Final Report

UGC Sponsored Project (2015-18)

“Development and Demonstration of Passive Solar Regenerator for Liquid Desiccant based Air Conditioning System”

Submitted by

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November 2018

Annexure -VIII
UNIVERSITY GRANTS COMMISSION
BAHADUR SHAH ZAFAR MARG
NEW DELHI – 110 002.

Annual/Final Report of the work done on the Major Research Project.

1. Project report No. ~~1st /2nd /3rd/~~ Final

2. UGC Reference No.F. No. 43-448/2014(SR) dated 29 December 2015

3. Period of report: from 01/07/2015 to 30/06/2018

4. Title of research project: ***"Development and Demonstration of Passive Solar Regenerator for Liquid Desiccant based Air Conditioning System"***

5. (a) Name of the Principal Investigator: Dr. Jignesh R. Mehta
Department of Mechanical Engineering

   (b) University/College where work has progressed:
   Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda

6. Effective date of starting of the project: 1/04/2016 (Fund received on 31/03/2016)

7. Grant approved and expenditure incurred during the period of the report:

   a. Total amount approved Rs. 8,42,200/-

   b. Total expenditure Rs. 8,40,458/-

   c. Report of the work done: Attached

SIGNATURE OF THE PRINCIPAL INVESTIGATOR **HOD**

Dean **Registrar**

c. Report of the work done

1. **Brief objective of the project**

   The objectives of the project were as follows:

   a. Demonstrate liquid desiccant regeneration and analyze the performance as function of various parameters like insolation, wind speed and concentration of LD
   b. Fabricate and install solar liquid desiccant regenerator for the purpose of liquid desiccant (LD) regeneration
   c. Improve acceptability of system by modifying cover system and improving yield (condensate produced per m^2 of area)
   d. Evaluate potential for cooling cum distilled water generation

2. **Work done so far and results achieved and publications, if any, resulting from the work**

   Following work has been done under this project:

   a. Fabrication of indoor test set up, where solar energy absorption by bottom surface is simulated by electric heater integrated in the base of the passive solar regenerator and wind (air flow) is simulated using a cross flow fan.
   b. Experimentation using above test set up at different heat fluxes, which represents different solar radiation fluxes. Wind speed is varied by changing the fan speed. The condensate output due to evaporation of water from LD and condensation over the glass cover are measured. This condensation or regeneration rate is indicator of latent cooling capacity of given size of regenerator. Many of the above experiments are done but a few are still remaining
   c. Purchase, installation and commissioning of solar global and diffuse radiation measurement facility using secondary standard pyranometers and datalogging facility
   d. Fabrication of outdoor solar passive regenerator, whose absorber is modified by using gravel over its surface and applying selective spray coating. The area of the regenerator is 1.5 m^2 and tests have been performed in summer of year 2018.

Details of the papers and names of the journals in which it has been published or accepted for publication:

Manuscript entitled "Development and Performance Evaluation of a Passive Solar Liquid Desiccant Regenerator" has been submitted is presently under consideration for publication in *International Journal of Green Energy*.

3. **Has the progress been according to original plan of work and towards achieving the Objective: if not, state reasons.**

   a. Project money was received late by around 9 months (31^{st} March 2015 in place of 1^{st} July 2014). Development of outdoor demonstration unit and experimental work on it is completed. One paper based on this work is submitted in International Journal of Green Energy (Taylor & Francis Publication). Acceptance of this paper is awaited.

b. Large part of experimental work on indoor simulated system is over but some experiments are still remaining. One more paper based on this work will be submitted in future.

4. Please indicate the difficulties, if any, experienced in implementing the project

Best possible efforts have been done to do the project as planned. Availability of dedicated JRF and timely release of funds would have been more beneficial.

5. If project has not been completed, please indicate the approximate time by which it is likely to be completed. A summary of the work done for the period (Annual basis) may please be sent to the Commission on a separate sheet.

NA

6. If the project has been completed, please enclose a summary of the findings of the study. One bound copy of the final report of work done may also be sent to University Grants Commission.

Attached herewith

7. Any other information which would help in evaluation of work done on the project.

(a) Manpower trained: One PhD thesis is continued, 2 M. E. dissertation work are done and 3 B.E. projects have been done thus giving good exposure to around 20 students

(b) Ph. D. awarded: One PhD is continued

(c) Publication of results: One paper submitted, one more to be submitted

(d) Other impact, if any

UNIVERSITY GRANTS COMMISSION
BAHADUR SHAH ZAFAR MARG
NEW DELHI – 110 002

PROFORMA FOR SUBMISSION OF INFORMATION AT THE TIME OF SENDING THE FINAL REPORT OF THE WORK DONE ON THE PROJECT

1. Title of the project: Development and Demonstration of Passive Solar Regenerator for Liquid Desiccant Based Air Conditioning System

2. Name and address of the principal investigator: Dr. Jignesh R. Mehta, Mechanical Engineering Department

3. Name and address of the institution: Faculty of Technology and Engineering, The Maharaja Sayajirao Univerisity of Baroda, Vadodara - 390001

4. UGC approval letter no. and date: F. No. – 43-448/2014(SR) dated 29 December 2015

5. Date of implementation: 01/07/2015 to 30/06/2018

6. Tenure of the project: 3 years

7. Total grant allocated: Rs. 8,56,200/-

8. Total grant received: Rs. 8,42,200/-

9. Final expenditure: Rs. 8,40,458/-

10. Objectives of the project ………………………………

The objectives of the project were as follows:

a. Demonstrate liquid desiccant regeneration and analyze the performance as function of various parameters like insolation, wind speed and concentration of LD
b. Fabricate and install solar liquid desiccant regenerator for the purpose of liquid desiccant (LD) regeneration
c. Improve acceptability of system by modifying cover system and improving yield (condensate produced per m^2 of area)
d. Evaluate potential for cooling cum distilled water generation

11. Whether objectives were achieved ………………………

Explanation is given about achievement on each objective:

a. An indoor testing unit is built, where absorbed solar energy is simulated by heating the bottom absorber plate of the unit. Wind flow is simulated by providing a crossflow fan coving the span of the unit. Insolation, wind speed, concentration and ambient temperature are to be set at three different levels, thus 81 number of experiments will be required. More than half of the experiments are over. Once experimental work is completed and results are analysed, a paper based on the same will be submitted to a journal.
b. An improved outdoor solar LD regenerator with 1.5 m^2 area was fabricated and tested in summer of this year for water desalination as well as LD regeneration. Very encouraging

results are achieved. A paper based on this work is submitted to International Journal of Green Energy.

c. The condensate production was (condensate produced per m^2 of area)
d. Evaluate potential for cooling cum distilled water generation

12. Achievements from the project ………………………..

a. Development of a simple and economical solar passive regenerator demonstration unit.
b. The novel regenerator was tested for water desalination, provided around 3.7 kg/m^2 in a day, which is one of the highest reported in literature.
c. LD regeneration is also demonstrated and evaluated for COP. Concentration of aqueous calcium chloride solution used as liquid desiccant with initial mass of 17.4 kg was increased from 32.2% to 37.7% over the day. The output for regeneration of aqueous solution of calcium chloride was 1.68 kg/m^2 over the day
d. Indoor testing unit will explain relative importance of variables like solar insolation, wind speed, ambient temperature and concentration. This knowledge will help deciding feasibility of the unit for various places in India.

13. Summary of the findings

A novel but simple and economical solar passive regenerator with 1.5 m^2 area for water removal from liquid desiccant was developed and tested in this work. Crushed stones (gravel) used in concrete were used to make absorber surface uneven. This helped to reduce heat losses from the device, giving high efficiency. Maximum daily output in desalination experiments 3.7 kg/m^2 which is higher than most other work reported in literature for a simple solar still design without costly enhancement techniques which make such systems economically unviable.

Concentration of aqueous calcium chloride solution used as liquid desiccant with initial mass of 17.4 kg was increased from 32.2% to 37.7% over the day. The output for regeneration of aqueous solution of calcium chloride was 1.68 kg/m^2 over the day. An area of 7.5 m^2 will be needed per kW of cooling for a period of 6 h (total cooling of 6 kWh) using this type of device.

The water desalination and LD regeneration experiments performed on the same device may be compared to appreciate the differences. The maximum fluid temperature was 10°C higher in case of regeneration as compared to desalination experiments. It was also observed that minimum temperature rise to initiate the condensation was just 6°C in desalination but as high as 20°C in regeneration. The maximum temperature difference between fluid and glass was 11.7°C in desalination and 23.5°C in regeneration, leading high heat losses in later case. While comparing the results of desalination and regeneration experiments, it was observed that the daily condensate output reduced from 3.7 kg/m^2 to 1.68 kg/m^2 in later case, leading to drop in efficiency from 0.385 to 0.176. During comparison of regeneration experiments performed on a clear day and cloudy day, it was found that when the diffuse radiation was high, the output reduced by 57 %, even if the global radiation values were similar.

From the parametric study carried out in indoor unit, the following points can be concluded:

i. In general, condensate output increases with increase in solar insolation and wind speed and decrease in concentration and air temperature
ii. Effect of solar insolation on condensate output is the most significant than any other parameter.
iii. At higher insolation, effect of other parameters decrease.
iv. Effect of air temperature on condensate output is least significant of all the parameters.

14. Contribution to the society ……………………………….
This work will help develop economically and practically viable solar liquid desiccant regenerators, which uses freely available energy on roof of a building. This device can produce concentrated LD, which can be used for dehumidification of air with nominal electrical power consumption. Thus, this unit will help propagate an environmentally benign and economical technology for air conditioning.

15. Whether any Ph.D. enrolled/produced out of the project:
One PhD is enrolled and the work is continued

16. Number of publications out of the project:
One journal paper submitted, one more to be submitted in future

Principal Investigator **Head**

Dean **Registrar**

<u>FINAL REPORT – PART 1</u>

Development and Performance Evaluation of a Passive Solar Liquid Desiccant Regenerator

Paper submitted to International Journal of Green Energy (Taylor and Francis Publication)

ABSTRACT

Almost all the air conditioning systems used today run on Vapour Compression Refrigeration (VCR) cycle which consumes electrical energy. Production of electrical energy is generally associated with fossil fuel consumption, emission of greenhouse gases and other types of pollutions. Air conditioning systems which use waste or renewable energy sources should be investigated for the purpose of possible replacement of VCR cycle based systems. Liquid desiccant based air conditioning system which can dehumidify air is one such potential candidate. The heat from a solar thermal collector can be supplied to regeneration process in liquid desiccant based air conditioning systems.

A novel solar collector with goal of no electrical power consumption, simplicity, low cost, modularity and high efficiency was developed in this work for regeneration of aqueous solution of calcium chloride which was used as liquid desiccant. Condensate output in this device used for water desalination was 3.7 kg/m^2, which is comparable with the best in literature. Results from LD regeneration experiments are compared with above to understand and appreciate the differences between them.

Keywords

Solar energy, Liquid desiccant, Regenerator, Air conditioning, Solar still

Nomenclature

I	Solar insolation (W/m^2)
I_g	Global solar insolation (W/m^2)
I_d	Diffuse Solar insolation (W/m^2)
T_w	Temperature of water (°C)
T_a	Temperature of ambient air (°C)
T_g	Temperature of glass (°C)

T_{ld} Temperature of liquid desiccant (°C)

T_l Temperature of liquid in basin (°C)

I_g Global Irradiance (W/m^2)

α_g Absorptivity of glass (-)

1. Introduction

1.1 Conventional air conditioning systems and their limitations

More and more area of buildings is now air conditioned due to craving for better living standards, growth of economy and new developments in this field which make air conditioning systems more attractive in different ways. Building energy is going to grow at 2.7% per annum in India, which is the highest in the world (https://www.eia.gov/todayinenergy/detail.php?id=33252). The highest portion of the building energy is consumed by the air conditioning facility. Currently, most of the air conditioning systems work on Vapour Compression Refrigeration (VCR) cycle. Air conditioning systems running on VCR cycle use electrical energy. In spite of some attractive features like compactness and lower initial cost, complete dependence on VCR cycle based systems needs to be reviewed.

Around 40 % of electrical energy in the world and 64% of electrical energy in India come from fossil fuel based thermal power plants (https://powermin.nic.in/en/content/power-sector-glance-all-india, https://ourworldindata.org/fossil-fuels#fossil-fuels-in-electricity-production). The fossil fuels are non-renewable source of energy and the thermal power plants are responsible for different types of emissions creating greenhouse effect as well as air and water pollution.

There is growing awareness about indoor air quality (IAQ) now a days. Higher amount of outdoor air is required to be inducted in conditioned space to control pollutants in conditioned space. But higher amount of outdoor air also increases sensible as well as latent load on the air conditioning system (ASHRAE, 2007). The VCR system can control humidity only indirectly by bringing dew point temperature down. If sensible heat ratio of space is low or outdoor air is very humid, overcooling of air to remove moisture and then reheating to avoid very cold air delivery may be needed. This scheme is very in-efficient from point of view of energy utilization.

1.2 Liquid desiccant based air conditioning (LDAC) system and energy input

A desiccant based air conditioning system may be recommended in place of VCR cycle based systems in above conditions. Desiccants are the materials having affinity for water vapour and can be in solid or liquid form. Desiccant based air conditioning systems can remove moisture from air without cooling them below their dew point temperature (Grossman and Johannsen 1981). Liquid desiccant based air conditioning systems have some potential advantages over solid desiccant systems like flexibility in laying ducts, storage of energy, lower regeneration temperatures, better suitability to solar energy usage, higher COP due to multi-staging or lower parasitic power, energy recovery and internal heating and cooling in contacting device (Lowenstein 1992, Kessling, Laevemann, and Peltzer 1998, Roth et al., 2002, Rane and Mehta 2013, Mehta and Gandhi 2014).

