it is either saline as in coastal regions or brackish in nature and therefore unfit for human consumption. The available fresh water resources in human habitations are rapidly being polluted due to urbanization, industrialization and population growth [2]. All the water desalination techniques utilize, either heat energy produced from fossil fuels and other sources or electricity produced from conventional sources of energy. Therefore, in places where conventional sources of energy are either not available or are not cost effective, solar desalination (solar distillation) is an attractive and viable alternative. However, in order to use solar energy in distillation process, the collection of solar energy must be efficient and efficiently transferred to impure water for evaporation, so that the overall efficiency of the system is high. Hence an optimized system may include combination of efficient solar collectors [3,4], better heat transfer [5], energy storage methods [6] and large sized desalination plants [7], which yields the minimum unit cost of distillate calculated on life cycle costing method [8].

This chapter discusses the concept of solar distillation and classification of solar stills. Further, the multiple effect diffusion stills have been classified on the basis of heat transfer to the first partition plate of multiple effect distillation section. Motivation for the present research work and selection of the type of still has been discussed and, aim and significance of the present research work has been emphasized. Finally, the specific objectives of the present research work have been highlighted.

1.2 SOLAR DISTILLATION AND SOLAR STILL

Distillation is a water purification process that uses a heat source to vaporize water and separate it from contaminants. The water vapour is then cooled, condensed and collected to form purified water. The solar distillation process produces distilled water much the same way by using solar radiation as heat source.

The device which utilizes solar radiation to convert saline water to distilled water is known as solar still. Fig. 1.1 shows the schematic diagram of conventional basin type solar still. Saline water is contained in a basin having black absorber liner and a sloping glass cover usually at 20° or more. The basin is having insulation to prevent the heat losses to surroundings and ground. The water in the basin evaporates with the rise of water temperature in the basin, due to addition of thermal energy from solar radiation. The vapour condenses on the glass cover and is collected through a channel in a container outside the still.

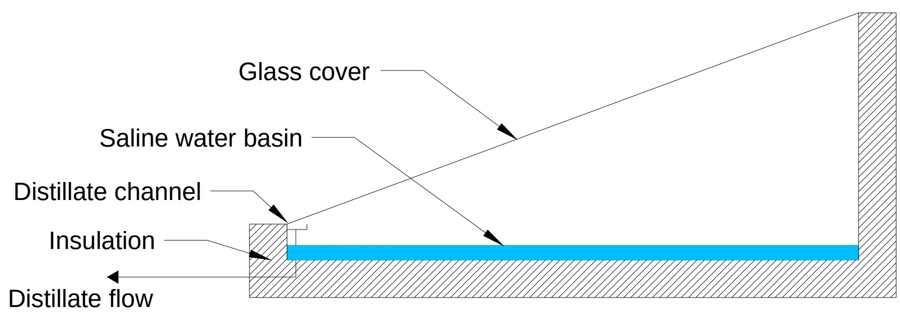


Fig. 1.1 Basin solar still

1.3 SOLAR STILL CLASSIFICATION

The basin solar stills are broadly classified into active and passive systems [2]. In the passive solar stills, no outside energy is supplied to the saline water in the still basin. In the active solar still systems, additional thermal energy from an external source (such as a flat plate or concentrator collector) is supplied to saline water in the still basin. Solar stills coupled with flat plate collectors are used with natural circulation or forced circulation with pump. The monthly performance of passive and active solar stills for different Indian climatic conditions was evaluated by Singh and Tewari [9]. The active solar distillation is further classified as follows [2]:

- High temperature distillation—Additional heat is supplied to the basin water from a solar collector panel.
- Pre-heated water application—Hot water is fed into the basin at a constant flow rate.
- Nocturnal production—Hot water is fed into the basin once in a day in the evening.

A literature review and survey of the various types of solar stills is carried out by Kalogirou [10]. He has mentioned the different types of solar still available in the literature as conventional solar stills, single-slope solar still with passive condenser, double condensing chamber solar still, vertical solar still, conical solar still, inverted absorber solar still and multiple effect solar still. Single sloped basin type stills with fixed porous fins in basin or with multiple floating porous absorbers have been studied by Srivastava and Agrawal [11,12]. Inclined wick solar stills have higher efficiencies due to low thermal inertia of wick and higher reception of solar radiation on the absorber surface [13,14].

Multiple effect solar still can be classified as multi-stage stacked tray solar still, horizontal multiple effect diffusion solar still, inclined multiple effect diffusion solar still and vertical multiple effect diffusion solar still. A Multi-stage stacked tray solar still produces higher distillate as the design provides an effective way of reutilizing latent heat of condensation of vapour of one stage for vaporization of saline water in next stage [15,16]. The total distillate output from the multi-stage stacked tray solar still increases when the number of the stages is increased; the fractional increase, however, is found to be lower for each of the added stages. The cost of the distillation system increases linearly as the number of stages increases. Adhikari [15] has found the optimum no. of stages to be 3 for a given solar flat plate collector area. Abakr et al. [17] have made performance study of a three stage evacuated solar still and found the maximum productivity to be about threefold of the maximum productivity of the conventional basin type solar still.

Vertical multiple effect diffusion (VMED) solar stills have productivities many times over that of single effect solar stills [18]. The VMED solar still consists of number of vertical plates which are arranged parallel to each other with a narrow gap between the plates. One side of each of the plates is covered with porous wick cloth to reduce the thermal inertia of evaporating surface. Heat is supplied to one side of the multiple plate arrangement and feed water is fed continuously to each of the wick sides of the plates. As heat is supplied to the first plate, water vapors generate from the wick side of the first plate, diffuse through the air gap between the plates and condense on the uncovered surface of the second plate. The latent heat released by condensing vapors conducts through the plate and further evaporate the water from the wick side of the second plate. In this way, the heat energy supplied to the first plate can be recycled several times to increase the productivity of the still. The VMED still can be of various types on the basis of different methods used for heat transfer to the multiple effect distillation section. The different types of VMED stills are discussed briefly in the following section.

1.4 TYPES OF VMED SOLAR STILL

Various methods have been tried for heat transfer to multiple effect diffusion stills and are in use for increasing the productivity and simultaneously to reduce the unit cost of distilled water produced.

1.4.1 Basin type VMED still

Fig. 1.2 shows schematic diagram of conventional basin type VMED solar still. It consists of tilted double glass cover, a horizontal basin liner in water filled basin and a number of closely spaced vertical partition plates placed side by side with wick attached on one side. The basin contains saline water which evaporates due to absorption of solar energy. The heat transfer to the first partition plate takes place from the latent heat released from condensing vapor and convective

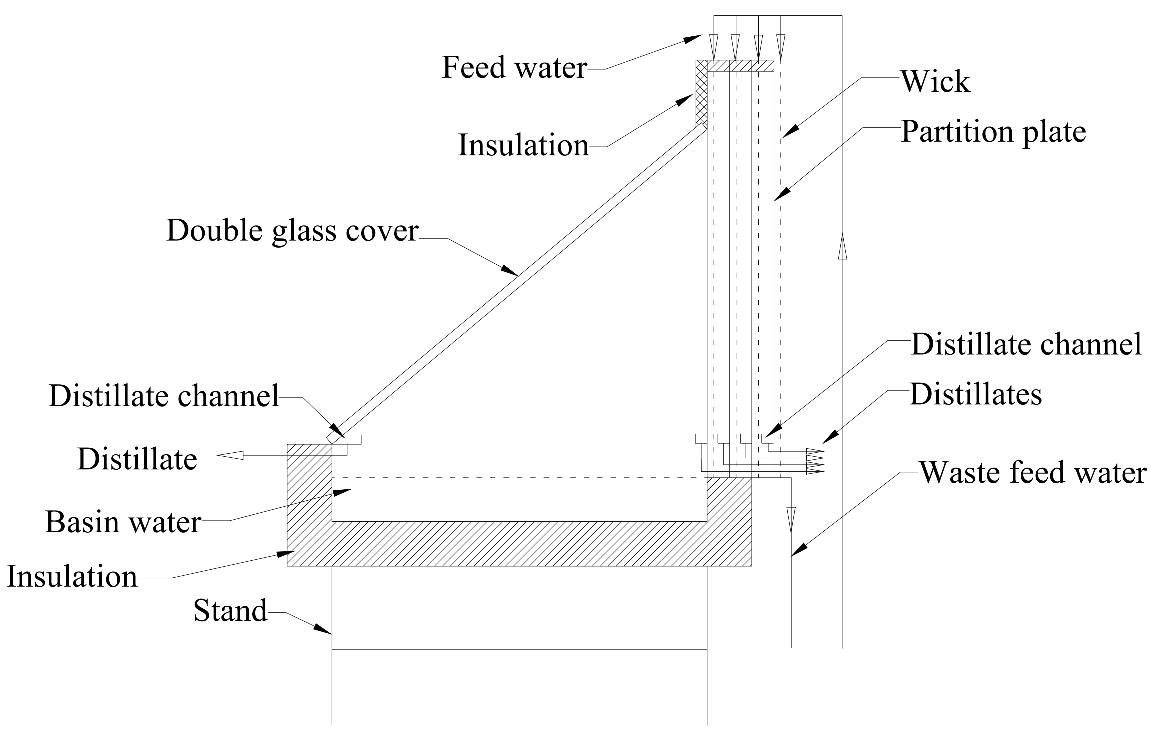


Fig. 1.2 Basin type vertical multiple effect diffusion solar still

heat transfer from hot basin air. In addition, the first partition plate receives direct solar radiation, as well as reflected solar radiation and thermal radiation from internal surfaces of basin side of the still. This total heat is utilized to cause the evaporation of feed water from the other side of first partition plate, which condenses on the second partition plate and transfers the latent heat to it. The feed water on the other side of second partition plate, in turn, again evaporates and condenses on the next plate. Tanaka et al. [18] studied experimentally the performance of a basin type VMED solar still.

1.4.2 VMED still coupled with heat pipe

Tanaka et al. [19–21] have studied the VMED still, coupled with a heat pipe flat plate solar collector, through a heat pipe loop, for heat transfer.

1.4.3 VMED still coupled with flat plate reflector

Tanaka et al. [22–24] conducted a study on a VMED solar still, coupled with a flat plate reflector, for boosting solar heat radiation to first partition plate absorber surface.

1.4.4 VMED still coupled with flat plate collector

Kiatsiriroat et al. [25] used a flat plate collector for collection of heat from solar energy, and heat transfer to VMED still was done by circulation of hot water by pump.

1.5 MOTIVATION FOR PRESENT RESEARCH AND SELECTION OF STILL

Human population in many areas of the world do not have access to safe drinking water. This often leads to health hazard from water borne diseases. In India, there are few places, inhabited by humans, which are regarded as desert. In few states, due to excessive use of groundwater for irrigation as for paddy sowing and industrial purposes, the groundwater level goes down considerably. This situation aggravates further in summer season as most of the surface water reservoirs also start drying up. Hence some states in India face acute water shortage in summer season. The summer season is also the peak load season for the electrical power consumption from household and industry sector. Moreover in future, the growing human population may have to move into areas which are presently considered deserts having water scarcity. The desalination techniques like vapour compression distillation, reverse osmosis and electrodialysis use electricity as the input energy. With the ever increasing demand for energy with population growth and rapid industrialisation and given the limited coal reserves and fossil fuels, developing and using of the non-conventional energy like solar energy for distillation is necessary. For the widespread use and commercialization of this technology, it must be cost competitive with other technologies used for generating pure water. To achieve this purpose, technology innovation is needed to improve the efficiency of the solar distillation devices and hence reduce their size and cost. Many efforts have been made to improve the efficiency of solar distillation and to increase the productivity, so as to reduce the per unit cost of distillate produced. A study of various factors affecting solar distillation and survey of available high productivity yielding technologies needs to be done, so that a new integrated design can be developed with locally available low cost materials and skills.

Of all the multiple effect stills, the vertical multiple effect diffusions stills were found to have compact distillation section, more productive and less prone to distillate contamination. Further, of all the vertical multiple effect stills, the basin type vertical multiple effect diffusion (VMED) solar still was found to be a rugged, all weather device which requires little maintenance and monitoring as compared to the VMED still coupled with flat plate reflector, and relatively less expensive when compared to VMED still coupled with heat pipe flat plate collector. It does not require any external energy consumption for pump power as in case of flat-plate collector coupled stills.

1.6 AIM AND SIGNIFICANCE OF PRESENT RESEARCH WORK

The present work aims at reducing the unit cost of distillate produced in a solar still by incorporating suitable improvements in the existing conventional design of basin type vertical multiple effect diffusion solar still. An improved and modified version of basin type VMED solar still, having floating wick in basin, and heat exchanger for waste heat recovery for feed water pre-heating, has been developed. The development of this improved vertical multiple effect diffusion still, due to its high productivity, will be a boon to the areas of the world which are inhabited by human population, but do not have access to safe drinking water. Knowledge of all the parameters – design, operational and weather, affecting the efficiency of the still, and their relative effect on the performance of the still, helps in achieving optimum productivity from the still. A commercial scale and site specific design can be developed, utilizing optimum parameters, resulting in minimum unit cost of water produced.

Apart from providing safe drinking water, this design of VMED still has applications in pharmaceutical industry which uses distilled water, mineral water industry, battery water, packed food and cosmetics industry, boiler water, heat exchangers and all applications and industry which utilize distilled water.

1.7 RESEARCH OBJECTIVES

Experimental investigation in outdoor conditions has been carried out to evaluate the performance of floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR) and conventional basin type VMED solar still (reference still), under similar operating conditions with the following specific objectives.

1. To design, fabricate and test the conventional basin type and floating wick basin type VMED solar still with waste heat recovery.
2. To investigate the effect of heat recovery from waste feed water on the performance of basin type VMED solar still.
3. To investigate the effect of feed water flow rate, number of effects and gap between partition plates on the performance of floating wick basin type VMED solar still with waste heat recovery.
4. To find the nocturnal productivity for the floating wick basin type VMED solar still with waste heat recovery. To develop an empirical correlation to predict the productivity of floating wick basin type VMED solar still with waste heat recovery.
5. To compute the per litre cost of distilled water based on a life cycle costing of 10 years of the floating wick basin type VMED solar still with heat recovery.

1.8 ORGANIZATION OF THESIS

This thesis contains six chapters and two Appendices. Chapter 1 covers the solar distillation process and its classification. Motivation for present research and selection of type of still for research problem has been discussed. Aim of present research work and its significance has been highlighted. Specific research objectives have been listed. Chapter 2 covers the literature survey carried out to find the current status of solar distillation technologies. The multiple effect stills, particularly the vertical multiple effect diffusion solar stills, have been covered. Finally, the limitations observed from literature survey are summarized and the improvements/modifications incorporated in the present work to overcome these limitations have been listed in concluding remarks. In chapter 3 the details of components of experimental test rigs used for various experiments have been given. Various instruments used in measurement and their specifications have been shown. Finally, detailed experimental procedure of all experiments have been provided. In chapter 4, tabular experimental results and graphical data of all experiments have been presented and their analysis have been discussed in detail. In chapter 5, economic analysis based on life cycle costing of floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery (FW-BVMED-HR) has been done for 2-7 effects. Chapter 6 covers the important conclusions of all the experiments. The design, dimensions and fabrication details have been provided in Appendix-A. Day and night productivities along with the important design, operational and weather parameters, for all experiments, have been provided date wise in tabular form in Appendix-B.

1.9 CONCLUDING REMARKS

The concept of solar distillation and general classification of solar stills has been discussed. Various methods of heat transfer to the first partition plate of multiple effect diffusion stills have been discussed. Motivation for the present research work and selection of the type of still has been discussed, and, aim and significance of the present research work has been highlighted. Finally, the specific objectives of the present research work have been listed, which have defined the scope of present research work.

Chapter 2

Literature review

2.1 INTRODUCTION

Vast literature was surveyed and studied, on various types of solar stills, of which the literature relevant with the present research work is reported in this chapter. For easy comprehension, the literature survey is summarized and organized under the following headings.

(a) Basin type single effect solar still

(b) Inclined wick still

(c) Multi-effect solar still

(i) Multi-tray type (ii) Horizontal diffusion type (iii) Inclined diffusion type (iv) Other types

(d) Vertical multiple effect diffusion solar still

(i) Basin type (ii) Flat plate reflector type (iii) Heat pipe type (iv) Flat plate collector type (v) Other types

2.2 BASIN TYPE SINGLE EFFECT SOLAR STILL

The conventional single slope basin type still, although simple in design, has low productivity. The solar radiation, beam as well as diffuse, enters through the single glass cover and strikes the still walls and the basin water. This leads to the rise of temperature of basin water and the still walls and the air enclosed in the triangular section. As the temperature of basin water rises, water vapor formation is accelerated and the air above basin water becomes saturated with water vapor. The water vapor starts condensing on the relatively cold glass cover by transfer of latent heat of condensation. This heat energy is then lost to the surrounding atmosphere. As the day progresses, with the rise of solar radiation heat input, the distillate production also increases. At the end of the day, after sunshine hours, distillate production continues, due to the residual energy in the hot basin water and stored energy in insulation.

Extensive literature survey was done for both passive and active stills. Many efforts have been made by researchers to improve the productivity of basin type stills. Some of these improvements are very simple in implementation and low in cost, but lead to significant rise of still efficiency.

2.2.1 Increasing free surface area of basin water: If the free surface area of water is increased the rate of evaporation increases. Free surface of water can be increased by placing sponges, wicks and fins in basin water. Simultaneously, thermal inertia of the evaporating water surface reduces and hence rate of evaporation increases. Abu-Hijleh and Rabab'h [26] studied experimentally the effect of placing sponge cubes in basin water of a single slope basin still. They found that the still productivity increased up to 273% due to increase of wetted surface area in contact with the hot air inside the still. Manikandan et al. [27] carried a detailed review of various types of wick type solar stills. Alaian et al. [28] experimentally investigated the performance of a solar still with pin finned wick surface in basin. They found a productivity enhancement of 23% over the conventional basin still. Srivastava and Agrawal [12] studied experimentally a modified basin type still, having extended porous fins (of fixed type wick) in the basin. The basin was divided into rectangular boxes with bamboo sticks and blackened cotton cloths were hanged on them. These cotton wicks remained partially dipped in basin water to form a porous fin arrangement. They obtained an increase in productivity by 48% and 15% over the conventional basin type still, for the months of February and May respectively. Velmurugan et al. [29] investigated theoretically and experimentally the performance of a single slope basin solar still and its various modifications separately by adding tilted wick, sponges in basin and fins in basin. They observed a productivity enhancement of 29.6% for tilted wick, 15.3% for sponges in basin and 45.5% for fins in basin, as compared to the single slope basin still. Nafey et al. [30] studied theoretically and experimentally the effect on productivity, of floating perforated black aluminium plate, in a basin still, at various depths of water. They reported a productivity enhancement of 40% for a brine water depth of 6 cm, for the modified still, as compared to the conventional basin still. Srivastava and Agrawal [11] studied theoretically and experimentally the performance of modified basin type solar still having floating type wick in the form of multiple floating porous absorbers placed on the basin water. The floating porous absorbers were made of blackened jute cloth resting on polystyrene pieces. A higher distillate productivity by 68% on clear day and 35% on partially clear day was obtained for the modified still over the conventional basin still. They also concluded that varying the basin water depth had a minimal effect on the still productivity. Omara et al. [31] examined experimentally the effect of modifying the conventional basin type still with corrugated basin liner and then adding a wick to it, and subsequently adding internal reflectors to this configuration. They obtained an increase of daily productivity up to 145% for this type of still over the conventional basin still. Matrawy et al. [32] investigated the performance of a solar still having corrugated cloth wick in basin and having external reflector. They found an enhancement of 34%, of daily productivity of the still, than that of the simple basin type still.

2.2.2 Using heat storage elements in basin: The excess heat of basin may be stored in heat storage elements like pebbles, sand and phase change materials (PCM) integrated with basin. This stored heat generates additional distillate during night, as ambient temperature is considerably lower than during daytime. El-Sebaii et al. [33] simulated the performance of an active single basin solar still integrated with a thin layer of sand under the basin liner. There was significant night productivity due to heat storage effect of sand layer. The annual average of daily productivity for the still with sand, over the still without sand was found to be 24%. Tabrizi and Sharak [34] conducted an experimental study of a basin solar still with sand reservoir as a heat storage medium below the basin liner. They found significant rise of night and overall productivity over the conventional basin still. El-Sebaii et al. [35] presented transient mathematical models, for single slope single basin solar still with phase change material (PCM) under the basin liner of the still, and conventional basin still. The simulated results showed that on a summer day the distillate productivity for the basin still with 3.3 cm of stearic acid (PCM) under the basin liner was found to be 9 kg/m^2/day as against 5 kg/m^2/day for the conventional basin still. The overnight productivity increases significantly with increase of mass of PCM material. El-Sebaii et al. [36] studied theoretically and experimentally the performance of a single slope single basin solar still, having a horizontally suspended absorber plate which acts as a baffle in basin water. Effect of vent area of aluminum baffle plate and the vertical position of baffle plate in basin water, on the daily productivity were studied. The daily productivity for the basin still with baffle plate was found to be 20% higher than the conventional basin still.

2.2.3 Supplying external heat energy (Active solar stills): External heat energy as from flat plate collectors, solar concentrators and solar pond may be utilized to augment the heat input to the basin water, to increase the day as well as night productivity of the basin still. Sampathkumar and Senthilkumar [37] studied experimentally the performance of an evacuated tube collector (ETC) solar water heater coupled single slope basin still. They found the productivity of their active still to be twice than that of single slope passive basin still. Abad et al. [38] studied experimentally the performance of a novel active solar desalination system which utilizes pulsating heat pipe loops to transfer heat from flat plate solar collector to the basin still. The peak production rates at noon were observed to be 0.875 kg/m^2/hr as compared to 0.50 kg/m^2/hr for the passive solar still. Abdel-Rehim and Lasheen [39] studied theoretically and experimentally the performance of an active basin still with heat augmentation to basin, from a parabolic trough solar collector, through heat exchanger. Oil was used as heat transfer fluid from solar concentrator to the basin water. The productivity for the active basin still-solar concentrator system was 18% higher than the conventional basin still.

Badran et al. [40] studied experimentally the performance of a pyramid shaped basin still coupled with a flat plate collector. They found 131% and 52% rise of productivity when fresh water and saline water (35,000 ppm) were circulated in the still and collector, respectively. Voropoulos et al. [41] studied experimentally a large single effect greenhouse type solar still with aluminium basin inside a large thermal storage of water. The heat was supplied to thermal storage through a heat exchanger from an external solar collector field of 24 flat plate solar collectors. They found a productivity enhancement of 100% for this type of active still system as compared to the system without external heating. They observed higher night productivity as compared to day productivity, due to larger temperature differences between basin water and condensing surfaces of still, at night.

El-Sebaii et al. [42] studied the performance of an active single slope basin solar still integrated with a shallow solar pond, numerically and experimentally. They found the annual average values of productivity and efficiency for this still to be 52% and 44% higher than the still without solar pond. Velmurugan et al. [43] studied experimentally the performance of fin type single basin solar still by modifying with black rubber, sponge and sand, and stepped solar still by modifying with fin, pebble and sponge. Both the stills were supplied preheated saline water from mini solar pond. Maximum productivity enhancement of 100% was obtained for the stepped solar still configuration having fin, pebble and sponge, and integrated with mini solar pond, as compared to stepped solar still without these modifications.

The monthly performance of passive and active solar stills for different Indian climatic conditions was evaluated from numerical simulation by Singh and Tiwari [9]. They found that the optimum inclination for the condensing glass cover of basin still as well as the flat plate collector, for maximum annual yield, are the latitude of a place. Gaur and Tiwari [44] carried an optimization study by numerical simulation, of the number of flat plate collectors for the photovoltaic-thermal (PV/T) hybrid active solar still.

2.2.4 Enhancing condensation: The distillate productivity can be increased if the condensation process is enhanced by use of increased cooling of vapor as achieved in condensers. Kabeel et al. [45] have reviewed in detail the solar stills with condensers by classifying them as having built-in, internal and external condensers. Ahmed [46] found experimentally that the productivity of a basin type still can be increased by 10% by placing an internal condenser on the top side of the still. Cooling water was circulated in a double pass copper tube condenser. Nijegorodov et al. [47] studied experimentally a thermal electrical basin still. Water vapor produced in the basin is removed by an exhaust fan having power consumption of 100 W/m^2 of basin area, to an external water cooled condensing coil placed in a condenser tank. In the condenser tank some additional distillate is formed and the heated condenser tank water is used as feed water for next charge in basin. At noon the productivity of the thermal-electrical basin still was 2.5 times that of conventional basin still. El-bahi and Inan [48] investigated theoretically and experimentally the performance of a new design of solar still having separate evaporator and condenser sections. The evaporator had a basin tray covered with horizontally placed double glass covers and integrated to condenser section through a horizontal slot. A vertical reflector to boost the solar radiation on evaporator was added, which also formed the back wall of condenser section. The cover of the condenser was inclined to collect the distillate. The still yield was 4 $kg/m^2/day$ which was increased to 6 $kg/m^2/day$ with cooling of condenser cover with water. The system efficiency increased from 48% to 70% with water cooled condenser cover. El-bahi and Inan [49] studied experimentally a modified basin type solar still having single glass cover at 4° inclination and an external vertical reflector. The basin section was connected with an external passive condenser section having inclined cover. Some vapor condensed on the basin glass cover while rest purged towards the condenser and condensed on its cover. Thermal efficiency of 75% and distillate yield up to 7 $l/m^2/day$ was obtained for this type of still.

2.2.5 Using reflectors: For a basin still to operate at high efficiency, maximum incident radiation should be absorbed by basin water. Internal reflectors help in reflecting the incident solar radiation, which is falling on the walls of the still, to the basin water. The external reflectors are used to boost the solar radiation which is incident on the glass cover of the still, and hence on the basin water. Tanaka and Nakatake [50] theoretically estimated that by adding internal and external reflectors to the single slope basin type still, its productivity can be enhanced by 48%. Tanaka and Nakatake [51] analyzed numerically the solar radiation absorbed by the basin liner and the distillate productivity for a basin solar still, having fixed internal and hinged external reflectors, on a winter solstice day at 30° N latitude. At a glass cover angle of 20° and external reflector at 15°, the daily amount of distillate from this still would be about 2.3 times than that of a still without internal and external reflectors. Tanaka [52] numerically computed a 67% rise of distillate over the basin still, for optimum external reflector inclination, at glass cover inclination of 50° and when the length of external reflector is half the still's length. Tanaka [53] theoretically studied a basin type solar still with external flat plate bottom reflector in addition to internal side wall and backwall reflectors. The daily amount of distillate was computed to be 62% higher than conventional basin still, on a winter solstice day. Khalifa and Ibrahim [54] experimentally investigated the performance of a basin type still with fixed internal and hinged external reflectors inclined at 0, 10, 20 and 30° to the vertical, for various seasons. They reported that with external reflector inclined at 20° to vertical, the maximum daily productivity of still, in winter, was 2.5 times the still without reflectors. Dev et al. [55] studied experimentally an inverted absorber solar still (conventional solar still with curved reflector under the basin) and found its productivity to be significantly higher than the conventional single slope basin still. Boubekri et al. [56] studied numerically the performance of an active solar basin still having internal and external reflectors and coupled with a photovoltaic/thermal solar water heater and found 138% increase in production over the basin still.

2.3 INCLINED WICK STILL

Tilted absorber surfaces can receive more solar radiation intensity if they are oriented nearly normal to the incident solar radiation. Hence the tilted absorber surfaces should be oriented close to the latitude angle. The wick surfaces on the tilted surfaces reduce thermal inertia which result in faster response to solar radiation and hence they achieve higher temperatures resulting in higher evaporation temperatures [57].

Sodha et al. [13] studied experimentally an inclined wick solar still. The evaporating surface had multiple wicks of blackened jute cloth pieces placed one above the other and separated by thin polythene sheets. The upper ends of these wicks were dipped in a saline water tank. They observed a rise of efficiency and more than 50% reduction in cost of the still as compared to the basin type still. Janarthanan et al. [14] predicted theoretically the performance of a part floating and part fixed tilted wick solar still and validated their results experimentally. The top side of wick (feeding side), was a corrugated wick surface on a polystyrene float placed inside a water reservoir. Tanaka and Nakatake [58] numerically predicted the seasonal optimum tilt angles and azimuth angles for the inclined wick still when the still was oriented once a day. The average seasonal increase of daily distillate productivity over the fixed still was found to be 30%, when the still was rotated once a day. The gain was further increased to 41% by putting a vertical flat plate reflector on the top side of inclined wick still. Tanaka and Nakatake [59] investigated the effect on distillate productivity, of placing a vertical flat plate external reflector on the top side of a tilted wick solar still, for spring and autumn equinox, and winter and summer solstice days, at 30° N latitude. The distillate productivity for the still with reflector increased for all days except summer solstice day, as compared to the still without reflector. The average rise of distillate productivity for all four days was found to be 9%. Tanaka and Nakatake [60] theoretically calculated that the daily amount of distillate produced by a tilted wick still with vertical flat plate reflector, on winter solstice day, can be increased by inclining the reflector as well as increasing the reflector length. The daily distillate gain was found to be 27% for a reflector of same length as the still. Mahdi et al. [57] studied experimentally an inclined solar still with charcoal cloth as the wick material. Tanaka [61] proposed a geometrical model to calculate the solar radiation reflected by a reflector, placed on bottom side of a tilted wick solar still, and absorbed on the evaporating wick surface. He found that the daily amount of the distillate for a tilted wick solar still with reflector can be increased up to 13% over that of a conventional tilted wick solar still. Hansen et al. [62] studied experimentally the effect of different wick materials for different configurations of inclined absorber plates. They studied experimentally the different wicking characteristics like water absorption, capillary rise, porosity, water repellence and heat transfer coefficient, which affect the wick performance. Rahim [63] studied experimentally an inclined solar still with black aluminium plate as absorber. Brackish water circulated with pump, from a collection tank, is allowed to fall slowly on the absorber plate in film form. The vapor formed in the tilted evaporator is extracted with a fan and made to pass through copper condenser immersed in a water tank. The thermal efficiency, and overall efficiency considering electrical power of fan and pump, of the inclined still with separate condenser, was found to be 70% and 60%, respectively.

2.4 MULTI-EFFECT SOLAR STILL

Multiple effect stills have higher productivities than single effect solar stills, since the latent heat of condensation is recycled several times in the multi-effect distillation section. Rajaseenivasan et al. [64] have reviewed different methods used by researchers to increase the distillate productivity of multi-effect solar stills. A clear understanding of various heat and mass transfer processes and the parameters affecting the productivity of the solar still is very necessary for designing an efficient solar system. It helps in adopting optimum design parameters while designing the solar still. Hence literature review was done to study various thermal models presented by researchers. Elango et al. [65] have conducted a comprehensive review of thermal models and design modifications of various basin and multi-effect solar stills.

2.4.1 Multi-stage stacked tray solar still

Adhikari et al. [16] carried a techno-economic analysis, of multi-stage horizontally stacked tray solar still, coupled with a flat plate solar collector through a heat exchanger. The solar heat from flat plate collector was supplied to the bottom most tray. The vapors rising from the water surface of bottom most tray condense on the underside of next tray above it, thereby releasing its latent heat to heat water in it. The vapor from this tray condense on underside of next tray and in this way heat is recycled many times in the distillation chamber. They optimized the number of stages and the ratio of collector area to the area of bottom tray, by minimizing the cost of unit mass of distilled water using life cycle costing method. Ahmed et al. [66] studied a new horizontally stacked multi-stage evacuated solar distillation system in which the first stage was supplied heat from flat plate solar collector. Fluent software was used to simulate the simultaneous heat and mass transfer processes in the still. From experimental results, the productivity of the still was found to be three times than that of the basin type still. Chen et al. [67] experimentally investigated the performance of a multistage stacked tray still in which heat was supplied to first stage by a solar collector and the top stage received additional heat as solar radiation through a transparent glass cover. They developed a mathematical model for heat and mass transfer in the still and found the coefficient of performance as 1.12. Xiong et al. [68] studied numerically and experimentally a novel multi-effect solar still in which the first stage is heated by heat pipe vacuum tube collector. The top cover of the uppermost stage is coated with black titanium alloy which absorbs additional solar heat for heating the water in top basin. The basin trays, three in number, are corrugated shaped for enhancing the condensation process. The maximum distillate produced was 43.4 kg distillate at performance ratio of 1.86. The night distillate accounted for nearly 40% of the total distillate output. Feilizadeh et al. [69] investigated experimentally the effect of increasing the collector to basin area ratio (CBA) on the performance of a multi-stage solar still. They found that on increasing the CBA from 3.45 to 10.35 the productivity increased by 141%. Schwarzer et al. [70] numerically simulated and Schwarzer et al. [71] studied experimentally the performance of a horizontally stacked multi-effect still. The heat to first stage heat storage was supplied from solar collector by thermosiphon circulation. By utilizing 5-7 stages in experimental work, this type of still produced 15-18 l/m^2/day. Shatat and Mahkamov [72] conducted experimental investigations in lab conditions, for the performance testing of a horizontal four stage tray solar still. The first stage of the still was coupled through a heat exchanger, with a heat pipe-in-evacuated tube solar collector, which was irradiated with 110 halogen floodlights simulating solar radiation. A mathematical model was developed which was in good agreement with the experimental results. This model was further used to find rational design parameters of the still. The optimum number of stages for the still were found to be 4 or 5, from cost benefit analysis. El-Sebaii [73] studied numerically the effect of, water mass in basin trays, and wind speeds, on the daily productivity, for a horizontally stacked triple basin solar still. The still could produce 12.6 kg/m^2/day in summer solar radiation.

2.4.2 Horizontal diffusion type

Use of wetted wicks in stills reduces the thermal inertia and increases the rate of heat transfer by evaporation-condensation. The multiple effect diffusion still consists of a multiple plate arrangement in which a number of plates are arranged parallel to each other with a narrow gap between the plates. One side of each of the plates is covered with porous wick cloth. Heat is supplied to the uncovered side of the multiple plate arrangement and feed water is fed continuously to each of the wick sides of the plates. As heat is supplied to the first plate, water vapors generate from the wick side of the first plate, diffuse through the air gap between the plates and condense on the uncovered surface of the second plate. The latent heat released by condensing vapors conducts through the plate and further evaporate the water from the wick side of the second plate. In this way, the heat energy received by the first plate can be recycled several times to increase the productivity of the still.

Toyama et al. [74] proposed a simulation model of a horizontal multi-effect diffusion solar still to study the effect of variation in number of effects in still and feed water rates to partition plates. Toyama et al. [75] numerically simulated the performance of a horizontal multiple effect diffusion solar still and validated their results experimentally. Fukui et al. [76] studied numerically the performance of a maritime lifesaving horizontal multiple-effect diffusion solar still consisting of a transparent cover film and a number of plastic partitions.

2.4.3 Inclined diffusion type

Inclined diffusion stills can receive increased solar radiation as compared to horizontally oriented stills. Elsayed [77] developed a mathematical model for parametric study of a directly solar operated inclined multiple-effect diffusion still. The simulation results showed that the still efficiency can be improved by reducing the diffusion gap, increasing the number of effects and reducing the feed rate to each effect. Ouahes et al. [78] studied experimentally an inclined three effect diffusion still consisting of aluminium partition plates and obtained a productivity of 15 $kg/m^2/day$. Ohshiro et al. [79] studied theoretically and experimentally an inclined plate single cell diffusion still having wicks on both evaporating and condensing surfaces. The plates were separated by thin polytetrafluoroethylene (PTFE) net. Bouchekima et al. [80] studied experimentally an inclined two effect diffusion still having aluminium partition plates and wicks on the underside of partition plates.

In spite of high productivity of inclined and horizontal multi effect diffusion stills, these type of stills have a serious design drawback, i.e. the position of saline soaked wicks is above the condensing surfaces which may lead to contamination of distillate.

2.4.4 Other types

Some multi-effect still designs were found in literature which do not fall directly in the above mentioned categories, and are covered in this section. Grater et al. [81] studied experimentally a four effect vertical plate still having heating and cooling plates. The still had paper wicks. They found increase of distillate output with the increase of heating inlet temperature and heating power. The gain output ratio GOR (measure of thermal efficiency) increased by 80% with heat recovery from hot distillate and hot brine flow. Madhlopa and Johnstone [82] numerically simulated the performance of a modified passive basin still with separately connected condenser section. While the distillate from basin of evaporator section – basin 1 was termed as the first effect, the condenser section had two basins, basin 2 and basin 3, one above the another which yielded the second and third effects. The basin 3 was covered with an opaque cover. Vapor escaped to condenser section from the evaporator section predominantly by purging. Simulated results for the modified still with condenser showed that the still had 62% higher productivity than the conventional basin still. Prasad and Tiwari [83] studied numerically the performance of a double effect active solar distillation unit. The basin water of the still is heated by compound parabolic collector (CPC) by thermosiphon mode. The basin has two glass covers separated by a gap. Cooling water is made to flow on the inner glass cover. The distillates formed on the inner glass and outer glass covers are termed as the first and second effects, respectively. The authors observed significant improvement in productivity of this still over the conventional basin still. The hourly total yield as well as total 24 hours yield of the double-effect still were found to decrease with increase of flow velocity on the inner glass cover. Elango and Murugavel [84] compared experimentally productivities of double slope solar stills, having single basin and double basin (double effect), at different water depths in basin. The productivity of the insulated double basin solar still was found to be 17% higher than the single basin still, for a basin water depth of 1 cm. Tiwari et al. [85] theoretically analyzed the performance of a multi-effect wick type solar still. They found that the daily yield for a double effect multiwick solar still increases by 20% as compared to single stage distillation. The optimum number of distillation stages is three, since beyond three stages the latent heat of vapor for next stage reduces significantly. Yeh and Ho [86] theoretically and experimentally investigated the performance of an inclined multiple effect solar still. The still had a bottom absorber plate with black colored jute wick on it and multiple glass sheets having weirs above it, at some gap. Brine was allowed to flow on absorber plate as well as glass plates. The vapor from last effect was taken to an external condenser. Significant improvement in productivity for a double effect distiller was observed, as compared to the distiller having no air flow in the last effect.

2.5 VERTICAL MULTIPLE EFFECT DIFFUSION SOLAR STILLS

Vertical multiple effect diffusion stills have a number of vertical plates placed side by side with wick attached on one side. In these stills, no bending of plates takes place due to self-weight and hence the risk of crossflow of saline water is reduced. Hence, gap between plates can be reduced to as low as 5 mm [18,23], leading to a compact design and increased productivity.

2.5.1 Basin type

In the basin type vertical multiple effect diffusion (VMED) solar still, water vapors are formed due to absorption of solar radiation on the basin surface and condensed on the basin-side surface of inner glass cover and the basin-side surface of the first partition plate. The latent heat of condensation and solar energy directly absorbed, on blackened surface of first partition plate, is conducted through the partition plate to the other side of partition plate covered with wet wick, and causes evaporation of water from wet wick. The water vapors formed from wet wick diffuses across the gap of distillation cell and condenses on the uncovered surface of the second partition plate. The latent heat released by condensing vapors conducts through the plate and further evaporate the water from the wick side of the second plate. In this way, the heat energy received by the first plate can be recycled several times in the multiple partition plate distillation section of the still.

In the basin type vertical multiple effect diffusion solar still, the hourly cumulative efficiency is expected to increase since the latent heat of distillate formed at the back wall surface is utilized to form vapor from wet wick on other side of back wall plate, which condenses on the next partition plate. Moreover, with expected increase of heat transfer from metallic back wall due to its high thermal conductivity as compared to the glass cover, more distillate is formed at the second partition plate and some distillate is formed at the first partition plate also. The heat transfer from one partition plate to another takes place predominantly by evaporation from wick surface of one partition plate and condensation on the next partition plate, after diffusion through the air gap. The heat transfer by convection is very less at small plate gaps of the order of 10 mm [87] and by conduction and radiation is very less at small temperature differences between two plates. Further it is desired that maximum heat transfer should occur towards the vertical partition plate distillation section for reutilizing the heat energy several times to increase the productivity of still. Since the heat of condensation of condensate at glass cover is lost to surroundings, providing double glass covers with a gap of 10 mm significantly reduces the loss of heat to environment through glass covers so that most of the energy available in the basin transfers towards multiple effect section. The heat transfer across the double glass covers to the surroundings is reduced due to insulating effect of entrapped air between the glass covers, as compared to the heat transfer in case of single glass cover.