Liquid desiccants remove moisture from air in a component called dehumidifier (Process 1-2 in conditioning cycle as shown in Figure 1). To continue dehumidification of air with LD circulated in a closed cycle, moisture has to be removed from LD in regenerator (process 6-7 in regeneration cycle). The regeneration process needs energy in the form of heat (process 5-6 in regeneration cycle). This heat can come from solar thermal collector or a waste heat source. Though there are other air conditioning technologies like vapour absorption / adsorption refrigeration systems, which are driven by heat, LDAC systems can be less complex, more economical and modular.

1.3 Literature review on regeneration of liquid desiccant using solar energy

When solar energy is used for regeneration of LD, the process may be done outside the solar collector or in the solar collector itself. When regeneration is done outside the solar collector, either the air used for regeneration or the LD itself is heated in solar collectors. Regeneration here takes place in air scavenged device, which uses ambient air for removing moisture from LD (Gommed and Grossman 2007).

In the other method, LD is heated in solar collector cum regenerator (C/R) and water vapour is removed by evaporation of water from LD surface or boiling of LD in the same device. Flat plate type solar collector, evacuated tube type solar collector and solar still have been used for this purpose in literature (Holland, 1963, Alizadeh and Saman 2002; Mehta and Rane 2014).

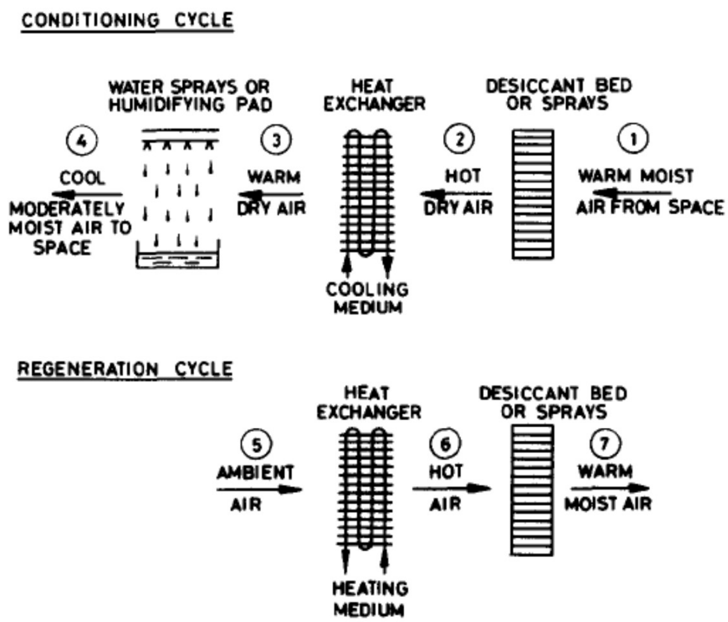


Figure 1. Equipment and Components of a Liquid Desiccant based Air Conditioner

(Grossman and Johannsen, 1981)

(Holland 1963) used a solar still for regeneration of aqueous solution of lithium chloride. The effect of various parameters such as LD concentration, solar radiation, ambient temperature, wind velocity etc. on regeneration capacity of still were studied. (Mullick and Gupta 1973) used a solar flat plate collector with 18° inclination with horizontal. Aqueous calcium chloride solution with concentration in the range of 41% to 49% was used. A thin film of LD was formed, flowing downward on the absorber plate, while the air moved upward by natural convection. The efficiency was in the range of 20% to 40%. It was shown that the solar still design cannot give any output below 406 W/m^2 solar irradiance but the proposed flat plate system can work satisfactorily with much lower insolation level than that. (Gandhidasan 1983) analysed tilted solar still for regeneration of calcium chloride. The solution trickled on inclined flat surface, but no outside air was used for regeneration. It was concluded that such closed type regenerator is more effective for hot and humid climate rather than hot and dry climate as mass transfer potential is high in the latter case as ambient air is used for regeneration. (Alizadeh and Saman 2002) performed experiment on flat plate solar collector/regenerator with forced flow of air. The highest rate of evaporation achieved was 3.1 kg/h for 500 kg/h mass flow rate of air using aqueous solution of calcium chloride as LD. (Kaudinya and Kaushik 2007) studied open and forced flow solar regenerator for regeneration of two different LDs, LiCl and LiBr. They performed experiment in hot and dry conditions and achieved COP between 0.36 to 0.57. (Mehta and Rane 2014) developed a two stage LD regeneration system using evacuated tube type solar collector as well as air scavenging regenerator in first and second stage respectively. Aqueous solution of potassium formate was used as LD and COP exceeding one was achieved.

(Mehta and Gandhi 2013) carried out the investigation of solar still as a LD regenerator using aqueous potassium formate solution as LD. The performance of an insulated FRP solar still for water desalination as well as regeneration of 60% concentration of LD was investigated. Water evaporation-condensation rate of 2.5 kg/day reduced to 1.2 kg/day in LD regeneration experiments as compared to water desalination experiments while temperatures in basin were much higher. (Modi and Shukla 2018) used a double sloped hybrid solar still for regeneration of calcium chloride at 40% concentration level and production of distilled water. Preheated LD at 50°C was supplied to hybrid solar still, the source of heat for the same is not mentioned. Condensate output of 1.417 kg/m^2 in one day was achieved at average solar irradiance value of 671 W/m^2. (Nafey et al. 2001) studied the effect of black gravel as a storage medium within a single sloped solar still. Solar still with 0.5 x 0.5 m^2 basin area were used. The gravel with size 20-30 mm increased productivity by 19%.

1.4 Advantages of Using Solar Passive LD Regenerator

There are several benefits of using a passive device (device with no electrical power consumption due to absence of pump and fan) like a solar still as a LD regenerator as explained below (Mehta and Gandhi 2013):

- It is simple in construction and can be easily integrated in roof of a building.
- It does not need a pump for liquid desiccant flow inside the collector.
- It does not expose LD directly to air and thus eliminates dust contamination.
- As the other types of solar Collector exposes LD to ambient air directly, there will be more sensible heat loss, reducing COP of system.
- LD temperature in solar still can be higher and heat can be recovered in a solution heat exchanger, helping to increase COP of system.
- The water removed from LD condenses on glass of solar still and is available as distilled water which is an additional utility

Use of solar passive regenerator in a device like solar still is not studied much in literature. But due to the advantages mentioned above, the current work investigated this type of regenerator. Hints regarding performance of this type of collector can be taken from the work on solar still in literature. Solar still is commonly used to produce distilled water from saline water (Hanane and Aburideh 2012). The performance of solar still is affected by many parameters broadly classified as controllable and uncontrollable parameters. The uncontrollable parameters are ambient temperature, wind speed, humidity, solar intensity etc. while the controllable parameters are fabrication material, glass cover thickness and its inclination, water depth etc.

A detailed review of research work done by various researchers on effect of controllable parameters on output of solar still was studied (Sharshir, Pang, and Yeng 2016). They also provided detailed review on studies done on different methods to improve performance of still such as use of phase change material, vacuum technique by external and internal condenser, vibratory harmonic effect, external and internal reflectors etc. (Feilizadeh et al. 2017) studied effect of dimensions on performance and optimization of dimensions of still for improvement of performance. (Nafey et al. 2001) showed that rubber or gravel used as storage media can be increase productivity up to 20%. An acrylic still provided 11.36% higher productivity compared to a still made galvanized iron (Manokar and Prince 2017). Here, the output increased from 2.46 kgm^{-2} to 2.84 kgm^{-2} per day while using insulation (Karaghouli and Alnaser 2004). Yield from solar still was enhanced by 16.5% with cover of 3 mm glass thickness as compared to that of 6 mm glass thickness (Mink et al. 1998). The annual solar yield reached a maximum value when the condensing glass cover inclination was equal to the latitude of the place (Singh and Tiwari 2004). (Modi and Shukla 2018) used a double sloped hybrid solar still for regeneration of calcium chloride at 40% concentration level. Preheated LD at 50°C is supplied to hybrid solar still. Condensate output rate of 1.417 kgm^{-2} at an average solar irradiance at 671 Wm^{-2} is reported. The source of heat for preheating the LD is not mentioned.

2. Energy Balance for Solar Still and Prediction of Condensate Output

Fig. 2 shows the schematic line diagram of a solar still which can be used for water desalination or LD regeneration. Saline water or LD is filled in the basin. The glass cover allows solar radiation to pass through it. Solar radiation falls on the basin absorber surface, passing through the glass.

Basin surface, which is black in colour, absorbs solar radiation and becomes hot. It gives its heat to water which in turn gets heated. Hot water gives out vapour to air above it and also heats it. Such air rises up and comes in contact with inner surface of glass cover. Glass is being cooled by ambient air (wind) flowing over it. So, water vapour is condensed over the inner surface of the glass. This condensate takes form of droplets, slide over the surface of glass and are collected at the lowest end of the tilted glass into a channel.

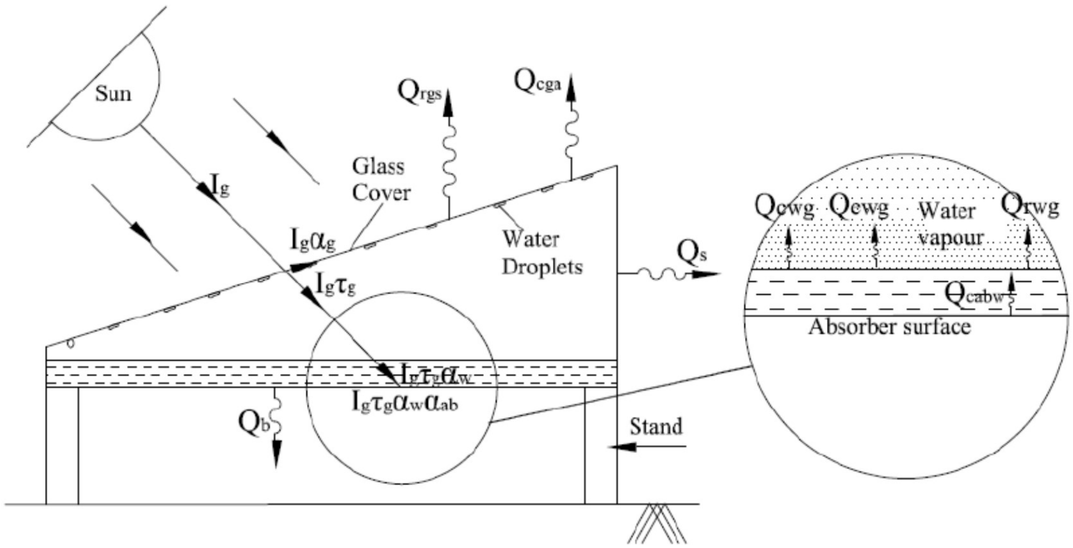


Figure 2: Schematic of Solar Still and Energy Exchange Processes

(Mehta and Gandhi, 2013)

The energy balance at glass surface, water and absorber surface can be shown with the help of following equations assuming the condition to be quasi-steady state or can be considered to be instantaneous energy balance equation.

Energy balance can be applied for heat exchange processes occurring at glass cover, water pool and absorber surface as expressed in eq. (1), (2) and (3) respectively:

$$I_g\alpha_g + h_{i.gw}(T_w - T_g) = h_{r.gs}(T_g - T_s) + h_{c.ga}(T_g - T_a) \qquad (1)$$

Left hand side (LHS) of Eq. (1) is heat gained by glass cover. First term on LHS is the radiation flux absorbed by glass cover. Second term is total heat transfer from hot water to glass. This term consists of convective, evaporative and radiative heat transfer components. RHS of the equation is the heat lost by glass. First term on RHS of Eq. 1 is radiative heat loss from glass to sky, while the second term is convective heat loss from glass surface to ambient air. Sky temperature is generally taken 6 K lower than ambient temperature and convective heat loss coefficient is function of wind velocity.

$$I_g \tau_g \alpha_w + h_{c.abw}(T_{ab} - T_w) = h_{i.gw}(T_w - T_g) + {dT_w}/{dt} \tag{2}$$

LHS of Eq. (2) is heat gain by water, while that on RHS is sum of heat loss and heat stored in water. First term on LHS is heat absorbed by water, second term is heat gained by water by natural convection heat transfer from absorber. First term on RHS is heat lost by water to glass and second term is the heat stored in water due to its temperature change in given period.

$$I_g \tau_g \tau_w \alpha_{ab} + h_{c.abw}(T_{ab} - T_w) = U_{l.tot}(T_{ab} - T_a) \tag{3}$$

LHS of Eq. (3) is heat gained by absorber surface by radiation. First and second terms on RHS are convective heat transfer from absorber surface to water and total heat loss from bottom and sides of the still respectively. Above three equations make three sets of equations with three unknowns: T_w, T_g and T_{ab}. The radiative heat transfer coefficient, h_{rwg}, convective heat transfer h_{cwg} and evaporative heat transfer coefficients from water to glass are calculated using Dunkle's model [Dunkle 1961].