Tanaka et al. [87] theoretically studied the performance of a basin type vertical multiple effect diffusion solar still having 11 partition plates with 5-mm partition plate gaps and conducted a parametric study for such a still [88]. Tanaka et al. [18] experimentally studied basin type VMED solar still with 11 stainless steel partition plates at 5 mm partition gaps and obtained maximum productivity of 18.7 $kg/m^2/day$. Kaushal et al. [89] have dealt in detail the development of an improved basin type vertical single distillation cell solar still and its maintenance aspects. The still had a partitioned wick structure with individual feed water tubes for each such sub-partitioned area, to improve the wick wetting characteristics. The temperature of second partition plate was controlled by placing a third external plate without wick. They studied its performance experimentally at different feed water rates. Kaushal et al. [90] studied the performance of an improved four effect basin type VMED solar still referred as FW-BVMED-HR still. The conventional VMED still was modified to FW-BVMED-HR still, by adding multiple floating wicks in basin, and by feed water pre-heating through a heat exchanger by heat recovery from waste feed water. On a clear sunny day the distillate productivity of FW-BVMED-HR solar still was found to be 21% higher than the conventional VMED solar still.

2.5.2 Flat plate reflector type

A VMED still with flat plate reflector and attached castors for azimuth manual tracking of the still, was studied both theoretically and experimentally by Tanaka [23] and Tanaka and Nakatake [22,24,91,92].

2.5.3 Heat pipe type

A VMED still coupled with a heat pipe solar collector was studied theoretically by Tanaka and Nakatake [19] and parametrically by Tanaka et al. [20]. Tanaka et al. [21] performed indoor experiments on a VMED still coupled with a heat pipe solar collector, using infrared heating lamps.

2.5.4 Flat plate collector type

Kiatsiriroat et al. [25] presented a mathematical model to predict the performance of a vertical multiple effect diffusion still coupled with flat plate solar collector. They performed experiments on a vertical two effect diffusion still, with aluminium partition plates. The first plate was heated by circulating hot water, with a pump, from a flat plate solar collector and the last plate was air cooled.

2.5.5 Other types

Elsayed et al. [93] numerically simulated performance for multi-effect diffusion still and validated their model experimentally for a three effect vertical plate diffusion still. The first partition plate was heated by circulation of hot water, with pump, from heat transfer bench. The last partition plate was cooled by circulating cold water. Tanaka [94] presented theoretical analysis of a VMED solar still coupled with a tilted wick still. The wick of the first partition plate of multiple effect section and the wick of the tilted wick section were connected and vapours evaporating from the wick of the tilted wick section were transported to the first partition plate by natural convection. The latent heat of condensing vapor and solar radiation directly absorbed on first partition plate surface, acted as heat source for the multiple effect distillation section. Tanaka and lishi [95] studied a single effect diffusion still integrated with a tilted wick still. They confirmed experimentally that vapor can be transported by convection from tilted wick to partition plate of single effect still in both seasons of summer and autumn (with changing solar altitude angles). Tanaka [96] conducted parametric investigation theoretically for a solar still consisting of a vertical multiple effect unit integrated with tilted wick unit. He concluded that the distillate productivity could be increased significantly by increasing the height of vertical partition plates with respect to the length of tilted wick unit. He found experimentally the distillate productivity of a four effect still to be 10% less than theoretical calculations, and under optimum conditions to be equivalent to other types of multiple effect diffusion stills.

Nosoko et al. [97] have theoretically analyzed the possibility of heat recovery from hot condensate and hot waste feed water for feed water preheating. Chong et al. [98] developed a multiple effect diffusion still with bended-plate design in distillation section, coupled with vacuum tube solar collector and thermosiphon heat pipe to transport the solar heat to distillation unit. The feed water was pre-heated by recovering heat from hot distillate and feed water waste through a heat exchanger. Huang et al. [99] made performance study of a novel design of a spiral shaped multiple effect diffusion solar still. Solar heat was supplied to the first plate of the still from a vacuum tube solar collector through a heat pipe loop. The authors have claimed performance enhancement due to lateral diffusion in the spiral cell in addition to diffusion in radial direction. Heat recovery was done from saline waste as well as hot distillate to pre-heat feed water, through separate heat exchangers.

2.6 OPTIMIZATION STUDIES

Experimental and numerical parametric study has been done by many researchers to find the optimum design and operational parameters for the solar stills. Correlations for performance variation with parameters have been developed, which are very useful for preliminary design purpose. Prakash and Velmurugan [100] reviewed literature for various parameters affecting the productivity of solar stills. They found that productivity of solar stills increase, with increase of area of evaporation, decrease of depth of basin water, increase of basin water-cover glass temperature difference and with increase of inlet water temperature to basin. Khalifa and Hamood [101] studied the data reported by various researchers regarding the effect of, basin depth, solar radiation, dye and cover glass tilt angle, on productivity of the basin still. They developed generalized correlations relating the productivity with parameters. Tripathi and Tiwari [102] found experimentally that the convective heat transfer coefficient decreases with water depth due to decrease in water temperature, for both passive and active basin stills. Dimri et al. [103] made a parametric study of an active basin still coupled with flat plate collector. The effect of, thickness of condensing cover, collector absorbing surface, wind velocity and water depth in basin, was found. It was found that condensing cover made of copper gave the greatest yield as compared to glass and PVC. Singh et al. [104] studied theoretically the performance of a basin still integrated with an evacuated tube solar collector in natural circulation mode. They found the optimum number of evacuated tubes to be 10 for a basin water depth of 3 cm, with the daily yield obtained as 3.8 kg/m^2. Maximum daily energy and exergy efficiencies for the still were calculated to be 33% and 2.5% respectively. Tripathi and Tiwari [105] have used solar fraction of back wall, of basin still, for computing effective solar irradiance on basin water and found its significant contribution in daily distillate output. Tiwari and Tiwari [106] made a thermal model based on solar fraction, for the single slope passive solar still, and validated their results experimentally. They studied the relative influence and dominance of different modes of heat transfer within the still for different water depths and seasons.

2.7 ECONOMIC ANALYSIS

The unit cost of generating distillate is an important parameter in deciding the choice of technology and the size of the distillation plant. El-Sebaii and El-Bialy [107] reviewed various designs of solar stills comprising double-effect, triple-effect, multi-effect and other solar stills. They made a detailed cost analysis of various designs of stills. The passive triple-basin solar still and stepped solar still with internal reflectors give the lowest distillate production cost. Khayet [108] carried out an extensive literature survey of the specific energy consumption and unit distillate cost of membrane distillation, and compared them with other desalination processes. He reported that of all desalination technologies, Reverse osmosis is very cost competitive, with unit distillate cost of \$0.55/m^3 for 30 m gallons/day capacity system. Ahsaan et al. [109] designed and fabricated an improved Tubular solar still (TSS). The fabrication cost and weight of the new TSS were reduced by 92% and 61% respectively compared to the old one. A cost comparison of various desalination technologies was made and the improved TSS cost was found to be nearly 33% of the basin type solar still. Fath et al. [110] carried a numerical study for thermal and economic comparison between pyramid shaped and single slope basin stills. The annual average daily efficiency of single slope basin still was found to be slightly higher than the pyramid shaped still. The unit cost of distillate for the single slope basin still was found to be marginally less than for pyramid shaped still. Kabeel et al. [8] have estimated the unit cost of distillate for 17 different design configurations of solar stills available in literature. Annual productivity, annual maintenance operational cost, annual salvage values, life cycles of stills were considered for estimating the annual cost and unit cost of distillate for these stills. They found minimum unit cost of distillate for the pyramid shaped solar still. Sharon et al. [111] studied experimentally the performance of tilted basin still with partitions. They found the annual average distillate for this still to be 20% higher than that of a tilted wick still. The unit cost of distillate for the tilted basin still with partitions was found to be lower than that for the tilted wick solar still.

Tsilingiris [112] has discussed in detail the sources of errors, arising out of improper installation of thermocouple beads, for condensing surface temperature measurement, which can lead to errors of upto 2° C magnitude.

Finally, the acceptable drinking water standards for human consumption are mentioned in detail in the latest WHO guidelines of 2017 [113].

2.8 CONCLUDING REMARKS

The comprehensive literature review reveals the fact that the basin type VMED solar still has productivity many times over the conventional basin type single effect solar still. However, on the basis of critical literature survey, it has been found that there are few limitations associated with existing technology, hence there is enough scope to further improve the performance of conventional basin type VMED solar still. These limitations observed from literature survey are summarized here and the improvements/modifications incorporated in the present work to overcome these limitations are also discussed below:

(1) Sensible heat of hot saline feed water is going waste to drain resulting in considerable heat loss for the still [18,21]. Also sensible heat of hot distillate is going waste to surroundings [18,21]. The heat from these two sources can be recovered by using separate heat exchangers and utilized to pre-heat saline feed water to VMED plates [97]. Although many researchers have utilized heat exchangers to pre-heat saline feed water, the effectiveness of heat exchanger and its cost implication has not been reported. Very few researchers have reported the gain in productivity from waste heat recovery, from experimental studies. In the present work, the effectiveness of heat exchanger, used for heat recovery from hot waste feed water only, has been reported. The increase of productivity resulting from pre-heating feed water, from heat recovery, has also been reported. The heat exchanger used is simple tube-in-tube

type with very less cost. The cost details of heat exchanger have been reported in the present work.

(2) The absorber in case of a basin type still used by most researchers is the basin water and black liner which is lying horizontally. Researchers have suggested to maintain minimum possible water depth in basin water for reducing thermal capacity of basin water in order to enhance evaporation rate of basin water. From literature survey it was found that fixed and float wicks have been used in the basin of basin type single effect stills, to reduce thermal inertia of evaporating surface [11,12]. However, there are no reports in the open literature that mention utilization of floating wick in the basin type VMED solar still to improve its performance. Hence to reduce the thermal capacity of basin water and to increase the free surface area of water, a floating wick in basin of conventional basin type VMED still is used in the present work. The floating wick accelerates the rate of evaporation from wick surface as wick temperature is high. The floats have been made from cheaper and lightweight polystyrene and polyurethane material with black cotton cloth wick as cover.

(3) The horizontal surface of basin water receives less radiation as compared to tilted surfaces. Few researchers have used reflectors in the side walls to reflect the radiation on the basin water of basin stills and first partition plate [18,50]. They have reported significant rise of productivity as compared to conventional basin stills without reflectors. Hence in the floating wick basin type vertical multiple effect diffusion solar still with heat recovery (FW-BVMED-HR) of present work, stainless steel reflectors with mirror finish polish, have been used on triangular side walls to boost solar radiation absorption on the cotton cloth wick surface of floats and first partition plate.

(4) From literature survey, few operational problems of VMED stills were identified. Dry patches formation, on partition plate wicks, takes place at low feed rates, which causes low productivity [87]. The feed channels were placed outside the partition plates on the top edge, causing sealing problem in distillation cell. The wick cloths were dipped in the feed channels so that wicks were wetted by capillary flow downwards, which often led to uneven wetting of wicks. Hence in the present FW-BVMED-HR still, partitioned wick structure with individual feed tubes to each such partitioned surface, has been used to achieve uniform and improved wick wetting. The feed water, waste feed water drain and distillate channels, were placed inside the sealed boundary, to prevent heat and vapor losses from distillation cells.

Cross flow and contamination of distillate has been reported in literature, along cubicle spacers, and when partition plates touch each other due to thermal expansion and bending, at very low partition plate gaps of 3 mm and 5 mm. Hence in the present FW-BVMED-HR still, uniform partition plate gaps of 10 mm has been maintained by using rectangular longitudinal neoprene rubber spacers, placed from top edge to bottom edge of partition plates. The amount of heat transfer from the basin section towards the multiple effect distillation section is vital for the total distillate productivity resulting from the FW-BVMED-HR still. For maximum heat transfer towards the multiple effect distillation section, thermal conductivity of first partition plate should be high. Tanaka et al. [18] had used stainless steel for first partition plate. In the present FW-BVMED-HR still, first partition plate of copper has been used, to improve the heat transfer from the basin section towards the distillation section. In the present FW-BVMED-HR still, all partition plates except the first partition plate, has been made of stainless steel 0.3 mm thick as against 0.5 mm thick used by previous researchers [18]. Reducing the partition plate thickness gives some cost advantage as well as helps in reducing the weight of the still.

(5) Most researchers have used wood for fabrication of framework of basin type stills or basin type VMED stills [18], since wood is a good insulator. However, due to deterioration of wood in external weather conditions and due to continuous contact with vapor and water, such stills have very less life cycles of 2 to 3 years. In the present FW-BVMED-HR still, mild steel frame work with corrosion resistant paint has been used to increase the life cycle up to 10 years. With annual re-painting and regular maintenance, this still is expected to have life cycle up to 25 years. All mild steel surfaces which were exposed to external environment were properly insulated using thick sheets of polyurethane sheathing, to prevent heat losses.

(6) From literature survey, very little information regarding maintenance problems in operation of vertical multiple effect diffusion solar stills have been reported. Hence, in the present work, maintenance problems of VMED stills have been dealt in detail and possible remedies for them have been suggested.

(7) Parametric study by numerical simulation for VMED stills have been adequately reported in literature. There is no experimental validation of such studies, as found from vast literature survey. In the present work, experiments were performed by varying various parameters

such as gap between partition plates, number of effects, feed rate and depth of basin water, in order to find the effect of these parameters on the performance of FW-BVMED-HR still under actual outdoor conditions. From the literature survey no correlation was found which can be used to estimate the productivity of the VMED still to carry out techno-commercial feasibility studies before installation of similar type of solar distillation unit in any part of the world. In the present research work, an empirical correlation has been developed to predict the productivity of FW-BVMED-HR still by considering all possible weather, design and operational parameters which affect the productivity of such type of still.

(8) From literature survey it was noted that although productivity of solar stills have been reported by all researchers, very few have reported the efficiency values. Very few researchers have reported the night distillates separately. The input saline water and distillate quality values have been reported by very few researchers. Very few research works were found, which reported the cost economics of the distillate produced. To overcome all these shortfalls in information existing in literature, the present research work incorporates all of them to fill the existing gap in information. Hourly cumulative efficiency and distillate productivity variations have been reported in the present work. The day and night distillates have been reported separately. Input saline water and distillate quality values have been reported. Cost economics of generating the distillate from FW-BVMED-HR still has been dealt in detail, in this work.

Chapter 3

Experimental Set-up and Data Acquisition

The major components of the experimental test rigs used for the various experiments were fabricated in the central workshop of the University and finally assembled at the experimental site. Based on the gaps and limitations identified from literature survey, few improvements were incorporated in the existing conventional basin type vertical multiple effect diffusion (VMED) solar still to obtain improved and modified still of present research work, with an objective to increase the overall productivity and cumulative efficiency. As against the previous design of basin type VMED solar still by researchers [18], the improved design of present study has first partition plate made of copper in order to increase the heat transfer to the multi-effect distillation section. The wick covered surface of partition plate was divided into six equal sections by gluing five longitudinal rubber rods running vertically from top to bottom of plate. Each such divided sections of a partition plate were covered with separate coarse cotton cloth wicks and separate feed water arrangements were used to feed water to each such wick sections, in order to achieve uniform and improved wick wetting. The longitudinal rubber spacers, used for dividing the wick covered surface of partition plate, also helped to maintain uniform diffusion gap between partition plates. The feed water, waste feed water drain and distillate, channels, were placed inside the sealed boundary, to prevent heat and vapor losses from distillation cell. Multiple floating wicks were placed in the basin to minimize the thermal inertia of evaporating surface. The heat going with hot waste feed water was recovered through a simple tube-in-tube counter flow heat exchanger to preheat the feed water. Details of all these design changes are provided in the following sections. The development drawings of various components of still and their fabrication details have been provided in Appendix-A. Since the basin type VMED solar still is basically a design improvement over the basin still (single effect basin still), a basin still was fabricated and its performance was studied, to serve as a reference for the gain in productivity for the basin type VMED solar still. Similarly, the conventional basin type VMED solar still served as a reference for performance comparison for the new improved basin type VMED solar still of present work. The measuring instruments, their range and accuracy have been provided. The calibration process of thermocouple and calibration curve has been shown. The detailed experimental procedure for all experiments has been provided.

3.1 BASIN STILL

A conventional basin still with single slope and single glass cover as shown in Fig. 3.1 was made and its performance was studied. The still had a black rubber liner in stainless steel basin tray and internal side reflectors of mirror polished stainless steel. The framework of the still was made with mild steel which was then painted white. The back wall plate was made of 0.5 mm thick copper sheet which was painted black with blackboard paint, on the basin side. The back wall plate was well insulated on the outer side. The distillate from glass cover was collected with a channel attached to the glass cover at the front edge of still frame.

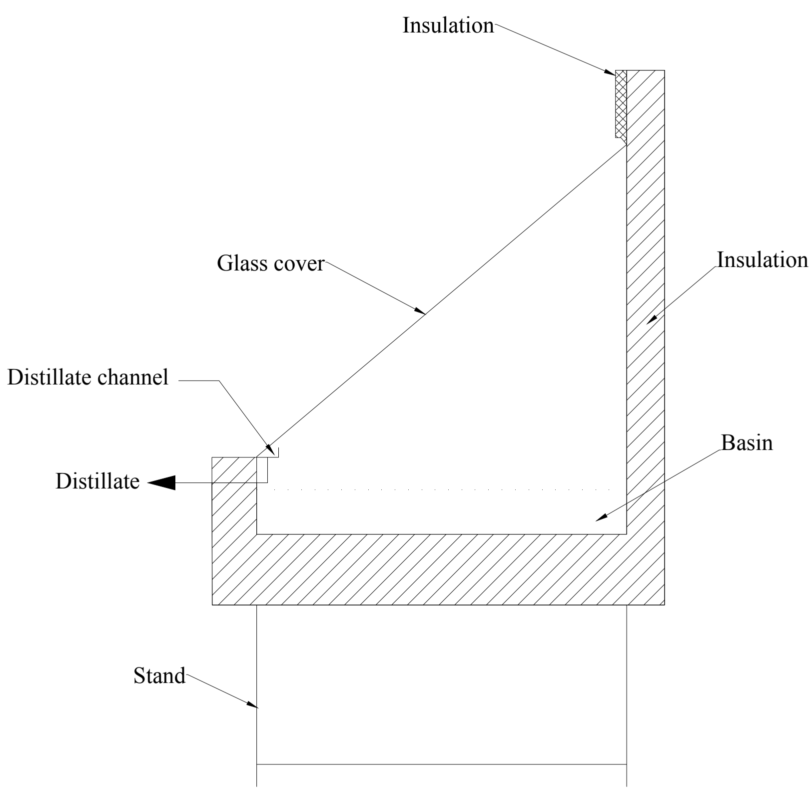


Fig 3.1 Schematic diagram of conventional basin still

3.2 FLOATING WICK BASIN TYPE VERTICAL MULTIPLE EFFECT DIFFUSION SOLAR STILL WITH WASTE HEAT RECOVERY (FW-BVMED-HR)

The basin type still as explained in section 3.1 and shown in Fig. 3.1, was converted into basin type vertical multiple effect diffusion (VMED) solar still, with component dimensions listed in Table 3.1. Two such stills with same dimensions and materials were fabricated, for comparison experiments. In one of these stills, modifications of adding heat exchanger for waste heat recovery and multiple float wicks in basin were incorporated. This still was referred to as floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery (FW-BVMED-HR) and schematic diagram of this still is shown in Fig. 3.2. The other still with no modifications in the existing conventional design of basin type VMED was referred to as reference still. The photograph of both the FW-BVMED-HR and reference stills installed side by side at test site is shown in Fig. 3.3. The number of partition plates in the multiple effect distillation section were varied from 2 to 7, depending on the type of experiment.

Table 3.1 Dimensions of floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery (FW-BVMED-HR)

Still component	Dimensions
Evaporating area of basin	1500 mm × 770 mm
Effective glass cover area	1470 mm × 900 mm
Effective evaporating and condensing area of distillation cell	1520 mm × 680 mm
Angle between glass cover and basin	40°
Gap between glass covers	10 mm
Thickness of glass cover plate	5 mm
Diffusion gap of distillation cells	10, 13, 16 mm

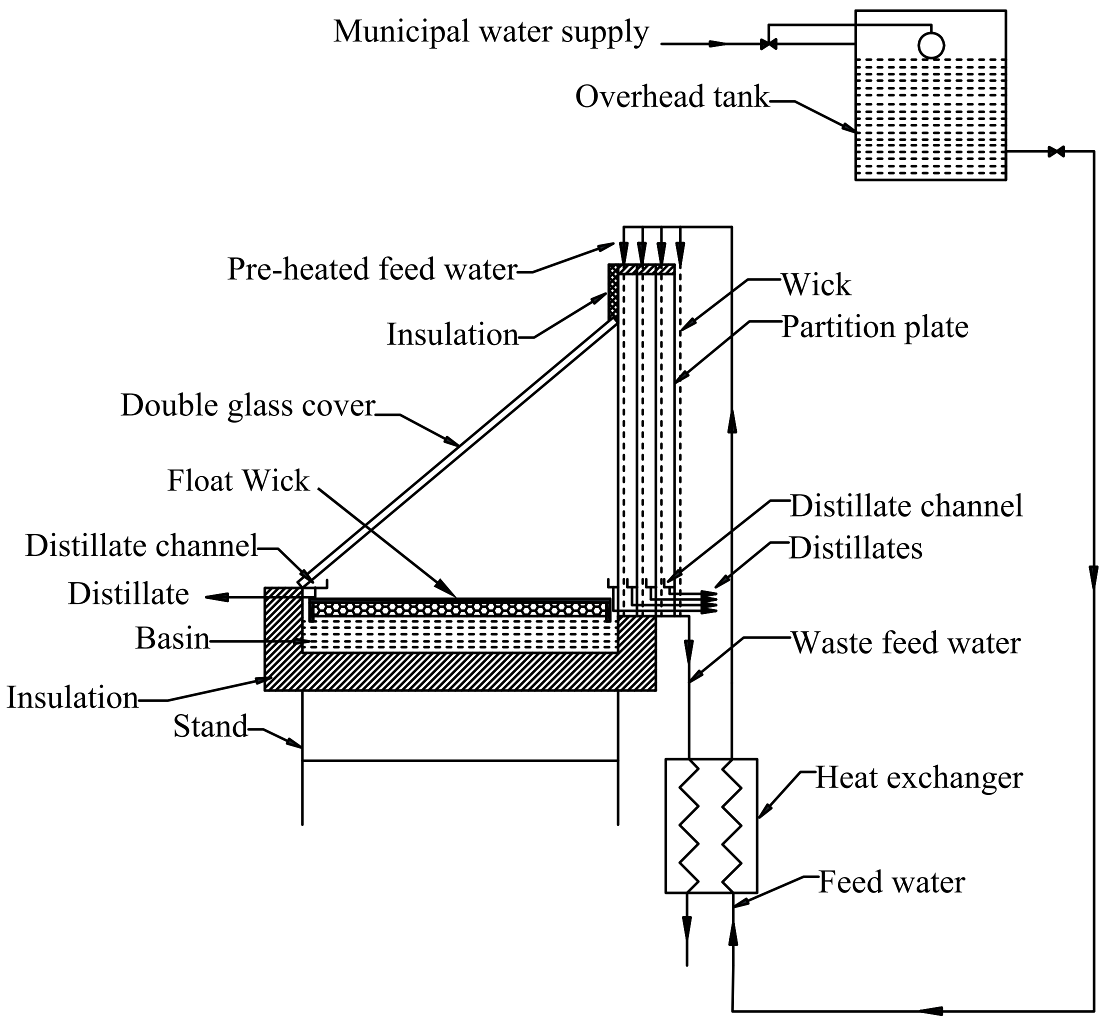


Fig. 3.2 Schematic diagram of FW-BVMED-HR still

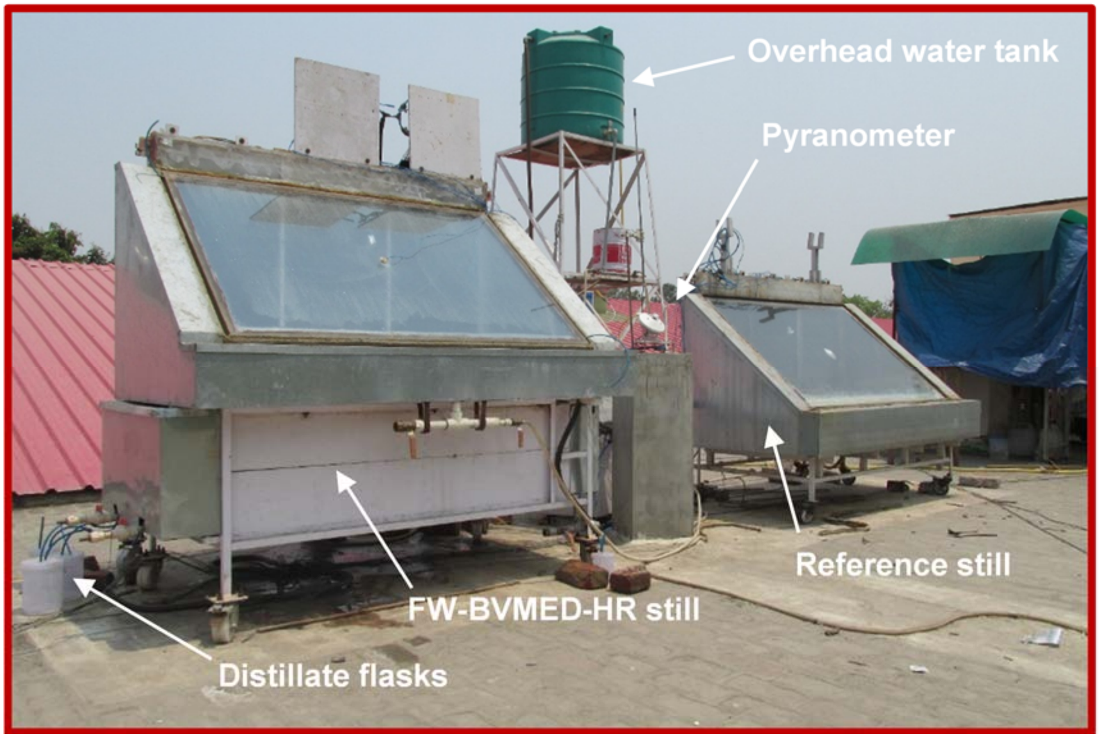


Fig. 3.3 Snapshot of FW-BVMED-HR and reference stills at test site

The FW-BVMED-HR and reference stills consisted of several components. These components are separately described below.

3.2.1 Triangular basin section

It consisted of stainless steel basin tray covered with black rubber liner, mirror finished side walls of stainless steel plates and sloping double glass cover. The back-wall of basin section was made of 0.5 mm thick copper sheet and its basin-side surface was painted black with blackboard paint. The basin tray and side walls were insulated with 100 mm thick polyurethane foam. The framework of the basin section was made with mild steel which was then painted white. Multiple float wicks were placed in the basin water of modified still (FW-BVMED-HR still). Multiple floating wicks were placed in the basin to minimize the thermal inertia of evaporating surface. A float must be light weight, strong, water resistant with time and able to withstand high temperatures in the basin section of still. Polystyrene (Thermocole) satisfies all these requirements below 80°C temperature. The float was made from 19 mm thick polystyrene sheet on which a 4 mm thick sheet of polyurethane foam was wrapped tightly to provide a protective layer. Initially, burnout due to high temperatures was observed for polystyrene floats. Hence a protective cladding of polyurethane foam was provided, since it can withstand temperatures up to 120°C. A blackened cotton cloth wick was hanged on both sides from this float and fastened with cotton thread as shown in Fig. 3.4. Each float was 63.5 mm wide and 725 mm in length. Sufficient clearance space between the floating wicks and basin sidewalls was given so that the floats do not get stuck up when the level of water in basin changes. Fig. 3.5 shows the multiple floating wicks placed in basin of FW-BVMED-HR solar still.

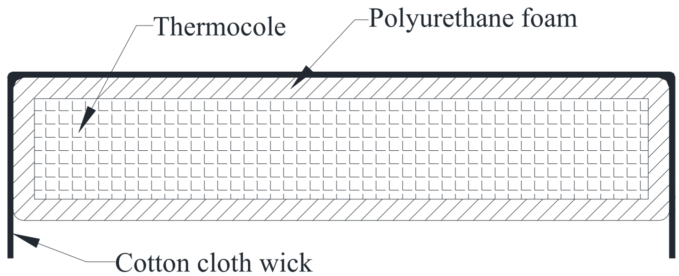


Fig. 3.4 Schematic diagram showing cross-sectional details of the float wick

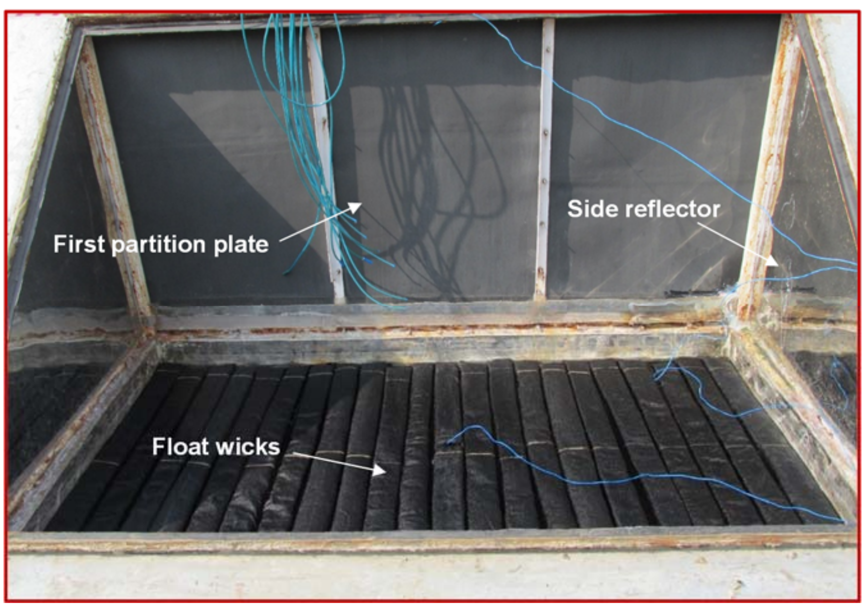


Fig. 3.5 Multiple floating wicks in basin of FW-BVMED-HR still

3.2.2 Vertical distillation section

It consisted of parallel vertical partition plates having gap (10-16 mm) between them. The copper back-wall of basin section, 0.5 mm thick, formed the first partition plate and stainless steel (304 grade) sheets of 0.3 mm thickness formed the second partition plate and other partition plates, of distillation section. The borders of distillation cell were effectively sealed, by sandwiching water proof wooden strips between the plates along with thick layer of silicon sealant on either side of wooden strips, and by pressing between the fixed basin frame and an outer removable frame, by nuts and bolts, through holes in welded projections bordering the two frames, as shown in Fig. 3.6.

Fig. 3.6 Snapshot of distillation section frames with projections for nuts and bolts

3.2.3 Partitioned wick structure

Coarse and porous cotton cloth of about 1 mm thickness was used as a wick to cover the evaporator sides of partition plates. The non-uniform wetting or part wetting of wick surface lowers the effectiveness of the wick and hence reduces the distillate output. Therefore partitioned wick structure was used to ensure uniform wetting of wick. As shown in Fig. 3.7, the evaporator sides of partition plates was partitioned into six equal partitions by gluing five rubber rods of 10 mm x 10 mm cross-section, with 1 mm thick layer of silicone sealant, vertically, from top to bottom of partition plate. Moreover, the rubber rods used for creating partitions on partition plate area, also acted as longitudinal spacers, to maintain uniform gap between the partition plates. A uniform space of 10 mm (or 13, 16 mm) was maintained between any two plates after compression. Each of these sub-partitions on the partition plate surface was covered with cotton cloth which was glued by wetting the cloth and removing air between the cloth and partition plate. Individual feed water channels were used to supply feed water to each of these sub-partitions to achieve uniform wetting of wick.

In order to avoid cross flow between partition plates through longitudinal spacers, the cotton cloth was pasted on each sub-partition with 3 mm gap, on both sides, between wick and longitudinal spacers. Since spacers were running from top to bottom of partition plate, therefore any drifting water stream from the wicks would drain downwards along the corners of spacers.

Fig. 3.7 Snapshot of partitioned wick structure in the FW-BVMED-HR still

3.2.4 Feed water channels

Individual stainless steel feed water channels of 37.5 mm depth (downwards) and 3 mm width (perpendicular to partition plate) in partition gap were used for each of the six sub-partitioned sections of the partition plate, as shown in Fig. 3.8. The feed water channels were made by screwing 37.5 mm wide stainless strips on top inside bordering surface of each sub-partitioned section and a gap of 3 mm between partition plate and stainless strip (perpendicular to partition plate) was maintained by sandwiching 3 mm thick layer of silicon rubber on both the side edges, between partition plate and stainless strip. While screwing the stainless strip, the multi-folded top end of cotton wick cloth was also sandwiched between partition plate and stainless steel strip. A common header pipe of 75 mm diameter was used to supply feed water to all the six feed water channels of the plate, through flexible capillary tubes of 2.5 mm internal diameter and control valves, dedicated for each channel. The wetting of the wick was by gravity flow of feed water and soaking and spreading in wick by capillary action. The feed flow rate was kept equal for all sub-partitioned wick surfaces, by individual control valves.

3.2.5 Distillate and waste feed water channels

Distillate channels made of polycarbonate sheet 37.5 mm depth (downwards) were attached with adequate slope, to the lower edge of condensate side of each partition plate, basin facing back-wall of basin section and inner glass cover, to collect the distillate water, as shown in Fig. 3.8. Similar to distillate channels, common waste feed water channels from all six partitioned areas, were attached to the wick side of partition plates. Plastic pipes of 6 mm internal diameter were attached to these channels to carry the distillate water and waste feed water to the collecting flasks.

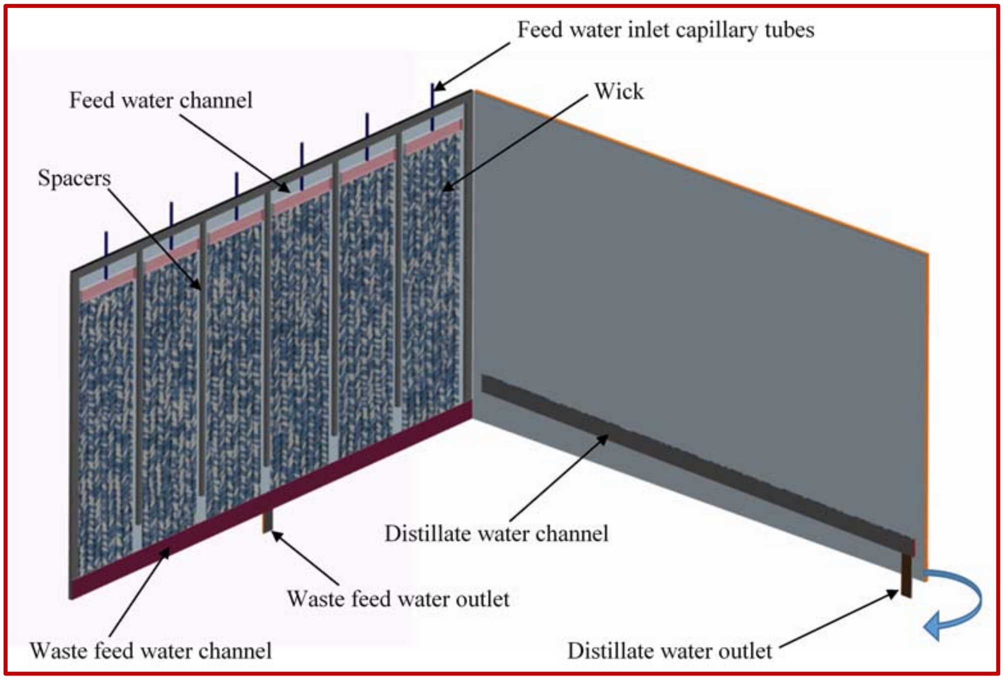


Fig. 3.8 Evaporating plate (left) showing feed water and waste feed water collection channels, and condensing plate (right) showing the distillate collection channel

3.2.6 Heat exchanger

The heat going with hot waste feed water was recovered through a simple coiled tube-in-tube counter flow heat exchanger to preheat the feed water, as shown in Fig. 3.9. The preliminary experimental results showed that the temperature of waste feed water from last partition plate, was not high enough and was close to ambient temperature. Therefore, hot waste feed water from all partition plates but last was sent for heat recovery in the heat exchanger. In the heat exchanger, the feed water was made to flow through the inner copper tube with internal diameter 5 mm, and the waste feed water from the partition plates was made to flow through the annular space between inner copper tube and outer PVC tube having internal diameter of 12.5 mm.

Fig. 3.9 Snapshot showing the tube-in-tube counter flow heat exchanger

3.3 INSTRUMENTATION AND MEASUREMENT

3.3.1 Solar radiation measurement

Global solar radiation, on glass cover surface of FW-BVMED-HR still, was measured by a Kipp and Zonen make pyranometer, shown in Fig. 3.10. The measuring range of the instrument is 0-4000 W/m^2 with an accuracy of 1 W/m^2. The pyranometer was installed at a central location between the FW-BVMED-HR and reference stills. The pyranometer was oriented at 40° to the horizontal, which is the angle of glass cover of the FW-BVMED-HR still. The global solar radiation data was logged at set interval of 10 min, by a Logbox SD data logger.

Fig. 3.10 Pyranometer

3.3.2 Wind speed measurement

The wind speed was measured by a hot wire anemometer (make: Lutron; model: AM-4224SD), shown in Fig. 3.11. The instrument is data logger type, i.e., the instrument can record the data automatically at the pre-set time interval and store it in the SD memory card. The recorded data is transferred into the laptop by inserting the SD card in the built-in card reader slot of laptop. The anemometer measurement range is 0.2–25 m/s. The accuracy of the instrument is 5% of the reading. The wind speed was logged at an interval of 10 min.

Fig. 3.11 Anemometer

3.3.3 Relative humidity

The relative humidity was measured by a data logger type relative humidity meter (make: Ebro; model: EBI 20-TH1), shown in Fig. 3.12. The measuring range of instrument is 0-100% RH. The accuracy of the instrument is 2% RH. The data was continuously logged at an interval of 10 min. The instrument is programmed by means of a PC. An instrument specific interface cable is used for programming the instrument, together with a 'Winlog.x' program on the PC. The interface cable is connected to the PC by the Universal Serial Bus (USB) and the same interface cable is used to transfer the recorded data from instrument to PC.

Fig. 3.12 Relative humidity meter

3.3.4 TDS measurement

Total dissolved solids TDS, of input saline water and distillate output, were measured by a TDS meter (make: Spectralab; model: COT-2), shown in Fig. 3.13. It is a micro-controller based TDS measurement instrument with graphic LCD display. The measuring range of instrument is 0.1 ppm – 200,000 ppm. The accuracy of the instrument is 2% of the reading. Hourly measurements of TDS of input saline water, and distillates from all partition plates and glass cover, were made.

Fig. 3.13 TDS meter

3.3.5 pH measurement

The pH of input saline water and distillate output, were measured by a pH meter (make: Spectralab; model: Eco-pH), shown in Fig. 3.14. The measuring range of pH meter is 0-14 pH. The accuracy of the instrument is 0.02 pH. Hourly measurements of pH of input saline water and distillates from all partition plates and glass cover, were made.