3. Development of Novel Solar Passive Regenerator and the Experimental Set Up

In solar passive regenerator, the heat transfer from absorber (basin) surface to inner surface of glass by mode of evaporative heat transfer is the only desired mode of heat transfer. The convective heat transfer between these two surfaces is completely coupled with evaporative heat transfer and cannot be altered. Effort should be made to reduce radiative heat transfer from absorber surface to glass, which is undesired as it doesn't help in moisture removal from LD. LD regeneration takes place at a temperature higher than those encountered in case of solar water desalination units, so emission losses would be higher. Therefore, it would be beneficial to apply selective coating on basin absorber surface, which has low emissivity for far infrared wavelength. Though not explicitly stated in literature, when the travel path of water droplets on glass to condensate collection channel is long, there are chances that they drop back into the basin in-between. This problem can be resolved by reducing the path length of the water droplets. Increasing slope of glass cover can help them slide early but this would increase size, cost and weight of glass per unit area of the horizontal basin surface area. Development of the solar passive LD regenerator in current work was done based on above ideas or understanding of the system.

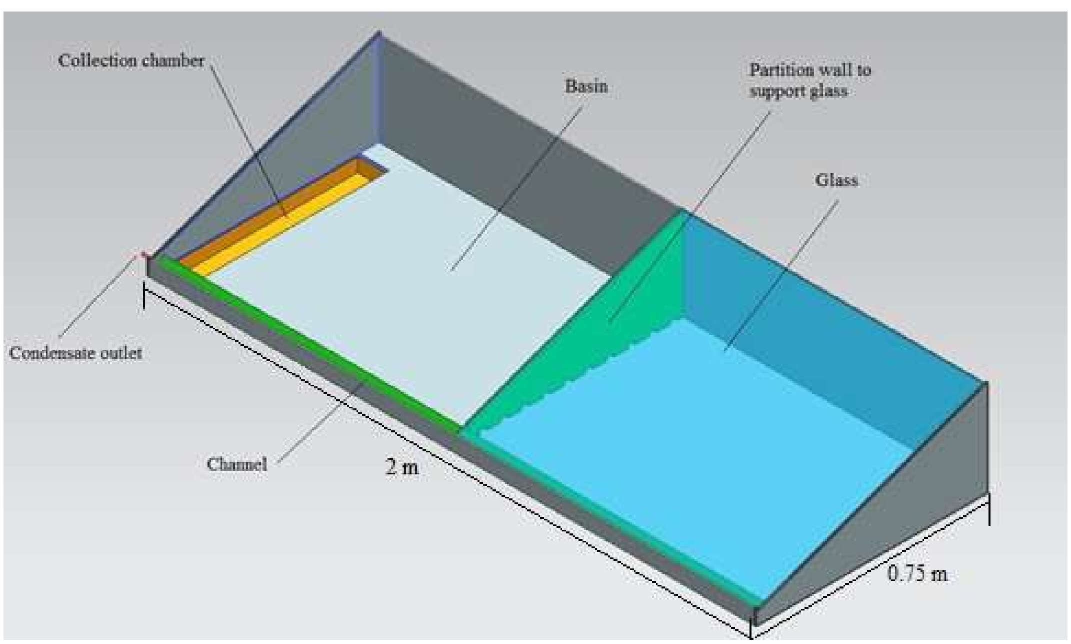
3.1 Objectives of current work

The objective of the current work is to develop a novel experimental prototype of a passive solar LD regenerator with higher yield by improving energy conversion efficiency and reducing heat losses. It is important that such improvement is not done using additional areas occupied by solar flat plate collector or evacuated tubes. Such improvements should also not be very costly, which make the system economically infeasible.

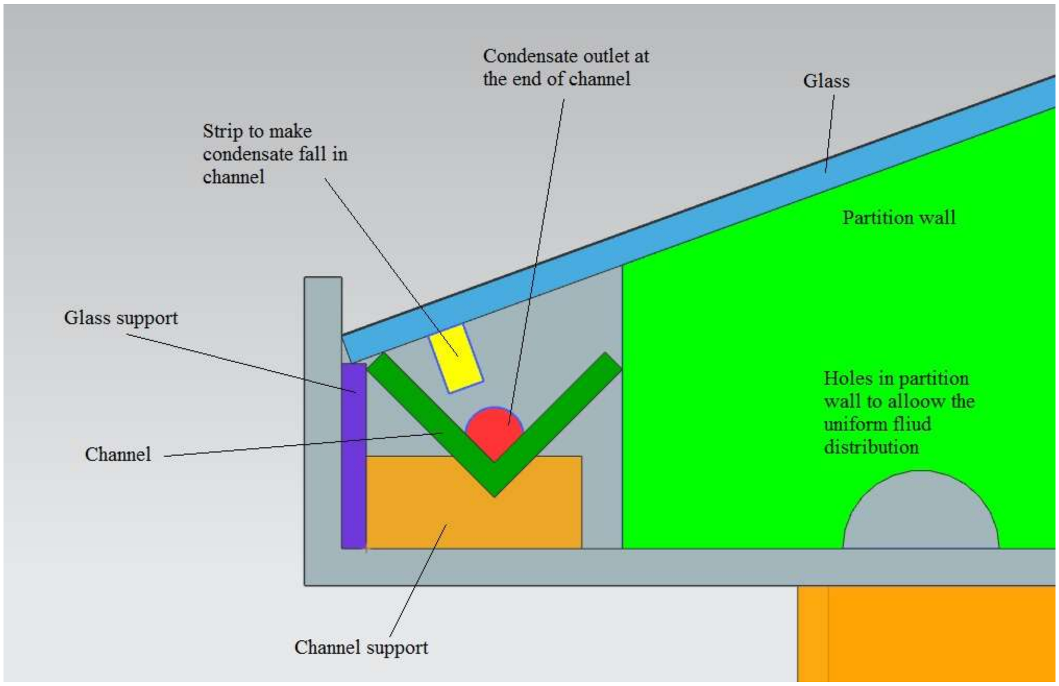
Performance (condensate or distilled water produced per unit area) of this unit would be evaluated for water desalination as well as liquid desiccant regeneration to understand the differences between the two phenomena. Performance will be analysed to understand inter-relation and interaction of various parameters related to the device.

3.2 Development and fabrication of solar LD regenerator

Fig. 3 shows solid model of the solar LD regenerator developed in this work. The width of basin is kept 0.75 m only to avoid dropping of water droplets in basin before reaching the condensate collection channel. Length of basin is kept 2 m, thus giving the basin area equal to 1.5 m^2. Higher front length to side length ratio also helped reducing the shadow of side wall on basin or absorber surface in morning and afternoon hours. Higher tilt angle of glasses will also increase the shadow size on basin surface. The tilt angle of glass in current work was kept 20º.



(a) Isometric view



(b) Detailed right hand side view

Figure 3: CAD model of Solar LD Regenerator

Translucent polycarbonate (PC) sheets were used for making the body of the regenerator. The reasons for this selection were ease of fabrication, good UV resistance of the material and compatibility with LD. Gravels used in making concrete mixture, of 5-12 mm height were spread on basin surface. This was done to increase surface area of absorber surface and reducing view factor between the glass and the absorber surface. While increase in surface area per unit projected area should help reducing temperature difference between absorber surface and LD; reduction in view factor due to irregular shape of the surface should help reducing emission losses from absorber surface through glass cover. Thurmalox 250^{TM} solar selective coating was uniformly sprayed on gravel bed with as less thickness as possible. The basin is divided in two symmetrical sections by a central support and two pieces of glass cover, each of 1 m length is used. Condensate collected in the front channel comes out through a tube and is collected in a small container. The complete body of the device was kept on a steel frame at comfortable height.

3.3 Instrumentation

The solar passive regenerator developed in this work is shown in Fig. 4 along with instruments used for measurements. Fig. 5 shows the weather parameter measurement facility used in current work. It consists of two secondary standard pyranometers, SR20 model from Huskesflux. One of the pyranometers was used to measure global radiation and the other was used in conjunction with shadow ring (HFSR01 from Hukesflux) to measure diffuse solar radiation. CR300 data logger from Campbell was used to automatically record the radiation and ambient temperature data. Ambient temperature was measured with T type thermometer and also logged using CR300. K type thermocouple sensors were used to measure basin temperature and glass surface temperature. Testo make 176T4 data logger was used to automatically record the temperature data measured by K type thermocouple. Table 1 provides the details of the instrumentation used.

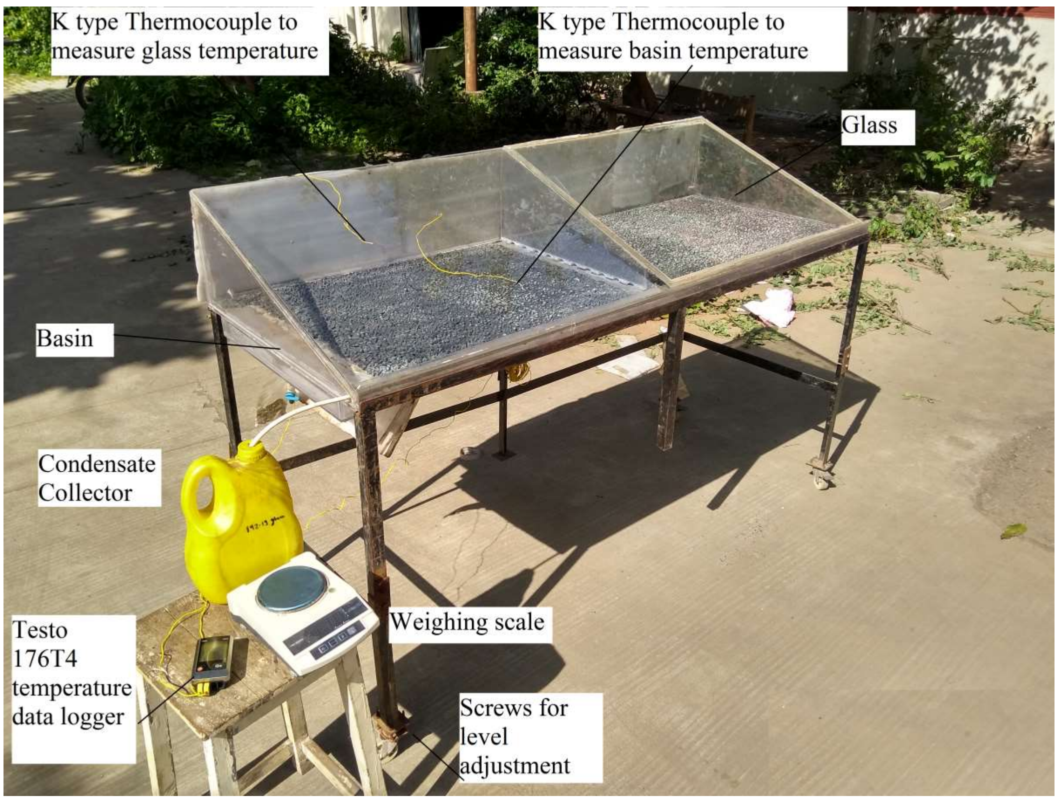


Figure 4: Experimental Setup for Solar Passive LD Regenerator

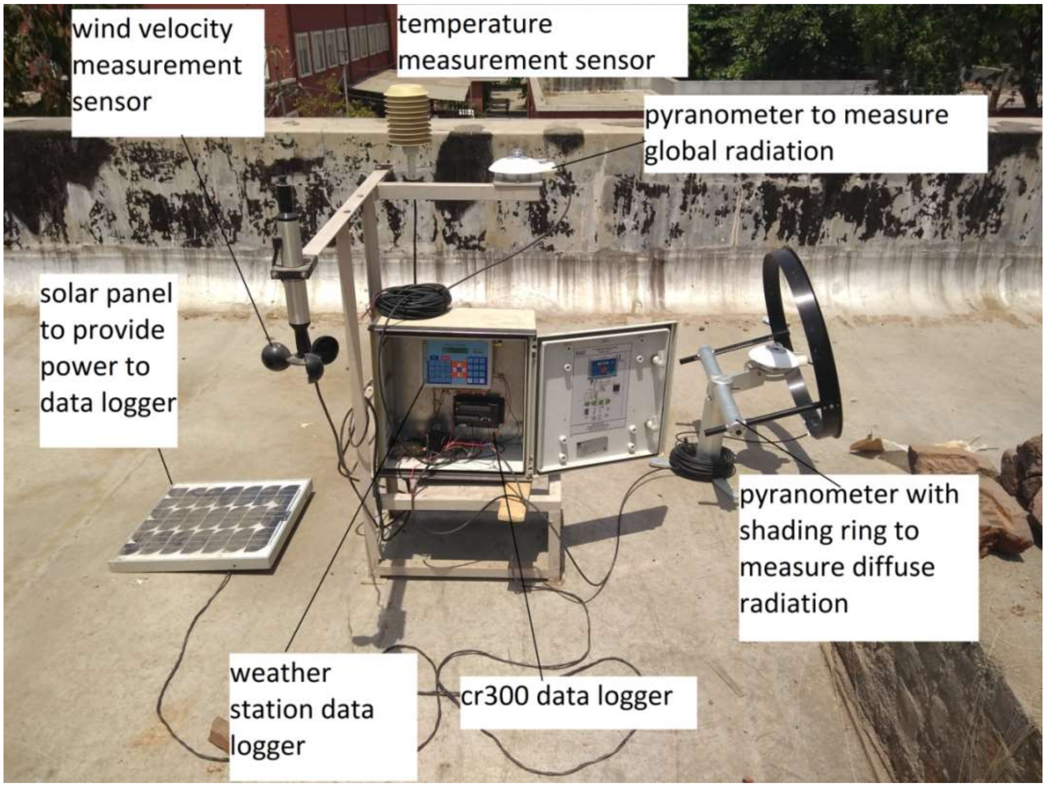


Figure 5: Weather Parameters Measurement Facility

Table 1: Instrumentation

Parameter	Instrument	Model and Make	Accuracy
Solar Irradiance (Global / Diffuse)	Pyranometer	SR01 from Hukesflux	$\pm 0.15 \times 10^{-6}$ V/(W/m^2)
	Shadow ring	HFSR01 from Hukesflux	
	Datalogger	CR300 from Campbell	±(0.04% of reading ±3 μV)
Wind velocity	Cup type anemometer	AWS 101, Komoline Aerospace	± 0.35 m/s (2 m/s to 35 m/s)
Temperatures (Ambient / liquid in basin / glass surface)	T type / K type thermocouple	CR300 / Testo 176T4	±0.3 % of mV

4. Experiments with Water

Two types of experiments were done using the device, one for water desalination and the other for LD regeneration. The description of the experiments follows:

There is little work done on regeneration of LD using such a device as the advantages described in section 1.4 are not understood and appreciated. Due to this reason, not much part experience or comparison is available for performance of current system. So, one of the objectives of this set of experiments was to find the water distillation capacity of the system developed, which can be compared with results in literature as. When results of this set of experiments would be compared with LD regeneration results, the differences between them can be observed, reasons can be investigated and appreciated. The other objective of this set of experiments is to streamline the procedure of experimentation before performing LD regeneration experiments. LD is comparatively costly material and any modification in device or experimental methodology should be done before LD regeneration experiments are performed.

4.1 Procedure for water desalination experiments

Experiments were performed between 9:00 to 18:00 at Vadodara, India; latitude 22.31°N and longitude 73.19°E. At 8:45 am the weather station and pyranometers were placed on terrace of the building and the experimental setup was prepared. Solar Irradiance was measured every 10 s and then averaged for 10 min. This reading is stored in the internal memory of datalogger and could also be seen online in PC. At 9:00 am 12.45 kg of water (required amount to completely submerge gravels) was filled in the basin of the device. T type thermocouple in conjunction with CR300 datalogger was used to measure ambient temperature. K type thermocouples were used to measure water temperature in each section of basin and glass surface temperature. All thermocouple sensors were covered by aluminium tape to avoid the effect of radiation in temperature readings. Temperature data was recorded at every minute using Testo 176 temperature data logger. Condensate was collected and measurement taken at every 30 minutes on small weighing scale.

4.2 Observations and calculations

Total condensate output of the system was 5.6 kg/day for 1.5 m^2 area. The daily efficiency is defined as the ratio of total heat utilized for water evaporation to the total heat supplied over a day.

$$daily\ efficiency(\eta) = \frac{\text{mass of condensate produced}/m^2\ \times\ \text{latent heat of vapourization}}{total\ insolation}$$

Total condensate produced from 9:00 to 18:00 pm duration was 3.741 kgm^{-2} while total heat input (isolation) in the same duration was 23.269 MJ m^{-2} or 6.463 kWh m^{-2}. Thus, the daily efficiency is equal to 38.52%.

4.3 Results and discussion

The change in global and diffuse radiation over the day and the condensate production in a given half an hour period are shown in Fig. 6. The condensation of water on glass cover started from about 9:20 am, which increased with rise in solar radiation. Solar irradiance reached its maximum at solar noon which is between 12:30 to 13:00 Indian standard time (IST) at Vadodara. Hourly condensate collection was highest around one hour after solar noon. The reason for this is the storage of heat in various forms in the device, so highest potential for condensation does not occur at highest irradiance point.

The variation of various temperatures along with condensate output over a day are shown in Fig. 7. The water temperature increased gradually, reached its maximum value at 13:00 h and started falling significantly only in late afternoon hours. The maximum output was available when water temperature was highest. Glass temperature remained nearly constant for around three hours about noon. It may be reminded that the temperature difference between water and glass is the potential for heat and water transfer.

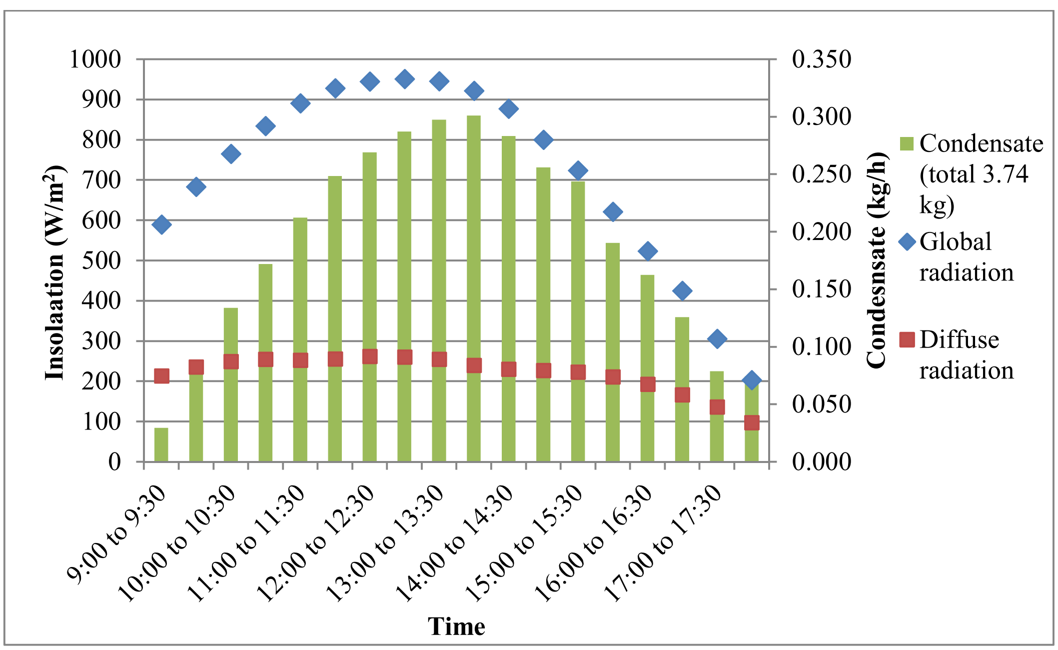


Figure 6: Insolation and Condensate Produced vs. Time

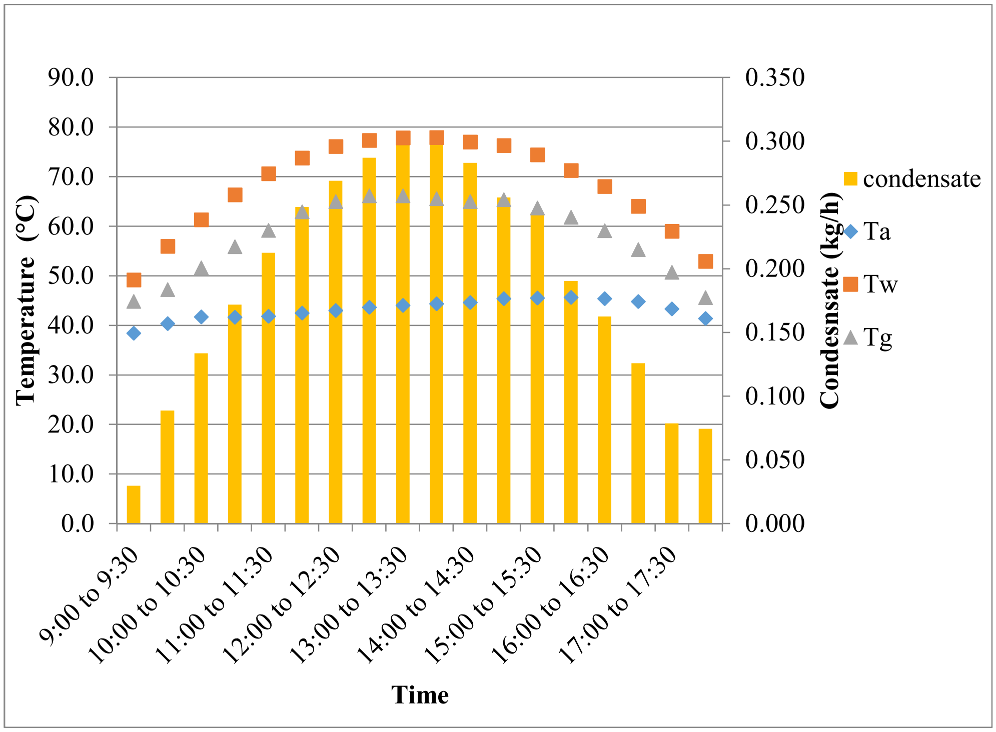


Figure 7: Temperatures and Condensate Production vs. Time

4.5 Comparison of experimental results with those reported in literature

The comparison of various parameters of above experiments is made with the experimental work of Mehta and Gandhi (2013) as all details related to experiments are available for comparison. The trends of condensate output as well as temperatures are compared. Mehta and Gandhi (2013) used a FRP solar still with glass wool insulation and 1 m x 1 m basin area. In current system solar still of 2 m x 0.75 m basin area is used. Polysyrene foam insulation of 10 mm thickness is provided on bottom and back side of the device, and not on side walls. Water quantity in basin was 12.45 kg as compared to 20 kg water in case of Mehta and Gandhi (2013). Total daily yield (condensate production) was 2.5 kg m^{-2} as reported by Mehta and Gandhi (2013), while the daily yield of current system was 3.7 kg/m^2 in current work. Thus the current system provided around 30% more output. Daily efficiency of system of Mehta and Gandhi (2013) was 29%, while daily efficiency of current system is 36%. Thus it can concluded that performance of current system is significantly improved compared to the previous system. The credit for improvement should be given the different features described in section 3.2.

Fig. 8 shows the variation in various temperatures as well as condensate output with time for current work and Mehta and Gandhi (2013). It may be observed that the response of the current is quicker. The condensate output started one hour earlier in current system as compared to previous system. Condensate output was much higher before solar noon, but the decrease in output after solar noon was also fast in current system due to lower heat storage and probably also due to poor insulation.

Fig. 9 shows the variation in various temperatures with time so that their effect on condensate output can be correlated. It may be observed that the water temperature in current system remained higher, while the glass temperature remained lower in spite of higher heat transfer rates in current system. This indicates reduced radiative heat supply from absorber surface to glass due to gravels put on it. The difference between glass and water temperature is mostly higher in current system which is one of the reason for higher output. After solar noon the water and glass temperatures decreases faster in current system due to lower thermal storage.

Singh and Tiwari (2004) used solar still with 1 m^2 area, depth of water was kept 0.03 m and glass cover inclination was 15º. The monthly yield in May was 100 litres which comes out to be 3.3 kg/day. Kumar et al. (2017) used solar still with basin area of 1 m^2 (0.5 m × 2 m) and 0.1 m water depth. The daily yield was 3.42 kgm^{-2}. Raj and Manokar (2016) used solar still of 0.5 × 1 m^2 area, 20 mm depth. The daily yield was 3.43 kgm^{-2}. ***In the current system with 1.5 m^2 area and water depth of 15 mm; daily yield was 3.74 kgm^{-2}, which is highest output as compared to above literature.***

5. LD Regeneration Experiments

5.1 Introduction

The main objective of the current work is to evaluate the performance of the novel solar passive LD regenerator. Experiments were carried out with aqueous solution of calcium chloride ($CaCl_2$) as the working fluid to find the LD regeneration capacity (kg or litre/day per m^2 area of collector) or COP of the system. COP of a LD regenerator is defined as follows:

$$\mathrm{COP_{reg}} = \frac{\text{Mass of condensate collected }(\mathrm{kgm^{-2}})\ \times \text{Latent heat of water }(\mathrm{kJkg^{-1}})}{\text{Energy Input from Sun }(\mathrm{kJm^{-2}})}$$