Fig. 3.14 pH meter

3.3.6 Mass measurement

Hourly measurements of mass of distillates from glass cover and all partition plates were made, by a digital weighing balance having a range of 0-5 kg. The accuracy of the balance is 0.1 g. An empty flask was placed on the weighing balance and the mass was set to zero by the tare button. Subsequently, distillate from a particular partition plate was poured into it and the reading was allowed to stabilize for nearly 30 secs. The stabilized reading was noted and mass was set to zero by tare button again, for measurement of distillate of next partition plate.

3.3.7 Temperature measurement

Temperature of the components of FW-BVMED-HR and reference stills were measured by T-type thermocouples. The temperatures measured by all the thermocouples were continuously logged by a 64 channel Ajinkya make data logger. Temperatures of inner surface of inner glass and outer surface of outer glass covers, partition plates and outlet feed water from storage tank and at entry to partition plates were measured for both FW-BVMED-HR and reference stills. Additionally, the temperatures of, saline feed water and waste feed water, at inlet to heat exchanger, and saline feed water and waste feed water, at outlet from heat exchanger, were measured for the FW-BVMED-HR still. The thermocouple on glass cover was glued with silicon sealant, at a central location, after making contact with the glass surface. It was shielded from direct sunlight by gluing an aluminium foil of size 2.5 cm × 2.5 cm over it. The thermocouples on partition plates were soldered on square 2 cm × 2 cm × 0.5 mm copper sheet pieces and screwed at mid-length of partition plates. Three thermocouples were placed vertically, at equal distance, starting from top edge of each partition plate. Basin water temperature of both the stills was measured at a height of 5 mm from basin liner and shielded by aluminium foil. The float wick temperature was measured by a thermocouple attached below the cotton cloth wick surface, by sewing with cotton thread so that the tip of thermocouple makes effective contact with the wick. The ambient temperature was measured by a thermocouple suspended in air and shielded by a Stevenson screen, within 2 m radius from pyranometer location (centre of both stills) and 1 m above the ground.

3.4 CALIBRATION OF THERMOCOUPLES

The thermocouples were calibrated at McCoy research and calibration laboratory, New Delhi. The thermocouples were calibrated with digital temperature indicator having sensor of Lutron make. The range of calibration was 0-100 °C with measurement uncertainty (at 95% confidence level) of ± 1.0 °C. The calibration was done in steps of 15 °C starting from 10 °C to 100 °C, since this is the operating range of the thermocouples in actual experimental conditions. One of such calibration curves of the thermocouples is as shown below in Fig. 3.15. A scatter plot between actual temperature and indicated temperature by thermocouple was plotted. The linear fit equation for actual temperature fits the data with R^2 = 0.99. After acquiring the temperature data of thermocouples, the data were corrected by using the equation of best fit, and used in subsequent calculations.

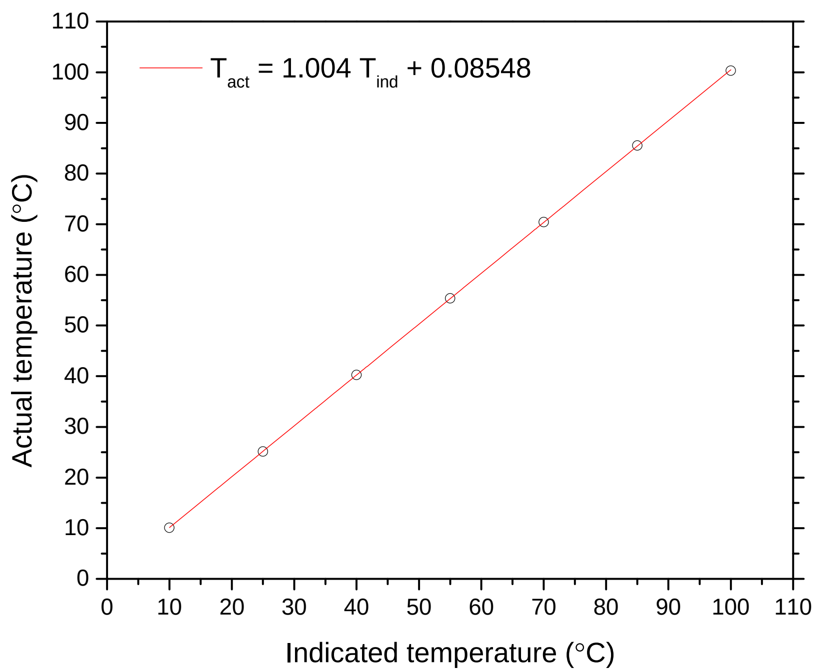


Fig. 3.15 Calibration plot of thermocouple

3.5 EXPERIMENTAL PROCEDURE

The present experimental work was carried out at Patiala, India, located at Latitude N 30.3° and Longitude E 76.4°. Before conducting the outdoor experiments, the experimental set-up was checked and tested for its proper functioning. The main check point was to ensure that there was no cross flow of feed water from evaporating surface to condensing surface of the distillation cells. The possible source of cross flow of feed water across the distillation cells were the longitudinal rubber spacers sandwiched between the partition plates of distillation cells, and protruding fibers of wick cloth touching the condensing surface of distillation cells. The test was done by collecting several samples of distillate and input saline water, and checking their TDS with TDS meter. No contamination from feed water was detected in the distillate. The uniform feed water distribution, through individual channels in partitioned wick areas, and uniform soaking in thick cotton cloth wicks, was also verified visually. Another check point was to ensure that the set feed rates are maintained for all partition plates. The distillate rates and waste saline water flow rates were measured hourly, with collecting flasks and stop watch. The sum of distillate rates and waste saline water flow rates from partition cells, must equal the set input saline water feed rates to the partition plates.

In the present study, the floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR) was fabricated in stages starting from constructing conventional basin still as a first stage. Few experiments were performed at each of the stages to ensure proper working of configuration of each stage. The conventional basin still is then converted into basin type vertical single distillation cell (VSDC) solar still. In other words the conventional basin still is converted into basin type VMED still with two effects. As stated earlier, few experiments were performed with this two effect basin type VMED still, to gain insight into the working and operation of basin type VMED still, and to find the effect of feed water rate for it. The two effect basin type VMED still is subsequently converted and modified into four effect basin type VMED still having heat exchanger for waste heat recovery. Few experiments were performed with this basin type VMED still with heat recovery (BVMED-HR), with simultaneous experiments being done under identical conditions on four effect conventional basin type VMED still (reference still), to find the effect of heat recovery from waste feed water on the performance of basin type vertical multiple effect diffusion (VMED) solar still. Finally, the four effect BVMED-HR was modified into four effect floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR) still by adding multiple floating wicks in the basin of BVMED-HR still, and the experiments were performed with four effect FW-BVMED-HR still and four effect conventional basin type VMED solar still (reference still), placed side by side, for comparison purpose. In order to find the effect of, varying the number of effects, on the performance of FW-BVMED-HR, additional experiments were conducted by varying the number of effects from 2 to 7. For these additional experiments, the partition plates of reference still were removed and used for 5th, 6th and 7th effect of FW-BVMED-HR still. Hence additional experiments for studying the effect of, varying the number of effects, on the performance of still were conducted only on FW-BVMED-HR still.

The total experiments that were performed have been classified under five sets of experiments. In the following paragraphs, the procedure for each set of experiment is mentioned.

3.5.1 Basin type still

In the first set of experiments, performance study of a conventional basin type still for whole day was done. Before the start of experiments, water in basin was filled to an initial level of 1 cm. Hourly distillates from glass cover were collected from 8:00 AM – 6:00 PM. Night distillate after 6:00 PM was collected in a can and measured next morning. The TDS and pH of input feed water and distillate was checked at the end of experiment. The performance results of these experiments have been provided in Appendix-B.

3.5.2 Basin type vertical single distillation cell (VSDC) solar still

In the second set of experiments, performance study was done on the improved basin type vertical single distillation cell (VSDC) solar still with partitioned wick arrangement and individual wick feed water distribution system. The gap between the partition plates was maintained as 10 mm. This still has only one vertical distillation cell, hence to maintain low temperature drop across the distillation cell, in order to suppress convective and radiative heat exchange between partition plates of distillation cell, and to maintain high mean cell temperature, the temperature of second partition plate (which is exposed to ambient) was kept considerably above the ambient by providing controlled evaporative cooling of outside surface of second partition plate. Fukui et al. [76] have shown analytically that at high mean temperatures of the partition cell, the vapor diffusion flux $\dot{m}_e$ is large even at small effective temperature drop across the cell. Hence, the outside surface of second partition plate was also covered with wet wick and a third external plate was placed, over the outer removable frame, at an effective gap of 25 mm from second partition plate of distillation cell, by fastening with nuts and bolts on all sides, without sealing the border. This meant that vapors formed at outside surface of second partition plate air could escape to surrounding atmosphere from all four sides. Thus function of using third external plate with borders open was to control the evaporative and convective cooling of outside surface of second partition plate and hence help in maintaining a high temperature film on the evaporating surface of the second partition plate. The presence of third external plate also prevented the blowing away of the wicks due to strong winds. Although in the present work, the third partition plate was of same material as that of partition plates, it could be of plastic material such as HDPE and PVC or a curtain of cloth also.

Initial water level in basin was kept at 1 cm. The main feed water supply tank was placed at a height of 1.70 m. It was fed water through municipal water supply, through a pre-filter and float valve. The feed rates in partition plate 1 and partition plate 2 were set to the required value. The valve settings of all the six capillary feeder tubes of each partition plate were adjusted so that they gave equal flow rates. The average feed water rate to each partition plate was measured, from the hourly measurement of waste feed water flow and distillate, separately. The performance of the improved basin type VSDC solar still was studied with flow rate variation over a range. Due to the heat energy loss from the cell with the waste feed water and distillate; and radiative, convective and vapor leakage losses, the feed flow rate on the second partition plate was kept at 80% value of feed flow rate of first partition plate. The distillate production rates between 8:00 AM to 6:00 PM were measured hourly. Night distillate after 6:00 PM was collected in a can and measured next morning at 8:00 AM. The readings of solar intensity and ambient air temperature were logged by their data loggers at an interval of 15 minutes and 10 minutes respectively. The temperatures at various key locations of still were recorded directly in a multi-channel temperature data logger, for 24 hrs, at a logging interval of 10 minutes. In order to verify and ensure that no cross flow between the plates was taking place during the entire experimental work, the TDS and pH of input feed water and distillate was regularly checked on hourly basis.

3.5.3 Basin type vertical multiple effect diffusion solar still with heat recovery from waste feed water (BVMED-HR)

In the third set of experiments, performance of four effect basin type vertical multiple effect diffusion solar still with heat recovery from waste feed water (BVMED-HR) was tested for few days. The BVMED-HR still was supplied pre-heated feed water by heat recovery from waste feed water through a heat exchanger. Performance testing of a four effect conventional basin VMED still called the reference still was also done, simultaneously, for comparison purpose. In order to verify and ensure that no cross flow between the partition plates was taking place during the entire experimental work, the TDS and pH of input feed water and distillates from each partition plate were regularly checked on hourly basis. Initially, both the stills were checked for any difference in distillate productivity arising out of design, material, fabrication, location and operation. The heat exchanger from the BVMED-HR still was removed and 1 cm of water was filled in the basin of both the stills. Equal feed water rates were set on the partition plates, of both the stills. Both the stills were run simultaneously from morning to evening for three continuous days. Both the stills were found to have synchronized distillate production with ± 1% difference in total productivity. Subsequently, comparison experiments for BVMED-HR still (with heat exchanger) and reference stills were done. The present experimental work was carried out with both the BVMED-HR and reference stills simultaneously, placed side by side at Patiala, India, located at Latitude N 30.3° and Longitude E 76.3°. Initially, before start of experiments at 9:00 AM, basins of both stills were filled with 1 cm of water. Both the stills had 4 effects and same feed rates to partition plates were set in both of them. The heat going with hot waste feed water was recovered through a simple coiled tube-in-tube counter flow heat exchanger to preheat the feed water. The preliminary experimental results showed that the temperature of waste feed water from last plate, i.e. fourth plate, was not high enough and was close to ambient temperature. Therefore, hot waste feed water only from first three plates was sent for heat recovery in the heat exchanger. In the heat exchanger, the feed water was made to flow through the inner copper tube with internal diameter 5 mm, and the waste feed water from the first three plates was made to flow through the annular space between inner copper tube and outer PVC tube having internal diameter of 12.5 mm. The global solar radiation on glass cover surface G_g, was measured by Kipp and Zonen pyranometer, located centrally between the two stills. T-type thermocouples attached at various locations of still were used to measure temperatures of still components. These temperatures were continuously logged by a multi-channel data logger. The logging interval for all measuring instruments was kept as 10 minutes. Distillates coming out from glass cover and partition plates were collected in plastic cans, hourly, between 9 AM to 5 PM, and weighed on a digital weighing balance having a least count of 0.1 g. The night distillate collected up to 9 AM next day morning was measured, separately.

3.5.4 Floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery (FW-BVMED-HR)

In the fourth set of experiments, the performance of four effect floating wick basin type vertical multiple effect diffusion solar still with heat recovery from waste feed water (FW-BVMED-HR) was tested for few days. Multiple float wicks were placed in the basin of BVMED-HR still, described for set 3 experiments, to convert it into FW-BVMED-HR still. The FW-BVMED-HR still was supplied pre-heated feed water by heat recovery from waste feed water through a heat exchanger. Performance testing of a conventional basin VMED still called the reference still was also done, simultaneously, for comparison purpose. Both the stills had 4 effects and partition plate gap of 10 mm. Both the stills had same basin water depth and feed rates during the experiments. Rest of the procedure is exactly same as described above in section 3.5.3. These experiments were performed from 18/4/2016 to 30/4/2016, and shown in Table B.4 of appendix B. However, the experiments done from 16/9/2016 to 19/10/2016, for constant basin water depth of 2 cm, are also classified under this set of experiments since they had 4 number of effects and partition plate gap of 10 mm.

3.5.5 Experimental parametric study of floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery (FW-BVMED-HR)

In the fifth set of experiments, the experiments were conducted between 7/5/2016 to 19/10/2016 by varying the parameters such as feed water flow rate, gap between partition plates, and number of effects in order to find the effect of these parameters on the performance of FW-BVMED-HR still. For studying the effect of feed water rate, the feed water rate was varied in the range of 0.19 – 0.48 $g/m^2/s$. The effect of partition plate gap was studied for three partition gaps of 10, 13 and 16 mm, at two feed rates of 0.27 $g/m^2/s$ and 0.34 $g/m^2/s$, for each partition plate gap. The number of effects (*n*) were varied from 2 to 7, at a fixed partition plate gap of 10 mm. The study of, number of effects, for each effect, was done at two feed rates 0.27 $g/m^2/s$ and 0.34 $g/m^2/s$.

The complete range of parameters for these experiments has been presented in Table 3.2. The details of these experiments have been shown in Table B.4 of Appendix B.

Table 3.2 Range of parameters for experimental parametric study

Design and operational parameters	
Number of effects (n):	2 – 7
Gap between partition plates (δ_p):	10, 13, 16 mm
Feed water rate (f):	0.19 – 0.48 g/m^2/s
Basin water depth (d):	1.0, 1.5, 2.0, 2.5, 3.0 cm

3.6 CONCLUDING REMARKS

Design, dimensions and fabrication details of components of FW-BVMED-HR and reference stills have been covered. The detailed drawings have been provided in Appendix-A. The measuring instruments, their range and accuracy have been provided. The calibration process of thermocouple and calibration curve has been shown. The detailed experimental procedure for all experiments has been provided. The design and operational range of parameters used for experimental parametric study of FW-BVMED-HR still has been provided.

Chapter 4

Experimental results and data analysis

This chapter presents the experimental results of all the five sets of experiments as mentioned in chapter 3. The experiments on basin type still were done to serve as a reference for comparing the productivity of the improved basin type vertical single distillation cell (VSDC) solar still. The performance results of experiments conducted simultaneously, with four effect basin type VMED solar still with heat recovery (BVMED-HR) and four effect conventional basin type VMED solar still (reference still), are presented to highlight the effect of heat recovery from waste feed water. Similarly, the experiments were performed with four effect floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR) and reference still, placed side by side, for comparison purpose. They were followed by experimental parametric study on FW-BVMED-HR still. A productivity correlation has been developed to predict the productivity of FW-BVMED-HR still using the experimental database of present study. Correlation between the nocturnal productivities and diurnal productivities for the FW-BVMED-HR still was found. The experimental results in each set mentioned below are of few typical days. The complete results of all experiments are presented in Appendix-B.

4.1 BASIN STILL

The conventional basin still was run for few days and the performance of the still on 3rd July, 2015, is reported. Fig. 4.1 shows the variation of solar radiation and ambient air temperature on 3rd July, 2015. It was a partially cloudy day which is quite obvious from the fluctuating pattern of solar radiation and ambient temperature. The cumulative solar radiation on this day was 16.4 MJ/m^2/day. The basin was filled with water to a level of 1 cm. Fig. 4.2 shows that the basin water temperature stays considerably above the glass cover temperature throughout the day.

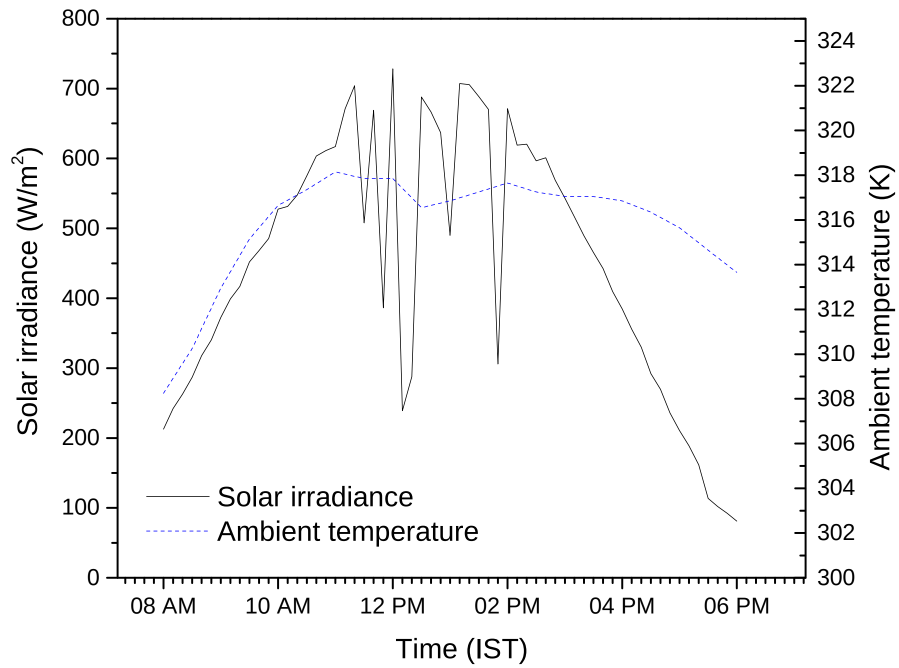


Fig. 4.1 Variation of solar radiation and ambient temperature for basin still on 3rd July, 2015

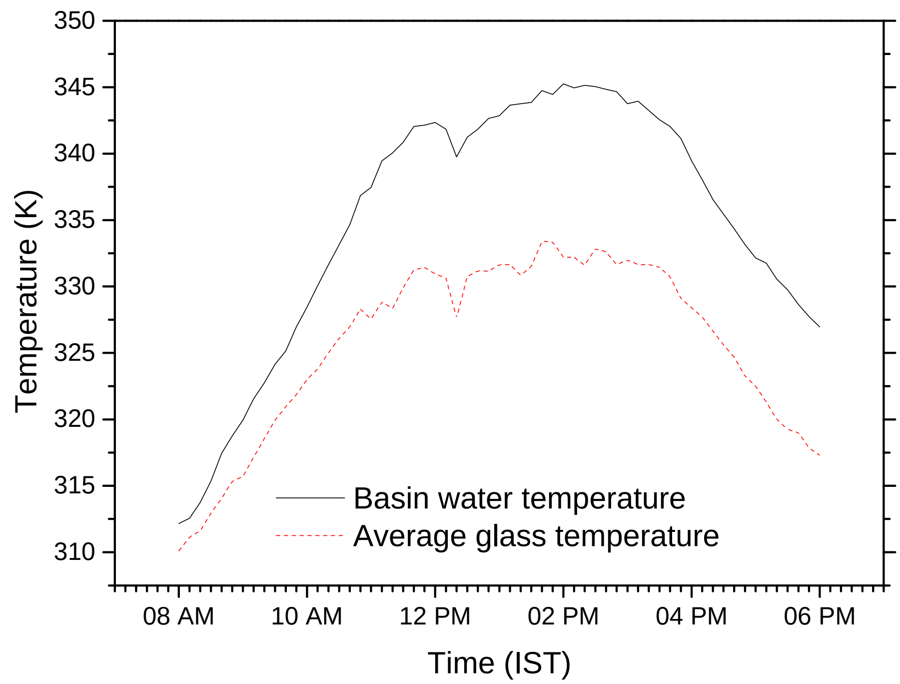


Fig. 4.2 Variation of basin water and glass cover temperatures for basin still on 3rd July, 2015

Fig. 4.3 shows the hourly increment of cumulative distillate output and cumulative efficiency of conventional basin still. The cumulative efficiency of conventional basin still at the end of i^{th} hour is calculated as:

$$\eta_{c_i} = \frac{\sum_{i=1}^{i=i}\left(m_d \times H_{fg}\right)_i}{\sum_{i=1}^{i=i}\left(\left(\text{hourly solar radiation on glass cover}\right)\times A_g\right)_i} \tag{4.1}$$

where, m_d is mass of distillate, H_{fg} is latent heat of vaporization of water and A_g is glass cover area.

The latent heat of vaporization of water (H_{fg}) in Eq. (4.1) is calculated by using the following expression [114]:

$$H_{fg}\,(J/kg) = 2.501\times10^{6} - 2.369\times10^{3}\,t + 2.678\times10^{-1}\,t^{2} - 8.103\times10^{-3}\,t^{3} - 2.079\times10^{-5}\,t^{4} \tag{4.2}$$

It can be observed from Fig. 4.3 that the cumulative distillate output over a period of 24 hours was 2.5 kg/m^2 based on the glass cover area and the cumulative efficiency at the end of 24 hours period was 35.2%.

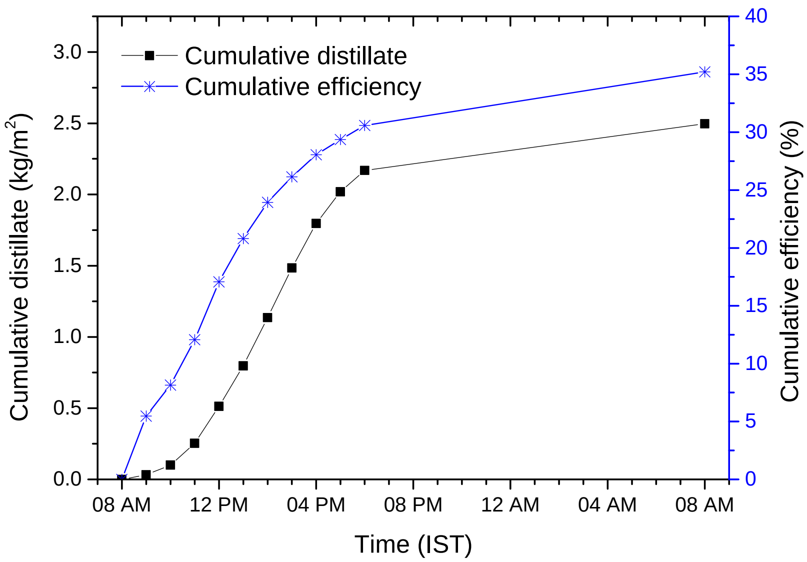


Fig. 4.3 Variation of cumulative distillate and cumulative efficiency for basin still on 3rd July, 2015

It was found from the water quality test that the TDS and pH of input basin water was 579 and 7.7 respectively, whereas the TDS and pH of distillate was found to be 17 and 4.5 respectively.

4.2 BASIN TYPE VERTICAL SINGLE DISTILLATION CELL (VSDC) SOLAR STILL

This section presents the results of experiments performed on the basin type vertical single distillation cell (VSDC) solar still.

Test runs were done on the improved basin type VSDC solar still to check its performance under varying weather conditions on several days, and varying feed flow rates on the first partition plate and second partition plate. The results of these tests are listed in Table 4.1.

Table 4.1 Test results of improved basin type vertical single distillation cell solar still

Date	Radiation condition	G_T MJ/m^2/day	P kg/m^2/day	η_c	f g/m^2/s	T_a °C	V_w m/s
18/08/2015	Partially cloudy	13.5	2.799	48.2	0.12	29 - 39	0.2 - 6.3
21/08/2015	Partially cloudy	15.8	3.034	45.3	0.10	31 - 39	0.4 - 1.9
25/08/2015	Partially cloudy	17.5	3.728	50.1	0.12	30 - 37	1.1 - 2.5
26/08/2015	Partially cloudy	16.2	3.472	50.2	0.12	31 - 38	0.6 – 2.0
28/08/2015	Partially cloudy	14.5	3.605	58.4	0.11	29 - 40	0.7 - 2.2
01/09/2015	Partially cloudy	15.5	3.310	50.2	0.09	30 - 40	0.6 – 3.0
14/09/2015	Partially cloudy	15.4	2.733	41.7	0.47	33 - 42	0.5 - 2.0

It can be seen that the cumulative efficiency of the improved basin type VSDC solar still stayed between 45 - 58%, higher than the best cumulative efficiency given by the conventional basin still as reported in section 4.1. Hence it can be concluded that significant improvement in the efficiency of a basin still was obtained by converting it into an improved basin type VSDC solar still of same basin and glass cover area. The improved basin type VSDC solar still showed a higher hourly cumulative efficiency than conventional basin still since the latent heat of distillate formed at the basin side of first partition plate is utilized to form vapor from wet wick on other side of first partition plate, which condenses on the next partition plate.

Table 4.1 shows that maximum cumulative efficiency of improved basin type VSDC solar still was obtained on 28th august, 2015. The cumulative efficiency on this day was 58.4%, cumulative distillate obtained was 3.60 kg/m^2/day at solar radiation of 14.5 MJ/m^2/day on glass cover. The average feed water rate maintained on this day was 0.11 g/m^2/s for the first partition plate. Higher cumulative efficiency resulted due to use of feed water rates near the optimum value. As the solar radiation increased from 13.5 MJ/m^2/day to 17.5 MJ/m^2/day at constant feed water rate of 0.12 g/m^2/s, the cumulative efficiency increased from 48% to 50%. Further, when the feed water rate increased from 0.09 g/m^2/s to 0.47 g/m^2/s at nearly constant solar radiation of 15.5 MJ/m^2/day, the cumulative efficiency decreased from 50% to 42%.

Hence it can be concluded from results of Table 4.1 that the constant feed flow rates matching with the average daily available solar radiation in that month of the year, should be chosen, in order to attain higher cumulative efficiencies. Moreover, it can be seen from Table 4.1 that the improved basin type VSDC solar still worked satisfactorily on partially cloudy days also, having high diffuse radiation component.

The test results given in Table 4.1 shows that maximum distillate was obtained on 25th august, 2015. Hence hourly performance of improved basin type VSDC solar still on this day is presented and explained.

The variation of solar radiation and ambient temperature on 25th august, 2015 is shown in Fig. 4.4. The fluctuating solar radiation and ambient temperature indicates that it was a partially cloudy day having total solar radiation of 17.5 MJ/m^2/day.

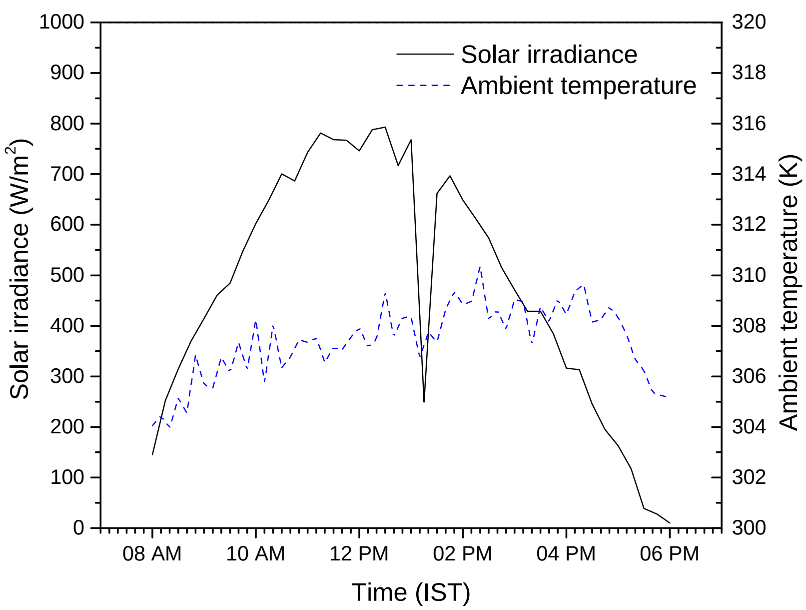


Fig. 4.4 Variation of solar radiation and ambient temperature on 25th august, 2015

The variation of basin water and still component temperatures in improved basin type VSDC solar still is shown in Fig. 4.5. It can be seen that the basin water temperatures remained the highest for most part of the day, while the inner glass and first partition plate temperatures remained nearly equal. The temperature drop from the first partition plate to the second partition plate was maintained between 2.5 °C to 15.5 °C at an average of 8.2 °C, on 25th August, 2015. On an average the temperature of second partition plate wick surface on 25th stayed above the ambient temperature by 10 °C. Thus, the third external plate worked well to control the temperature drop across the partition plates. Overall, the third external plate contributed significantly in enhancing the improved basin type VSDC solar still efficiency, by maintaining high cell temperature between first and second partition plates and high wick surface film temperatures at second partition plate. Fukui et al. [76] have shown analytically that at high mean temperatures of the partition cell, the vapor diffusion flux $\dot{m}_e$ is large even at small effective temperature drop across the cell.

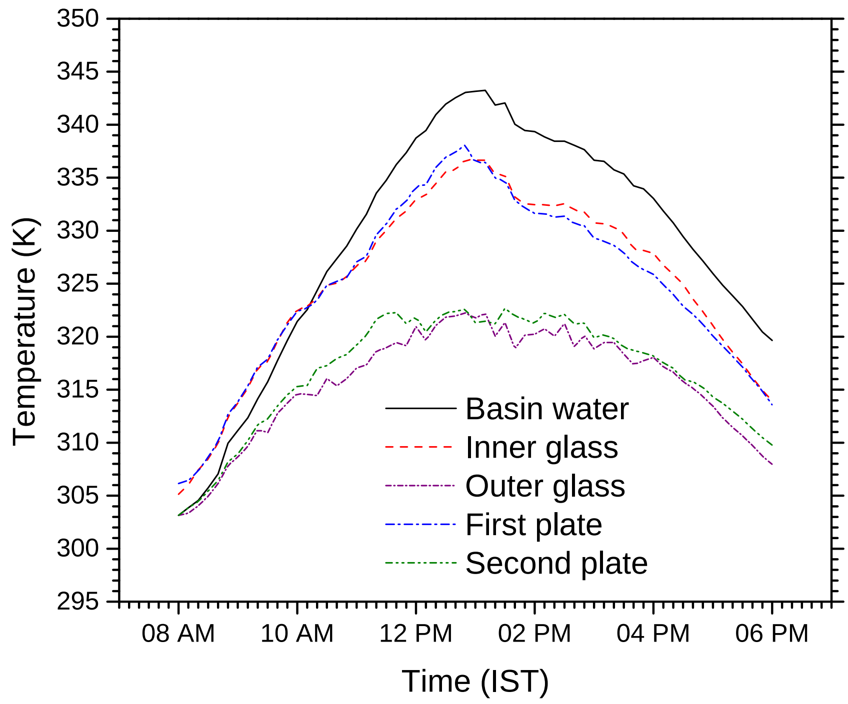


Fig. 4.5 Variation of basin water and still component temperatures in improved basin type VSDC solar still on 25th august, 2015

Fig. 4.6 shows the variation of distillate production rates in components of improved basin type VSDC solar still. It can be seen that significant amount of distillate is obtained on second partition plate throughout the day. It is due to use of copper plate as first partition plate, which resulted in increased heat transfer from basin to distillation cell. The high distillate on second partition plate also indicates that the wick wetting on first and second partition plates improved by using partitioned wick structure and improved the evaporation efficiency (mass flux due to evaporation process), considering that the effective wick evaporation area was only 77% of the plate area. Hence the use of copper plate as first partition plate and use of partitioned wick structure contributed significantly in the improved performance of the basin type vertical single distillation cell (VSDC) solar still.

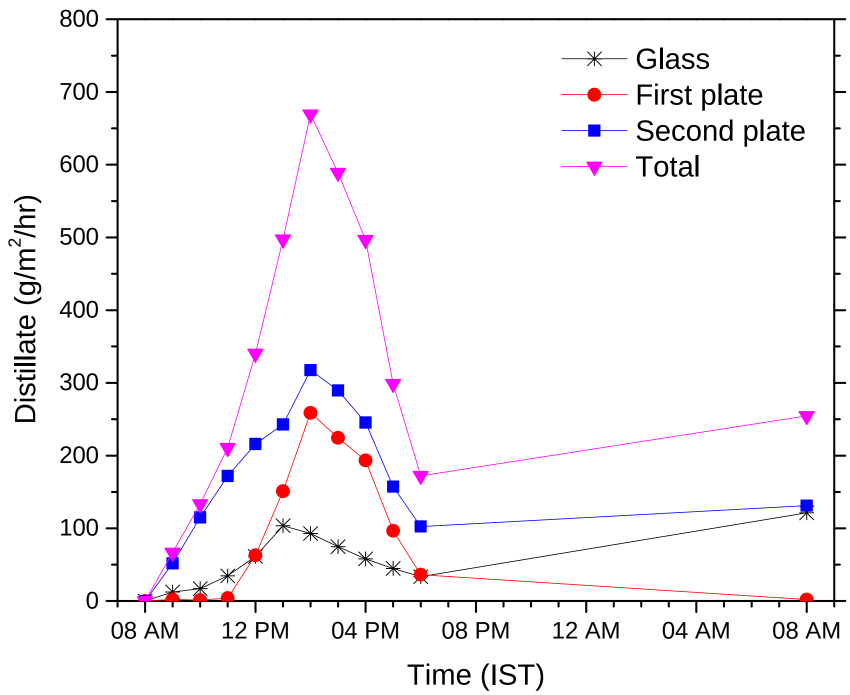


Fig. 4.6 Variation of distillate production rates in components of improved basin type VSDC solar still on 25th august, 2015

Fig. 4.7 shows the hourly increment of cumulative efficiency of basin type VSDC solar still. The cumulative efficiency of basin type VSDC solar still at the end of i^{th} hour is calculated as:

$$\eta_{c_i} = \frac{\sum_{i=1}^{i=i}\left(\sum_{j=0}^{j=2}\left(m_d \times H_{fg}\right)_j\right)_i}{\sum_{i=1}^{i=i}\left(\left(\text{hourly solar radiation on glass cover}\right)\times A_g\right)_i} \tag{4.3}$$

Where j = 0, 1, 2 represents glass cover, first partition plate (basin facing back-wall of basin) and second partition plate of distillation cell.

It can be observed from Fig. 4.7 that the cumulative efficiency at the end of 24 hours period was 50.1%.

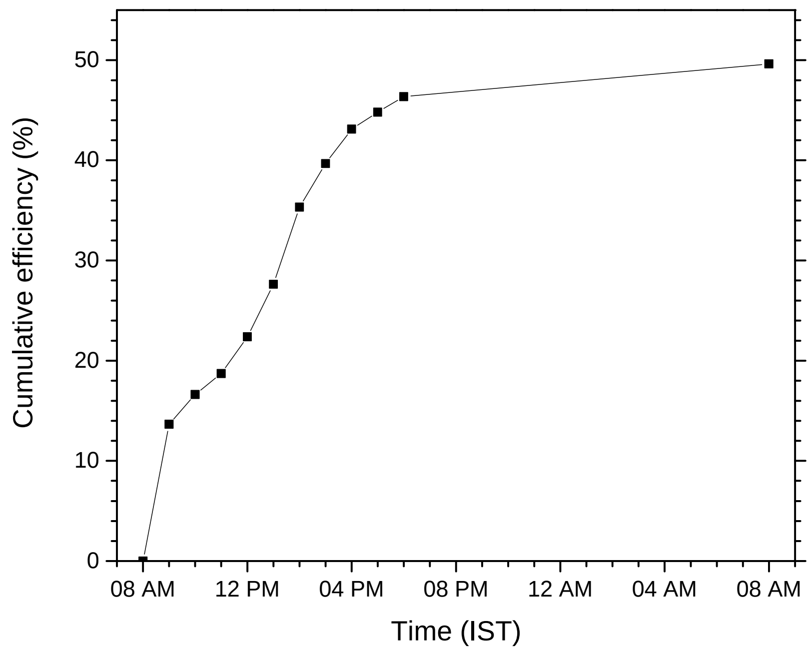


Fig. 4.7 Variation of hourly cumulative efficiency in improved basin type VSDC solar still on 25th august, 2015

The partitioned wick structure along with the longitudinal rubber spacers worked well and no contamination from saline water was found, which is ascertained from the TDS and pH quality testing of the distillate done on hourly basis. It was found from the hourly water quality tests that the TDS and pH of input water to the partition plates of still, was in the range of 390 - 410 and 7.20 – 7.40 respectively, while the TDS and pH of distillate output, was in the range of 1 – 4 and 5.43 – 6.73 respectively.

As no experimental values for performance of improved basin type VSDC solar still were available from literature survey, the present work's results were compared with the results computed from basin type vertical multiple effect diffusion still by Tanaka et al. [18]. He had obtained 3.85 $kg/m^2/day$ after adding the second partition plate productivity of his basin type multiple effect diffusion still, with glass and first partition plate productivity, at a solar radiation of 19.6 $MJ/m^2/day$. The still had 11 partition plates which were placed at a gap of 5 mm. All the partition plates, including the first partition plate, were of stainless steel. Single effect results can be computed from multiple effect results of a VMED still without introducing any error [77]. Tanaka et al. [87] have shown through simulation results that for a basin type vertical multiple effect diffusion still with 10 partition cells, decreasing the partition gap width from 10 mm to 5 mm results in an increase of productivity by about 24%. The higher results obtained with the improved basin type vertical single distillation cell (VSDC) solar still of present work, at a partition gap width of 10 mm than Tanaka's still at 5 mm gap, clearly indicates the contribution of higher thermal conductivity of first partition plate of copper and divided wick structure for better wick wetting and better sealed boundary to prevent heat and vapor losses from distillation cell

The reduced stainless steel plate thickness of 0.3 mm along with the addition of the third external plate also contributed significantly for improving the performance of basin type vertical single distillation cell (VSDC) solar still of present study. The uniform wetting and soaking and uniform evaporation from the whole wick area is confirmed by the temperatures indicated by five uniformly placed thermocouples on the first and second partition plates. The maximum deviation of the thermocouple temperatures from the mean plate temperature on first partition plate was 4.30 °C for whole day. For the second partition plate, the maximum deviation of the thermocouple temperatures from the mean plate temperature was 9°C around noon and 9.5°C for whole day.

The following key conclusions have been drawn from the experimental results of conventional basin still and basin type vertical single distillation cell (VSDC) solar still:

- Significant improvement in the efficiency of a basin still was obtained by converting it into an improved basin type VSDC solar still of same basin and glass cover area.
- The new wick surface arrangement, in which the whole wick area was divided into six partitions in case of improved basin type VSDC solar still, and individual feed water given to each area, worked effectively, in increasing the wick wetted area and hence evaporation efficiency of the wick surface, which is confirmed by the temperature distribution of the

partition plates. The effective wick evaporation area was only 77% of the total partition plate area, yet the performance of the improved basin type VSDC solar still was comparable with previously reported results by other researchers due to better soaking, high evaporation efficiency and high rate of temperature equalization within the copper plate.