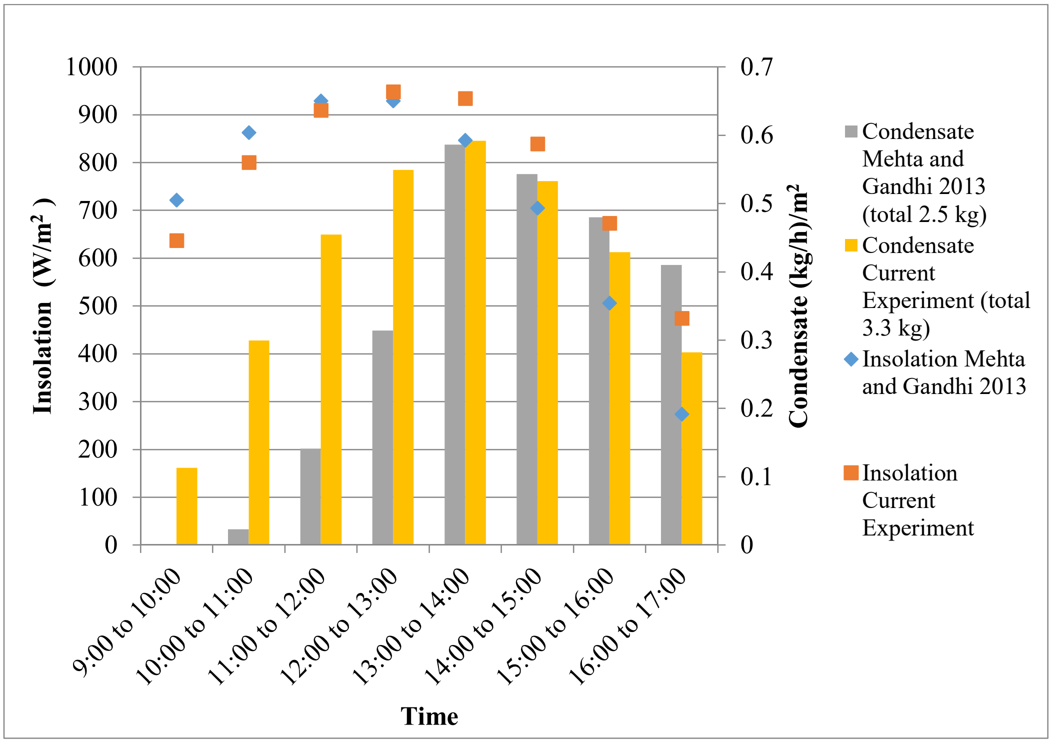


Figure 8: Insolation and Condensate Output vs. Time

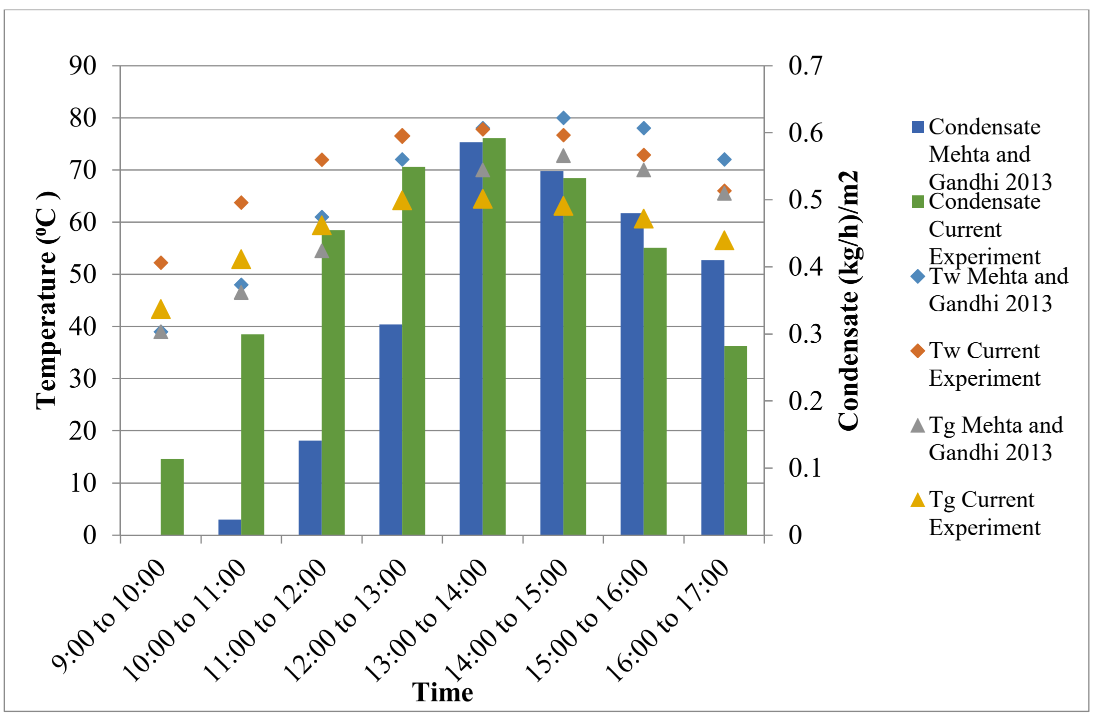


Figure 9: Temperatures and Condensate Output vs. Time

Experiments carried out on two different days, on one day the sky was clear and on the other day, it was partially cloudy. The results are useful to compare the performance of the solar passive regenerator under different type of sky conditions.

5.2 Results and discussion

The experimental procedure was similar as the desalination experiments. LD regeneration experiment was performed on 25th May 2018 at Vadodara, India with 32.2% initial concentration of calcium chloride and initial total mass of 17.4 kg of LD. The condensate output obtained on this day was 1.68 kg/m^2. Final concentration of LD in the basin at the end of the day was 37.7%. If this solution is used for dehumidification of air, it can provide 4262 kJ of cooling. Latent cooling rate of around 200 W can be provided over a period of 6 h. This means that around 7.5 m2 area would be required per 1 kW cooling rate over 6 h period when air conditioning can be provided. It may be realized that it is very convenient to store this cooling as concentrated LD.

Fig. 10 shows the variation of solar irradiance and half-hourly condensate output over the clear sky sunny day. The condensation started after 10:00 am though the device was put in sun from 9:00 am. Condensate output increased sharply as the irradiation increased. The maximum output was achieved in the solar noon hour. The condensate output decreased as energy input decreased in the afternoon. A sudden drop in condensate output was observed between 15:30 to 16:00 pm.

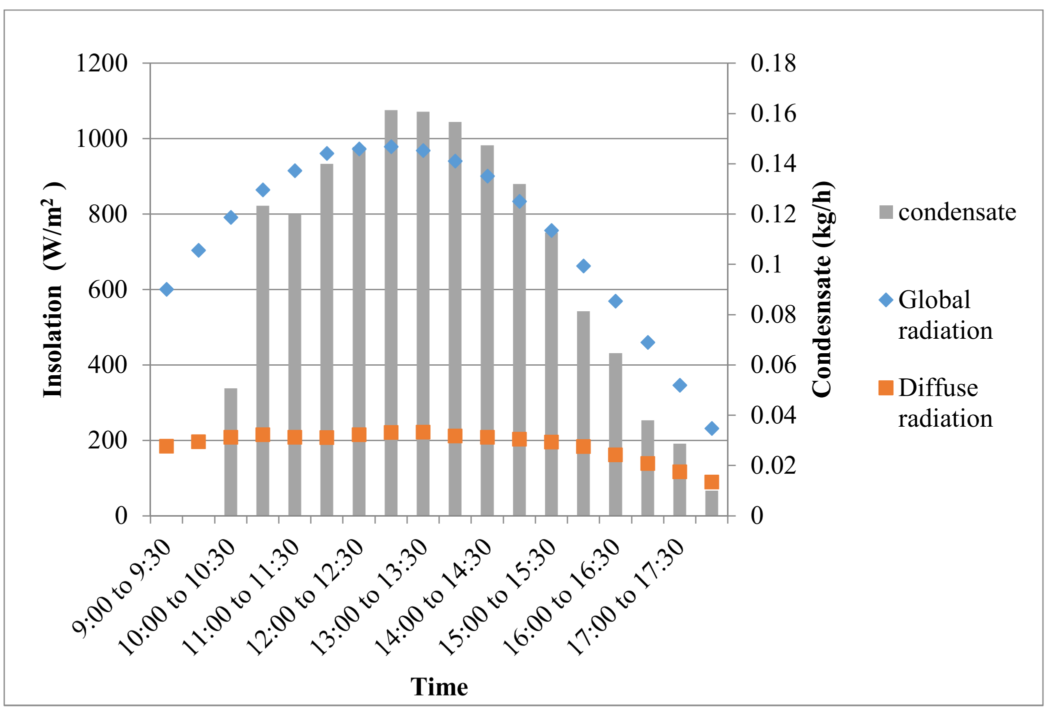


Figure 10: Insolation and Condensate Output vs. Time

Fig. 11 shows the variation of different temperatures as well as condensate output over the day. There was no condensate output till a threshold temperature difference between LD and glass. The LD temperature as well as condensate output increased as the day progressed. It reached maximum when LD temperature as well as temperature difference between LD and glass reached its maximum. As the solar irradiance decreased in afternoon, LD temperature decreased slowly with time in afternoon, but the reduction in output was fast as energy input was low. Glass temperature reduced slowly as compared to LD temperature, narrowing the gap. It may be understood that the vapour pressure relation with temperature is exponential. So, a small change in temperature potential can lead to big drop in condensate output. It may be observed that the temperature difference between glass and air is narrowing down in afternoon, which adversely affects effective rejection of heat of condensation and thus condensate output. Some condensate comes out in evening when sky and ambient temperature reduce and collected next morning.

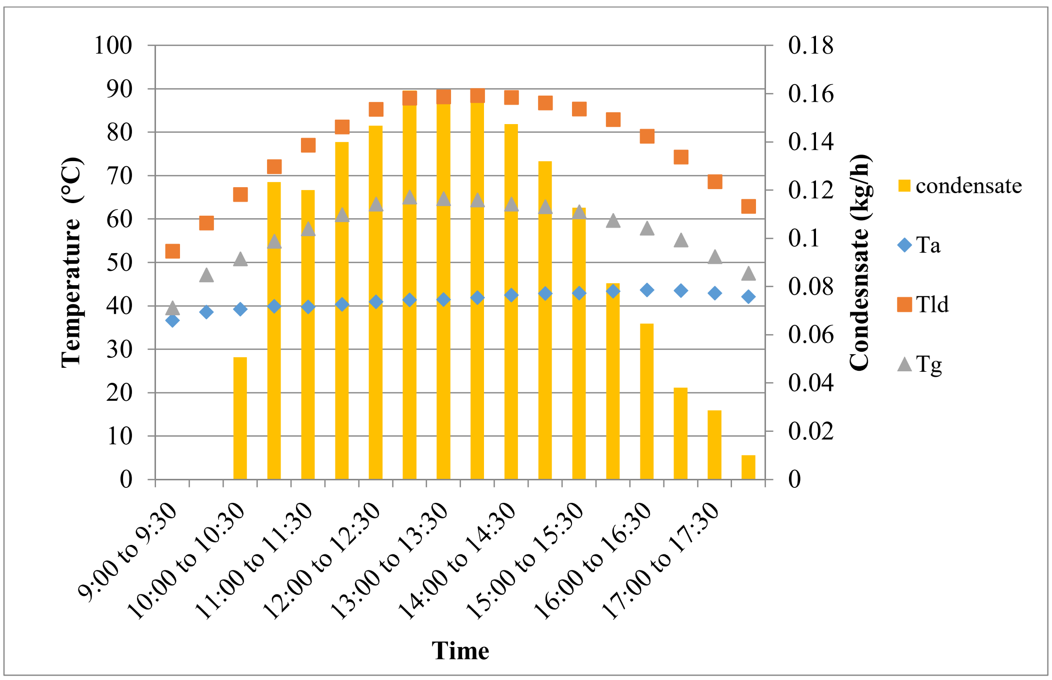


Figure 11: Temperatures and condensate output vs. Time

5.3 Comparison of desalination and regeneration experiments

Comparison of desalination and regeneration experiments was carried out to understand and appreciate the difference between the two processes. Fig. 12 shows variation of solar irradiance and condensate output for desalination as well as LD regeneration experiments. It is seen that though solar energy input is nearly same, the output in case of LD regeneration experiments is much lower in each period. Condensate output starts late in morning and drops fast in afternoon. LD exerts lower water vapour pressure than water. Thus, LD regeneration needed higher temperature potential as compared to water desalination, in spite of lower condensate output in the same device.

Fig. 13 shows the variation of LD and glass temperature with time along with condensate output over the day for the two experiments. It is seen that LD remains at much higher temperatures as compared to water as only at higher temperature of LD, evaporative heat transfer rate and condensation heat rejection rate from glass gets balanced. At highest value, LD temperature is 10°C higher than corresponding water temperature in desalination experiment. Higher LD temperatures obviously lead to higher losses from bottom of the basin as well as emission losses through glass resulting in lower efficiency of the solar collector. The glass temperature remained nearly same in regeneration as well as water desalination experiments.

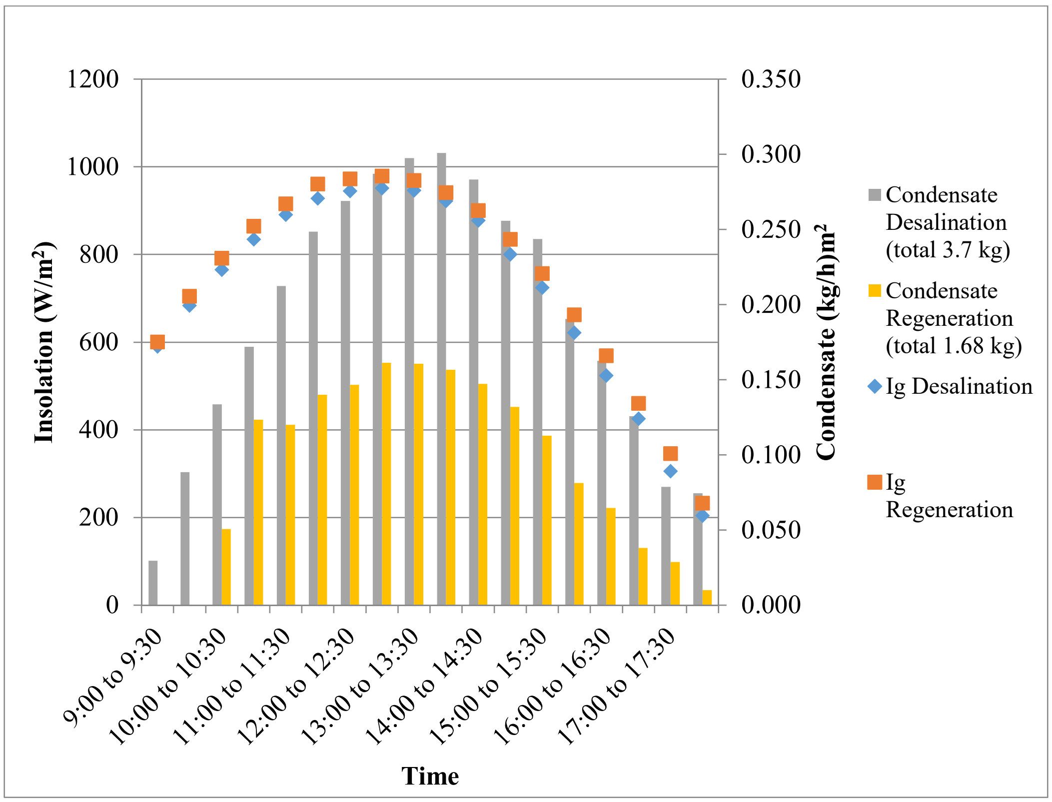


Figure 12: Insolation and Condensate Output vs. Time

The effect of difference between fluid temperature and glass temperature can be considered to be the potential for evaporative as well as other modes of heat transfer between the glass and the LD in a given experiment. The variation of various temperatures over the day is shown in Fig. 13

while the temperature differences over the day are shown in Fig. 14 for both desalination and LD regeneration experiments. The difference reached around 25°C in case of LD regeneration, while it reached only around 13°C in case of water desalination. The higher temperature difference in case of LD is due to lower evaporative heat transfer potential due to lower water vapour pressure on surface of LD.