- The water feeding mechanism to wicks was changed to gravity feeding, as against the capillary action feed mechanism by Tanaka et al. [18]. Longitudinal rubber spacers were used to separate the 0.3 mm thick stainless steel partition plates. By use of this arrangement no cross flow of saline feed water was observed, as confirmed by the water quality tests. By placing the feed water channels inside the sealed borders of plate, vapor loss and convection heat loss by escaping hot air and vapor mixture was also possibly reduced.
- The use of third external partition plate without evaporative cooling at a gap of 25 mm from the second partition plate, proved effective in maintaining the average temperature drop from first partition plate to second partition plate, up to 8 °C. On an average the temperature of the second partition plate stayed above the ambient temperature by 10 °C. This resulted in consistently high distillate outputs from the second partition plate. Due to the shielding by the third external plate, not only the effect of wind velocity fluctuations on the convective heat transfer and evaporation from the second partition plate was minimized but also the blowing away of wicks from the plate surface was prevented.
- The feed water flow rates have to be decided by matching with the expected solar radiation for the day, based on monthly average solar radiation obtained from previous year's data, once a performance chart of the still is available. At a constant feed water flow rate of 0.12 $g/m^2/s$ the distillate productivity showed a rise with rise of solar radiation. The improved basin type VSDC solar still worked satisfactorily on partially cloudy days also, thereby indicating that it utilized the diffuse component of solar radiation effectively.

4.3 BASIN TYPE VERTICAL MULTIPLE EFFECT DIFFUSION SOLAR STILL WITH HEAT RECOVERY FROM WASTE FEED WATER (BVMED-HR)

This section presents the results of experiments performed on basin type vertical multiple effect diffusion solar still with heat recovery from waste feed water (BVMED-HR), having four effects. Experimental results of conventional basin type VMED still have also been shown for comparison purpose.

The performance testing of BVMED-HR still was done on several days in the month of April, 2016. The test results of experiments conducted on 8th April, 2016 are presented here in graphical form and explained in detail. The experimental data of all the days with complete details like design, operational and weather conditions, and distillate output are provided in tabular form in Appendix-B.

From the weather parameters reported in Fig. 4.8, it can be seen that 8th April, 2016 was a clear sunny day having high cumulative solar radiation of 23.5 $MJ/m^2/day$. Full day performance results on this date for BVMED-HR and reference stills are presented in Fig. 4.9 to Fig. 4.15.

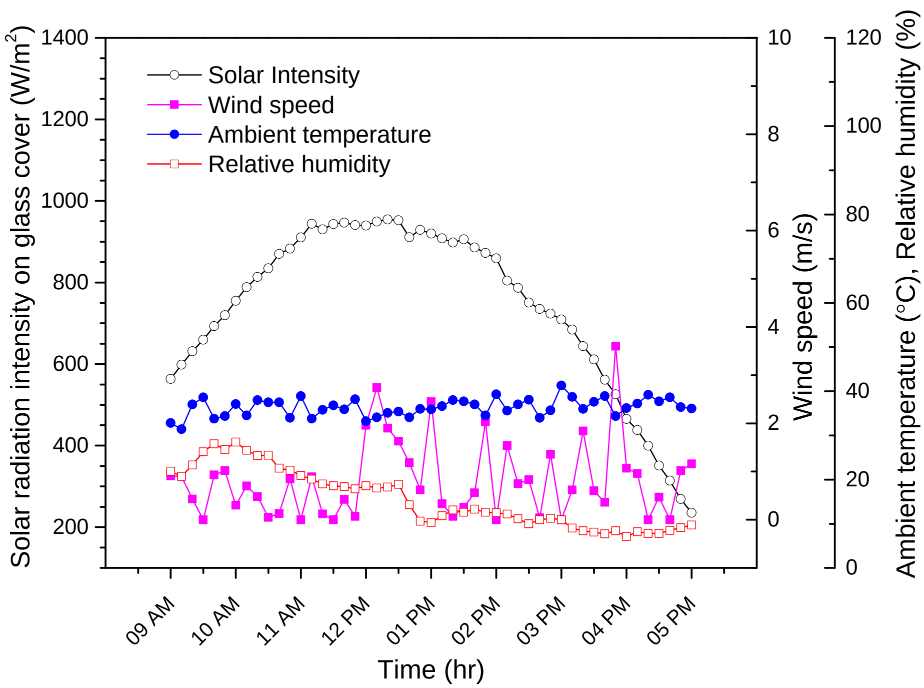


Fig. 4.8 Variation of weather parameters on 8th April, 2016

Fig. 4.9 and Fig. 4.10 show the temperature variations for basin water, glass covers and partition plates for BVMED-HR and reference stills respectively. The average temperatures of basin water, inner glass, first to fourth plates of BVMED-HR still for period between 9 AM to 5 PM stayed above the reference still by 4.8, 2.8, 8.3, 8.1, 0.5 and 1.2°C respectively. The reason for comparatively higher temperatures observed in the BVMED-HR still is due to the fact that the preheated water in BVMED-HR still requires less sensible and total heat for evaporation. Also, since the cell temperatures for BVMED-HR still were higher than that for reference still, it led to rise of evaporation rates from partition plates and increase of diffusion rates in the cell [76]. Hence the hourly productivity component wise for BVMED-HR still also stayed above the reference still as can be seen from Fig. 4.11 and Fig. 4.12.

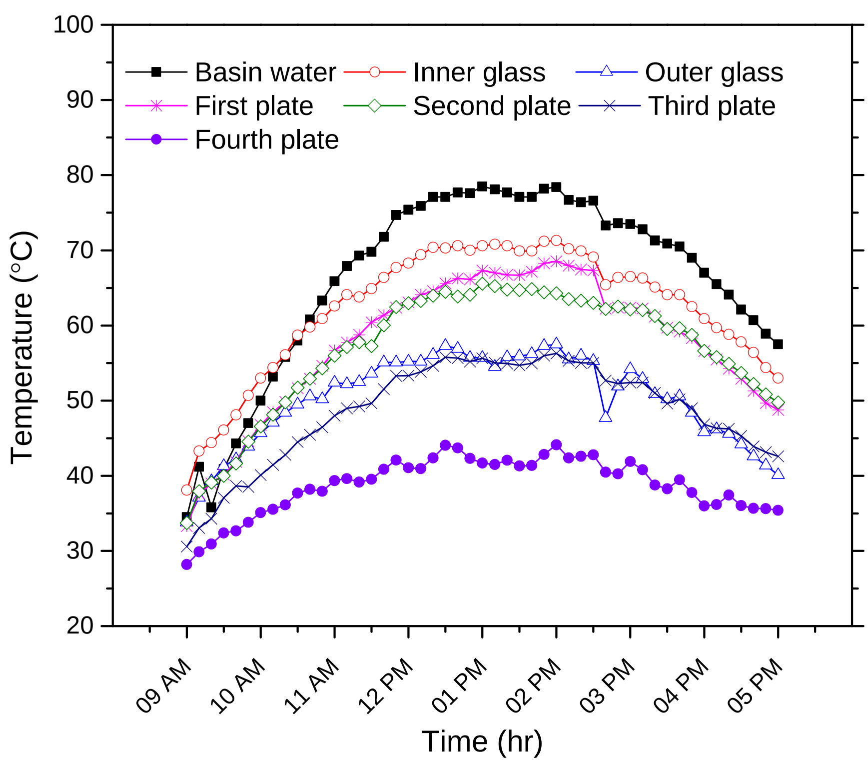


Fig. 4.9 Variation of basin water and components temperatures for BVMED-HR still on 8th April, 2016

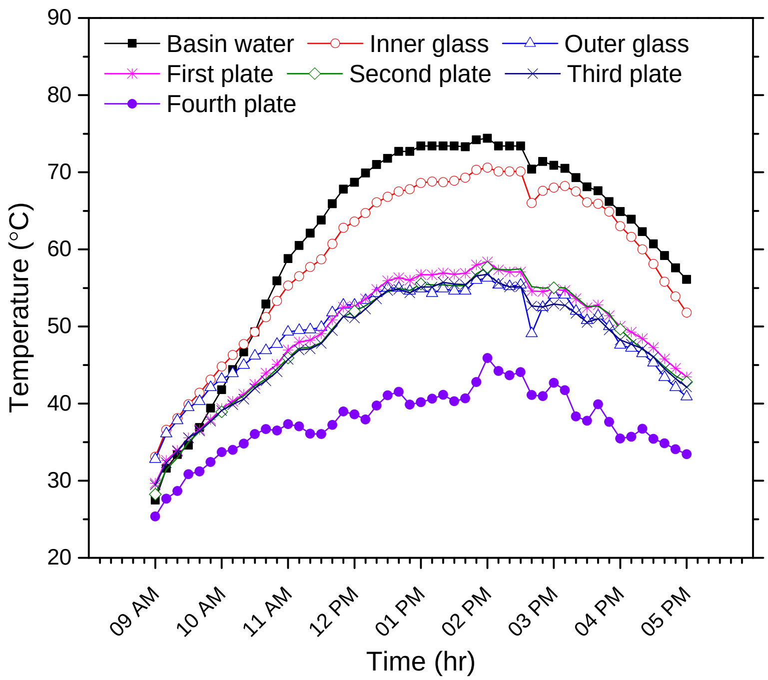


Fig. 4.10 Variation of basin water and components temperatures for reference still on 8th April, 2016

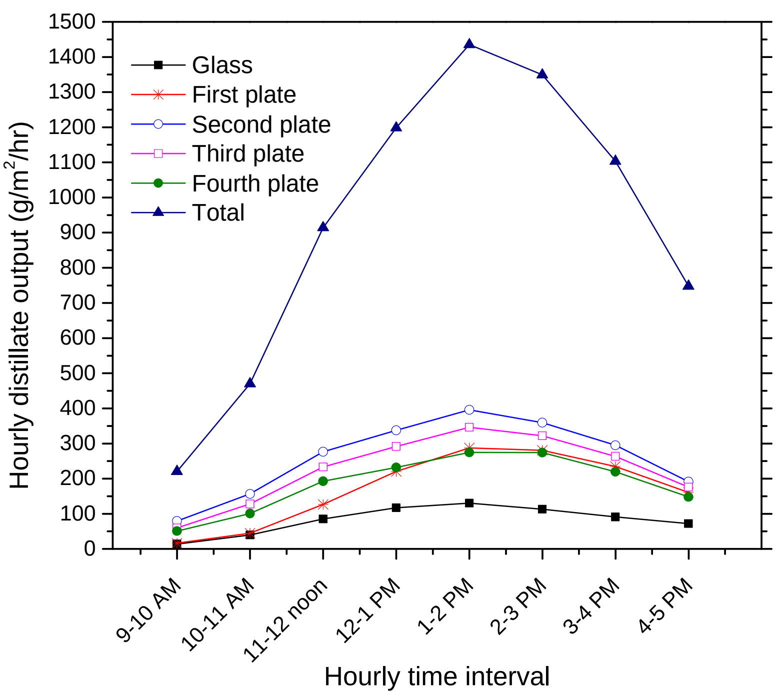


Fig. 4.11 Hourly distillate output in each component of BVMED – HR still on 8th April, 2016

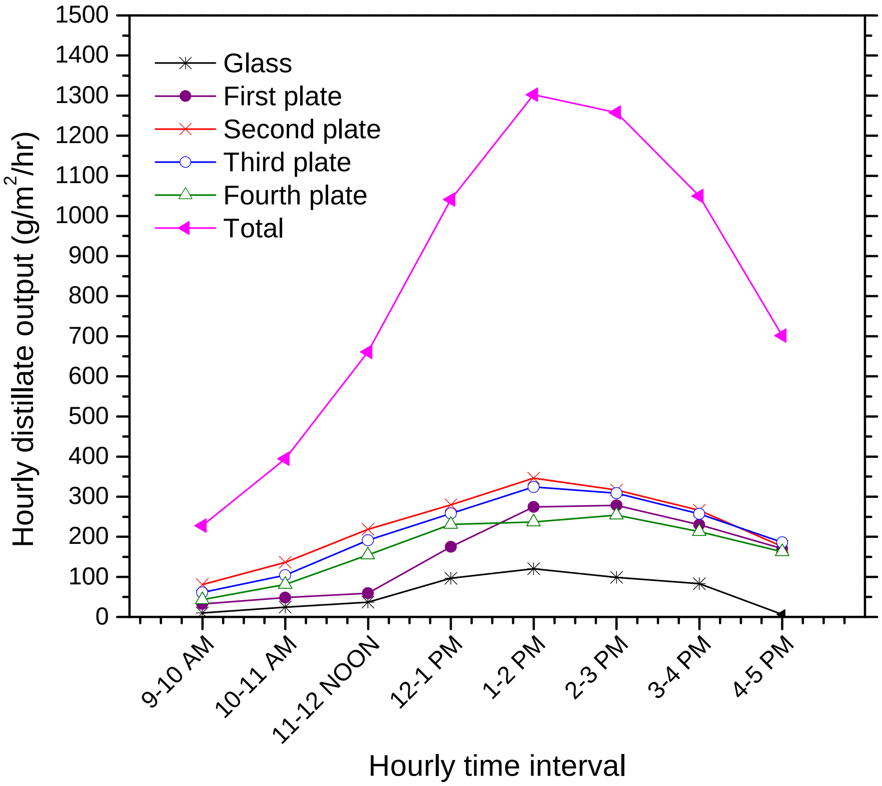


Fig. 4.12 Hourly distillate output in each component of reference still on 8th April, 2016

Fig. 4.13 shows the hourly total distillate productivity of BVMED-HR and reference stills between 9:00 AM to 5:00 PM on 8th April, 2016, along with hourly average solar radiation intensity on the same plot, to see its effect on the hourly total distillate productivity. It can be seen that the peak in hourly distillate productivity occur two hours after the solar radiation peak, due to large thermal capacity of the still components and the basin water.

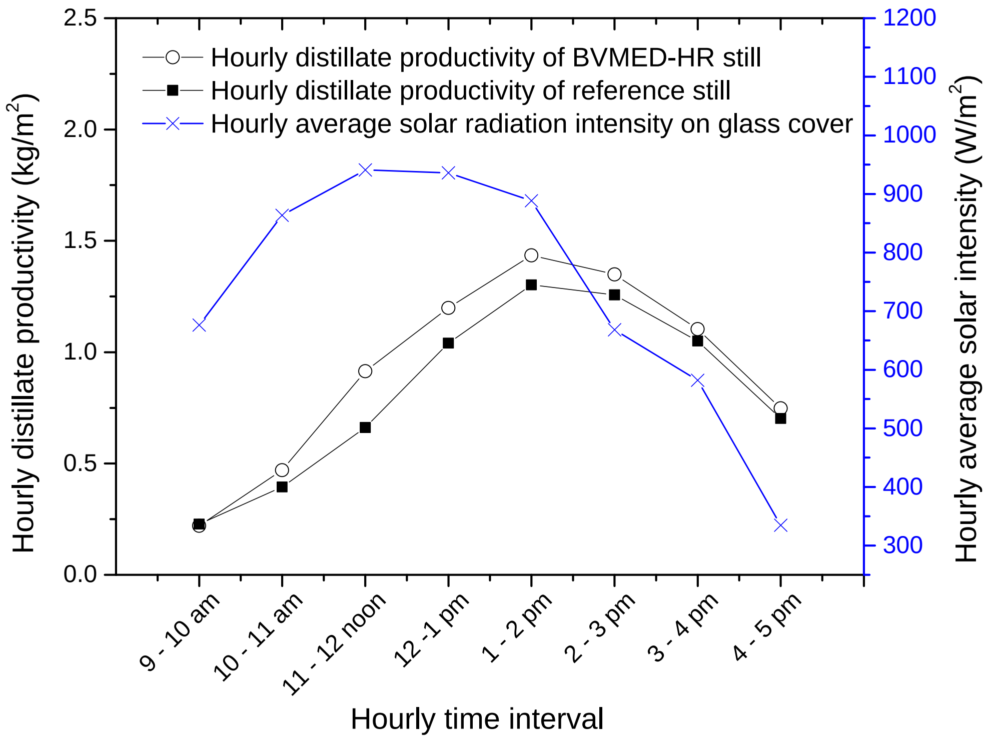


Fig. 4.13 Comparison of hourly distillate output of BVMED-HR and reference stills on 8th April, 2016

From Fig. 4.14 and Fig. 4.15, it can be seen that the hourly values of cumulative distillate output and cumulative efficiency for the BVMED-HR still stayed above the reference still throughout the day. This is clearly the effect of feed water preheating by heat recovery from waste feed water in conformity with reported work by previous researchers [20,75,80]. They have found that productivity increases by at least 10% for 10° C rise of feed water temperature above ambient. The total distillate output of BVMED-HR still on this day was 8.842 kg/m^2/day which was 10.6% above the total distillate output obtained on this day for reference still. Correspondingly, a rise of 8.2% in the cumulative efficiency of BVMED-HR still over the reference still was observed for this day.

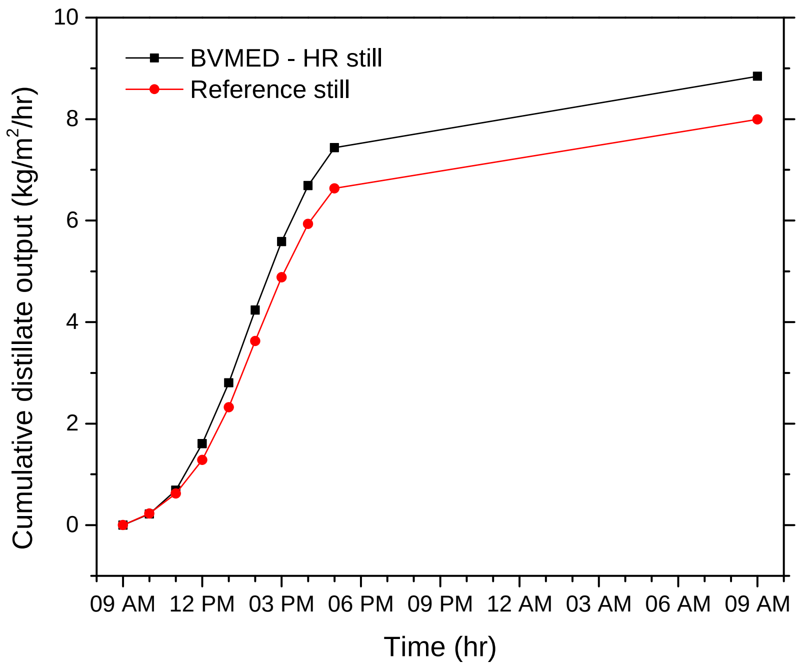


Fig 4.14 Comparison of cumulative distillate output for BVMED-HR and reference stills for 24 h. on 8th April, 2016

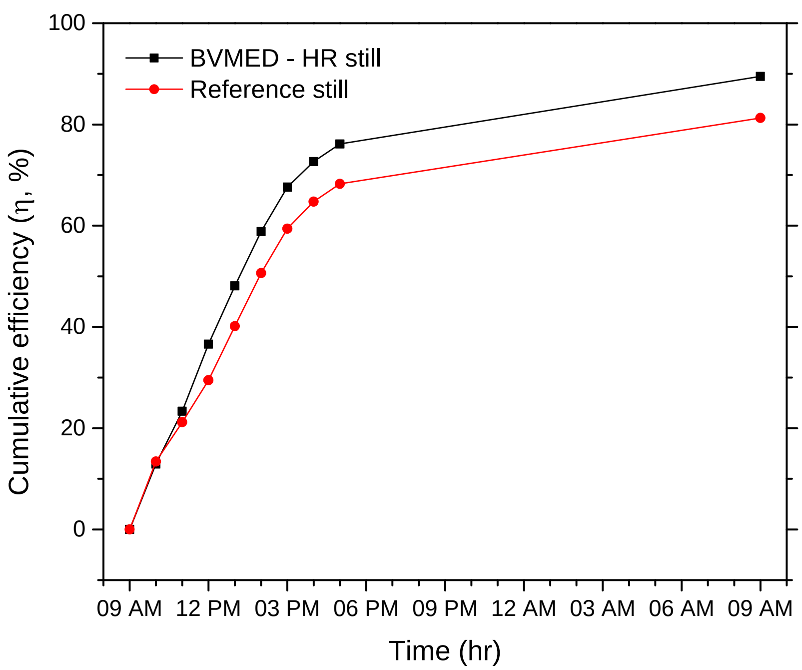


Fig 4.15 Comparison of cumulative efficiency for BVMED-HR and reference stills for 24 h. on 8th April, 2016

Fig. 4.16 shows the variation of effectiveness (ε) of heat exchanger of BVMED-HR still and variation of feed water temperatures in both the BVMED-HR and reference stills, throughout the day, on 8th April, 2016. While the mean effectiveness of the heat exchanger for the day stayed at 0.67, the mean temperatures of feed water for the day, for BVMED-HR and reference stills stayed at 39.4°C and 33°C respectively. The experimental results revealed that the average daily effectiveness of the heat exchanger on various days ranged between 0.4 to 0.67. The use of waste heat recovery heat exchanger resulted in the average daily rise of feed water temperature, above the reference still, in the range of 5.5 to 8° C.

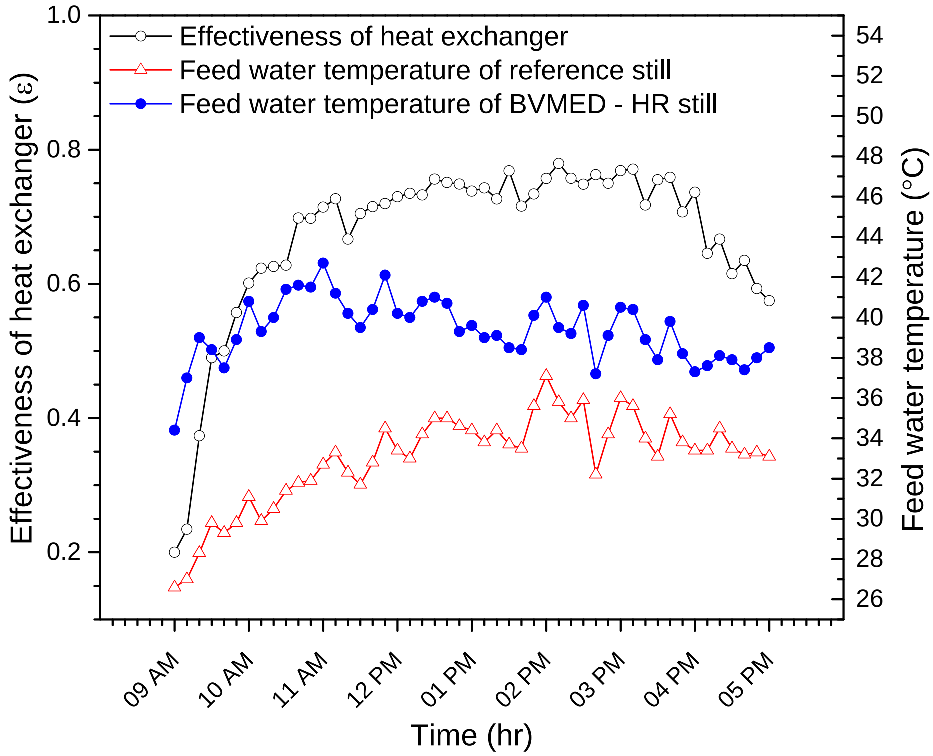


Fig. 4.16 Variation of effectiveness of heat exchanger and variation of feed water temperatures in both BVMED - HR and reference stills on 8th April, 2016

4.3.1. Development of productivity correlation for BVMED-HR still

An empirical correlation has been developed to predict the productivity of four effect BVMED-HR still using the experimental database of present study. The productivity of a VMED solar still depends upon the weather parameters such as daily total insolation, daily average ambient temperature, daily average wind velocity and daily average relative humidity. For VMED still, the feed rate and feed water temperature are the operating parameters which significantly influence the productivity of VMED still. Thus the productivity of BVMED-HR solar still can be represented as function of several parameters as given below:

$$P = f(G_T\ , T_a\ , V_w\ , R_H\ , f, T_f) \tag{4.4}$$

where, G_T is cumulative solar radiation for the day expressed in MJ/m^2/day, T_a is average daily ambient temperature in °C, V_w is average daily wind velocity in m/s, R_H is average daily relative humidity in %, f is average daily feed water rate in g/m^2/s and T_f is average daily temperature of feed water in °C.

The correlation for productivity is generated in non-linear power law form with the independent influencing parameters as given in Eq. (4.4). Therefore rewriting Eq. (4.4) in a generic form of non-linear power equation as given below:

$$P = C \times (G_T)^{a_1}\ (T_a)^{a_2}\ (V_w)^{a_3}\ (R_H)^{a_4}\ (f)^{a_5}(T_f)^{a_6} \tag{4.5}$$

The values of constant C and exponents of independent variables in Eq. (4.5) are determined by applying the multivariate non-linear regression analysis on the experimental database. Finally the correlation obtained for productivity of four effect BVMED - HR solar still is as given below:

$$P = 0.004 \times (G_T)^{1.213}\ (T_a)^{0.129}\ (V_w)^{-0.009}\ (R_H)^{-0.221}\ f^{0.048}(T_f)^{1.102} \tag{4.6}$$

The productivity correlation (Eq. 4.6) for the four effect BVMED - HR solar still is applicable for the range of values of various parameters, provided in Fig. 4.17.

The proposed correlation has a regression coefficient of 0.91 which suggests that the correlation has a fairly good closeness with the experimental database used for the development of correlation. The validity of proposed correlation is assessed by comparing the predicted productivities obtained from proposed correlation with those measured experimentally. This comparison is depicted in Fig. 4.17. Fig. 4.17 shows that the proposed correlation predicts the experimental data within the deviation range of -8% to +11% with a mean deviation of 4%. Therefore, it can be concluded that the predictions by the proposed correlation yield a good agreement with the experimental measurements. Such correlation as shown in Eq. (4.6) is useful in estimating the productivity of this type of still in any part of the world, for feasibility studies taken before installation of a solar distillation unit.

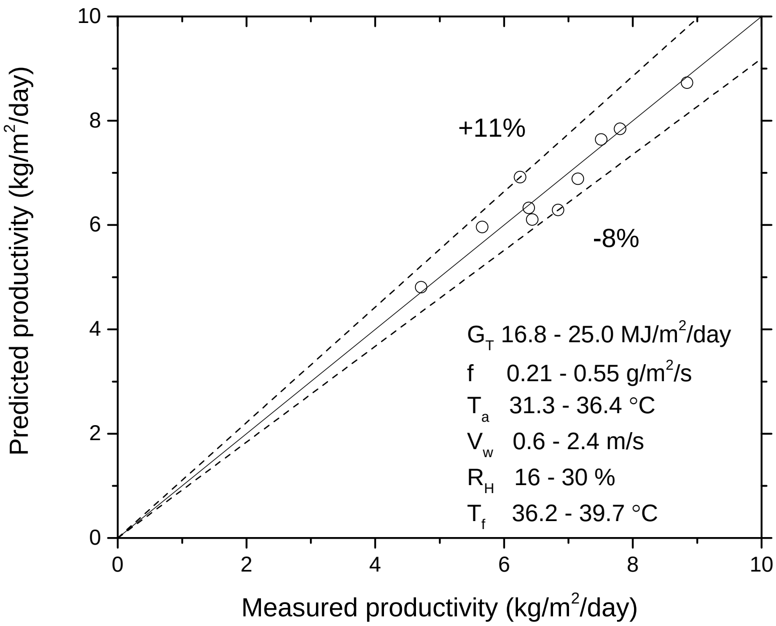


Fig. 4.17 Validation of proposed correlation for productivity of BVMED-HR solar still

The following key conclusions have been drawn from the experimental results of basin type VMED solar still with heat recovery (BVMED-HR) and conventional basin type VMED solar still (reference still).

— The pre-heating of feed water by recovering heat energy from waste feed water results in an appreciable increase in the cumulative efficiency and productivity of the BVMED-HR still. It was found that there was a rise up to 8.2% in cumulative efficiency and 10.6% in the distillate productivity for the BVMED-HR still over the reference still.

— The heat exchanger used to recover waste heat was simple in design and compact in size. Moreover it was made of inexpensive materials. Therefore, the incorporation of heat recovery heat exchanger has led to hardly any cost addition in the total cost of the BVMED-HR still.

— An empirical correlation has been proposed to predict the productivity of BVMED-HR solar still. The correlation predicts the productivity very well with mean deviation of 4% from the experimental values. Since the correlation has been developed by considering all possible parameters which affect the productivity of the still, therefore, within the parametric range used for development of the correlation, this correlation can be used to predict the productivity of a similar type of VMED still with good accuracy in any part of the world.

4.4 FLOATING WICK BASIN TYPE VERTICAL MULTIPLE EFFECT DIFFUSION SOLAR STILL WITH WASTE HEAT RECOVERY (FW-BVMED-HR)

This section presents the results of experiments performed on Floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery (FW-BVMED-HR), having four effects. The performance of FW-BVMED-HR still was studied in comparison to reference still at various feed flow rates and basin water depths. The partition plate gap was kept constant at 10 mm. Experimental results of conventional basin type VMED still have also been shown for comparison purpose. Experimental results of only few typical days have been shown in this chapter. The complete experimental data on design, operational and weather parameters, and distillate are provided in Appendix-B.

The performance testing of FW-BVMED-HR still was done on several days during the period April, 2016 to October, 2016. The test results obtained on 13th October, 2016 are reported here. It was a clear sunny day as can be seen from weather parameters shown in Fig. 4.18. Solar radiation intensity reached its peak at 12:10 pm while ambient temperature reached its peak temperature at 1:00 pm.

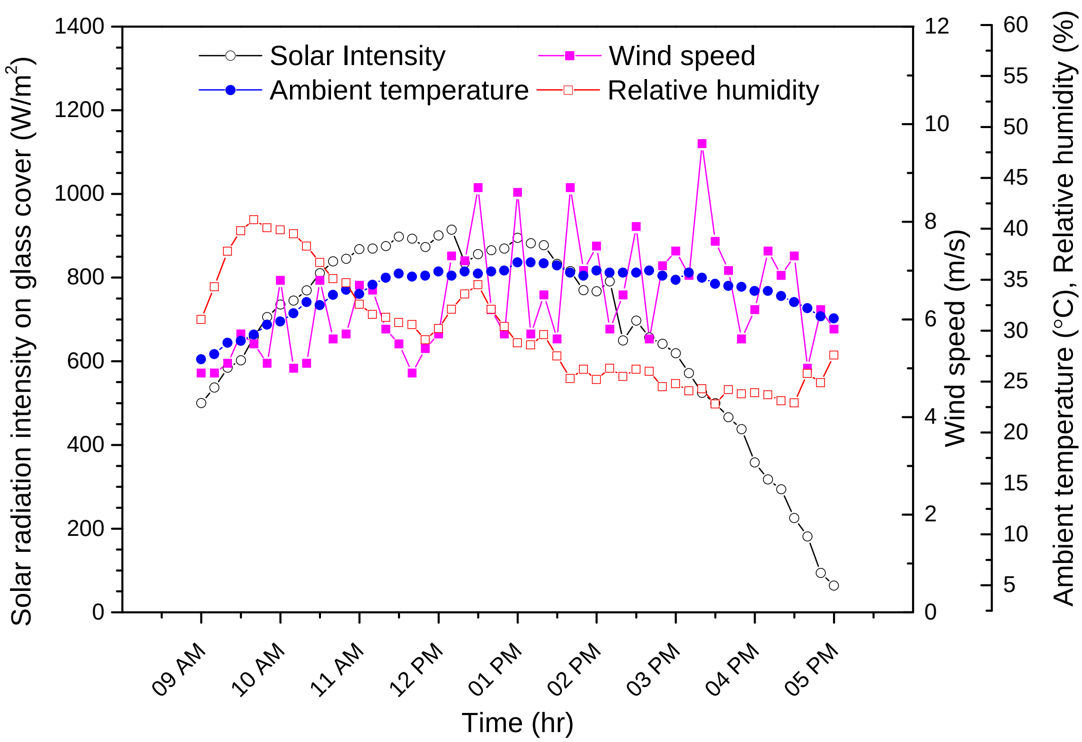


Fig. 4.18 Variation of weather parameters on 13th October, 2016

Fig. 4.19 and Fig. 4.20 show the variation of component temperatures in the FW-BVMED-HR and reference stills respectively during the period 9:00 am to 5 pm. The basin water temperatures reported in these figures are the mean bulk temperatures and the basin surface temperatures are expected to be significantly higher than these temperatures, due to stratification in basin water [106]. As can be seen from Fig 4.19, the inner glass temperature of FW-BVMED-HR still is higher than the float wick temperature till about 2:30 pm and also stays higher than the first partition plate temperature throughout the day. The reason for this is explained in the following lines. The inner glass cover absorbs some of the direct solar radiation which passes through it. It also absorbs the radiations reflected from basin inner surfaces. However, it does not lose this heat to the basin air convectively at a fast rate, as the basin air is sufficiently hot due to diffusion of hot water vapors from basin water into it. On the other side, the second glass cover and air entrapped in the gap between glass covers provide sufficient insulation to prevent heat loss at a fast rate to external environment, as confirmed by the large temperature difference between the two glass covers. On the other hand, the solar radiation absorbed in the float wick is readily released to basin air by way of evaporation due to low thermal inertia of float wick surface. Moreover, a part of the absorbed energy continuously transfers to the basin water underneath the float wick. As regards the first partition plate, the total energy absorbed by it, is also released continuously towards the multiple effect distillation section. It is for these reasons that the inner glass temperature remains above the float wick temperature till 2:30 pm and also stays above the first partition plate temperature throughout the day. For similar reasons, the inner glass temperature of reference still as seen from Fig. 4.20, also stays above the basin water temperature till about 1:30 pm. From Fig. 4.19, it can be seen that the float wick temperature lags behind the first partition plate temperature till 11:10 am, after which it leads the first partition plate temperature till evening. Further as expected, all successive partition plate temperatures after the first partition plate, lag behind the previous partition plate temperatures, throughout the day. The float wick temperature stays above the basin water temperature till about 3:30 pm after which it lags behind, due to rapidly falling solar energy intensity. The basin water on the other hand, has stored energy, cools at a slower rate, due to float cover insulation.

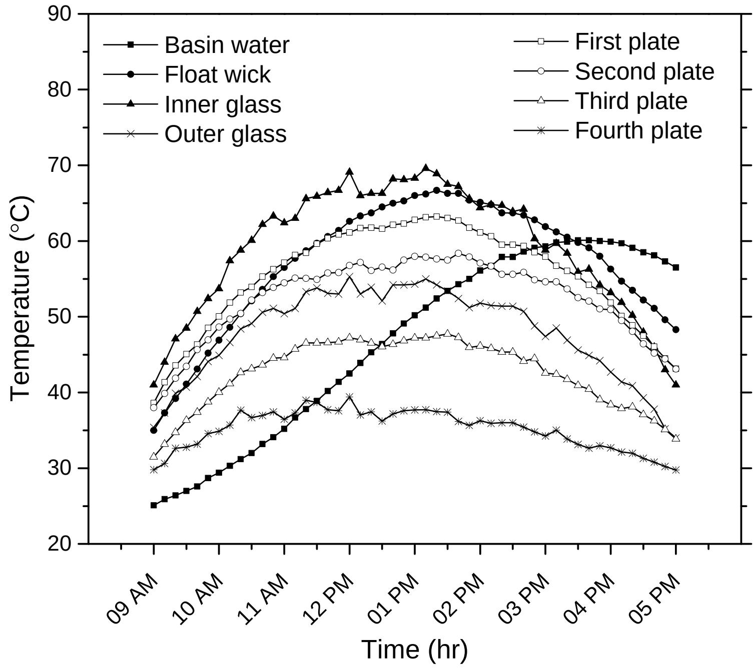


Fig. 4.19 Variation of component temperatures in FW-BVMED-HR still on 13th October, 2016

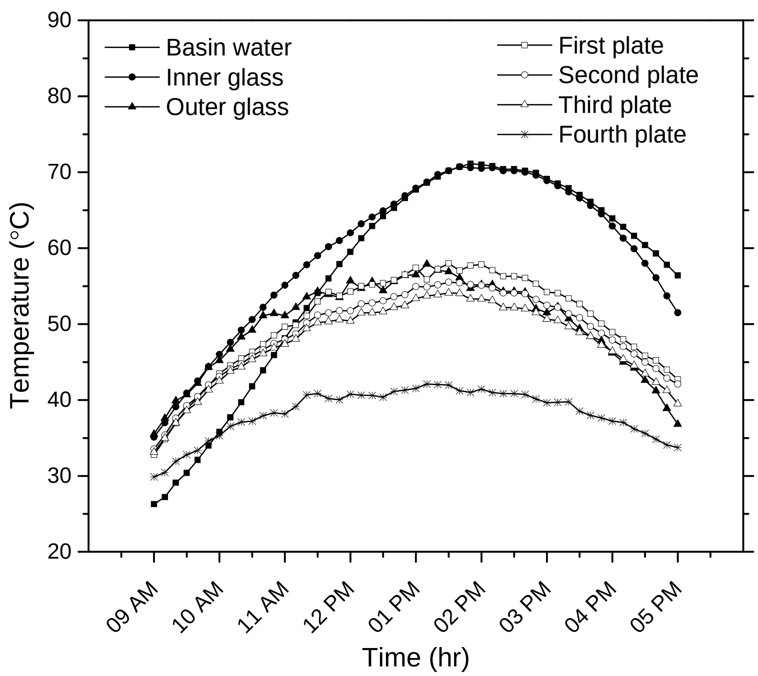


Fig. 4.20 Variation of component temperatures of reference still on 13th October, 2016

Fig. 4.21 has been drawn to show the comparison of temperatures, of various basin section components of both the stills. It can be seen that the float wick temperature of FW-BVMED-HR still stayed considerably above the basin water temperature of reference still, till around 12:30 pm, facilitating an early lead in distillate production for the FW-BVMED-HR still. The basin water temperature of the FW-BVMED-HR still continuously rises till around 4 pm and then falls, whereas it first rises till about 2 pm and then falls for the reference still. At 5 pm, basin water temperatures for both stills became equal. Throughout the day, the basin water temperature of FW-BVMED-HR still stays below the basin water temperature of reference still. It is due to the fact that the basin water of reference still absorbed majority of the solar radiation to raise its temperature in the first part of the day due to its large thermal capacity, whereas, due to low thermal inertia of float wick, the solar energy absorbed by float wick is readily transferred to the glass and first partition plate through heat transfer by convective, evaporation-condensation and radiative mode. Thus, only a small fraction of absorbed energy in float wick is transferred to the basin water of FW-BVMED-HR still. As a result, the basin water temperature of FW-BVMED-HR still stays below the basin water temperature of reference still. Further, the lower basin water temperature of FW-BVMED-HR still results in lesser heat losses through the sides and bottom of basin, thus improving its efficiency. As can be seen from Fig. 4.21, the float wick temperature, and basin water temperature of reference still, both are falling after 2 pm, corresponding to the falling solar intensity. However, the basin water temperature of reference still stays considerably above the float wick temperature of FW-BVMED-HR still, after 1 pm, due to direct absorption and storage effect of basin water in reference still. It can also be observed that the temperature of first partition plate of FW-BVMED-HR still remained higher than first partition plate of reference still, throughout the day. It could be attributed to the fact that the heat transfer by all modes, between high temperature float wick surface and first partition plate of FW-BVMED-HR still, was higher, than between the basin water surface and first partition plate of reference still. For similar reasons, the temperature of inner glass of FW-BVMED-HR still stayed above the inner glass of reference still till about 1 pm, after which it lagged behind.

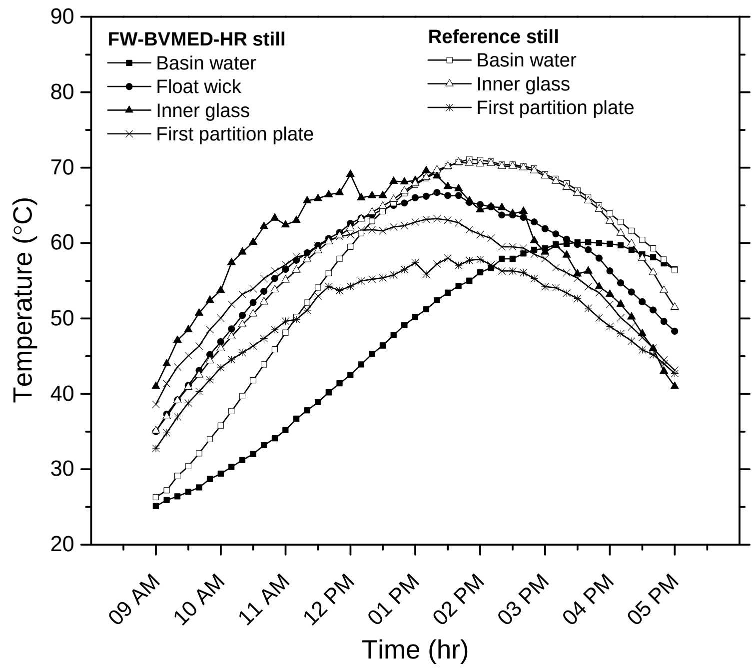


Fig. 4.21 Comparison of temperatures of various basin section components in FW-BVMED-HR and reference stills on 13th October, 2016

Fig. 4.22 and Fig. 4.23 show the component wise, hourly, distillate outputs for the FW-BVMED-HR and reference stills respectively.

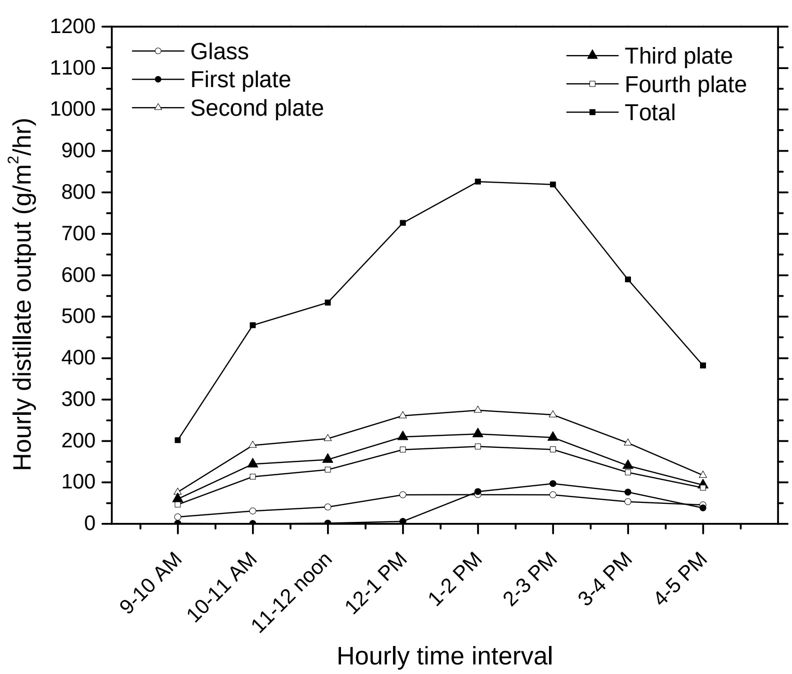


Fig.4.22 Variation of hourly distillate production in components of FW-BVMED-HR still on 13th October, 2016

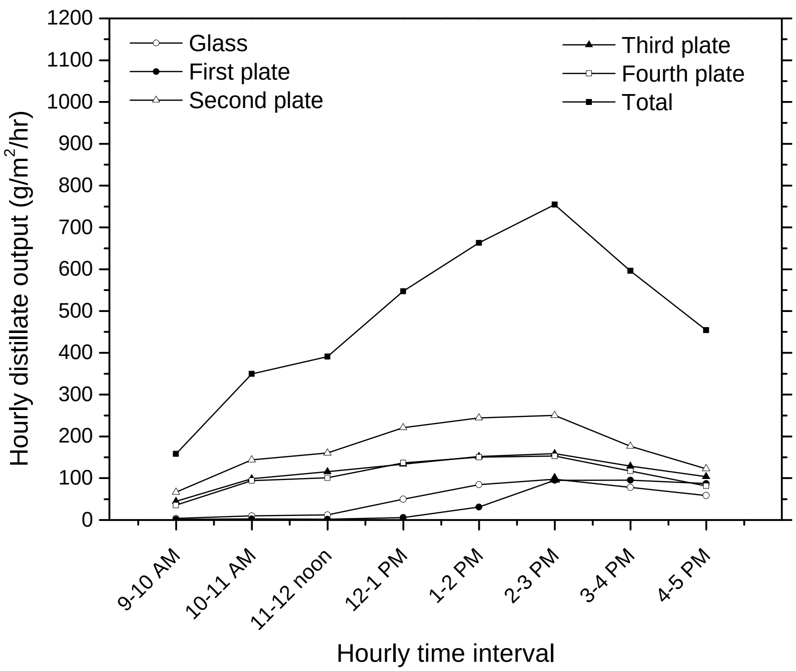


Fig.4.23 Variation of hourly distillate production in components of reference still on 13th October, 2016

As can be seen from Fig. 4.22, some amount of distillate starts coming out from the glass cover of FW-BVMED-HR still, from the first hour in the morning, even though the float wick temperature is lagging behind the inner glass cover temperature as can be seen from Fig. 4.19. Since the float wick-inner glass temperature difference is negative in the morning hours, this distillate cannot be the result of condensation on the main glass cover area. This distillate could be the result of the condensation which might have occurred in the relatively cold glass cover distillate output channel and its vicinity on the glass cover, and on the area bordering side edges. As the float wick temperature rises and becomes more than the inner glass temperature in the later part of the day, i.e. after 1:30 pm, condensation takes place on whole glass cover area also. The distillate formed at the glass cover of reference still, as seen from Fig. 4.23, is corresponding to the rising basin water temperature as shown by Fig. 4.20. The distillate formed at the glass cover is low in the initial hours of first part of the day, since the basin water temperature is low. With the rise of basin water temperature, the distillate production at glass cover also increases. This is due to the fact that as the basin water temperature increases, the fraction of evaporative heat transfer between basin water and glass cover increases, while convective fraction and radiative fraction between the same reduces [106].

For easy comparison of two stills, the hourly distillate outputs of glass, first plate and second plate, and night distillates for the two stills have been simultaneously shown in Fig. 4.24.

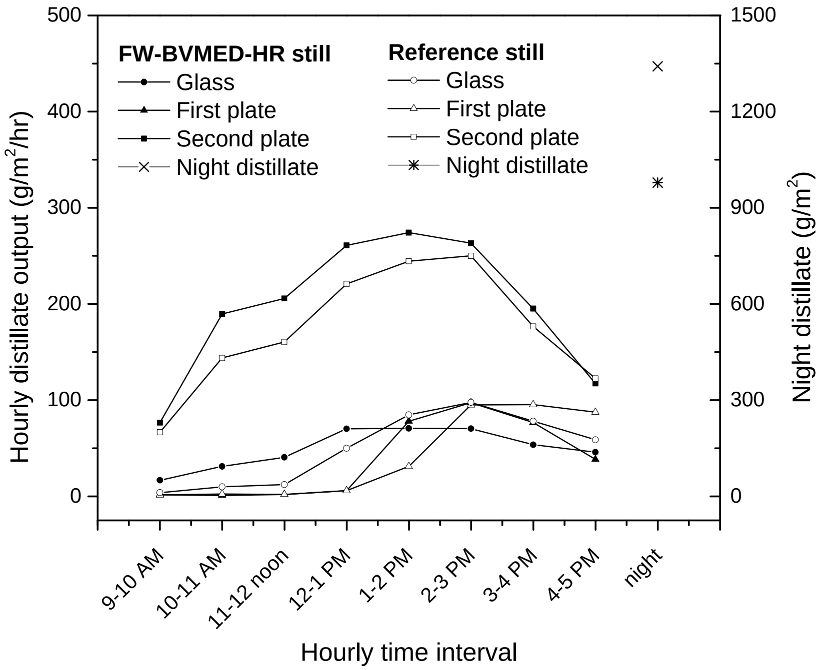


Fig. 4.24 Comparison of distillates of first partition plate, second partition plate and night for FW-BVMED-HR and reference stills on 13th October, 2016

From Fig. 4.24, it can be seen that the hourly distillate output at first partition plate of FW-BVMED-HR still was negligibly small and almost equal to the distillate output at first partition plate of reference still, till 1 pm, and higher than the reference still from 1 pm to 3 pm, after which it lagged behind. This may be due to the reason that during first part of the day, the first partition plate temperature stays above the basin air temperature due to absorption of direct solar radiation falling on the first partition plate and hence no condensation takes place at first partition plate of both the stills. As the basin air temperature rises above the first partition plate temperature, corresponding to the rising solar radiation, and rising temperatures of float wick and basin water of both stills, the condensate production at the first partition plate of both the stills also rises after 1 pm. The reason as to why FW-BVMED-HR still maintained lead in distillate output of first plate, over the reference still, from 1 pm 3 pm, after which it lagged behind can be explained as follows. In the first half of the day, majority of solar radiation entering the reference still is absorbed by the basin water due to its large thermal capacity. Whereas due to low thermal inertia of float wick, this energy absorbed by the float wick is readily utilized for evaporation of water from its porous surface. With the rising solar radiation till noon, the high temperature float wick is able to add vapor at a faster rate to the basin air than the low temperature basin water of reference still. As a result, the distillate production in first plate of FW-BVMED-HR still maintained lead over the reference still from 1 pm to 3 pm. However, in the second half of the day, the basin water of reference still, as seen from Fig. 4.20, has been sufficiently raised in temperature due to continuous absorption of direct radiation in it and it also stays above the float wick surface temperature of FW-BVMED-HR still in the afternoon and hence it is able to add vapor at a faster rate to the basin air than FW-BVMED-HR still. This phenomenon is reflected in the higher distillate production at first partition plate of reference still, than the FW-BVMED-HR still, from 3 pm till evening. For similar reasons, the distillate output at glass of the FW-BVMED-HR still maintained lead over the reference still, till 1 pm only, after which it lagged behind. The hourly distillate output at second partition plate of FW-BVMED-HR still stayed above the corresponding reference still output, throughout the day. This can be attributed to the fact that the higher temperature of first partition plate of FW-BVMED-HR still, due to higher convective heat transfer from float wick, in comparison to the reference still, as well as the pre-heated feed water from heat recovery in case of FW-BVMED-HR still, increased the evaporation heat flux from the first partition plate towards the second partition plate. The reason for higher convective heat transfer by humid air, from float wick surface to first partition plate of FW-BVMED-HR still, in comparison to convective heat transfer from basin water surface to first partition plate of reference still, is explained in the following lines. From Fig. 4.21 it can be observed that the temperature difference between float wick and first partition plate of FW-BVMED-HR still is considerably less than the temperature difference between basin water surface and first partition plate surface of reference still, indicating higher heat transfer between the two surfaces of FW-BVMED-HR still. Also as seen from Fig. 4.24 the distillate on second partition plate of FW-BVMED-HR still is higher than the distillate on second partition plate of reference still, throughout the day. The distillate formed on second partition plate is an indicator of total heat transfer from basin section by all modes. From Fig. 4.24 it can be seen that the distillates formed on first partition plates are nearly same for both stills, particularly in the first half of the day, indicating nearly same evaporation-condensation heat transfer. Hence possibly now, the difference of heat transfer is due to convective and radiation heat transfer. The radiation heat transfer to first partition plate is also expected to be nearly same and of small magnitude due to relatively low temperature values between heat exchanging surfaces. Moreover, first partition plate of both the stills is expected to receive nearly same amount of direct solar radiation and reflected radiation from basin internal surfaces as both the stills have identical basin section dimensions. Hence from above discussion it can be concluded that the higher heat transfer from float wick surface to first partition plate of FW-BVMED-HR still, resulting in its higher temperature, is a result of higher convective heat transfer by humid air as heat transfer by evaporation-condensation and radiative mode were nearly same for both stills. Further, as a result of increased evaporation heat flux from the first partition plate towards the second partition plate, the distillate production in other successive plates, i.e., third and fourth plates of FW-BVMED-HR still maintained lead over the corresponding plates in reference still as can be observed by comparing Fig. 4.22 and Fig. 4.23. The night distillate of FW-BVMED-HR still at 1.34 kg/m^2 was significantly higher than the reference still at 0.98 kg/m^2, as seen from Fig. 4.24. This could be due to the extra heat stored in multiple floating wicks. Moreover, due to presence of float cover, the radiative and convective heat losses from basin water surface of FW-BVMED-HR still were reduced in comparison to those from the basin water surface of reference still and hence most of the stored energy in basin water of FW-BVMED-HR still was utilized for evaporation of its basin water during night.

The cumulative distillate output curve for the FW-BVMED-HR still stayed above the corresponding reference still curve, for the entire 24 hour period, as seen from Fig. 4.25. Its productivity for the 24 hour period was 21% higher than the reference still. The same still without float wicks i.e. BVMED-HR still gave 11% higher productivity over the reference still, as seen from results of section 4.3.

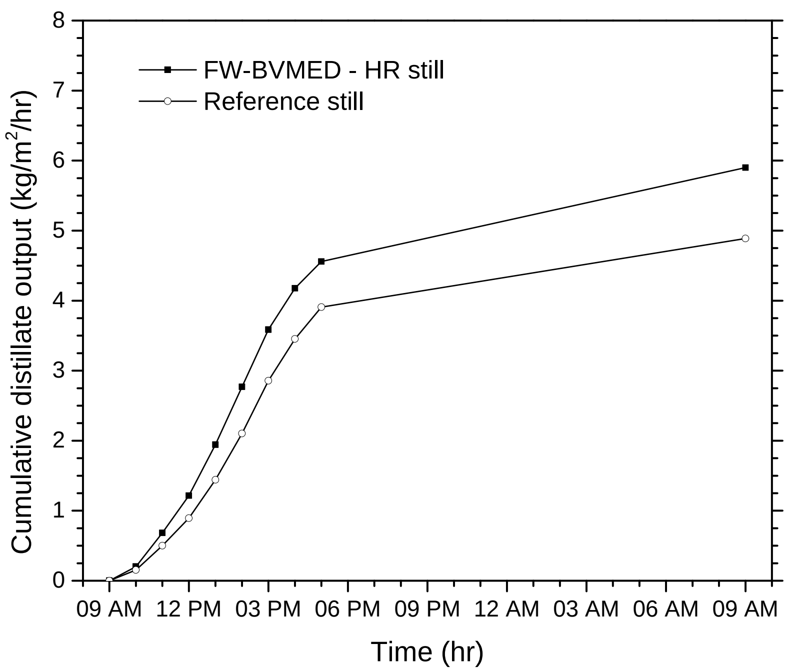


Fig. 4.25 Hourly variation of cumulative distillate output for FW-BVMED-HR and reference stills on 13th October, 2016

As expected, the cumulative efficiency curve for the FW-BVMED-HR still also stayed above the corresponding curve for the reference still, for 24 hour period, as seen from Fig. 4.26. The cumulative efficiency of four effect floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery, at ith hour is calculated as:

$$\eta_{c_i} = \frac{\sum_{i=1}^{i=i}\left(\sum_{j=0}^{j=4}\left(m_d \times H_{fg}\right)_j\right)_i}{\sum_{i=1}^{i=i}\left(\left(\text{hourly solar radiation on glass cover}\right)\times A_g\right)_i} \quad (4.7)$$

where, j = 0, 1, 2, 3 and 4 represents glass cover, first partition plate (basin facing back-wall of basin), second, third and fourth partition plates respectively, m_d is mass of distillate, H_{fg} is latent heat of vaporization of water and A_g is glass cover area.

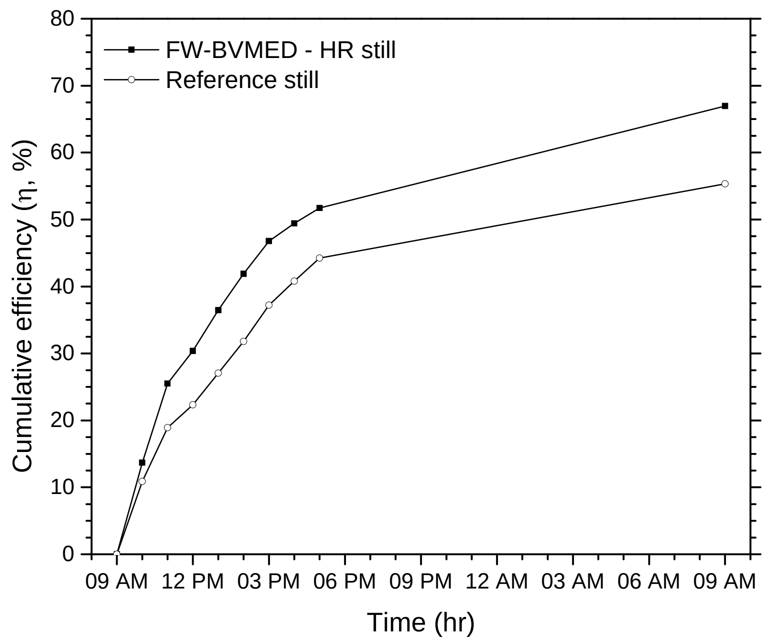


Fig. 4.26 Hourly variation of cumulative efficiency for FW-BVMED-HR and reference stills on 13th October, 2016

Component wise, total day and night distillates have been comparatively shown in Fig. 4.27 for the FW-BVMED-HR and reference stills. It can be observed that total day and night distillate outputs, in each component of FW-BVMED-HR still, are higher than in corresponding components of reference still. Fig. 4.28 shows the variation of feed water temperatures of FW-BVMED-HR still and reference still. The feed water temperature entering the FW-BVMED-HR still stays above the reference still throughout the day. It is obviously due to the preheating of feed water by heat recovery from hot waste feed water. Fig. 4.29 shows the total distillates for the glass cover, first partition plate and second partition plate, for FW-BVMED-HR and reference stills, on the experimental dates. It can be seen that the distillate formed on the second partition plate of FW-BVMED-HR still, is higher than the corresponding plate of reference still, on all experimental dates. This indicates that the total heat transfer towards the multiple effect distillation section is higher for the FW-BVMED-HR still than the reference still. The distillate formed at the first partition plate, indicates the heat transfer by evaporation-condensation mode, from the basin section towards the partition plate distillation section and it remained higher for the FW-BVMED-HR still than the reference still, on all dates. The distillate formed on the glass cover also, remained higher for the FW-BVMED-HR still than the reference still, on all dates. The reasons for these phenomena have already been explained in the preceding paragraphs. Simply said, the higher rate of heat transfer from basin section towards the partition plate distillation section, due to presence of low thermal inertia floating wick in FW-BVMED-HR still and supply of preheated feed water from heat recovery, were the reasons for higher distillate output in all the components of FW-BVMED-HR still in comparison to the reference still. It was found from the hourly water quality tests that the TDS and pH of input water to the partition plates of still, was in the range of 390 - 410 and 7.20 – 7.40 respectively, while the TDS and pH of distillate output, was in the range of 1 – 4 and 5.43 – 6.73 respectively.

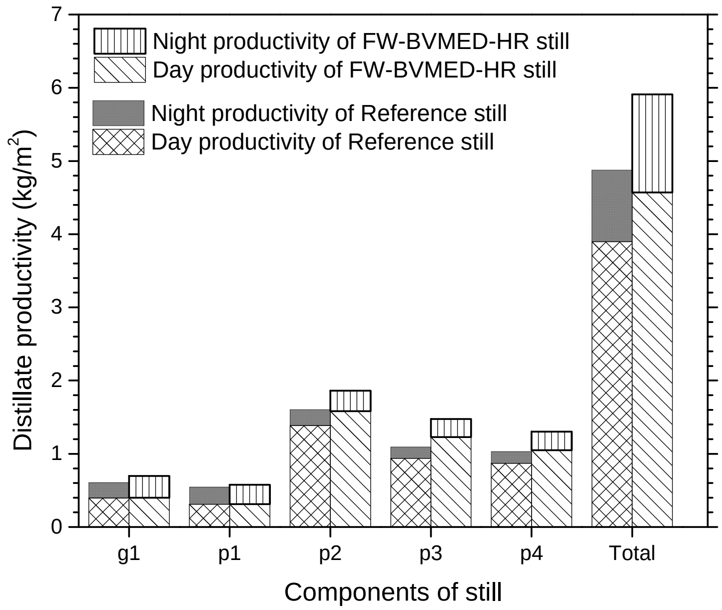


Fig. 4.27 Day and night distillate productivities in components of FW-BVMED-HR and reference stills on 13th October, 2016

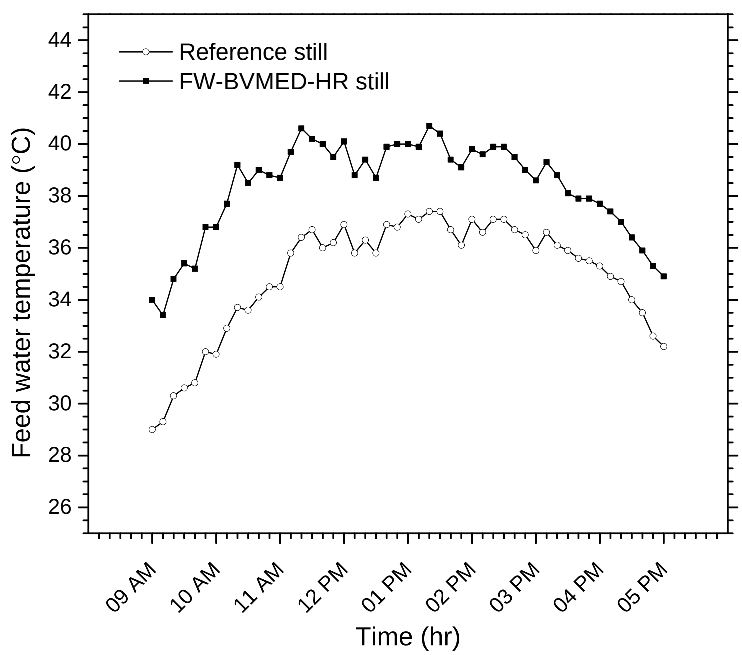


Fig. 4.28 Variation of feed water temperatures to FW-BVMED-HR and reference stills on 13th October. 2016

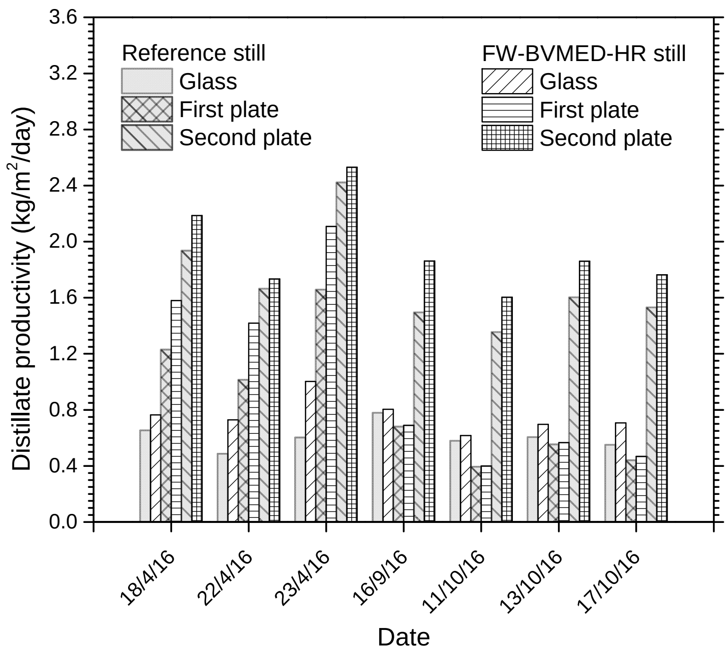


Fig. 4.29 Total distillates for glass, first and second partition plates on the experimental dates, for FW-BVMED-HR and reference stills

As can be observed from the results shown in Table 4.2, the productivity for the FW-BVMED-HR and reference stills was highest in the month of April. The pre-heated feed water temperature of FW-BVMED-HR still was also the highest. The gain in productivity for the FW-BVMED-HR still over the reference still for the month of April, however, was limited to only 14% on 18th April, 2016. This can be explained as follows. The ambient temperature was high and hence the basin bottom losses for the reference still were reduced. The basin air temperature of FW-BVMED-HR still was higher than reference still due to the high temperature of float wick, in the first part of the day. Pre-heated feed water was fed at equal rates to all the partition plates. Although the first partition plate temperature was high, there must be a minimum temperature gradient between partition plates in the partition plates section, for evaporation-condensation heat transfer between plates and heat rejection to external environment. If the heat rejected by the last plate to external environment is less than the heat input from the basin side, the temperature gap between plates may become very low, of the magnitude of as low as 0.5 °C as observed during the experiments. If the heat rejected by the last plate to external environment is more than the heat input from the basin side, the temperature gap between partition plates may become large. In both cases, it can reduce the efficiency of the FW-BVMED-HR still due to reduction in the evaporation-condensation heat transfer between partition plates. In the first case, the distillate production in the plates reduces since no temperature gradient is available for condensation to take place. In the second case the distillate production rates in partition cells reduces due to reduction in mean cell temperatures and hence resulting reduction in vapor diffusion flux across partition plates [76]. For the case of 18^{th} April, 2016 the last plate cooling was non-optimum for efficient heat transfer from the basin side to the external environment. The heat loss by heat of condensation through glass cover was also higher than reference still. An optimum feed water rate, less than from rest of the partition plates is needed for the last plate of FW-BVMED-HR still [18,23,87], for transferring the high available heat in the basin section to the external environment. In the present experiment of 13^{th} October, 2016, feed rates to all partition plates were kept same for both FW-BVMED-HR and reference stills. As a result, the excess heat in basin section of FW-BVMED-HR still was lost to the environment from basin glass covers by radiative, convective and evaporation-condensation heat transfer. The reference still on the other hand was able to absorb the solar radiation directly in basin water and store it. Due to high ambient temperature, this stored heat resulted in high distillate production rates in second half of the day, and high night distillate, for the reference still. Therefore, while the FW-BVMED-HR showed poorer performance than its optimum, the reference still performed better, thus reducing the gap between their productivities. Moreover, the percentage gain in productivity for FW-BVMED-HR still, for April, is also low due to the large value of the productivity of the reference still, as compared to other months.

Table 4.2 Test results of experiments

Date	Radiation condition	G_T (MJ/m^2/day)	T_a (°C)	f (g/m^2/s)	ΔT_f (°C)	Productivity (kg/m^2/day)		Gain in productivity (%)
						FW-BVMED-HR still	Reference still	
18/4/2016	Partially cloudy	18.5	40.8	0.27	7.3	8.117	7.132	13.8
22/4/2016	Partially cloudy	18.5	37.7	0.27	6.0	6.785	5.978	13.5
23/4/2016	Clear sunny	24.6	37.0	0.21	5.7	9.890	8.783	12.6
16/9/2016	Partially cloudy	20.9	35.0	0.19	2.0	6.226	5.245	18.7
11/10/2016	Clear sunny	19.0	33.0	0.29	2.5	5.144	4.350	18.2
13/10/2016	Clear sunny	21.1	33.9	0.38	3.4	5.910	4.876	21.2
17/10/2016	Clear sunny	20.4	32.3	0.32	2.7	5.442	4.699	15.8

Ambient temperature and initial temperature of basin water have very important bearing on the daily productivity of the FW-BVMED-HR still, as observed from the experimental results. In summers, the night distillate remains high due to high stored energy in basin water and its slow cooling after sun set, due to high ambient temperature. In winters, the initial basin water temperature is as low as 10°C in the morning and ambient temperature also remains low throughout the day, as compared to summers, at the location of experiment. Hence for basin water depths of 2 cm or more, the gain in productivity of FW-BVMED-HR still is expected to be quite high, as compared to reference still. The basin water temperature of reference still is expected to remain much below the float wick temperature, for most part of the day, owing to low thermal inertia of float wick surface. High temperature of float wick surface and basin air will increase the heat flux towards the partition plate section for the FW-BVMED-HR still, as compared to the reference still. Night distillate for the reference still is also expected to remain less, due to higher radiative and convective heat losses from its basin water after sunset, in comparison to FW-BVMED-HR still which is having float wick for covering basin water.

The following key conclusions have been drawn from the experimental results of floating wick basin type VMED solar still with heat recovery (FW-BVMED-HR) and conventional basin type VMED solar still (reference still).

- The FW-BVMED-HR still performed significantly better than the reference still. Its productivity was 21% higher than the reference still. The rise of productivity in FW-BVMED-HR still over the reference still, was due to contribution of both, float wick, and feed water pre-heating from heat recovery.
- It was observed that floating wick attained high temperature very quickly owing to low thermal inertia of float wick surface. Hence, it is expected that the FW-BVMED-HR still can provide reasonable distillate even on low insolation days.
- The higher temperature of first partition plate, due to the higher heat transfer from the high temperature float wick surface, as well as the pre-heated feed water from heat recovery, in case of FW-BVMED-HR still, increased the evaporation heat flux from the first partition plate towards the second partition plate and external environment through partition plates.
- Distillates from glass cover and first partition plate in the FW-BVMED-HR still, maintained lead over the corresponding components of reference still, in the first part of

the day, on 13th October, 2016, after which they lagged behind. It happened because the float wick has low thermal inertia and hence its temperature stayed above the basin water of reference still in the first part of day. However, in the second half of the day, the float wick had lower temperature corresponding to falling solar radiation, as compared to basin water of reference still due to energy stored by it.

— The total distillate productivity on second partition plate, was higher for FW-BVMED-HR still than reference still, on all experimental days, indicating its higher heat transfer towards the partition plate section than for the reference still.

— The night distillate of FW-BVMED-HR still at 1.34 kg/m^2 was significantly higher than for the reference still at 0.98 kg/m^2, at a basin water depth of 2 cm, on 13th October, 2016. This is due to the extra heat stored in floating wick and reduced radiative and convective heat losses due to presence of float covers on the basin water.

— The present design of float worked very well for over a year without any maintenance problem. The simple tube-in-tube type of counter flow heat exchanger also worked successfully to pre-heat feed water by recovering heat from hot waste feed water. Both these modifications had very less cost addition to the total cost of FW-BVMED-HR still, when measured against the gains in distillate productivity resulting from them.

4.5. EXPERIMENTAL PARAMETRIC STUDY OF FW-BVMED-HR STILL

This section presents the variation of cumulative efficiency of the FW-BVMED-HR still with the parameters such as feed water flow rate, gap between partition plates, basin water depth and number of effects. In this fifth set of experiments, done between 7/5/2016 to 19/10/2016, experiments were done for studying the effect of number of effects and effect of partition plate gap. The number of effects (n) were varied from 2 to 7, at a fixed partition plate gap of 10 mm. The study of number of effects, for each effect, was done at two feed rates 0.27 $g/m^2/s$ and 0.34 $g/m^2/s$. The effect of partition plate gap (δ_p) was studied for three partition gaps of 10, 13 and 16 mm, at two feed rates of 0.27 $g/m^2/s$ and 0.34 $g/m^2/s$, for each partition plate gap. For effect of number of effects (n) and effect of gap between partition plates (δ_p), the basin water depth was kept constant at 2 cm. The range of parameters for these experiments has been presented in Table 3.2 of chapter 3. For effect of basin water depth (d) the experimental data base of section 4.4 has been used. For effect of feed rate (f), complete experimental data base of FW-BVMED-HR still, including section 4.4, has been used.

The experiments were performed by varying a particular parameter, preferably on continuous days. From the complete range of experiments conducted on several days over a period of April to October, 2016, readings of only those days were selected for which the weather conditions such as total solar radiation and average ambient temperature, lie in narrow range, in order to find the sole effect of variable parameter on the performance of still. Separate scatter plots were plotted, with cumulative efficiency (η_c) on y axis; and feed rate (f), basin water depth (d), number of effects (n) and gap between partition plates (δ_p), on x-axis. Polynomial fits were given to the data points to obtain a trend curve between plotted variables.

The overall cumulative efficiency of FW-BVMED-HR still at the end of 24 hrs. period is calculated by using the following expression for multiple effect stills [88].

$$\eta_c = \frac{m_d \times H_{fg}}{G_T \times A_g} \tag{4.8}$$

where, m_d is the total amount of distillate in kg, H_{fg} is the latent heat of vaporization of water in J/kg, G_T is the total solar radiation on glass cover in MJ/m^2/day and A_g is the glass cover area in m^2.

The complete range of values for design and operational parameters, used in the present parametric study are listed in Table 4.3. The weather conditions during the experimental days are also reported in Table 4.3. Complete details of design, operational and weather parameters have been provided in Table B.4 of Appendix B.

Table 4.3 Values of design and operational parameters, and weather conditions

Design and operational parameters	
Number of effects (n):	2 – 7
Gap between partition plates (δ_p):	10, 13, 16 mm
Feed water rate (f):	0.19 – 0.48 g/m^2/s
Basin water depth (d):	1.0, 1.5, 2.0, 2.5, 3.0 cm
Feed water temperature (T_f):	33.9 – 49 °C
Weather conditions	
Total solar radiation (G_T):	16.3 – 22.9 MJ/m^2/day
Average ambient temperature (T_a):	34 – 41 °C
Wind velocity (V_w):	0.3 – 7.2 m/s

4.5.1 Effect of feed water flow rate

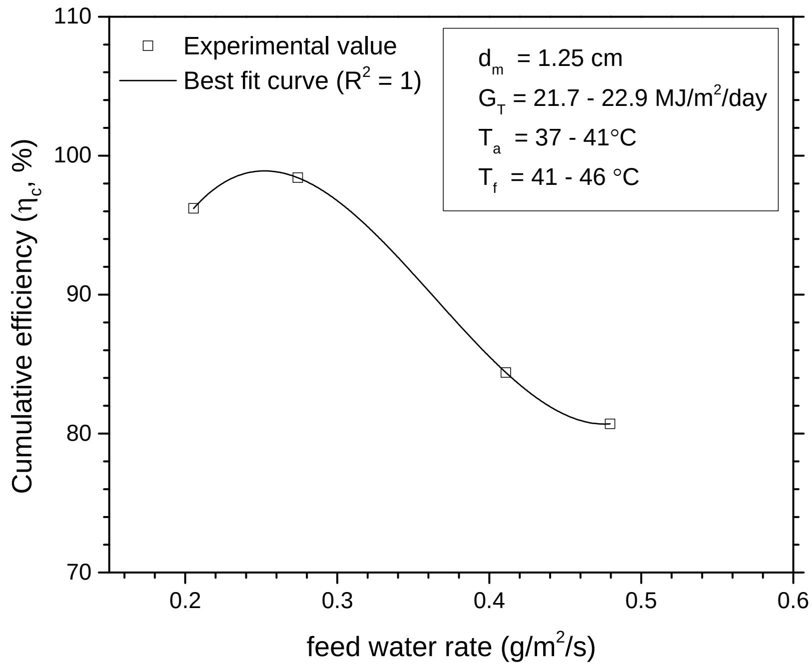
The experiments conducted on 20th, 21st, 29th and 30th April, 2016 were sorted out from database to find the effect of feed rate on the performance of FW-BVMED-HR still, since the total solar radiation and average ambient temperature on these days were in the narrow range, as can be seen from Table 4.4. The basin water depth on these dates were either 1.0 cm or 1.5 cm. Since the variation of basin water depth is very small, hence the mean value, i.e., 1.25 cm can be conveniently taken as constant mean basin water depth (d_m) for these experiments. Similarly, another set of experiments performed on 25th April, 26th April, 16th September and 13th October, 2016 with constant mean basin water depth of 2.25 cm, was selected from database to find the effect of feed rate on the performance of still. The total solar radiation and average ambient temperature on these days were in a narrow range, as can be seen from Table 4.4. The number of effects was 4 at a partition plate gap of 10 mm for all these experiments.

Table 4.4 Test results of four effect FW-BVMED-HR still with varying feed water rate at mean basin water depths of 1.25 cm and 2.25 cm, at partition plate gap of 10 mm

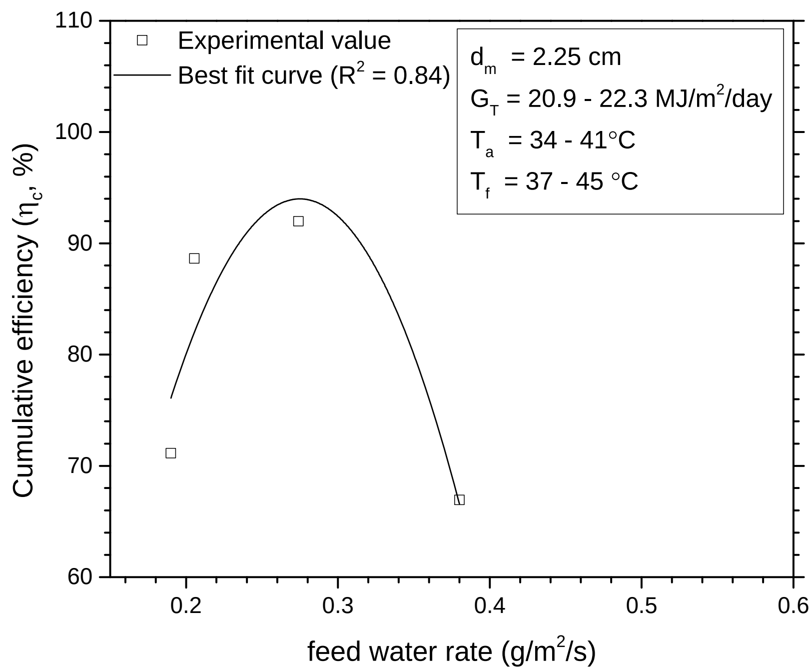
Date	d_m (cm)	G_T (MJ/m^2/day)	T_a (°C)	f (g/m^2/s)	P (kg/m^2/day)
20/4/2016	1.25	22.3	37.1	0.41	7.860
21/4/2016	1.25	22.9	37.6	0.48	7.726
29/4/2016	1.25	22.7	40.5	0.21	9.169
30/4/2016	1.25	21.7	41.4	0.27	8.971
25/4/2016	2.25	22.0	38.8	0.21	8.154
26/4/2016	2.25	21.7	41.4	0.27	8.599
16/9/2016	2.25	20.9	35.0	0.19	6.226
13/10/2016	2.25	21.1	33.9	0.38	5.898

Figs. 4.30(a) and 4.30(b) show the effect of feed water flow rate variation on the cumulative efficiency of four effect FW-BVMED-HR still, at mean basin water depths (d_m) of 1.25 cm and 2.25 cm respectively. The feed water rate to each partition plate has been kept same and it has been calculated per unit partition plate area. The Figs. 4.30(a) and 4.30(b) have been plotted with experimental results of those days which have nearly same amount of total solar radiation, and average ambient temperature and feed water temperature variation in a narrow range, in order to find the sole effect of feed water flow rate variation on the performance of still. It can be seen from Figs. 4.30(a) and 4.30(b) that as the feed water rate is varied in the range of 0.19 g/m^2/s to 0.48 g/m^2/s, the cumulative efficiency first increases, reaches a maximum value at about 0.27 g/m^2/s

feed water rate and then decreases continuously. At very low feed rates the partition plate wicks do not get wet fully and hence the cumulative efficiency is low due to low evaporation rates. As feed rate is increased in the lower range of feed rates, the wick wetted area increases and hence rate of evaporation increases, leading to corresponding rise in cumulative efficiency. In this range of feed rate, the amount of waste feed water leaving from the bottom of vertical plates is very low and hence the loss of heat associated with hot waste feed water is negligibly small. Beyond feed rate of 0.27 $g/m^2/s$, as the feed water flow rate increases, the amount of waste feed water leaving from the bottom of vertical plates also increases, resulting in increased loss of heat. Only a fraction of this waste heat is recoverable through tube-in-tube type heat exchanger. At a mean basin water depth (d_m) of 1.25 cm, as the feed rate increases from 0.27 $g/m^2/s$ to 0.48 $g/m^2/s$, the cumulative efficiency decreases by 18%. At a mean basin water depth (d_m) of 2.25 cm, as the feed rate increases from 0.27 $g/m^2/s$ to 0.38 $g/m^2/s$, the cumulative efficiency decreases by 25%. Finally, it can be concluded that feed rate to partition plates should not be very low, as it can result in dry patches on partition plate wicks, leading to low evaporation rates, and at the same time it should not be very high, as it can result in significant loss of heat associated with large amount of hot waste feed water. Hence from the above discussion and results shown in Fig. 4.30 (a) and 4.30 (b), the optimum feed rate for four effect FW-BVMED-HR still is found to be 0.27 $g/m^2/s$, when the total solar radiation is in the range of 21-23 $MJ/m^2/day$. It is not possible to obtain such optimum feed rate value accurately with numerical simulation or experiments done in laboratory conditions. Moreover, it is not possible to obtain the increasing trend of cumulative efficiency with increase of feed rate, in the lower range of feed water rate, from numerical results. Tanaka et al. [88] predicted theoretically that the productivity of a basin type VMED still decreases as the feed water rate increases since the amount of waste heat leaving from bottom of plates increases and heat flux decreases from first to last effect.