The difference between fluid temperature and ambient temperature can be considered to be potential for heat loss. The variation of this temperature difference with time is shown in Fig. 15 for both desalination and LD regeneration experiments. This difference is much higher in case of LD regeneration experiment as compared to the other. Obviously heat losses are higher in LD regeneration case and efficiency would be lower.

The effect of variation in difference between glass temperature and ambient temperature with time is shown in Fig. 16 for both Desalination and LD Regeneration experiments. The difference is not much between the two experiments. Actually, there is less heat to be rejected from glass to air in regeneration case due to lower condensation. Still, glass temperature is not low as there is more radiative heat transfer between basin and glass in LD regeneration case, which needs to be rejected to sky by the glass.

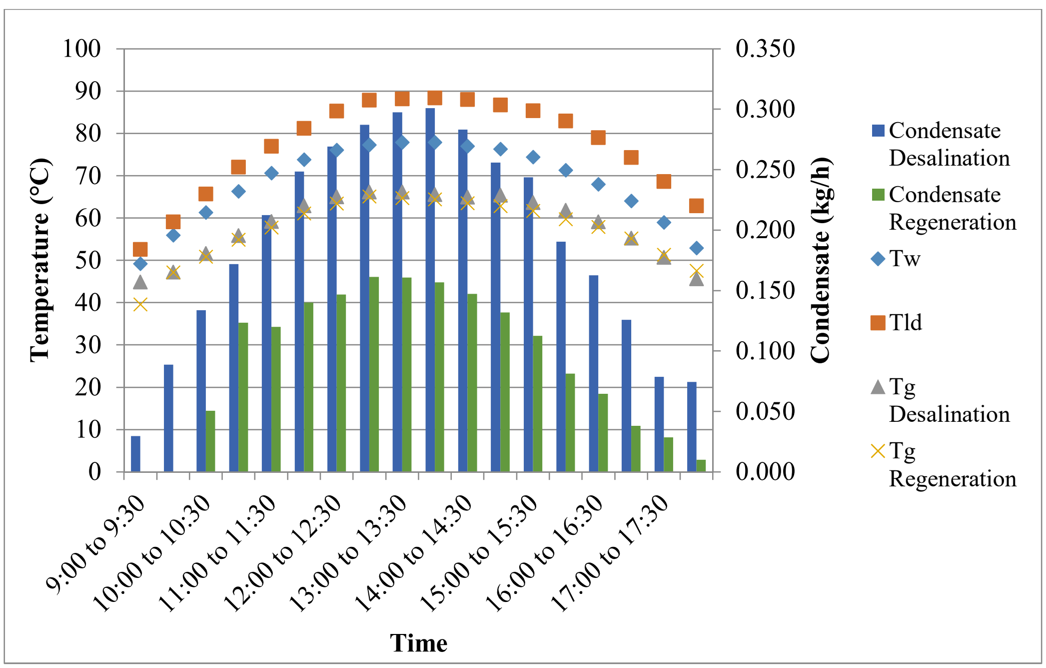


Figure 13: Temperatures and Condensate Output vs. Time

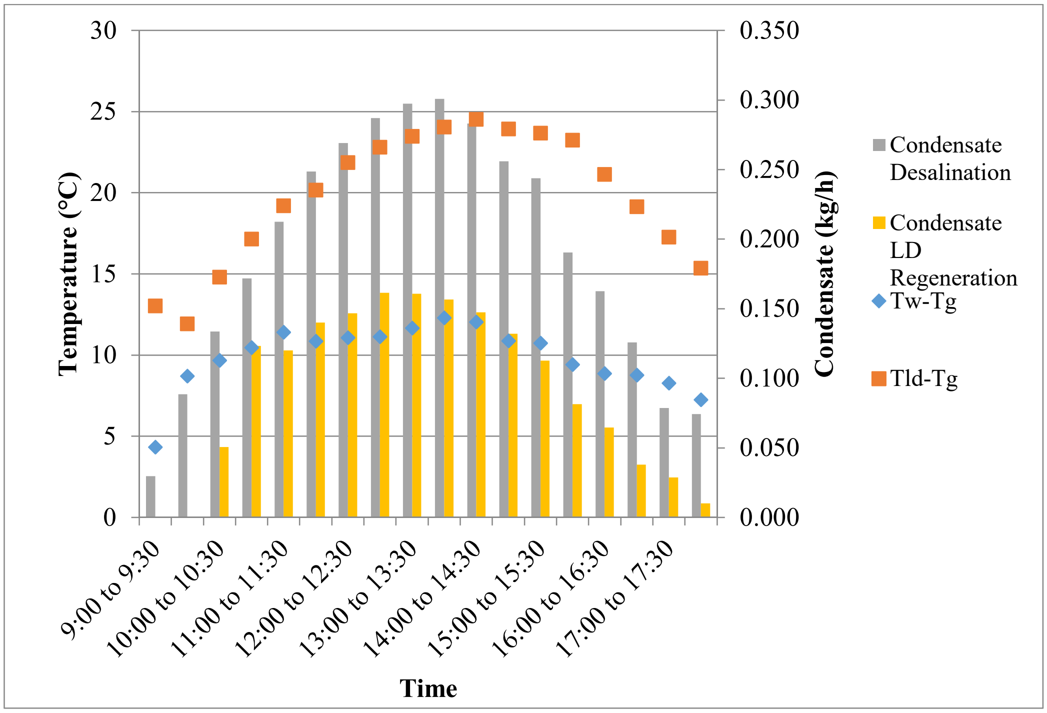


Figure 14: Temperature Differences and Condensate Output vs. Time

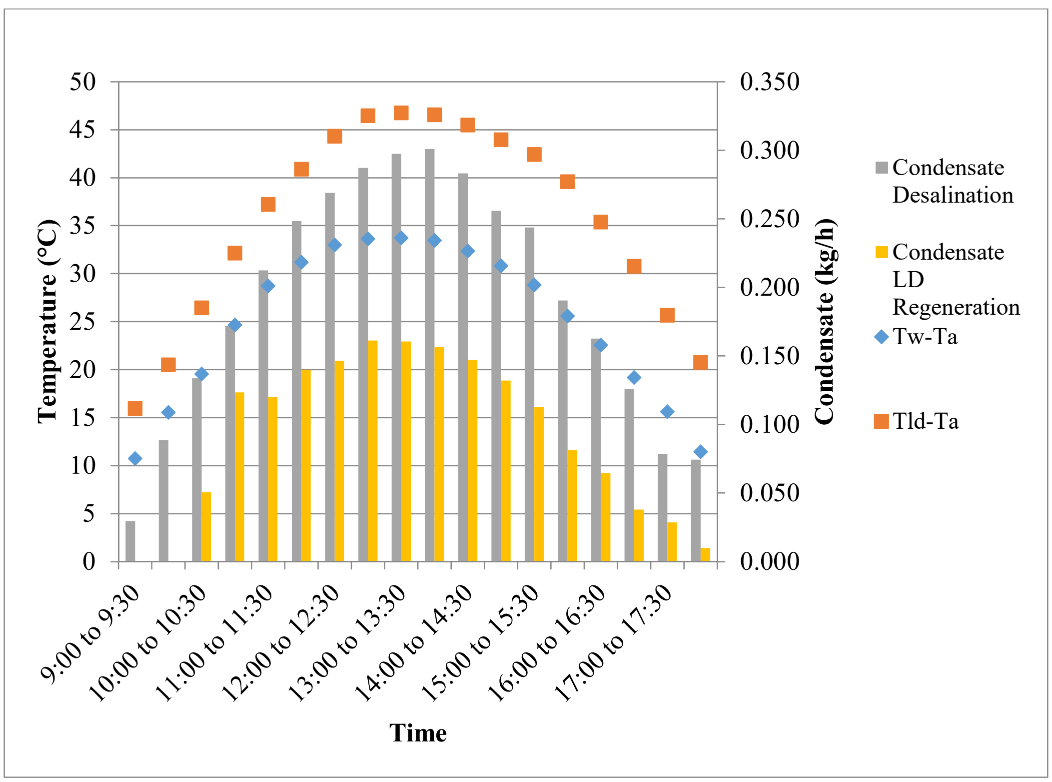


Figure 15: Temperature difference and condensate output vs. Time

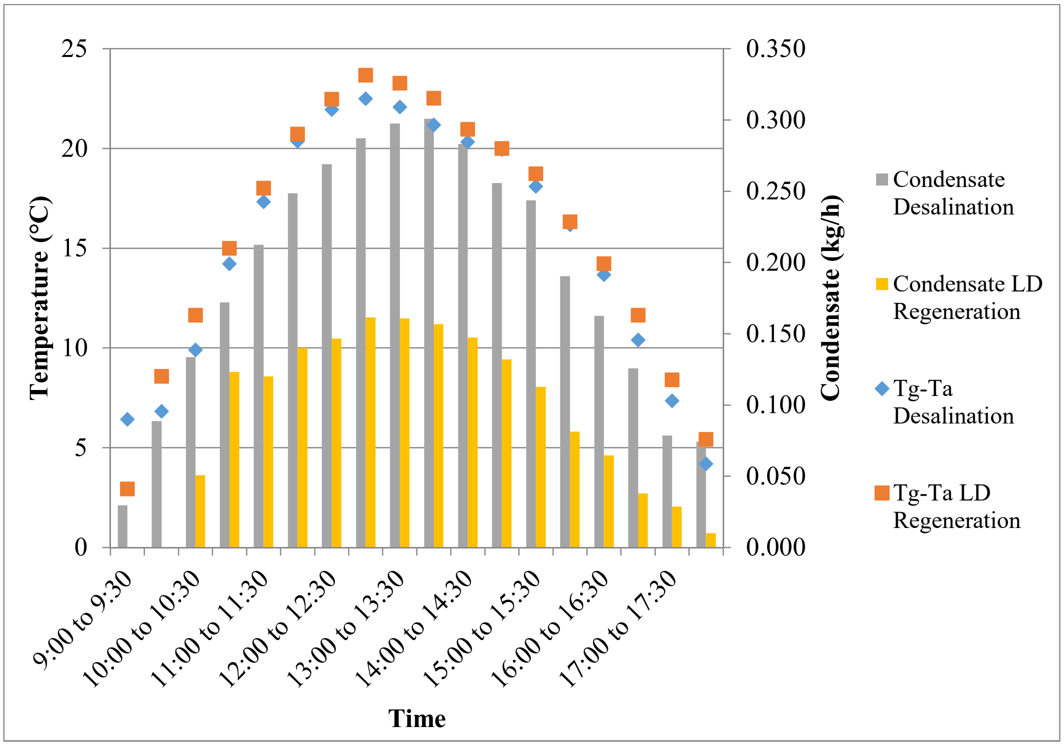


Figure 16: Temperature Differences and Condensate Output vs. Time

5.4 Effect of various parameters on performance

The effect of solar insolation on condensate output for desalination as well as regeneration experiments for forenoon hours is shown in Fig. 17, while the same for afternoon hours is shown in Fig. 18. The results of forenoon hours and afternoon hours have to be shown separately as the trend for the two periods are different due to storage and release of heat in the device in those periods respectively.