(a)



(b)

Fig. 4.30 Variation of cumulative efficiency of four effect FW-BVMED-HR still with feed water rate at mean basin water depths of (a) 1.25 cm, and (b) 2.25 cm

4.5.2 Effect of gap between partition plates

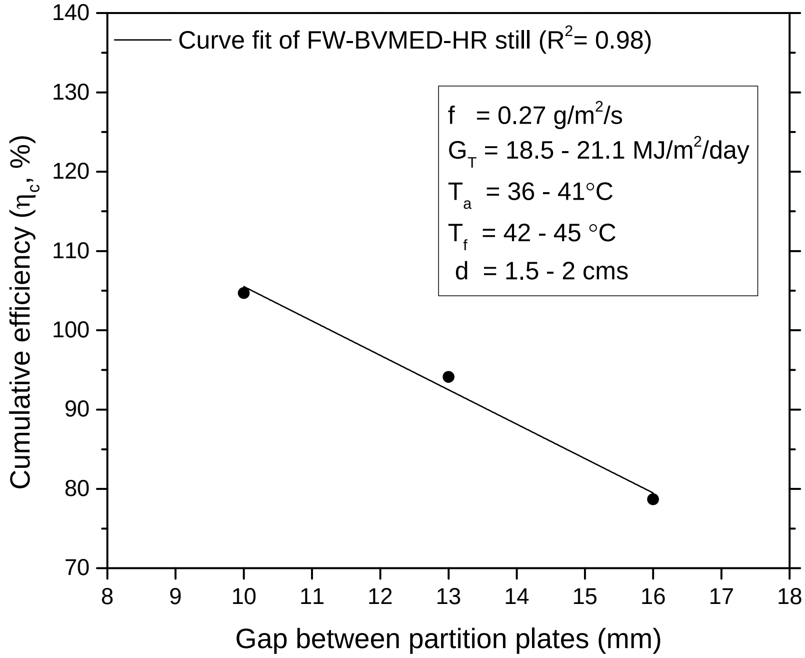
The experiments conducted on 18th April, 26th May and 31st May, 2016 were sorted out from database to find the effect of diffusion gap on the performance of FW-BVMED-HR still at constant feed water rate of 0.27 g/m^2/s, since the total solar radiation and average ambient temperature on these days were in the narrow range, as can be seen from Table 4.5. Similarly the experiments conducted on 19th April, 27th May and 1st June, 2016 were selected from database to find the effect of diffusion gap on the performance of still at constant feed water rate of 0.34 g/m^2/s, as the total solar radiation and average ambient temperature on these days were in the narrow range, as can be seen from Table 4.5. The number of effects was 4 for all these experiments.

Table 4.5 Test results of four effect FW-BVMED-HR still with varying diffusion gap at constant feed water rates of 0.27 g/m^2/s and 0.34 g/m^2/s

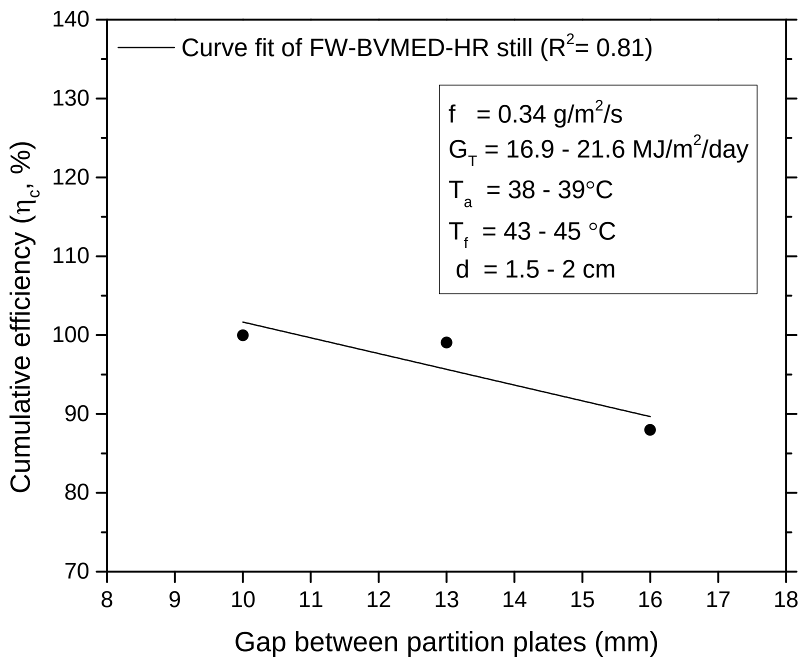
Date	f (g/m^2/s)	G_T (MJ/m^2/day)	T_a (°C)	d (cm)	δ_p (mm)	P (kg/m^2/day)
18/4/2016	0.27	18.5	40.8	1.5	10	8.117
26/5/2016	0.27	20.6	35.8	2	13	8.116
31/5/2016	0.27	21.2	35.6	2	16	6.995
19/4/2016	0.34	16.9	38.8	1.5	10	7.078
27/5/2016	0.34	21.6	38.8	2	13	8.307
1/6/2016	0.34	19.8	37.9	2	16	7.397

Figs. 4.31(a) and 4.31(b) show the variation of cumulative efficiency of four effect FW-BVMED-HR still with diffusion gap between partition plates, at constant feed water rates of 0.27 g/m^2/s and 0.34 g/m^2/s respectively. As expected, it can be seen from Figs. 4.31(a) and 4.31(b), cumulative efficiency decreases with increase of diffusion gap, for both the feed rates. However, the slope of the curve for feed rate of 0.34 g/m^2/s is lesser than the slope of the curve for feed rate of 0.27 g/m^2/s. This may be explained as follows. As discussed in section 4.5.1, 0.27 g/m^2/s is the optimum feed rate for the four effect FW-BVMED-HR still. Hence the evaporation flux at feed rate of 0.27 g/m^2/s is higher than at feed rate of 0.34 g/m^2/s. Tanaka et al. [87] estimated that natural convection does not occur at small partition plate gaps of 10 mm. In the present FW-BVMED-HR still, as the partition plate gap is increased beyond 10 mm, vapor transport by convection currents also begins in addition to vapor diffusion transport. Possibly, it is due to the dominance of vapor diffusion transport over convection transport of vapor at feed rate of 0.27 g/m^2/s that even at large diffusion gaps more sensitivity to change in diffusion gap is observed for feed rate of 0.27 g/m^2/s than for feed rate of 0.34 g/m^2/s. Tanaka et al. [88] predicted theoretically that the productivity of a basin type VMED still increases by 31% when the diffusion gap is decreased from 10 mm to 5 mm, since evaporation and condensation rates are inversely proportional to diffusion gap. The cumulative efficiency of the four effect FW-BVMED-HR

increases by 33% and 13.6% for feed rates of 0.27 g/m^2/s and 0.34 g/m^2/s respectively, when gap between partition plates is decreased from 16 mm to 10 mm.



(a)



(b)

Fig. 4.31 Variation of cumulative efficiency of four effect FW-BVMED-HR still with gap between partition plates at feed rates of (a) 0.27 g/m^2/s, and (b) 0.34 g/m^2/s

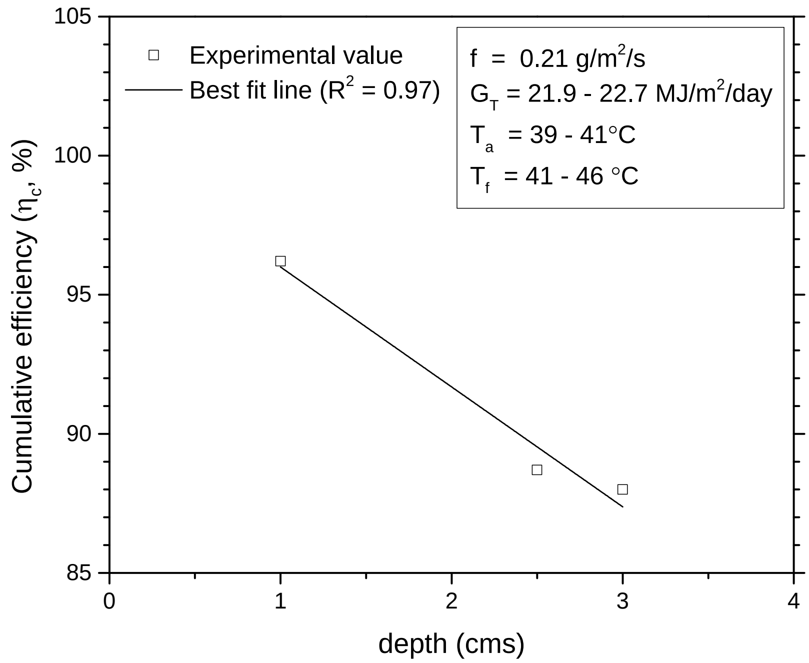
4.5.3 Effect of basin water depth

The study of effect of basin water depth on performance of FW-BVMED-HR still was done at two feed rates 0.21 $g/m^2/s$ and 0.27 $g/m^2/s$. The dates of experiments which were conducted for finding the effect of basin water depth are given in Table 4.6. The test results of these experiments are also reported in Table 4.6. The number of effects was 4 for all these experiments.

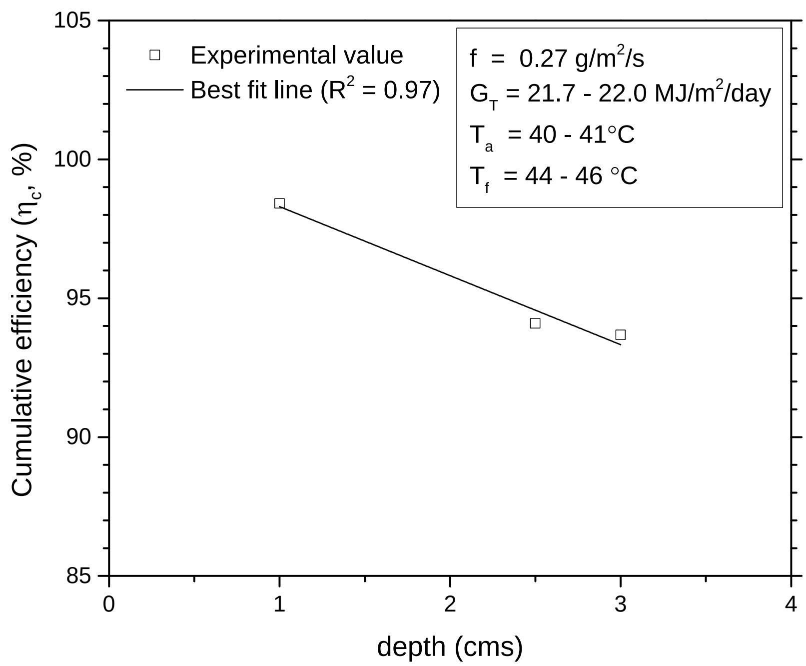
Table 4.6 Test results of four effect FW-BVMED-HR still with varying basin water depth at constant feed water rates of 0.21 $g/m^2/s$ and 0.27 $g/m^2/s$, at partition plate gap of 10 mm

Date	f ($g/m^2/s$)	G_T ($MJ/m^2/day$)	T_a (°C)	d (cm)	P ($kg/m^2/day$)
25/4/2016	0.21	22.0	38.8	2.5	8.154
28/4/2016	0.21	22.3	39.3	3	8.275
29/4/2016	0.21	22.7	40.5	1	9.169
26/4/2016	0.27	21.7	41.4	2.5	8.599
27/4/2016	0.27	22.0	40.6	3	8.649
30/4/2016	0.27	21.7	41.4	1	8.971

Figs. 4.32(a) and 4.32(b) show the variation of cumulative efficiency of FW-BVMED-HR still with basin water depth, at constant feed rates of 0.21 $g/m^2/s$ and 0.27 $g/m^2/s$, and partition plate gap of 10 mm. It can be seen that the cumulative efficiency decreases with increase of basin water depth, for both the feed rates. At a feed rate of 0.21 $g/m^2/s$ and 0.27 $g/m^2/s$, the cumulative efficiency of the FW-BVMED-HR still decreases by 8.5% and 4.8% respectively, when the basin water depth increases from 1 cm to 3 cm. Tanaka et al. [88] predicted theoretically that the productivity of a basin type VMED still decreases with increase of basin water depth. It happens because larger heat capacity of basin water slows down the temperature rise of basin water, leading to lesser heat transfer from basin to first partition plate. In FW-BVMED-HR still, for both feed rates, it is observed that the decrease of cumulative efficiency with increase of water depth is quite low. It is due to presence of low thermal inertia floating wick surface on the basin water of FW-BVMED-HR still. Since the evaporation takes place from the high temperature porous surface of the float wick, it is less affected by the increase of basin water depth.



(a)



(b)

Fig. 4.32 Variation of cumulative efficiency of four effect FW-BVMED-HR still with basin water depth at constant feed rates of (a) 0.21 $g/m^2/s$, and (b) 0.27 $g/m^2/s$

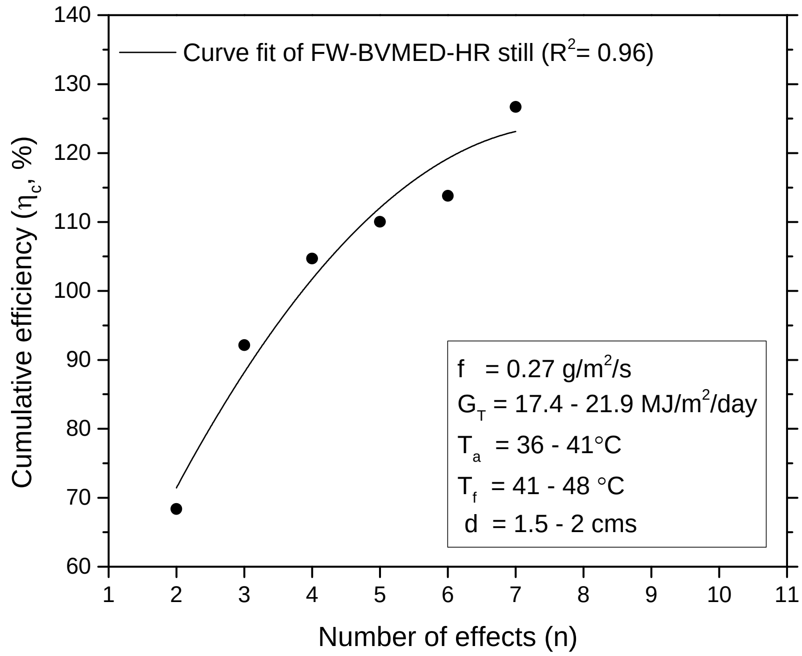
4.5.4 Effect of number of effects

The study of effect of number of effects on performance of FW-BVMED-HR still was done at two feed rates 0.27 g/m^2/s and 0.34 g/m^2/s. The dates of experiments which were conducted for studying the effect of number of effects are given in Table 4.7. The test results of these experiments are also reported in Table 4.7.

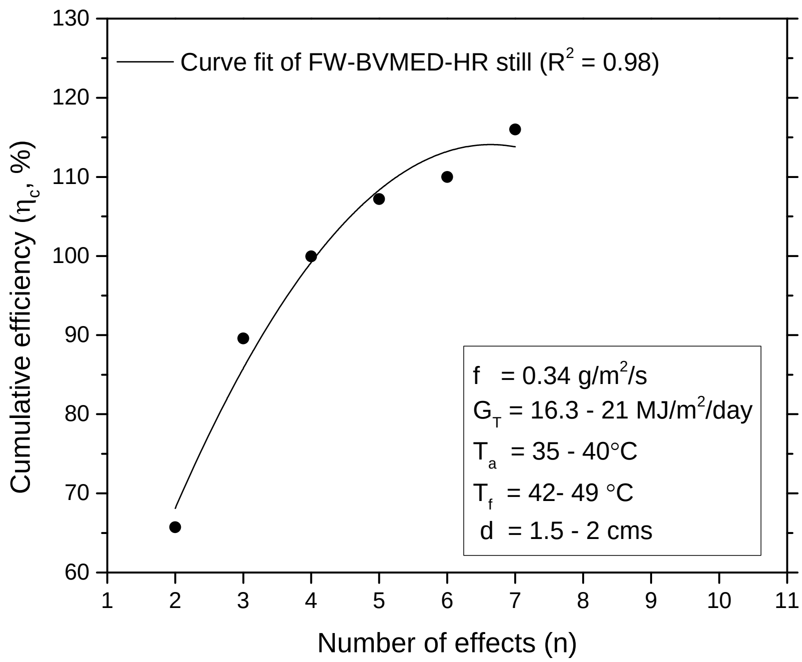
Table 4.7 Test results of FW-BVMED-HR still with varying number of effects at constant feed water rates of 0.27 g/m^2/s and 0.34 g/m^2/s, and partition plate gap of 10 mm

Date	f (g/m^2/s)	d (cm)	G_T (MJ/m^2/day)	T_a (◦C)	n	P (kg/m^2/day)
20/5/2016	0.27	2	19.7	37.4	2	5.619
18/5/2016	0.27	2	21.1	40.1	3	8.129
18/4/2016	0.27	1.5	18.5	40.8	4	8.117
9/5/2016	0.27	2	17.7	35.7	5	8.126
10/5/2016	0.27	2	17.4	36.7	6	8.274
17/5/2016	0.27	2	21.9	39.4	7	11.629
21/5/2016	0.34	2.0	18.7	36.3	2	5.122
19/5/2016	0.34	2.0	19.9	37.3	3	7.460
19/4/2016	0.34	1.5	16.9	38.8	4	7.078
7/5/2016	0.34	2.0	16.3	35.6	5	7.280
11/5/2016	0.34	2.0	21.1	34.6	6	8.649
13/5/2016	0.34	2.0	20.5	39.9	7	9.640

Figs. 4.33(a) and 4.33(b) show the variation of cumulative efficiency of FW-BVMED-HR still with number of effects (equal to number of partition plates) at constant feed water rates of 0.27 g/m^2/s and 0.34 g/m^2/s, and partition plate gap of 10 mm. As expected, it can be seen from the best fit curve that cumulative efficiency increases with the increase in number of effects. It can be observed from Figs. 4.33(a) and 4.33(b) that as the number of effects are increased from 2 to 7, the cumulative efficiency of FW-BVMED-HR still increases by 58% and 50%, at feed rates of 0.27 g/m^2/s and 0.34 g/m^2/s respectively. It is due to the obvious reason that the number of times input energy in multi-effect diffusion still is recycled, is proportional to the number of effects, and hence as the number of effects increases, the cumulative efficiency also increases. Since the cost of adding an effect, consisting of a partition plate and wicks, is a small fraction of the total cost of FW-BVMED-HR still, the use of reasonable number of effects (partition plates) in multi-effect still contributes significantly in reducing the generation cost of per liter of distilled water.



(a)



(b)

Fig. 4.33 Variation of cumulative efficiency of FW-BVMED-HR still with number of effects at constant feed water rate of (a) 0.27 g/m^2/s (b) 0.34 g/m^2/s

4.5.5 Development of productivity correlation

A productivity correlation has been developed to predict the productivity of FW-BVMED-HR still using the experimental database of present study. The productivity of a VMED solar still depends upon the weather parameters such as daily total insolation and daily average ambient temperature, and the design parameters like gap between partition plates and number of effects. For VMED still, the feed rate and feed water temperature are the operating parameters which significantly influence the productivity of VMED still. Thus the productivity of FW-BVMED-HR solar still can be represented as function of several parameters as given below:

$$P = f(G_T, T_a, f, T_f, n, \delta_p) \quad (4.9)$$

where, P is the daily distillate productivity per unit glass area of the FW-BVMED-HR solar still, expressed in $kg/m^2/day$, G_T is the total solar radiation on glass cover, expressed in $MJ/m^2/day$, T_a is the average daily ambient temperature in °C, f is the average daily feed water rate in $g/m^2/s$, T_f is the daily average temperature of feed water in °C, n is the number of effects in still and δ_p is the gap between partition plates in mm.

The correlation for productivity is generated in non-linear power law form with the independent influencing parameters as given in Eq. (4.9). Therefore rewriting Eq. (4.9) in a generic form of non-linear power equation as given below:

$$P = C \times (G_T)^{a_1} (T_a)^{a_2} (f)^{a_3} (T_f)^{a_4} (n)^{a_5} (\delta_p)^{a_6} \quad (4.10)$$

The values of constant C and exponents of independent variables in Eq. (4.10) are determined by applying the multivariate non-linear regression analysis on the experimental database. Finally the correlation obtained for productivity of FW-BVMED-HR solar still is as given below:

$$P = 0.0004 \times (G_T)^{0.730} (T_a)^{1.585} (f)^{-0.102} (T_f)^{0.377} (n)^{0.401} (\delta_p)^{-0.068} \quad (4.11)$$

Eq. (4.11) is applicable for the range of values of various parameters, given in Fig. 4.34. It can be seen from Eq. (4.11) that the exponent of cumulative solar radiation is of large positive value. Since solar energy is the source of input energy for the basin section of still, the large positive value of exponent is in tune with expectation. Similarly, since all thermal losses to ambient are proportional to the difference between temperatures of still components and the ambient temperature, the high positive value of exponent for T_a is also in line with expectation. The small negative value of exponent for feed rate shows a small decrease of productivity with a large increase of feed rate. A rise of feed water temperature results in increase of distillate productivity, as shown by the positive value of exponent in the expression. Similarly, on increasing the number of effects, the productivity of multi-effect still increases, as shown by the positive value of its exponent. The productivity of the still reduces by small value with a large increase of the gap between partition plates, as shown by the small negative value of the exponent. This is in line with the behavior shown by numerically simulated results by Tanaka et al. [88], for the increase of gap between partition plates from 10 mm to 16 mm. The proposed correlation has a regression coefficient of 0.88 which suggests that the correlation has a fairly accurate closeness with the experimental database used for the development of correlation. The accuracy of proposed correlation is verified by comparing the predicted productivities obtained from proposed correlation with those measured experimentally. This comparison is depicted in Fig. 4.34. Fig. 4.34 shows that the proposed correlation predicts the experimental data within the deviation range of -17% to +14% with a mean deviation of 6.6%. Therefore, it can be concluded that the predictions by the proposed correlation yield a fairly good agreement with the experimental measurements.

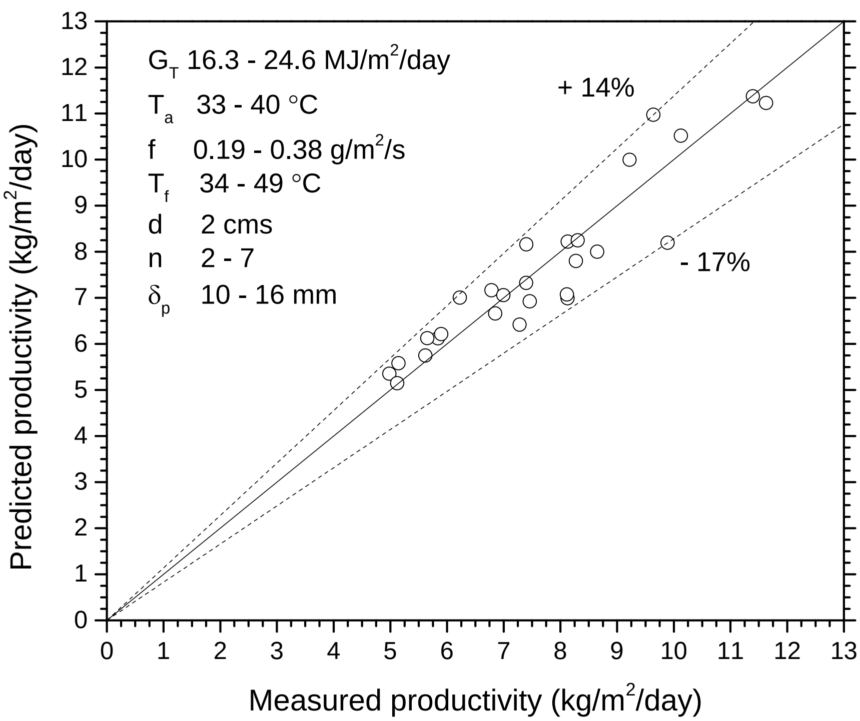


Fig. 4.34 Validation of proposed correlation for productivity of FW-BVMED-HR solar still

An experimental parametric study under outdoor conditions, of FW-BVMED-HR still, leads to the following conclusions:

- The optimum feed water rate for the four effect FW-BVMED-HR still was found to be 0.27 $g/m^2/s$, when the total solar radiation lies in the range of 21-23 $MJ/m^2/day$.
- Beyond an optimum feed water rate, the cumulative efficiency decreases with increase of feed water rate. The cumulative efficiency decreases with increase in partition plate gap and basin water depth. The cumulative efficiency increases with increase of number of effects. These trends obtained from experimental results of FW-BVMED-HR still, are broadly in agreement with the numerically simulated and experimental results obtained by previous researchers.
- The effect of basin water depth on cumulative efficiency was found to be low. That means FW-BVMED-HR still can be effectively used with high basin water depth, which reduces the frequency of refilling the still.
- The cumulative efficiency showed a maximum rise of 58% when the number of effects were increased from 2 to 7, at constant feed rate of 0.27 $g/m^2/s$. Since the cost of adding an effect, which consists of a thin plate and wick cloth, is a small fraction of the total cost of FW-BVMED-HR still, the multi-effect stills with reasonable number of effects can significantly reduce the generation cost of per liter of distilled water.
- The productivity correlation has been developed by considering all possible parameters which affect the productivity of the FW-BVMED-HR still. Hence this correlation can be used to estimate the productivity with fair degree of accuracy, within the investigated range of parameters, to carry out techno-commercial feasibility studies before installation of similar type of solar distillation unit in any part of the world.

4.6 NOCTURNAL PRODUCTIVITY

In the present work, each of the experimental tests were started at 9 AM and continued till 9 AM of the next day. Distillates coming out from various still components were collected and recorded hourly between 9 AM to 5 PM to investigate hourly performance of still during the sunny hours. At 5 PM, the glass cover of the still was covered with stainless steel sheet of thickness 0.3 mm, to stop solar radiation, if any, entering the still, so that distillate obtained during 5 PM to 9 AM of the next day is only due to the storage effect of still. The distillate formed during these nonsunny hours was collected only once, at 9 AM next day, and it is referred to as nocturnal productivity of the still.

The nocturnal productivity was found to be in the range of 14-25% of total daily productivity. Fig. 4.35 shows the nocturnal productivities plotted against diurnal productivities for the dates of experimental period. A linear fit curve line fits the data points with $R^2 = 0.8$, which shows that there is a direct dependence of night productivity on day productivity.

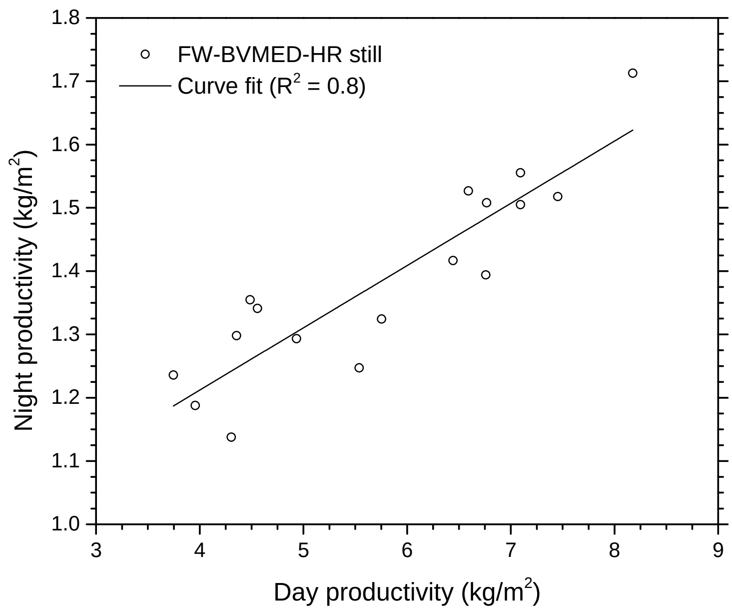


Fig. 4.35 Relation between night productivity and day productivity of four effect FW-BVMED-HR still

4.7 UNCERTAINTY ANALYSIS

The uncertainty in calculation of cumulative efficiency is presented in this section. The uncertainties of the measuring devices may be classified as type B (systematic error). Assuming the measurands to be distributed uniformly, the standard uncertainty for this case may be expressed as [115],

$$u = \frac{a}{\sqrt{3}} \tag{4.12}$$

where 'a' is the accuracy of the instrument and 'u' is the standard uncertainty. The standard uncertainty values of all measurands are shown in Table 4.8.

When y depends on an arbitrary number of input variables x_i and $u(x_i)$ are the uncertainties in measurement of x_i, then the uncertainty of y is calculated by [116],

$$u(y)=\left[\left(\frac{\partial y}{\partial x_1}\right)^2 u^2(x_1)+\left(\frac{\partial y}{\partial x_2}\right)^2 u^2(x_2)+.......\right]^{1/2} \tag{4.13}$$

The cumulative efficiency of FW-BVMED-HR still at the end of 24 h period is calculated by using the following expression for multiple effect stills [88]

$$\eta_c=\frac{m_d\times H_{fg}}{G_T\times A_g} \tag{4.14}$$

Table 4.8 Instruments, accuracy, range and standard uncertainty

S.No.	Instrument	Accuracy	Range	Standard uncertainty
1	Pyranometer- Kipp and Zonen	1W/m^2	0-4000 W/m^2	0.58 W/m^2
2	Anemometer	5% of reading	0.2 – 25 m/s	2.9% of reading
3	Relative humidity	2% RH	0-100 %	1.15% RH
4	Digital weighing balance	0.1 g	0- 5 kg	0.06 kg
5	Thermocouple (T type)	0.5 ^{o}C	-120 ^{o}C to 200 ^{o}C	0.29 ^{o}C
6	pH meter	0.02 pH	0- 14 pH	0.01 pH
7	TDS meter	2% of reading	0.1 ppm – 200,000 ppm	1.15% of reading
8	Measuring tape	0.001 m	0 – 5 m	0.00058 m

The uncertainty in cumulative efficiency for the FW-BVMED-HR solar still can be derived from Eq. (4.13) and Eq. (4.14) as,

$$u(\eta_c)=\eta_c\left[\left(\frac{u(m_d)}{m_d}\right)^2+\left(\frac{u(G_T)}{G_T}\right)^2+\left(\frac{u(H_{fg})}{H_{fg}}\right)^2+\left(\frac{u(A_g)}{A_g}\right)^2\right]^{1/2} \tag{4.15}$$

The maximum uncertainty of cumulative efficiency for the FW-BVMED-HR solar still was determined to be 1.5% by using Eq. (4.15).

4.8 MAINTENANCE ASPECTS OF EXPERIMENTAL SET-UP

The FW-BVMED-HR solar still has to be regularly monitored for its proper working, to obtain its optimum productivity. The glass cover transmissivity for solar radiation may be reduced due to dust, bird droppings and moisture presence between the two glass covers. Scaling may occur in the feed water delivery tubes, control valves and the heat exchanger pipes, which may alter the set feed water rates. Another serious problem encountered was of algae growth in the overhead feed water supply tank and the feed water supply tubes and control valves. A filter with 5 micron pore size was installed at the entry side of supply water to overhead tank, to check the entry of algae and other solid materials into the tank.

After two months of continuous running, the cotton wicks attached on partition plates were found saturated with salt. The water retention capacity of such wicks reduces. Also, since the capillary spread of water, laterally, in the fibers of the wick reduces, the wetted area of wick reduces. All these factors reduce the productivity of the FW-BVMED-HR still. The salt saturated wicks were cleaned by immersing them in boiling demineralized water for 30 minutes. The wicks were then taken out and squeezed to remove salt saturated water. Heavy salt deposition was observed on the partition plates, after continuous running of still for longer period, as seen in Fig. 4.36. Due to high thermal resistance of salt deposition on partition plates, heat transfer from partition plate surface to water flowing on the surface of wick reduces. The salt deposition on the partition plates was mechanically and chemically removed. The float wicks were also found saturated with salt after two months of continuous running of still as seen in Fig. 4.37. When float wicks get saturated with salt, its capillarity to raise basin water to the top surface of float reduces, resulting in dry spots on the floating wicks and reduced evaporation rates. The salt saturated float wicks were taken out, cleaned by immersing in boiling demineralized water, squeezed and replaced.

Fig. 4.36 Snapshot showing heavy salt deposition on the first partition plate

Fig. 4.37 Snapshot of cotton cloth wicks of floats showing salt deposition

PVC tubes were used for transferring distillates from glass cover and first plate distillate channels to plastic cans. After some days, these tubes were found to be degraded and developed cracks due to excessive temperatures and ultraviolet light of solar spectrum. These tubes were replaced with new PVC tubes after applying a layer of silicone sealant and polyurethane sheathing above it.

4.9 CONCLUDING REMARKS

In all, five sets of experiments were performed, of which, experimental results have been presented in this chapter. The experiments on basin type still were done to serve as a reference for comparing the productivity of the improved basin type vertical single distillation cell (VSDC) solar still. The performance results of experiments conducted simultaneously, with four effect basin type VMED solar still with heat recovery (BVMED-HR) and conventional basin type VMED solar still (reference still), are presented to highlight the effect of heat recovery from waste feed water. Similarly, the experiments were performed with four effect floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR) and reference still, placed side by side, for comparison purpose. They were followed by experimental parametric study on a single FW-BVMED-HR still, with varying number of effects. Significant improvement in the efficiency of a basin still was obtained by converting it into an improved basin type VSDC solar still of same basin and glass cover area. The new wick surface arrangement, in which the whole wick area was divided into six partitions in case of improved basin type VSDC solar still, and individual feed water given to each area, worked effectively, in increasing the wick wetted area and hence evaporation efficiency of the wick surface, which is confirmed by the temperature distribution of the partition plates. The water feeding mechanism to wicks was changed to gravity feeding, as against the capillary action feed mechanism by Tanaka et al. [18]. Longitudinal rubber spacers were used to separate the 0.3 mm thick stainless steel partition plates. By use of this arrangement no cross flow of saline feed water was observed, as confirmed by the water quality tests. The use of third external partition plate without evaporative cooling at a gap of 25 mm from the second partition plate, proved effective in maintaining the average temperature drop from first partition plate to second partition plate, up to 8 °C. On an average the temperature of the second partition plate stayed above the ambient temperature by 10 °C. This resulted in consistently high distillate outputs from the second partition plate. The improved basin type VSDC solar still worked satisfactorily on partially cloudy days also, thereby indicating that it utilized the diffuse component of solar radiation effectively. The pre-heating of feed water by recovering heat energy from waste feed water results in an appreciable increase in the cumulative efficiency and productivity of the BVMED-HR still. It was found that there was a rise up to 8.2% in cumulative efficiency and 10.6% in the distillate productivity for the BVMED-HR still over the reference still. The heat exchanger used to recover waste heat was simple in design, compact in size and of low cost. An empirical correlation has been proposed to predict the productivity of BVMED-HR solar still, which predicts the productivity very well with mean deviation of 4% from the experimental values. The FW-BVMED-HR still performed significantly better than the reference still. Its productivity was 21% higher than the reference still. The rise of productivity in FW-BVMED-HR still over the reference still, was due to contribution of both, float wick, and feed water pre-heating from heat recovery. It was observed that floating wick attained high temperature very quickly owing to low thermal inertia of float wick surface. Hence, it is expected that the FW-BVMED-HR still can provide reasonable distillate even on low insolation days. The higher temperature of first partition plate, due to the higher heat transfer from the high temperature float wick surface, as well as the pre-heated feed water from heat recovery, in case of FW-BVMED-HR still, increased the evaporation heat flux from the first partition plate towards the second partition plate and external environment through partition plates. The total distillate productivity on second partition plate, was higher for FW-BVMED-HR still than reference still, on all experimental days, indicating its higher heat transfer towards the partition plate section than for the reference still. The night distillate of FW-BVMED-HR still at 1.34 kg/m^2 was significantly higher than for the reference still at 0.98 kg/m^2, at a basin water depth of 2 cm, on 13th October, 2016. This is due to the extra heat stored in floating wick and reduced radiative and convective heat losses due to presence of float covers on the basin water. The present design of float worked very well for over a year without degrading. The simple tube-in-tube type of counter flow heat exchanger also worked successfully to pre-heat feed water by recovering heat from hot waste feed water. Both these modifications had very less cost addition to the total cost of FW-BVMED-HR still, when measured against the gains in distillate productivity resulting from them. From parametric study, the optimum feed water rate for the four effect FW-BVMED-HR still was found to be 0.27 g/m^2/s, when the total solar radiation lies in the range of 21-23 MJ/m^2/day. Beyond an optimum feed water rate, the cumulative efficiency decreases with increase of feed water rate. The cumulative efficiency decreases with increase in partition plate gap and basin water depth. The cumulative efficiency increases with increase of number of effects. These trends obtained from experimental results of FW-BVMED-HR still, are broadly in agreement with the numerically simulated and experimental results obtained by previous researchers. The effect of basin water depth on cumulative efficiency was found to be low. The cumulative efficiency showed a maximum rise of 58% when the number of effects were increased from 2 to 7, at constant feed rate of 0.27 g/m^2/s. Since the cost of adding an effect, which consists of a thin plate and wick cloth, is a small fraction of the total cost of FW-BVMED-HR still, the multi-effect stills with reasonable number of effects can significantly reduce the generation cost of per kg of distilled water. The data analysis of experimental results of FW-BVMED-HR still showed that the night productivity has almost linear dependence on day productivity. A productivity correlation has been developed by considering all possible parameters which affect the productivity of the FW-BVMED-HR still. Hence this correlation can be used to estimate the productivity with fair degree of accuracy, within the investigated range of parameters, to carry out techno-commercial feasibility studies before installation of similar type of solar distillation unit in any part of the world.

Chapter 5

Economic analysis

In this chapter economic analysis of FW-BVMED-HR still, based on life cycle costing of the system has been carried out. It covers the fifth and last objective of the present research work - *To compute the per litre cost of distilled water based on a life cycle costing of 10 years of the floating wick basin type VMED solar still with heat recovery*. The capital cost of this still with increasing number of effects, from 2 to 7, has been calculated. The annual cost of operating this still based on a life cycle of 10 and 25 years is estimated. The average annual distillate and unit cost of distillate, for increasing number of effects from 2 to 7, is evaluated. The effect of varying the rate of interest, on the unit cost of distillate, is also studied, for interest rates 0.12 and 0.16. The effect of cost sensitivity of raw material, on the unit cost of distillate, is also determined. Payback periods for various conditions is also computed.