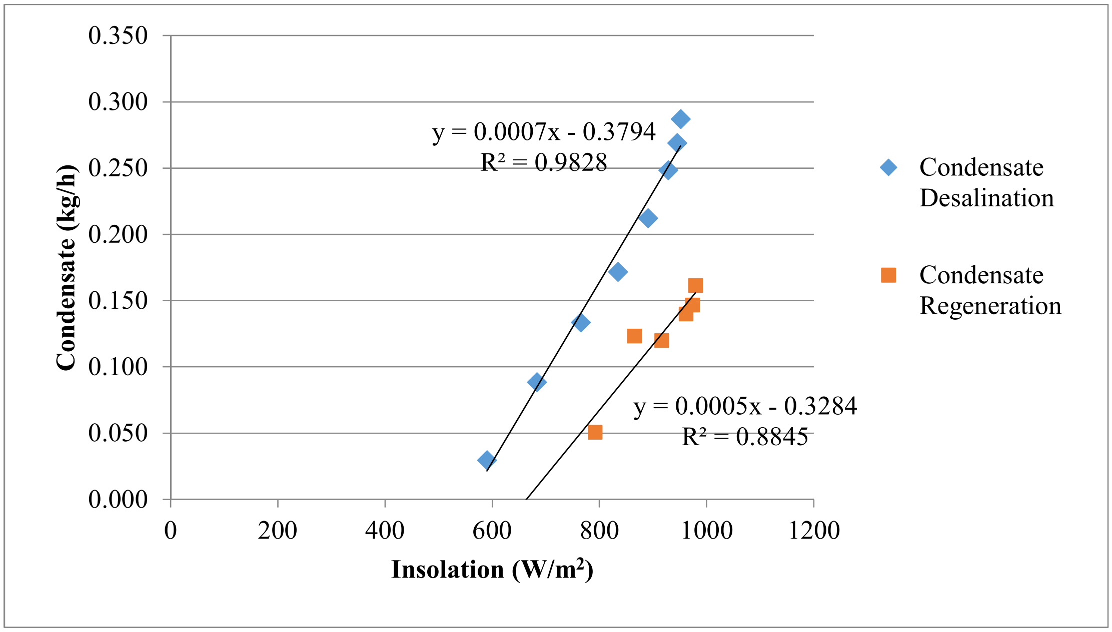


Figure 17: Condensate Output vs. Insolation (Forenoon)

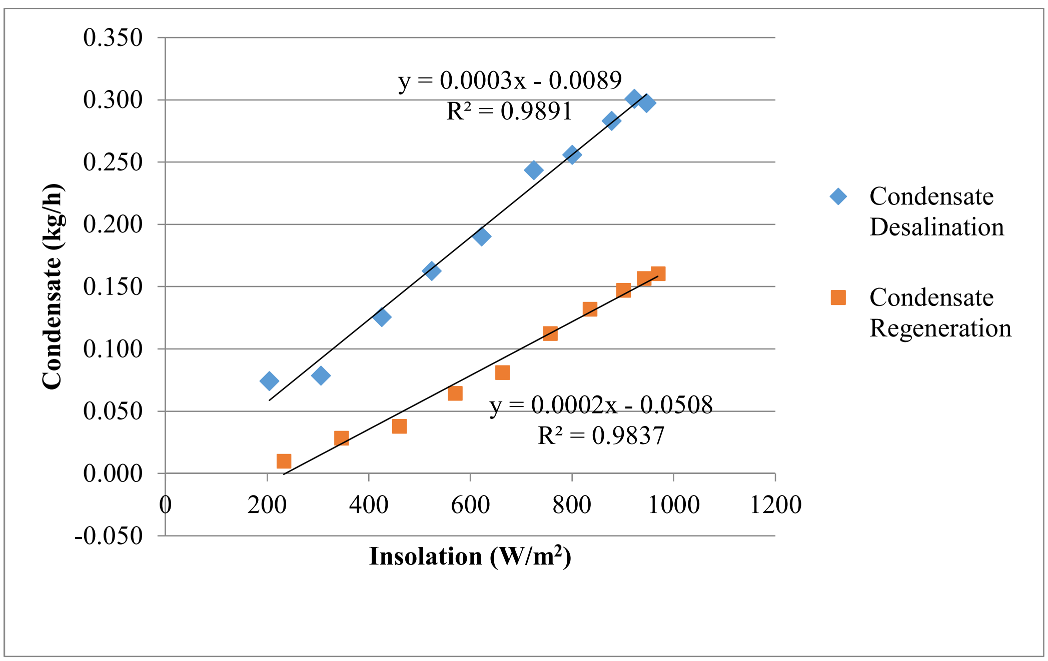


Figure 18: Condensate Output vs. Insolation (Afternoon)

It is seen that a linear fit is quite good for correlating condensate output with insolation in morning as well as afternoon hours. There is sharp rise in condensate output with insolation in morning hours. The rise is more rapid for water than LD (higher slope of desalination line) and the start is also late in case of LD regeneration experiment in the morning hours. During afternoon periods the reduction in condensate output was slow due to availability of stored heat in system as compared to morning period rise. The drop for water desalination experiment is more rapid, though it starts from a higher rate. The intercept for LD regeneration on insolation axis is higher, meaning that LD regeneration stops earlier than the water desalination in afternoon as the peak condensate output is much lower.

The temperature difference between fluid (water/LD) and glass is the potential for water transfer from basin to glass. The relation between them is shown graphically in Fig. 19 for morning hours for desalination as well as regeneration experiments. The condensate output increases very sharply in morning hours for desalination experiment. Actually, the difference between basin and glass cover temperatures becomes steady and output increases as solar irradiance increase in forenoon hours. The rise in condensate output is not as sharp in case of LD regeneration experiments and flattens out as the noon is approached, in spite of rise in solar insolation. The reason for this could be the rapid rise in radiative heat loss from glass due to high LD temperatures. The line for condensate output rate in afternoon has little less slope as compared to forenoon line as seen from Fig. 20. The condensate output in afternoon drops exponentially as LD and glass temperature difference reduce in case of LD regeneration experiment.

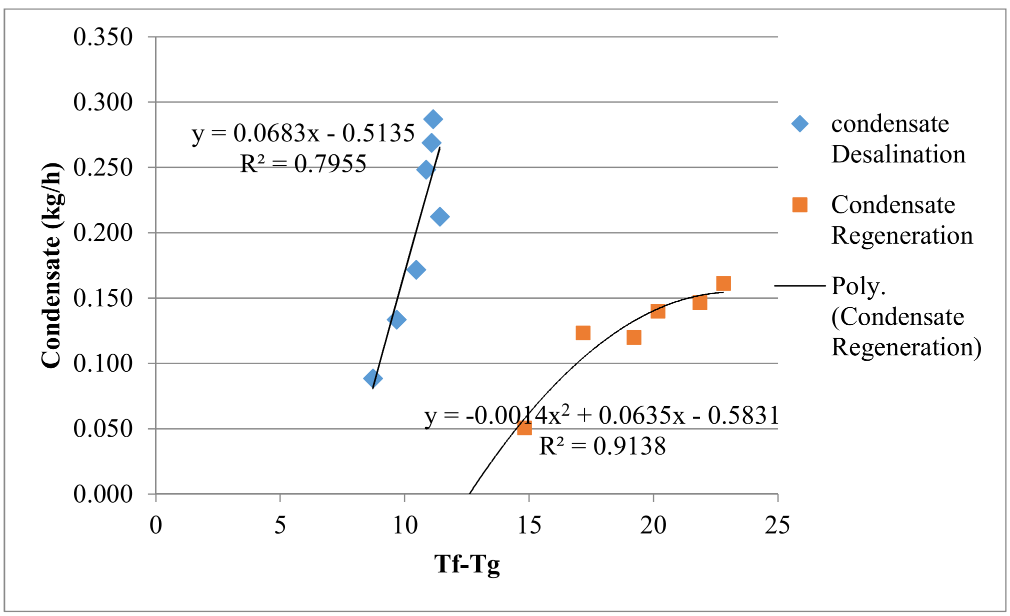


Figure 19: Condensate Output vs. Temperature difference (Morning)

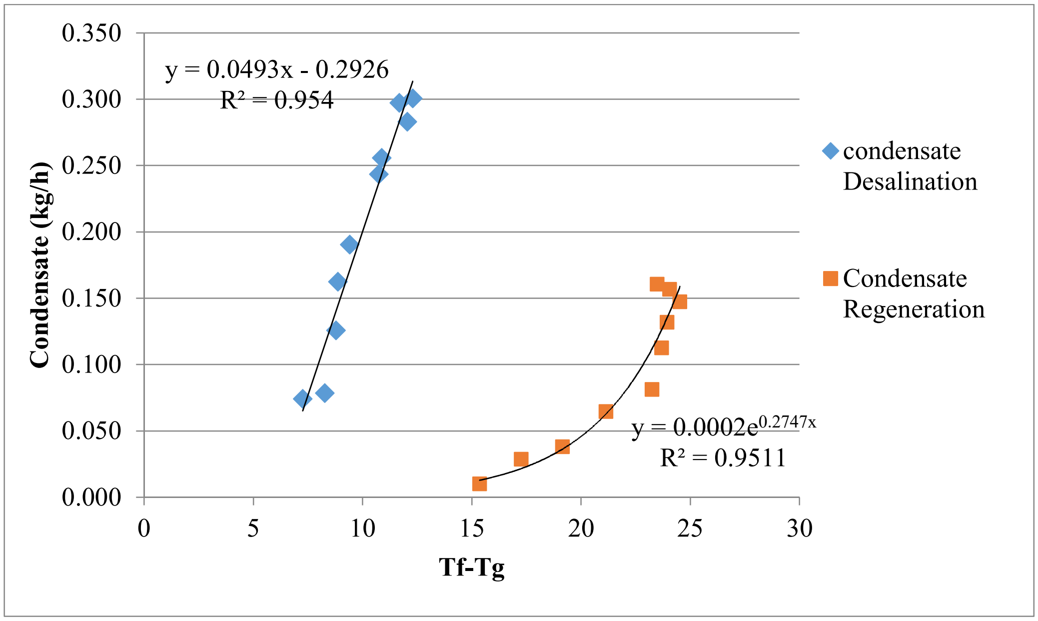


Figure 20: Condensate vs. Temperature Difference (Afternoon)

5.5 Comparison of results between clear day and partially cloudy day

The effect on condensate output on the sky condition can be understood from Fig. 21. The values of global radiation as well as diffuse radiation on a clear and partially cloudy day are plotted against time. It is seen that the global radiation on cloudy day was only slightly lower than that on clear day but the contribution on diffuse radiation was large. It is seen that the condensate output reduced by 55% on the day when sky was partially cloudy. Thus, it is important to get more direct (beam) radiation for better performance of the device.

6. Conclusions

A novel but simple and economical solar passive regenerator with 1.5 m^2 area for water removal from liquid desiccant was developed and tested in this work. Crushed stones (gravel) used in concrete were used to make absorber surface uneven. This helped to reduce heat losses from the device, giving high efficiency. Maximum daily output in desalination experiments 3.7 kg/m^2 which is higher than most other work reported in literature for a simple solar still design without costly enhancement techniques which make such systems economically unviable.

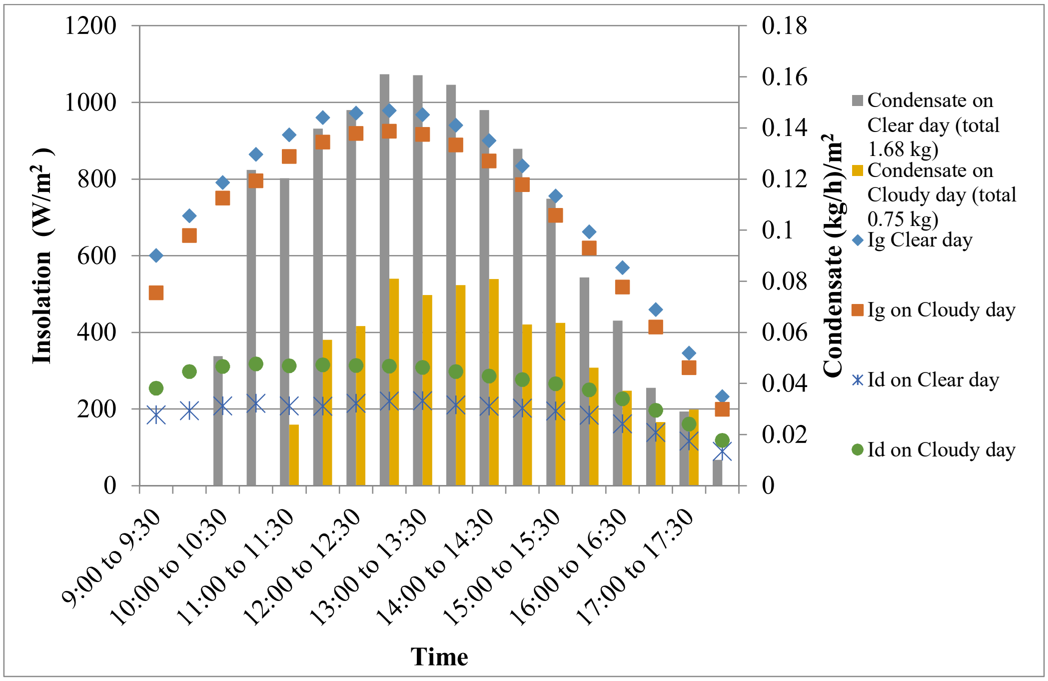


Figure 21: Insolation and Condensate output vs. Time

Concentration of aqueous calcium chloride solution used as liquid desiccant with initial mass of 17.4 kg was increased from 32.2% to 37.7% over the day. The output for regeneration of aqueous solution of calcium chloride was 1.68 kg/m^2 over the day. An area of 7.5 m^2 will be needed per kW of cooling for a period of 6 h (total cooling of 6 kWh) using this type of device.