5.1 ECONOMIC ANALYSIS OF FW-BVMED-HR STILL

The annual distillate generated by a still depends on the number of clear days in a year and weather conditions like ambient temperature and solar insolation. The weather conditions vary from month to month, round the year. The annual distillate can be estimated with a fair degree of accuracy with the help of either simulation program or a productivity correlation, by considering proper values of weather conditions. For the economic analysis of FW-BVMED-HR still, the correlation for daily productivity of FW-BVMED-HR solar still developed in chapter 4 is used, and the same correlation is reproduced below:

$$P = 0.0004 \times (G_T)^{0.730} (T_a)^{1.585} (f)^{-0.102} (T_f)^{0.377} (n)^{0.401} (\delta_p)^{-0.068} \tag{5.1}$$

The total annual distillate generated by the FW-BVMED-HR still was computed with the help of correlation for daily productivity shown in Eq. (5.1) and by using the following expression:

$$D = \sum_{i=1}^{i=12} P_i M_i \tag{5.2}$$

where, D is the total annual distillate per unit glass area in kg/m^2/year, P_i is average daily distillate output of ith month per unit glass area in kg/m^2/day, M_i is number of clear days of ith month.

The total annual cost (C_T) per unit glass area of the FW-BVMED-HR solar still, expressed in Rs./m^2/year is calculated by using the following expression given in Adhikari and Kumar [15]:

$$C_T = (C_b + C_d + C_m)\, f_c + (C_b M_b + C_d M_d + C_m M_m) - (C_b S_b + C_d S_d + C_m S_m)\, F \qquad (5.3)$$

where C_b, C_d, C_m are the capital costs of basin section, distillation section and miscellaneous components respectively of FW-BVMED-HR still. The capital costs of basin and distillation sections include material, labor and overhead costs. The material cost of various components used in basin section and distillation section is listed in Table 5.1, and the labor and overhead cost considerations used to estimate capital costs of these two sections is provided in Table 5.2. From Table 5.2, it can be seen that the labor cost is taken to be 15% and the overhead cost is taken to be 20%, of their respective material costs. The overhead cost includes cost of utilities like electricity, water, rent and maintenance of factory premises, and salary of administrative staff. It is to be understood that the total capital cost of the FW-BVMED-HR still is high since it was a prototype built for experimental purpose. This capital cost will come down significantly, if it is produced on mass scale and procurement of raw material is done in bulk quantity at bulk rates. Hence the capital cost taken in present study can be assumed to include a decent profit margin and therefore separate profit margin factor has not been considered in computation. M_b, M_d, M_m are the annual maintenance cost factors for basin section, distillation section and miscellaneous components respectively, as shown in Table 5.2. These annual maintenance cost factors have been taken as fractional percentage of their respective capital costs. The glass sealing gaskets, float and float wicks, double glass spacer rubber and discharge pipes need to be changed on annual basis for preventive maintenance of basin section. The cost of these items is estimated to be around 3% of basin section cost and hence its annual maintenance factor (M_b) has been taken to be 0.03. Similarly, spacer rubber and wick cloth of all partition plates of distillation section need to be changed on annual basis and the cost of these items is estimated to be around 6% of distillation section cost, hence its annual maintenance factor has been taken to be 0.06. Among the miscellaneous items which incur annual maintenance cost are heat exchanger tubes, mechanical pre-filters, transparent tubes for water feed rate viewing, PVC valves, PVC joints, PVC tees, PVC pipes, polyurethane insulation and heat resistant powder coating. Hence its maintenance factor has been taken to be 0.1. S_b, S_d and S_m are salvage value factors for basin section, distillation section and miscellaneous components respectively, as shown in Table 5.2 and Fig. 5.1. Since scrap values of copper and stainless steel (SS 304) show some price appreciation with time, their salvage values have been calculated from their weights [117]. Since basin section comprises mainly of basin tray and side reflectors made of stainless steel (SS 304), and double glass covers, its salvage value factor has been taken to be 0.35. The distillation section comprises mainly of first partition plate of copper and variable number of stainless steel partition plates. Hence its salvage value factor is variable and taken ranging from 0.58 – 0.54, as number of effects increase from 2 to 7, as shown in Fig. 5.1. Miscellaneous items have variable salvage value factors ranging from 0.21 – 0.16, as number of effects increases from 2 to 7, as shown in Fig. 5.1.

Table 5.1 Material cost of various components used in FW-BVMED-HR still

Component name	Description	Quantity	Rate per unit (INR)	Total amount (INR)
	Basin section			
Basin tray	SS 304 sheet 0.3 mm thick	4.15 kg	367.5	1527
Basin frame	M.S. angle (25 mm × 25 mm × 3 mm)	33.78 kg	48.36	1634
	and			
	M.S. square pipe (25 mm × 25 mm × 3 mm)	11.09 kg	49.92	554
Bolt seat projections	M.S. flat strip (50 mm × 6 mm)	2.88 kg	52	150
Side reflectors	SS 304 sheet 0.3 mm thick	1.56 kg	393.75	614
Glass covers	Glass toughened sheet 5 mm thick	3.14 m^2	1152.29	3618
Silicone rubber	Silicone rubber sheet 3 mm thick	0.49 kg	950	467
Float	Polystyrene sheet (1 m × 0.5 m × 20 mm)	1.5 m^2	40	60
	and			
	Polyurethane sheet 4 mm thick	1.5 m^2	125	188
Float wick	Black cotton cloth sheet 1 mm thick	2 m^2	150	300
Silicone sealant	Silicone	3 pcs	112.5	338
Insulation	Rock wool sheet (1 m × 0.5 m × 50 mm)	-	-	1500
G.I. sheathing	G.I. sheet 0.5 mm thick	17.2 kg	80	1376
Glass spacer rubber	Neoprene rubber sheet 10 mm thick	2.62 kg	63	165
Trolley wheels	Size 100 mm	6 pcs	194.25	1166
	Distillation section			
First partition plate	Copper sheet 0.5 mm thick	7.32 kg	735	5381
Other partition plates	SS 304 sheet 0.3 mm thick	3.43 kg	367.5	1261
Tightening Frame	M.S. square pipe (25 mm × 25 mm × 3 mm)	15.48 kg	49.92	773
Spacer rubber*	Neoprene rubber sheet 10 mm thick	3.41 kg	63	215
Channels*	Polycarbonate sheet 1.5 mm thick	0.18 m^2	773.13	139
Wick cloth*	Cotton cloth 1 mm thick	1.5 m^2	150	225
	Miscellaneous			
Heat exchanger	Copper/PVC pipe	1	-	831
Water storage tank	HDPE tank capacity 300 liters	1	-	1200
Tank Stand	M.S. stand 2.28 m height	23 kg	48.36	1113
Pre-filter	5 micron pore size	1 pc	500	500
Items per plate	Valves, tees, visual display tubes, pipes, insulation, sealant, screws	-	-	1400
Other items	Nozzle, wheel valve, elbow, nipple, nuts & bolts, rivets, solder, pipe and powder coating of M.S. components	-	-	2737

*Cost per plate

Table 5.2 Various cost factors used for cost analysis of FW-BVMED-HR still

Parameter	Value
Annual maintenance cost factors	
Basin section (M_b) as % of its cost	0.03
Distillation section (M_d) as % of its cost	0.06
Miscellaneous items (M_m) as % of its cost	0.1
Salvage value factors	
Basin section (S_b) as % of its cost	0.35
Distillation section (S_d) as % of its cost	0.54 - 0.58
Miscellaneous items (S_m) as % of its cost	0.16 - 0.21
Other cost factors	
Labor as % of its material cost	0.15
Overhead as % of its material cost	0.20
Net rate of interest, i	0.16, 0.12
Life of system in years, N	10, 25

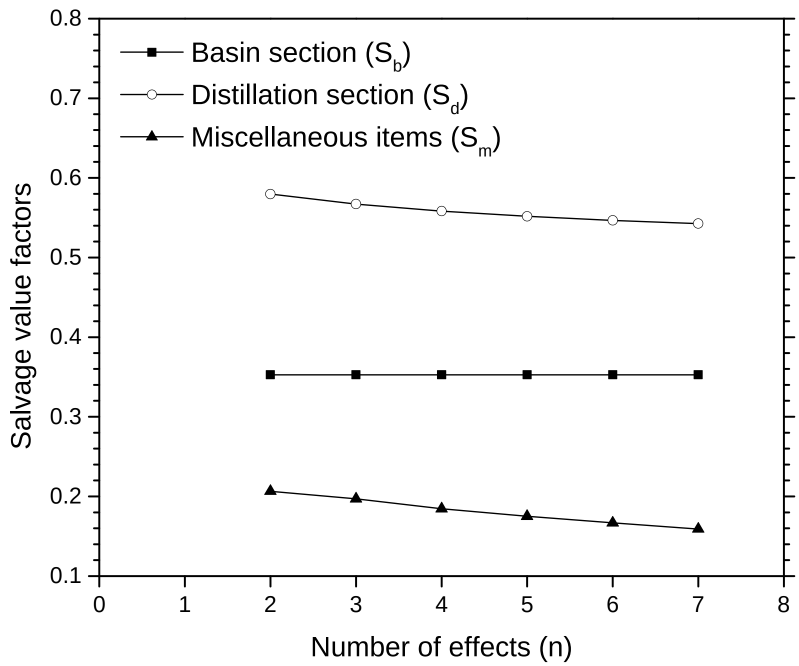


Fig. 5.1 Variation of salvage value factors with number of effects for the FW-BVMED-HR solar still

Capital recovery factor (f_c) used in Eq. (5.3) is calculated as:

$$f_c = \frac{i \times (1+i)^N}{(1+i)^N - 1} \quad (5.4)$$

where, i is the annual rate of interest and N is the expected life period of still in years.

Sinking fund factor (F) used in Eq. (5.3) is calculated as:

$$F = \frac{i}{(1+i)^N - 1} \quad (5.5)$$

The cost of generating a kg of water, C_u, in Rs./kg is given by,

$$C_u = \frac{C_T}{D} \quad (5.6)$$

Payback period has been calculated by using the following expression given in Kumar and Tiwari [117],

$$n_p = \frac{\ln\left(\frac{CF}{CF - i \times C_{ts}}\right)}{\ln(1+i)} \quad (5.7)$$

where, CF is the annual cash flow from sale of distilled water, which is calculated as:

CF = (total annual distillate output in kg) $\times$ (selling price of distillate in Rs./kg)

and C_{ts} is the total capital cost per unit glass area of the FW-BVMED-HR still, which is given by,

$$C_{ts} = C_b + C_d + C_m \quad (5.8)$$

5.2 Results and discussion

The framework of the present still is of mild steel which has been painted with ordinary white paint for protection against corrosion. With annual repainting, this still has expected life cycle of 10 years. With heat resistant powder coating on the mild steel frame, and regular maintenance, its life expectancy can go up to 25 – 30 years. Therefore, in the economic analysis of the present study, the expected life cycle of the still has been taken as 10 and 25 years. The economic analysis based on the life cycle costing of the system has been carried out with interest rate of 0.16 which is the approximate rate of interest on capital, presently in the Indian market. Many government agencies in India offer interest subsidy to promote use of renewable sources of energy. Hence cost analysis has also been done at another rate of interest 0.12, to see the effect of interest rate on unit cost of distillate and annual cost of operation of the still.

Fig. 5.2 shows the capital costs of basin section (C_b), distillation section (C_d), miscellaneous items (C_m) and total capital cost (C_{ts}), with increasing number of effects n. The capital costs include material, labor and overhead costs. As can be seen from Fig. 5.2, C_b remains constant while C_d, C_m, and C_{ts} increase as n increases, from 2 to 7. The total capital cost (C_{ts}) per unit glass area, of the 2 effect FW-BVMED-HR still is Rs. 30,293 which increases to Rs. 41,905 for the 7 effect still. Fig. 5.3 shows the average daily distillate output (P_i) for each month, at various number of effects, for FW-BVMED-HR still. The average daily distillate output (P_i) of the i^{th} month is computed by using Eq. 5.1, at monthly average total solar insolation and monthly average ambient temperature of the i^{th} month, for the experimental site location. The number of clear days in each month (M_i) of a year is also shown in Fig. 5.3. The number of clear days have been taken as found by Kumar and Tiwari [117] from actual experiments, since there location is a nearby station and weather conditions are expected to be the same as for the present still location. The number of clear days in i^{th} month along with Eq. 5.2 is used to compute annual distillate output (D) which is shown in Fig. 5.4. Fig. 5.4 shows that the annual distillate output of the FW-BVMED-HR still increases as n increases from 2 to 7. The annual distillate output of 2 effect FW-BVMED-HR still is 1031 kg/m^2 which increases to 1704 kg/m^2 for the 7 effect still. The total annual cost (C_T) of FW-BVMED-HR still increases almost linearly with number of effects for life cycles of 10 and 25 years, at i = 0.16, as seen from Fig. 5.5. The curve for C_T, of 25 year life cycle, lies below the curve for 10 year life cycle, at i = 0.16. It is so, predominantly due to the lower value of capital recovery factor (f_c) of 0.16 at life cycle of 25 years as compared to capital recovery factor (f_c) of 0.21 at life cycle of 10 years. If the interest rate is reduced from 0.16 to 0.12 due to subsidy from government agencies, the total annual cost (C_T) at life cycle of 25 year further goes down as shown in Fig. 5.5. It is again due to decrease in f_c with decrease in interest rate. Another cost iteration for reducing C_T was considered. It is a realistic assumption that when the raw material and miscellaneous items needed for mass production of FW-BVMED-HR still will be procured in bulk quantities, the prices will be at least 10% cheaper than the costs taken in present calculation of costing of FW-BVMED-HR still. Hence we calculated C_T for capital cost of components at price discount (C_{dt}) = 10% on previous capital costs, at i = 0.12 and N = 25 years. It can be seen from Fig. 5.5 that total annual cost goes further down with this assumption of price discount of 10% on cost of components.

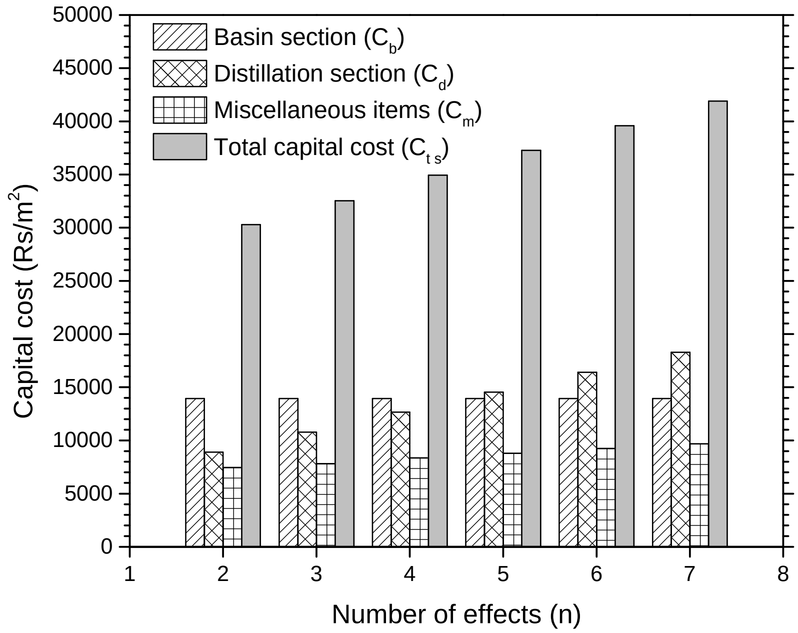


Fig. 5.2 Capital cost variation with number of effects, for components of FW-BVMED-HR solar still

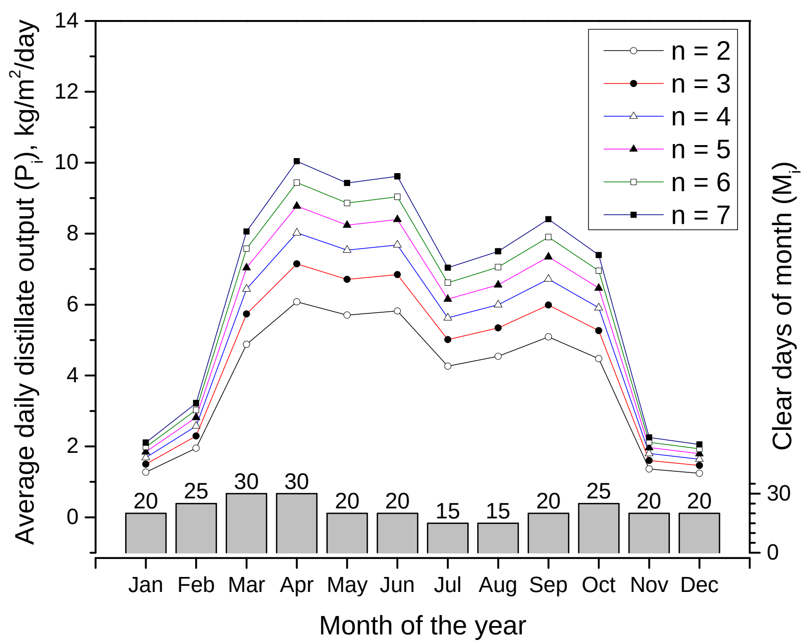


Fig. 5.3 Average daily distillate output in each month at various number of effects and month-wise number of clear days in a year

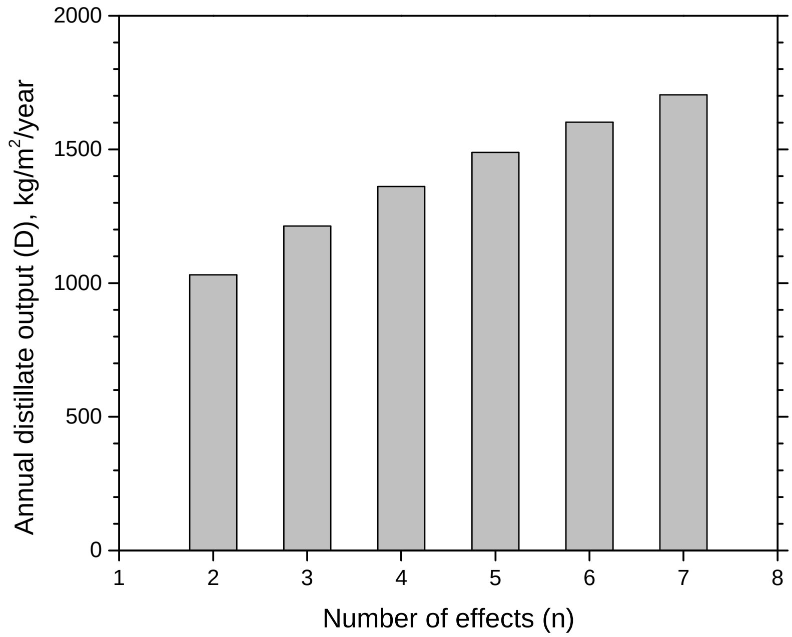


Fig. 5.4 Variation of annual distillate output with number of effects for the FW-BVMED-HR solar still

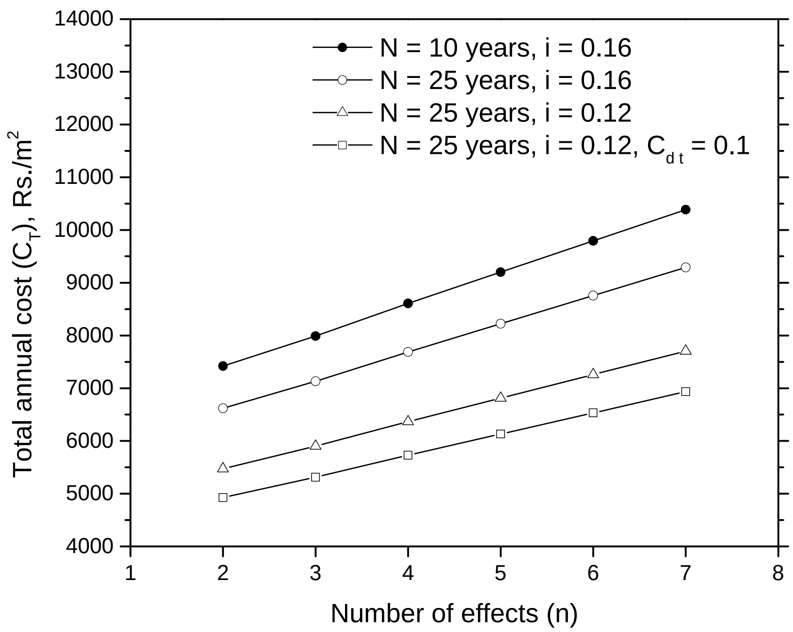


Fig. 5.5 Variation of total annual cost with number of effects, for the FW-BVMED-HR solar still

The unit cost of distillate (C_u) as calculated from Eqs. (5.1) – (5.6), with increasing number of effects is shown in Fig. 5.6. The C_u for 2 effect FW-BVMED-HR still is Rs. 7.20/kg which reduces to Rs. 6.10/kg for the 7 effect still, when N = 10 years and i = 0.16. The C_u for 2 effect FW-BVMED-HR still is Rs. 6.42/kg which reduces to Rs. 5.45/kg for the 7 effect still, when N = 25 years and i = 0.16. As seen from Fig. 5.6, the C_u curve for N = 25 years, i = 0.16 is considerably below the curve for N = 10 years and i = 0.16. This is due to lower C_T values at N = 25 years as shown in Fig. 5.5. However, it is seen that initially there is a sharp decrease in the C_u with the addition of an effect which becomes gradual when n approaches 7, for both life cycles. This is due to the fact that the increase in distillate gain becomes smaller in magnitude with each additional effect from n = 2 to n = 7, as can be observed from Fig. 5.4.

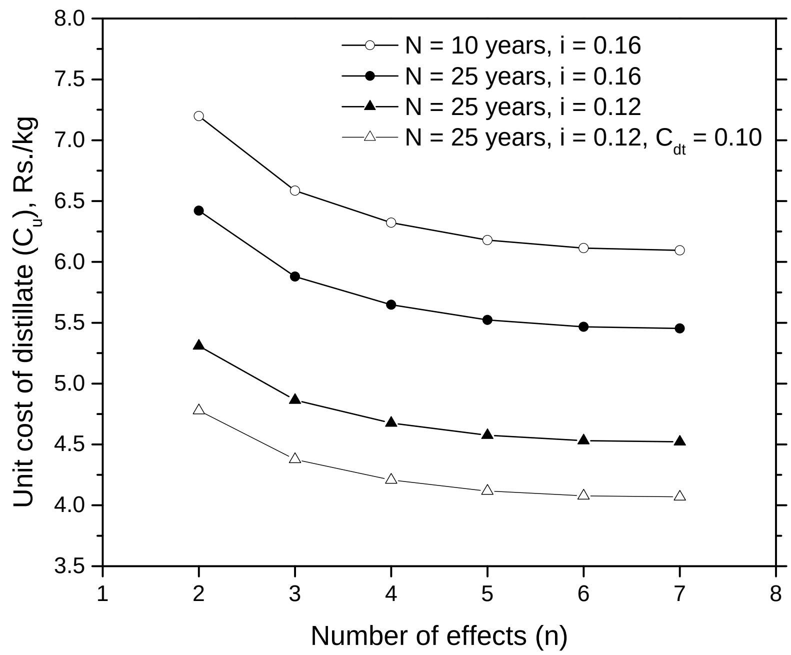


Fig. 5.6 Variation of unit cost of distillate with number of effects for the FW-BVMED-HR solar still

We also calculated C_u at subsidized rate of interest, i.e., i = 0.12, at N = 25 years, to see the effect of interest rate on unit cost of distillate. The C_u at i = 0.12 and N = 25 years, for 2 effect FW-BVMED-HR still, is Rs. 5.31/kg, which reduces to Rs. 4.52/kg for the 7 effect still. As seen from Fig. 5.6 the curve for C_u at i = 0.12 and N = 25 years is considerably below the curve for i = 0.16 and N = 25 years. This is due to the lower value of C_T resulting from reduced f_c = 0.13 at i = 0.12, down from f_c = 0.16 at i = 0.16. The unit cost of distillate (C_u) was also computed at price discount (C_{dt}) of 10%, at N = 25 years and i = 0.12. From Fig. 5.6 it can be seen that C_u for 2 effect FW-BVMED-HR still is Rs. 4.78/kg which reduces to Rs. 4.07/kg for the 7 effect still, when price discount of 10% is considered at N = 25 years and i = 0.12. Payback period n_p as calculated from Eq. (5.7) for i = 0.16, i = 0.12; i = 0.12 and price discount C_{dt} = 10%, is found to be 3.4 years, 3.1 years and 2.7 years respectively, assuming a selling price S_p of distillate at Rs. 10/kg.

Another calculation for unit cost of distillate of 7 effect FW-BVMED-HR still at i = 0.12 and N = 30 years was made, to have valid comparison with unit cost of distillate of single slope basin still at i = 0.12 and N = 30 years, computed by Kumar and Tiwari [117]. This comparison is shown in Table 5.3. As can be seen from Table 5.3, the unit cost of distillate produced from 7 effect FW-BVMED-HR still at N = 30 years is higher than the unit cost of distillate produced from single slope basin still. However, the unit cost of distillate produced from FW-BVMED-HR still can be further reduced with addition of more effects and when the still is produced on mass scale. Moreover, there is an appreciable price increase in all items since the reported work on single slope basin still of Kumar and Tiwari [117], which is another reason of higher C_u for present FW-BVMED-HR still. Table 5.3 also shows the comparison of specific energy consumption of 7 effect FW-BVMED-HR still with single slope basin still. It can be observed that specific energy consumption of both 2 effect and 7 effect FW-BVMED-HR still is far less than the single slope basin still, which suggests that 7 effect FW-BVMED-HR still consumes far less energy to produce same amount of distillate as compared to single slope basin type still.

Table 5.3 Comparison of cost of distillate, productivity and specific energy consumption

Description of still	i	N (years)	Cost (Rs/kg)	Total annual average distillate (kg/m^2)	Specific energy consumption (kWh/kg)
FW-BVMED-HR (2 effect)	0.12	25	5.31	1031	0.973
FW-BVMED-HR (7 effect)	0.12	30	4.47	1704	0.531
Single slope basin still [117]	0.12	30	3.42	298	2.64*

*Estimated for month of April for daily solar radiation of 19 MJ/m^2/day on glass cover

The following conclusions can be drawn from the economic analysis of FW-BVMED-HR still:

— The minimum unit cost of distillate for the FW-BVMED-HR solar still is estimated to be Rs. 4.07/kg, for the 7 effect still, for life cycle of 25 years, interest rate of 0.12, and at price discount of 10% on capital cost for mass production of still.

— Although the capital cost and annual cost of the FW-BVMED-HR solar still increase almost linearly with the addition of effects, the unit cost of distillate decreases due to relatively higher increase of annual distillate output.

— At large number of effects, the reduction in unit cost of distillate with further addition of an effect diminishes. It happens because the distillate gain becomes smaller in magnitude with the addition of each effect and hence addition of an effect beyond a reasonable number does not contribute much in reducing the unit cost of distillate.

— The unit cost of distillate reduces significantly with decrease in interest rate and/or increase in life cycle of the still, due to reduction in total annual cost resulting from reduced value of capital recovery factor.

— The FW-BVMED-HR still is found to be economically viable with low payback period.

Chapter 6

Conclusions

This chapter summarizes the conclusions drawn from the present experimental investigation on basin still, basin type vertical single distillation cell (VSDC) solar still, four effect basin type vertical multiple effect diffusion solar still with waste heat recovery (BVMED-HR), and four effect floating wick basin type VMED solar still with waste heat recovery (FW-BVMED-HR). The key conclusions of experimental parametric study of FW-BVMED-HR still and economic analysis of FW-BVMED-HR still, for number of effects varying from 2-7, are also summarized.

6.1 BASIN STILL AND BASIN TYPE VERTICAL SINGLE DISTILLATION CELL (VSDC) SOLAR STILL

The following conclusions have been drawn from the experiments done on the basin still and basin type vertical single distillation cell (VSDC) solar still:

- Significant improvement in the efficiency of a basin still was obtained by converting it into an improved basin type VSDC solar still of same basin and glass cover area.
- The new wick surface arrangement, in which the whole wick area was divided into six partitions in case of improved basin type VSDC solar still, and individual feed water given to each area, worked effectively, in increasing the wick wetted area and hence evaporation efficiency of the wick surface, which is confirmed by the temperature distribution of the partition plates. The effective wick evaporation area was only 77% of the plate area, yet the performance of the improved basin type VSDC solar still was comparable with previously reported results by other researchers due to better soaking, high evaporation efficiency and high rate of temperature equalization within the copper plate.
- The water feeding mechanism to wicks was changed to gravity feeding, as against the capillary action feed mechanism by Tanaka et al. [18]. Longitudinal rubber spacers were used to separate the 0.3 mm thick stainless steel partition plates. By use of this arrangement no cross flow of saline feed water was observed, as confirmed by the water quality tests. By placing the feed water channels inside the sealed borders of plate, vapor loss and convection heat loss by escaping hot air and vapor mixture was also possibly reduced.

- The use of third external partition plate without evaporative cooling at a gap of 25 mm from the second partition plate, proved effective in maintaining the average temperature drop from first partition plate to second partition plate up to 8 °C. On an average the temperature of the second partition plate stayed above the ambient temperature by 10 °C. This resulted in consistently high distillate outputs from the second partition plate. Due to the shielding by the third external plate, not only the effect of wind velocity fluctuations on the convective heat transfer and evaporation from the second partition plate was minimized but also the blowing away of wicks from the plate surface was prevented.
- The feed water flow rates have to be decided by matching with the expected solar radiation for the day, based on monthly average solar radiation obtained from previous year's data, once a performance chart of the still is available. At a constant feed water flow rate of 0.12 $g/m^2/s$ the distillate productivity showed a rise with rise of solar radiation. The improved basin type VSDC solar still worked satisfactorily on partially cloudy days also, thereby indicating that it utilized the diffuse component of solar radiation effectively.

6.2 BASIN TYPE VERTICAL MULTIPLE EFFECT DIFFUSION SOLAR STILL WITH HEAT RECOVERY FROM WASTE FEED WATER (BVMED-HR)

The following conclusions have been drawn from the experiments done on the four effect basin type vertical multiple effect diffusion solar still with heat recovery from waste feed water (BVMED-HR):

- The pre-heating of feed water by recovering heat energy from waste feed water results in an appreciable increase in the cumulative efficiency and productivity of the BVMED-HR still. It was found that there was a rise up to 8% in cumulative efficiency and 10.6% in the distillate productivity for the BVMED-HR still over the reference still.
- The heat exchanger used to recover waste heat was simple in design and compact in size. Moreover it was made of inexpensive materials. Therefore, the incorporation of heat recovery heat exchanger has led to hardly any cost addition in the total cost of the BVMED-HR still.
- An empirical correlation has been proposed to predict the productivity of BVMED-HR solar still. The correlation predicts the productivity very well with mean deviation of 4% from the experimental values. Since the correlation has been developed by considering all possible parameters which affect the productivity of the still, therefore this correlation can be used to predict the productivity of a similar type of VMED still with good accuracy in any part of the world.

6.3 FLOATING WICK BASIN TYPE VERTICAL MULTIPLE EFFECT DIFFUSION SOLAR STILL WITH WASTE HEAT RECOVERY (FW-BVMED-HR)

The following conclusions have been drawn from the experiments done on the four effect floating wick basin type vertical multiple effect diffusion solar still with heat recovery from waste feed water (FW-BVMED-HR) :

- The FW-BVMED-HR still performed significantly better than the reference still. Its productivity was 21% higher than the reference still. The rise of productivity in FW-BVMED-HR still over the reference still, was due to contribution of both, float wick, and feed water pre-heating from heat recovery.
- It was observed that floating wick attained high temperature very quickly owing to low thermal inertia of float wick surface. Hence, it is expected that the FW-BVMED-HR still can provide reasonable distillate even on low insolation days.
- The higher temperature of first partition plate, due to the higher heat transfer from the high temperature float wick surface, as well as the pre-heated feed water from heat recovery, in case of FW-BVMED-HR still, increased the evaporation heat flux from the first partition plate towards the second partition plate and external environment through partition plates.
- Distillates from glass cover and first partition plate in the FW-BVMED-HR still, maintained lead over the corresponding components of reference still, in the first part of the day, on 13th October, 2016, after which they lagged behind. It happened because the float wick has low thermal inertia and hence its temperature stayed above the basin water of reference still in the first part of day. However, in the second half of the day, the float wick had lower temperature corresponding to falling solar radiation, as compared to basin water of reference still due to energy stored by it.
- The total distillate productivity on second partition plate, was higher for FW-BVMED-HR still than reference still, on all experimental days, indicating its higher heat transfer towards the partition plate section than for the reference still.
- The night distillate of FW-BVMED-HR still at 1.34 kg/m^2 was significantly higher than for the reference still at 0.98 kg/m^2, at a basin water depth of 2 cm, on 13th October, 2016. This is due to the extra heat stored in floating wick and reduced radiative and convective heat losses due to presence of float covers on the basin water.

- The present design of float worked very well for over a year without any maintenance problem. The simple tube-in-tube type of counter flow heat exchanger also worked successfully to pre-heat feed water by recovering heat from hot waste feed water. Both these modifications had very less cost addition to the total cost of FW-BVMED-HR still, when measured against the gains in distillate productivity resulting from them.

6.4 EXPERIMENTAL PARAMETRIC STUDY OF FW-BVMED-HR STILL

The following conclusions have been drawn from experimental parametric study of FW-BVMED-HR still:

- The optimum feed water rate for the four effect FW-BVMED-HR still was found to be 0.27 g/m^2/s, when the total solar radiation lies in the range of 21-23 MJ/m^2/day.
- Beyond an optimum feed water rate, the cumulative efficiency decreases with increase of feed water rate. The cumulative efficiency decreases with increase in partition plate gap and basin water depth. The cumulative efficiency increases with increase of number of effects. These trends obtained from experimental results of FW-BVMED-HR still, are broadly in agreement with the numerically simulated and experimental results obtained by previous researchers.
- The effect of basin water depth on cumulative efficiency was found to be low. That means FW-BVMED-HR still can be effectively used with high basin water depth, which reduces the frequency of refilling the still.
- The cumulative efficiency showed a maximum rise of 58% when the number of effects were increased from 2 to 7, at constant feed rate of 0.27 g/m^2/s. Since the cost of adding an effect, which consists of a thin plate and wick cloth, is a small fraction of the total cost of FW-BVMED-HR still, the multi-effect stills with reasonable number of effects can significantly reduce the generation cost of per liter of distilled water.
- The data analysis of experimental results of FW-BVMED-HR still showed that the night productivity has almost linear dependence on day productivity.
- The productivity correlation has been developed by considering all possible parameters which affect the productivity of the FW-BVMED-HR still. Hence this correlation can be used to estimate the productivity with fair degree of accuracy, within the investigated range of parameters, to carry out techno-commercial feasibility studies before installation of similar type of solar distillation unit in any part of the world.

6.5 ECONOMIC ANALYSIS OF FW-BVMED-HR STILL

The following conclusions have been drawn from life cycle cost analysis of FW-BVMED-HR still:

- The minimum unit cost of distillate for the FW-BVMED-HR solar still is estimated to be Rs. 4.07/kg, for the 7 effect still, for life cycle of 25 years, interest rate of 0.12, and at price discount of 10% on capital cost for mass production of still.
- Although the capital cost and annual cost of the FW-BVMED-HR solar still increase almost linearly with the addition of effects, the unit cost of distillate decreases due to relatively higher increase of annual distillate output.
- At large number of effects, the reduction in unit cost of distillate with further addition of an effect diminishes. It happens because the distillate gain becomes smaller in magnitude with the addition of each effect and hence addition of an effect beyond a reasonable number does not contribute much in reducing the unit cost of distillate.
- The unit cost of distillate reduces significantly with decrease in interest rate and/or increase in life cycle of the still, due to reduction in total annual cost resulting from reduced value of capital recovery factor.
- The FW-BVMED-HR still is found to be economically viable with very low payback period.

6.6 SCOPE FOR FUTURE WORK

Following are the recommendations for future work:

- In the present work, the experiments were conducted on the FW-BVMED-HR still with maximum of 7 effects. Previous researchers have used 11 or more effects to increase the productivity of VMED stills. Future work on FW-BVMED-HR still can be done with number of effects greater than 7 used in present work, in order to determine optimum number of effects on the basis of minimum unit cost of distillate.
- The present work was done with 10 mm partition plate gap. It is an established fact that reducing the partition plate gap enhances the distillate output. Previous researchers have used partition plate gap of 5 mm. Hence further work on FW-BVMED-HR still can be done with 5 mm partition plate gap along with number of effects greater than 7 used in present work.

- In floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery, the basin side of first partition plate receives direct solar radiation, as well as reflected solar radiation from side internal surfaces of basin section. We have used black paint for black coloring of basin side of first partition plate. Since selective coating increases the solar radiation absorption, it must be used on the first partition plate, for future research, to enhance the distillate productivity.
- Since heat storage in basin enhances the night distillate output, heat storage medium like PCM (phase change materials), pebbles and sand may be added to basin water, to increase the night distillate output.
- In the present research work on FW-BVMED-HR solar still, recovery of waste heat to pre-heat the feed water, was done only from waste feed water and not from the hot distillate. However, in future work, by suitable design changes in the distillate outlets of all sources, for purpose of heat recovery, the pre-heating temperature of feed water can be increased, by waste heat recovery from waste feed water as well as hot distillate. The increased heat recovery will lead to increased distillate output and cumulative efficiency.
- An up scaled distillation plant based on the developed technology, of 500 kg to 5000 kg per day capacity, must be made, to test the commercial and technical viability for large scale plants.

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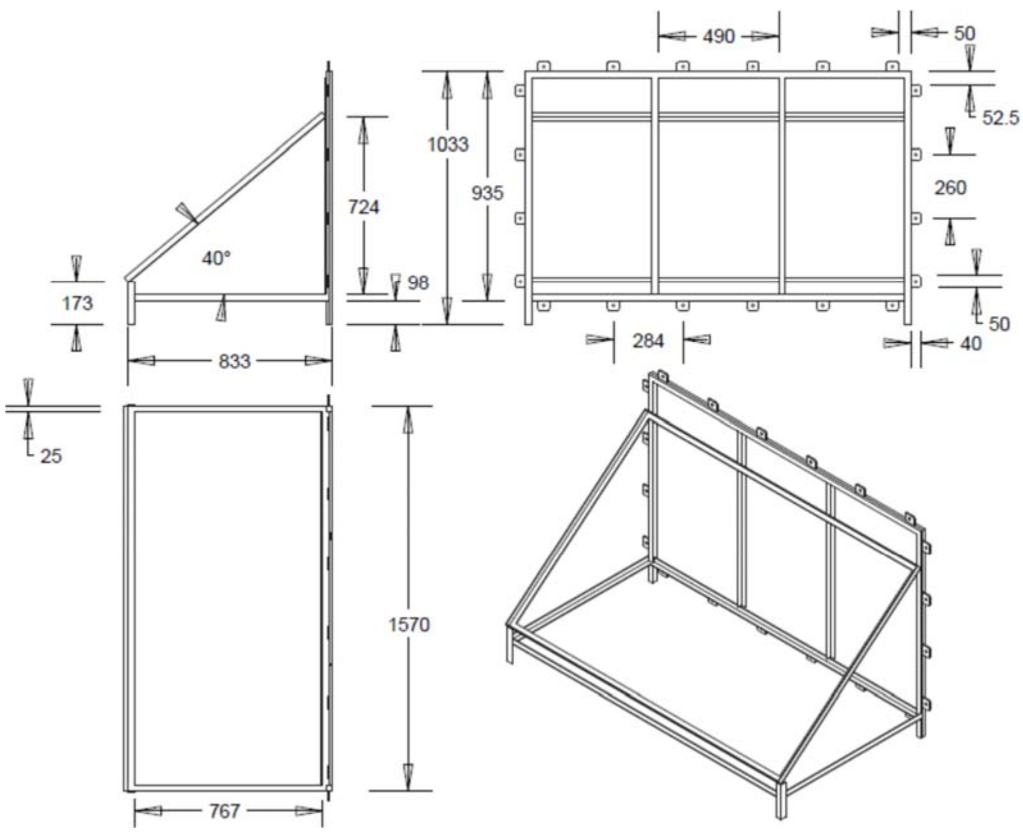
Appendix - A

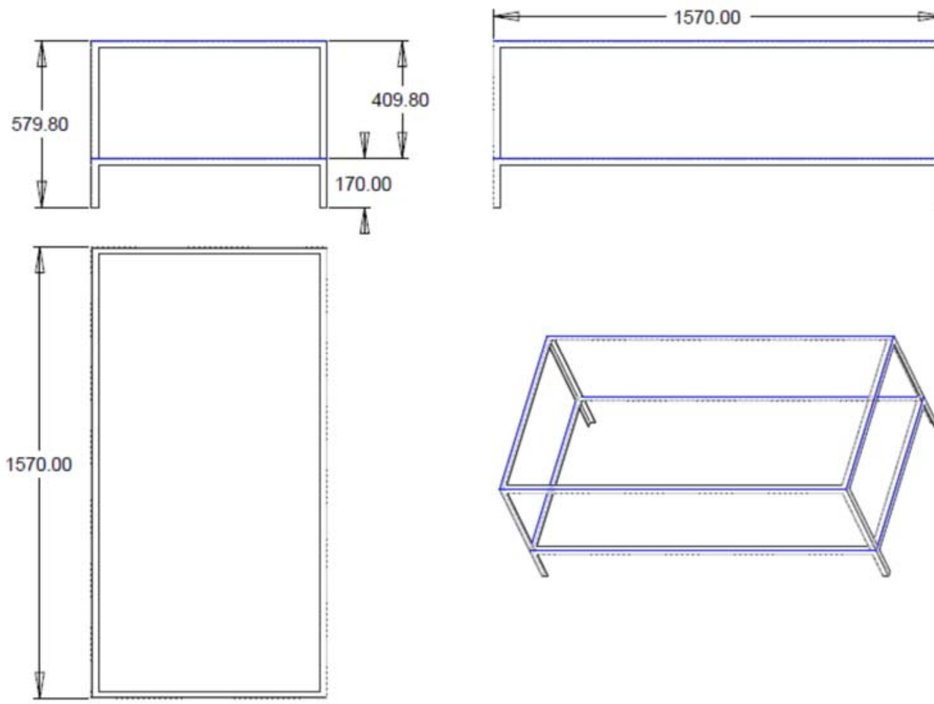
DEVELOPMENT DRAWINGS, DIMENSIONS AND FABRICATION OF FW-BVMED-HR STILL

A 1 DEVELOPMENT DRAWINGS (All dimensions in mm)

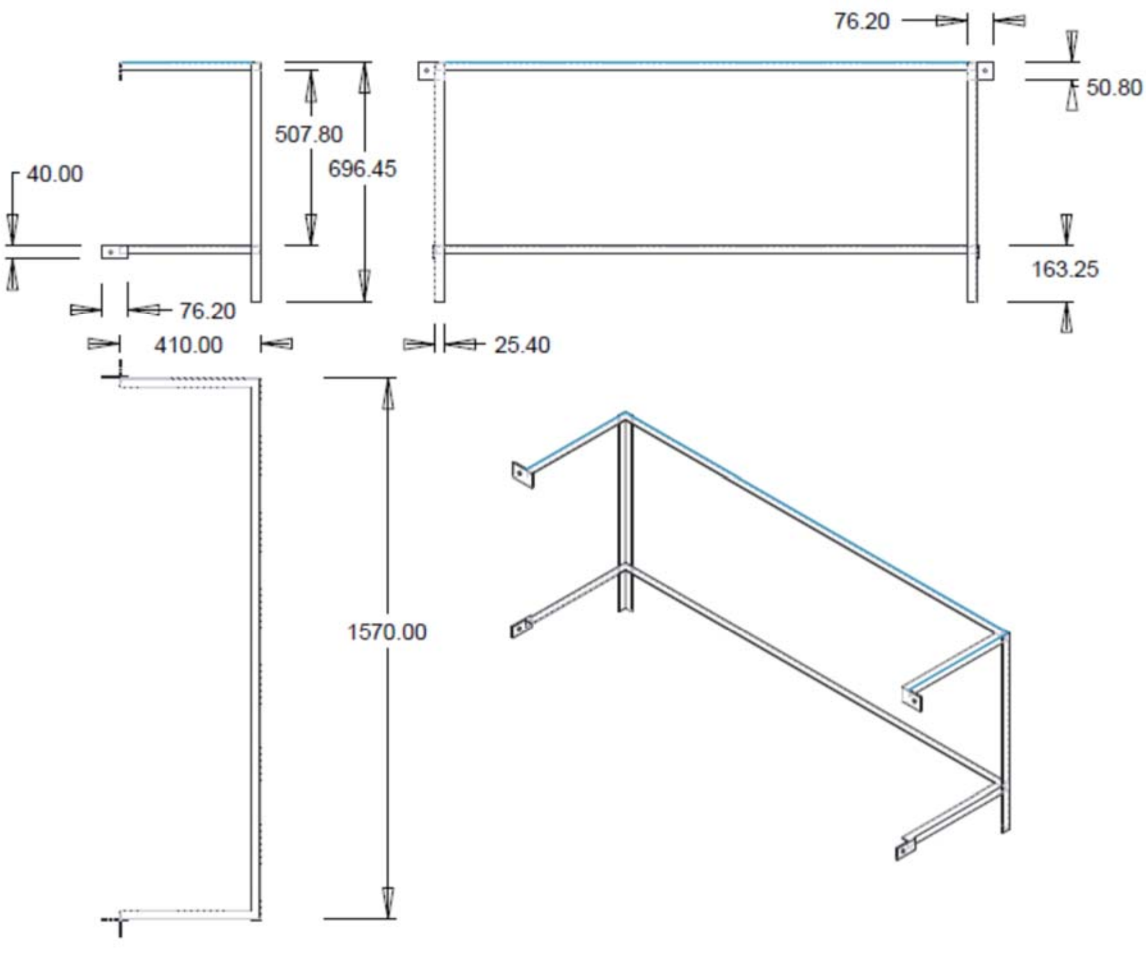
A 1.1 DESIGN DETAILS OF BASIN FRAME



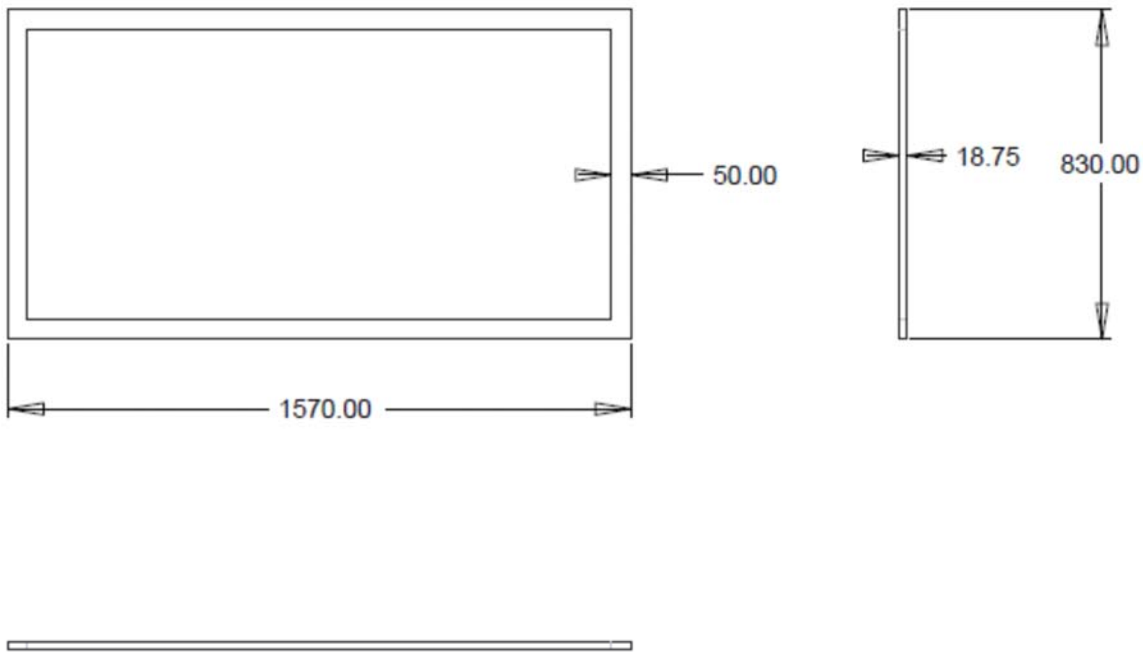
A 1.2 BASIN FRAME BOTTOM SUPPORT



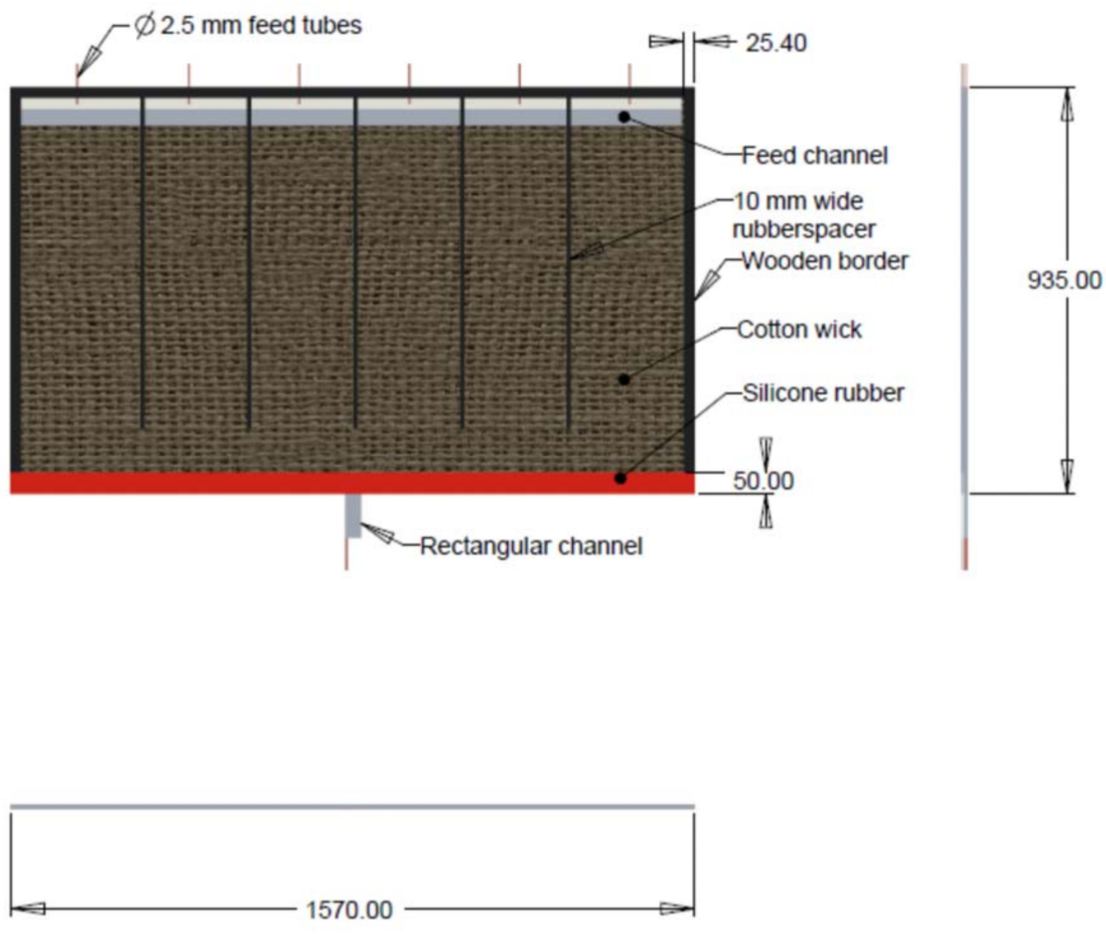
A 1.3 BASIN FRAME BACK SUPPORT



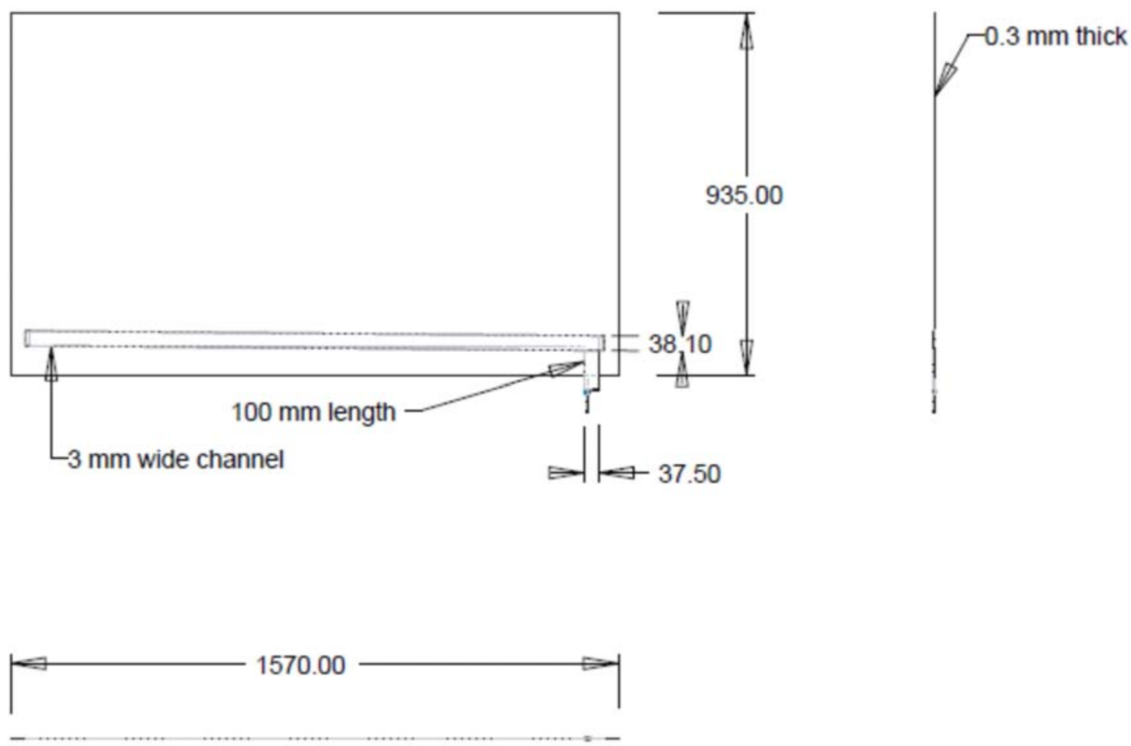
A 1.4 BASIN FRAME BOTTOM WOODEN ISOLATOR



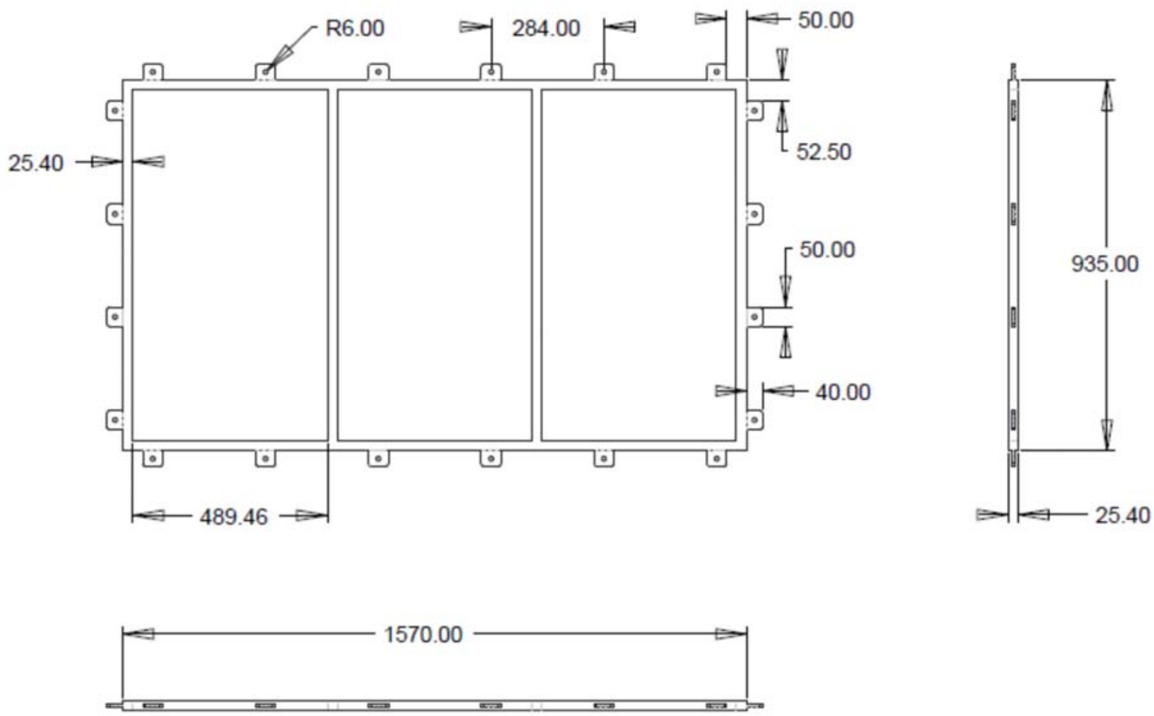
A 1.5 EVAPORATING SIDE OF PARTITION PLATE



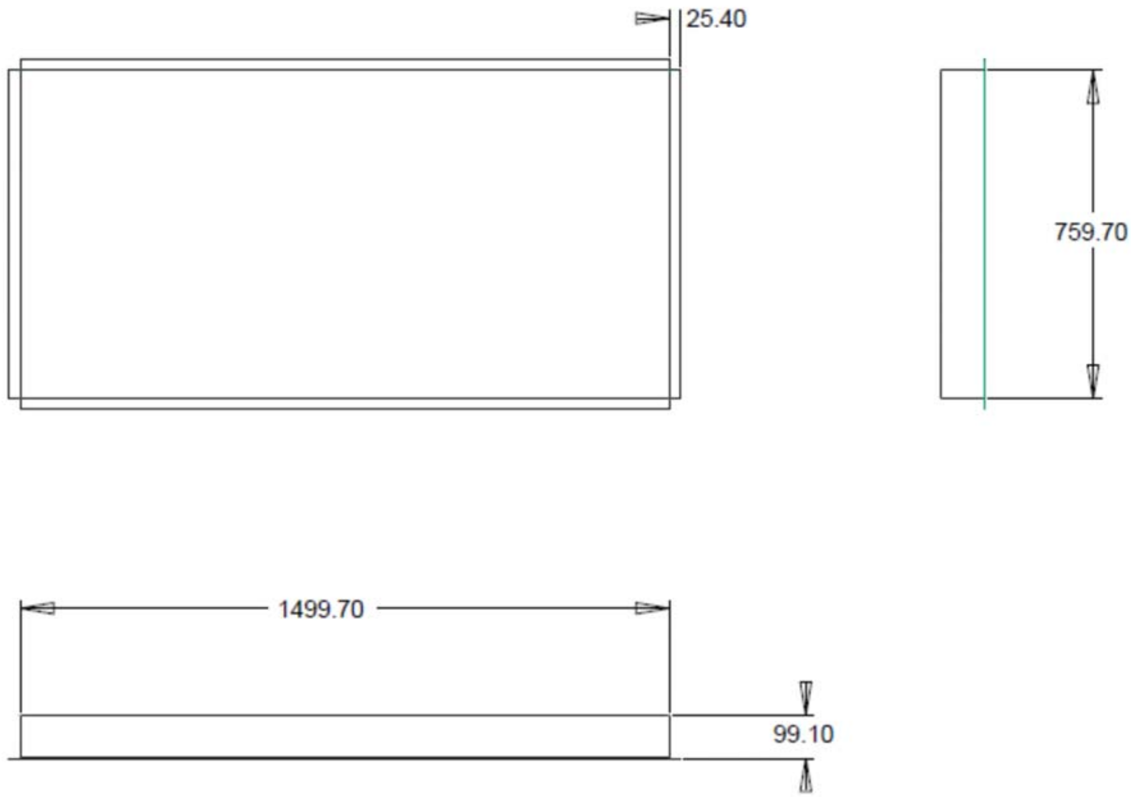
A 1.6 CONDENSING SIDE OF PARTITION PLATE



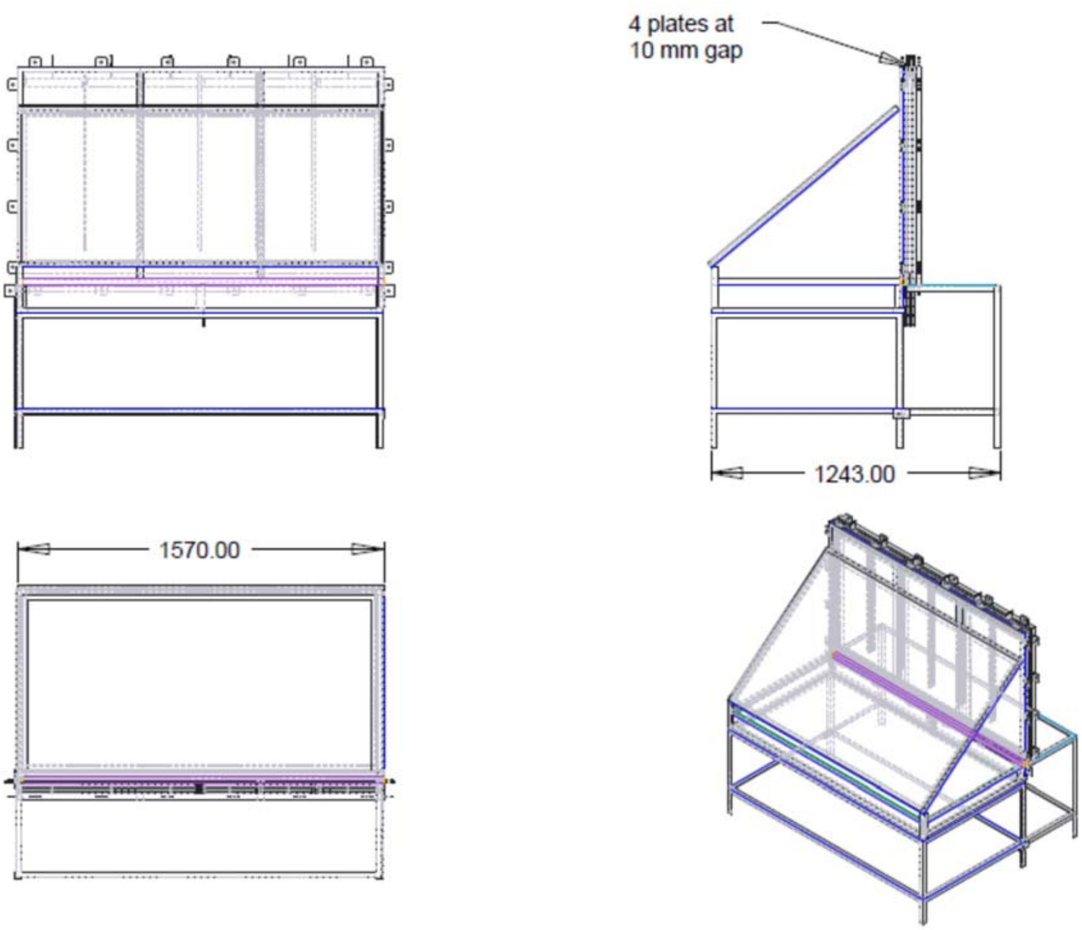
A 1.7 PARTITION PLATE TIGHTENING FRAME



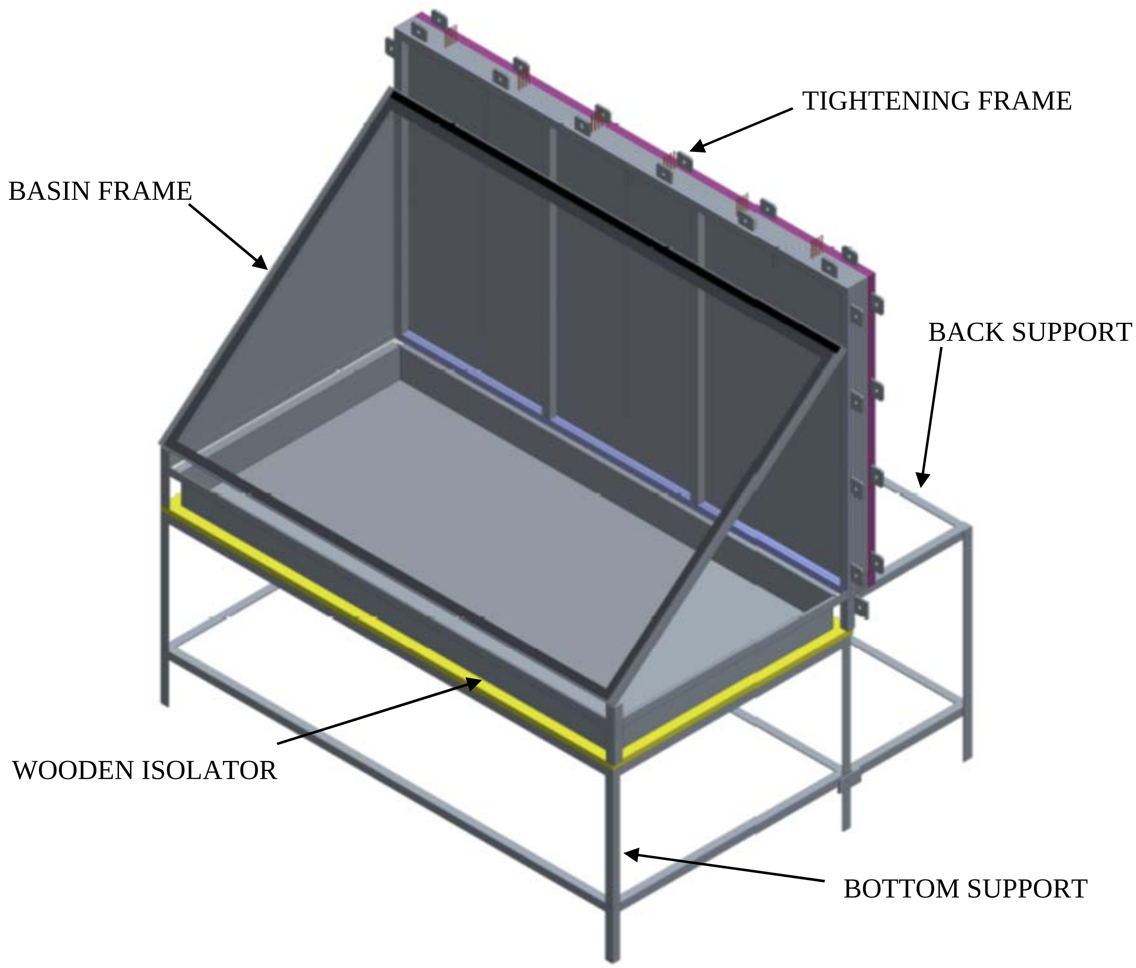
A 1.8 BASIN TRAY



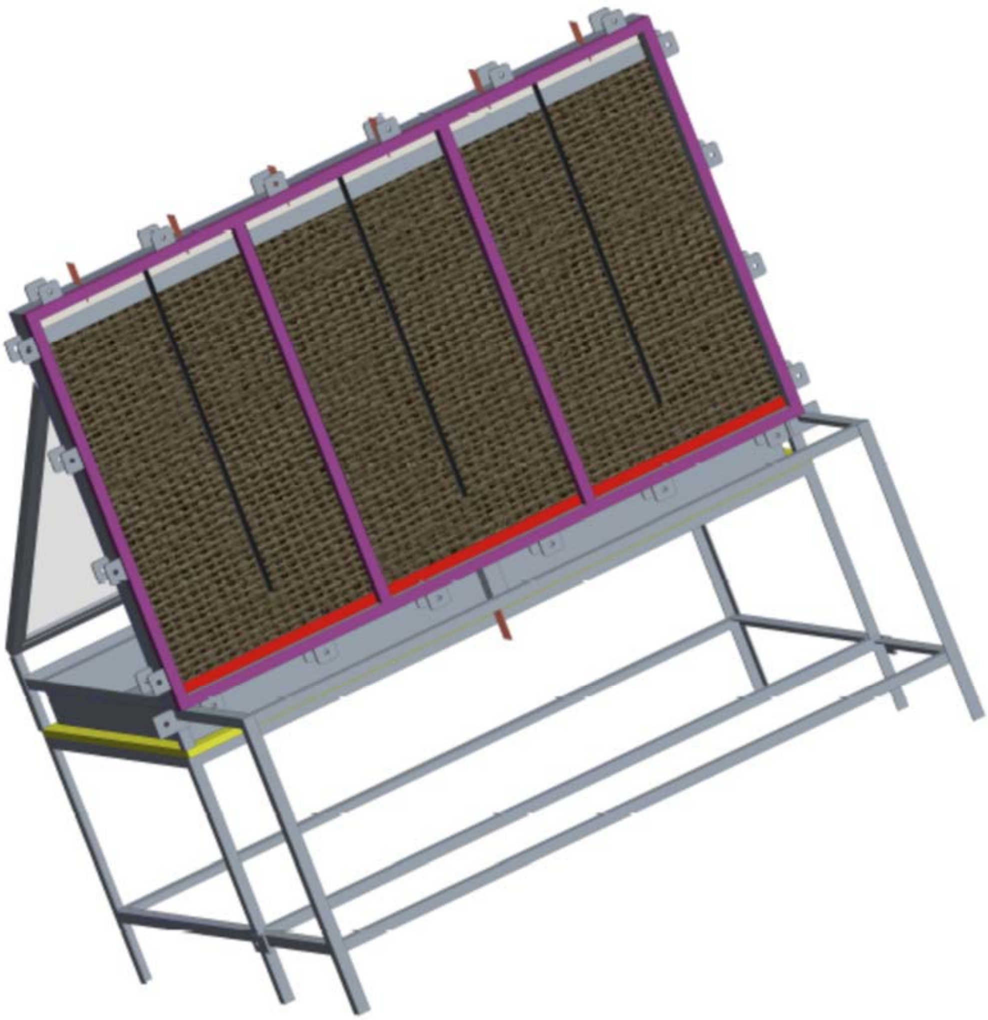
A 1.9 ASSEMBLED VIEW OF FW-BVMED-HR STILL



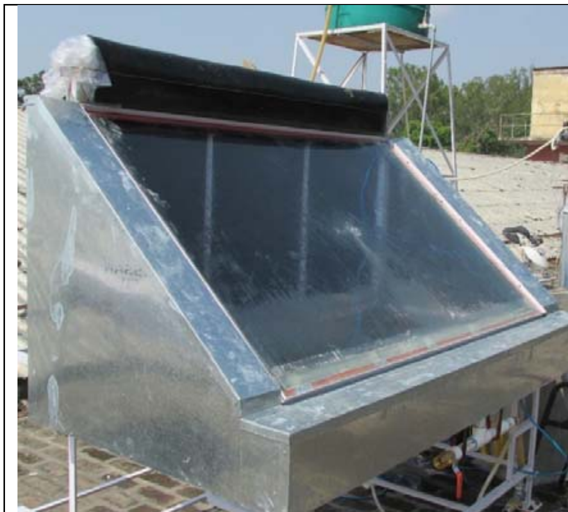
A 1.10 ASSEMBLED BASIN SIDE VIEW OF FW-BVMED-HR STILL



A 1.11 ASSEMBLED REARVIEW OF FW-BVMED-HR STILL



A 2 FABRICATION STAGES OF FW-BVMED-HR STILL

	
FW-BVMED-HR STILL	**REFERENCE STILL**

FW-BVMED-HR AND REFERENCE STILLS SIDE BY SIDE

EXPERIMENTAL DATA

Table B.1 Experimental data of basin still

Date	d (cm)	G_T MJ/m²/day	T_a °C	P (kg/m²/day) Basin still	
				Total	Night
2/07/2015	1	17.855	37.4	2.265	0.299
3/07/2015	1	16.382	39.5	2.497	0.328

Table B.2 Experimental data of basin type VSDC still

Date	n	δ_p (mm)	d (cm)	f g/m²/s	G_T MJ/m²/day	T_a °C	P (kg/m²/day) VSDC	
							Total	Night
18/08/2015	2	10	1	0.12	13.469	34.0	2.799	0.200
21/08/2015	2	10	1	0.10	15.762	35.0	3.034	0.492
24/08/2015	2	10	1	0.17	18.027	34.0	3.998	0.268
25/08/2015	2	10	1	0.12	17.506	33.5	3.728	0.254
26/08/2015	2	10	1	0.12	16.218	34.5	3.472	0.268
28/08/2015	2	10	1	0.11	14.469	34.5	3.605	0.578
31/08/2015	2	10	1	0.10	17.831	34.5	3.828	0.302
1/9/2015	2	10	1	0.09	15.463	35.0	3.310	0.311

Date	n	δ_p (mm)	d (cm)	f g/m²/s	G_T MJ/m²/day	T_a °C	P (kg/m²/day) VSDC Total	Night
2/9/2015	2	10	1	0.23	17.003	34.0	3.655	0.279
3/9/2015	2	10	1	0.22	17.882	34.5	4.121	0.483
8/9/2015	2	10	1	0.32	17.684	36.5	3.549	0.337
9/9/2015	2	10	1	0.44	19.664	37.0	4.138	0.321
10/9/2015	2	10	1	0.38	19.664	38.0	4.282	0.341
11/9/2015	2	10	1	0.48	19.306	37.0	4.138	0.331
14/9/2015	2	10	1	0.47	15.385	37.5	2.733	0.247

Table B.3 Experimental data of BVMED-HR still

Date	n	δ_p (mm)	d (cm)	f g/m²/s	T_f °C	G_T MJ/m²/day	T_a °C	P (kg/m²/day) BVMED-HR		Reference	
								Total	Night	Total	Night
28/3/2016	4	10	1	0.55	36.4	22.968	31.7	7.148	1.133	6.752	1.115
29/3/2016	4	10	1	0.45	36.2	21.140	31.3	5.660	1.116	5.617	0.858
30/3/2016	4	10	1	0.34	39.0	23.431	35.1	7.510	1.209	7.503	0.862
31/3/2016	4	10	1	0.24	39.7	21.234	35.6	6.249	1.450	6.698	0.884
1/4/2016	4	10	1	0.21	38.1	20.998	34.7	6.841	1.222	6.561	0.840
6/4/2016	4	10	1	0.21	36.4	16.786	33.9	4.712	1.027	4.185	0.876
7/4/2016	4	10	1	0.27	39.7	19.292	34.5	6.437	1.174	6.176	1.068

Date	n	δ_p (mm)	d (cm)	f g/m^2/s	T_f °C	G_T MJ/m^2/day	T_a °C	P (kg/m^2/day)			
								BVMED-HR		Reference	
								Total	Night	Total	Night
8/4/2016	4	10	1	0.34	39.4	23.536	36.4	8.842	1.404	7.994	1.358
9/4/2016	4	10	1	0.41	38.4	19.871	33.8	6.386	0.860	5.687	0.775
12/4/2016	4	10	1	0.21	37.6	25.009	33.6	7.803	1.461	7.199	1.452

Table B.4 Experimental data of FW-BVMED-HR still

Date	n	δ_p (mm)	d (cm)	f g/m^2/s	T_f °C	G_T MJ/m^2/day	T_a °C	P (kg/m^2/day)			
								FW-BVMED-HR		Reference	
								Total	Night	Total	Night
18/4/2016	4	10	1.5	0.27	45.3	18.518	40.8	8.1172	1.5267	7.1317	1.5373
19/4/2016	4	10	1.5	0.34	44.8	16.931	38.8	7.0779	1.3243	6.3126	1.4666
20/4/2016	4	10	1.5	0.41	44.6	22.264	37.1	7.8596	1.4169	7.6127	1.6169
21/4/2016	4	10	1.5	0.48	41.3	22.900	37.6	7.7264	1.0989	7.6324	1.3959
22/4/2016	4	10	2.0	0.27	41.2	18.483	37.7	6.7850	1.2472	5.9777	1.2014
23/4/2016	4	10	2.0	0.21	33.9	24.637	37.0	9.8896	1.7128	8.7833	1.6132
25/4/2016	4	10	2.5	0.21	41.1	21.994	38.8	8.1535	1.3940	7.4945	1.6871
26/4/2016	4	10	2.5	0.27	45.0	21.681	41.4	8.5988	1.5051	8.1371	1.5633
27/4/2016	4	10	3.0	0.27	44.1	22.028	40.6	8.6487	1.5555	7.9140	1.7241
28/4/2016	4	10	3.0	0.21	44.8	22.258	39.3	8.2751	1.5080	7.3864	1.6497
29/4/2016	4	10	1.0	0.21	45.8	22.688	40.5	9.1693	1.2522	8.6071	1.3804

Date	n	δ_p (mm)	d (cm)	f $g/m^2/s$	T_f °C	G_T $MJ/m^2/day$	T_a °C	P ($kg/m^2/day$)			
								FW-BVMED-HR		Reference	
								Total	Night	Total	Night
30/4/2016	4	10	1.0	0.27	46.1	21.708	41.4	8.9709	1.5178	8.3101	1.4671
7/5/2016	5	10	2.0	0.34	42.2	16.261	35.6	7.2802	1.7122	--	--
9/5/2016	5	10	2.0	0.27	41.6	17.684	35.7	8.1265	1.7206	--	--
10/5/2016	6	10	2.0	0.27	42.2	17.388	36.7	8.2743	1.4562	--	--
11/5/2016	6	10	2.0	0.34	41.9	21.146	34.6	8.6490	1.3650	--	--
12/5/2016	7	10	2.0	0.27	45.2	20.644	37.5	9.2223	1.3760	--	--
13/5/2016	7	10	2.0	0.34	48.5	20.461	39.9	9.6397	1.8439	--	--
14/5/2016	7	10	2.0	0.34	45.8	21.542	38.4	10.1240	2.1337	--	--
16/5/2016	7	10	2.0	0.27	46.4	21.786	39.5	11.3958	2.1899	--	--
17/5/2016	7	10	2.0	0.27	44.7	21.900	39.4	11.6289	2.2592	--	--
18/5/2016	3	10	2.0	0.27	48.0	21.088	40.1	8.1291	1.5200	--	--
19/5/2016	3	10	2.0	0.34	49.0	19.910	37.3	7.4596	1.4654	--	--
20/5/2016	2	10	2.0	0.27	44.0	19.695	37.4	5.6186	1.1176	--	--
21/5/2016	2	10	2.0	0.34	43.5	18.698	36.3	5.1217	1.0340	--	--
25/5/2016	4	13	2.0	0.21	42.2	20.068	34.2	6.8514	1.3526	--	--
26/5/2016	4	13	2.0	0.27	41.9	20.606	35.8	8.1163	1.6800	--	--
27/5/2016	4	13	2.0	0.34	43.5	21.648	38.8	8.3071	1.6153	--	--
31/5/2016	4	16	2.0	0.27	42.0	21.174	35.6	6.9953	1.2789	--	--
1/6/2016	4	16	2.0	0.34	43.2	19.836	37.9	7.3967	1.6311	--	--
2/6/2016	4	16	2.0	0.21	43.5	19.595	39.5	7.3986	1.7023	--	--
16/9/2016	4	10	2.0	0.19	38.0	20.870	35.0	6.2262	1.2933	5.2449	1.3137
11/10/2016	4	10	2.0	0.29	35.9	18.980	33.0	5.1441	1.1878	4.3502	1.2125

Date	n	δ_p (mm)	d (cm)	f g/m²/s	T_f °C	G_T MJ/m²/day	T_a °C	P (kg/m²/day)			
								FW-BVMED-HR		Reference	
								Total	Night	Total	Night
12/10/2016	4	10	2.0	0.20	36.1	19.900	33.4	5.8409	1.3548	5.1577	1.2480
13/10/2016	4	10	2.0	0.38	37.3	21.080	33.9	5.8978	1.3411	4.8798	0.9785
14/10/2016	4	10	2.0	0.33	37.5	20.320	33.9	5.6539	1.2982	5.0230	1.1014
17/10/2016	4	10	1.0	0.32	35.7	20.430	32.3	5.4419	1.1378	4.6994	0.5601
19/10/2016	4	10	2.0	0.30	35.2	17.770	33.4	4.9824	1.2358	4.3695	1.0335