The water desalination and LD regeneration experiments performed on the same device may be compared to appreciate the differences. The maximum fluid temperature was 10°C higher in case of regeneration as compared to desalination experiments. It was also observed that minimum temperature rise to initiate the condensation was just 6°C in desalination but as high as 20°C in regeneration. The maximum temperature difference between fluid and glass was 11.7°C in desalination and 23.5°C in regeneration, leading high heat losses in later case. While comparing the results of desalination and regeneration experiments, it was observed that the daily condensate output reduced from 3.7 kg/m^2 to 1.68 kg/m^2 in later case, leading to drop in efficiency from 0.385 to 0.176. During comparison of regeneration experiments performed on clear day and cloudy day, it was found that when the diffuse radiation was high, the output reduced by 57 %, even if the global radiation values were similar.

Acknowledgement

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FINAL REPORT – PART 2

Experimental study for characterization of- Solar LD Regenerator

Report by PhD research scholar: Mr. Shailesh M. Gandhi

1. Introduction

The objective of the proposed work is to study the effects of various parameters like ambient temperature, solar irradiance, air temperature and wind velocity on performance of the Solar Passive Liquid Desiccant Regenerator under indoor simulated environment and thus characterizing the device.

During previous period of reviews, 7 different representative cities of India were identified and the range of variation of these parameters for the month of March to May for the period: 09:00 am to 05:00 pm were found considering their geographical location and type of atmosphere at this location. This includes Ahmedabad, Mumbai, New Delhi, Kolkata, Varanasi, Vishakhapatnam and Bhopal. Three levels of each of these parameters were considered for full factorial experimental study for uniform spread over the entire range of each. Table 1 shows the level of these parameters.

Table 1: Levels of parameters for full factorial study

Sr No	Parameter	Unit	Range			Level 1	Level 2	Level 3
1	**Solar Irradiance**	W/m^2	400	To	908	550	730	910
2	**Wind Speed**	m/s	0.805	To	5.944	0.8	3.35	5.9
3	**Air Temperature**	°C	19.7	To	40.4	24	32	40
4	**Concentration**	%	36	To	39	36	37.5	39

Table 3 shows the 4 × 3 array for experimentation.

Table 3: 4 × 3 arrays for Experimentation for characterization of LD regenerator

Experiment No.	Solar Irradiance (W/m^2)	Wind Speed (m/s)	Air Temperature (°C)	Concentration (%)
1	550	0.8	24	36
2	550	0.8	24	37.5
3	550	0.8	24	39
4	550	0.8	32	36

5	550	0.8	32	37.5
6	550	0.8	32	39
7	550	0.8	40	36
8	550	0.8	40	37.5
9	550	0.8	40	39
10	550	3.35	24	36
11	550	3.35	24	37.5
12	550	3.35	24	39
13	550	3.35	32	36
14	550	3.35	32	37.5
15	550	3.35	32	39
16	550	3.35	40	36
17	550	3.35	40	37.5
18	550	3.35	40	39
19	550	5.9	24	36
20	550	5.9	24	37.5
21	550	5.9	24	39
22	550	5.9	32	36
23	550	5.9	32	37.5
24	550	5.9	32	39
25	550	5.9	40	36
26	550	5.9	40	37.5
27	550	5.9	40	39
28	730	0.8	24	36
29	730	0.8	24	37.5
30	730	0.8	24	39
31	730	0.8	32	36
32	730	0.8	32	37.5
33	730	0.8	32	39
34	730	0.8	40	36
35	730	0.8	40	37.5
36	730	0.8	40	39
37	730	3.35	24	36
38	730	3.35	24	37.5
39	730	3.35	24	39
40	730	3.35	32	36
41	730	3.35	32	37.5
42	730	3.35	32	39
43	730	3.35	40	36
44	730	3.35	40	37.5
45	730	3.35	40	39
46	730	5.9	24	36
47	730	5.9	24	37.5
48	730	5.9	24	39
49	730	5.9	32	36
50	730	5.9	32	37.5
51	730	5.9	32	39
52	730	5.9	40	36
53	730	5.9	40	37.5
54	730	5.9	40	39
55	910	0.8	24	36
56	910	0.8	24	37.5
57	910	0.8	24	39

58	910	0.8	32	36
59	910	0.8	32	37.5
60	910	0.8	32	39
61	910	0.8	40	36
62	910	0.8	40	37.5
63	910	0.8	40	39
64	910	3.35	24	36
65	910	3.35	24	37.5
66	910	3.35	24	39
67	910	3.35	32	36
68	910	3.35	32	37.5
69	910	3.35	32	39
70	910	3.35	40	36
71	910	3.35	40	37.5
72	910	3.35	40	39
73	910	5.9	24	36
74	910	5.9	24	37.5
75	910	5.9	24	39
76	910	5.9	32	36
77	910	5.9	32	37.5
78	910	5.9	32	39
79	910	5.9	40	36
80	910	5.9	40	37.5
81	910	5.9	40	39

2. Experimental setup

Figure 1 show the experimental set up used for characterization of passive solar LD regenerator. It shows the main components of the system such as regenerator, blower to simulate for wind blowing over the glass cover, a line heater of 3 kW capacity to heat up LD to simulate for absorbed solar energy and air heater of 2 kW capacity placed in the path of flow of air with controller to achieve desired air temperature. Simulation for absorbed solar energy is obtained by heating of LD using a line heater of serpentine shape provided at the bottom of the basin. A variac is used to control the heat input rate. Energy input is measured by an energy meter and can be set to a desired value depending on solar insolation to be set by reading it from the meter and adjusting using variac. Assuming absorptivity of the basin and transmissivity of glass cover both to be 0.9, solar irradiation can be calculated as:

$$Solar\ Radiation = \frac{Energy\ as\ measured\ by\ the\ energy\ meter\ (W)}{0.81}$$

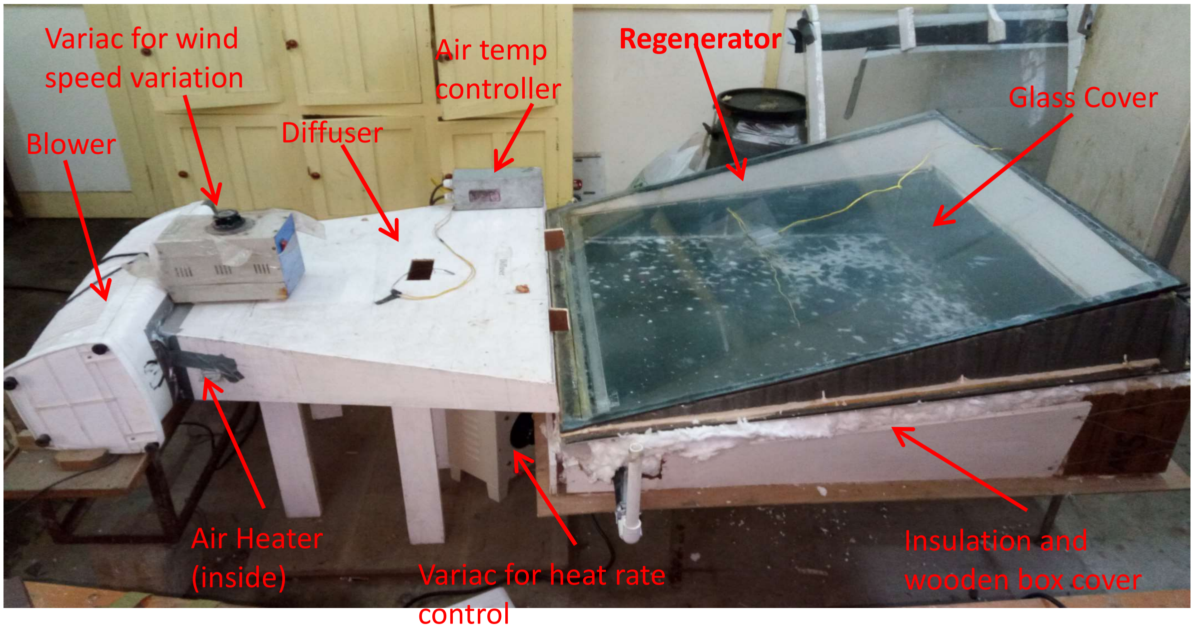


Figure 1: Experimental setup for characterization of passive solar LD regenerator in indoor simulated environment

Simulation for wind blowing over glass cover is obtained by blowing air by a fan having rectangular outlet area using a wooden diffuser. A rectangular slit has been provided in the upper wall of the diffuser to measure the wind velocity using an anemometer. Wind velocity is measured by Testo make anemometer and can be set to a desired value by a variac connected to the fan. Simulation for air temperature is obtained by heating air using an air heater provided in the path of air flow in the diffuser. Air heater has been connected to a temperature controller to get desired air temperature constant throughout the experiment.

Density of LD is found by calculating its specific gravity. This is done by measuring weight of water and LD solution in a glass flask for known volume and finding their ratio. Concentration of LD is calculated by knowing temperature and density of LD and using related formulae. Temperature of LD in the basin is measured using a thermocouple connected to a temperature meter. 4 no of thermocouple are inserted through a hole made in the wall of the regenerator such that they measure temperature at the center of four different segments of the basin. Surface temperature of outer surface of glass is measured using a thermocouple attached to the upper surface of glass and covering it with grey gum tape to avoid absorption of diffuse radiation. Condensate collected is measured using high accuracy weigh balance.

Table 3 shows the list of instruments used for the experimentation.

Table 4: Instruments used for experimentation

Sr No	Parameter	Name of Instrument	Make	Accuracy
1	LD temperature	Temperature meter with thermocouple	Testo – 176 T4 K type	± 0.3 °C
2	Wind velocity	Vane type Anemometer	Testo - 480	±(0.1 m/s, +1.5 % of measured value)
3	Mass of Condensate	Weigh balance	Scale-tec (CWS - 602)	0.01 gram
4	Ambient Temperature	Psychrometer	Rotronic (HL – 1D)	± 0.3°C
5	Power input	Energy meter	Meco	Precision: 1 class

Figure 2 shows the instruments used for experimentation.

Energy meter

Temperature meter

Psychrometer

Vane type anemometer **Weigh Balance**

Figure 2: Instruments used for experimentation

3. Experimental Methodology for characterization of Solar LD regenerator:

a. Known quantity of LD (mass) is kept in the basin. Minimum quantity of LD is to be kept in the basin such that no area of basin is directly exposed and also thermal inertia of the system remains at minimum level.
b. Parameters such as solar insolation, wind velocity and air temperature is set to the desired value. Experiment is continued till steady state is achieved.
c. After achieving steady state conditions, experiment is further continued for an hour and parameters such as LD temperature, glass temperature ambient temperature and condensate collected are measured at the middle and end of an experimental hour.
d. Moisture removed from LD is collected in an air tight measuring cylinder and measured every half an hour. The moisture collected thus is added to the LD in the basin every half an hour after measurement to have constant concentration of LD in the basin throughout the experiment.
e. To change the experiment conditions to a new set of parameters, entire unit is to be allowed to cool to the room temperature and the experiment is to be repeated.

f. To change concentration of LD in the basin, required quantity of water is either added or removed from the LD in the basin. Same amount of LD is either removed or added to have constant mass of LD in the basin.

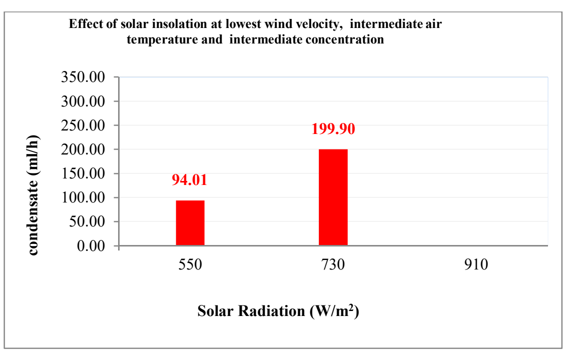
During the last period of evaluation different methodology of experimentation were checked to have best methodology for better results of experiments. This included quasi steady state study to investigate the effects of different parameters on the performance of the regenerator, steady state experiments with putting acrylic sheet or removing it from the glass cover. After studying the results of experiments finally steady state experimental methodology was adopted. Initial 8 steady state experiments were performed on the experimental setup. Other experiments were performed in this period of evaluation.

4. Results and Discussions

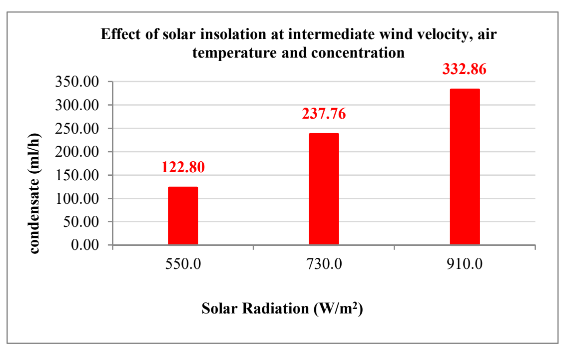
Effects of various parameters on the performance of solar still as LD regenerator is as discussed now.

A. Effect of solar insolation on condensate output

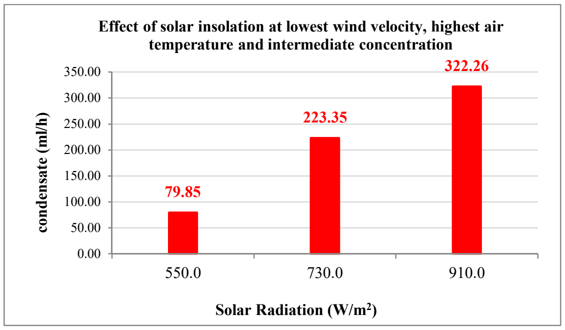
Effects of solar insolation on the performance of solar still as LD regenerator by keeping other variables constant is presented here.



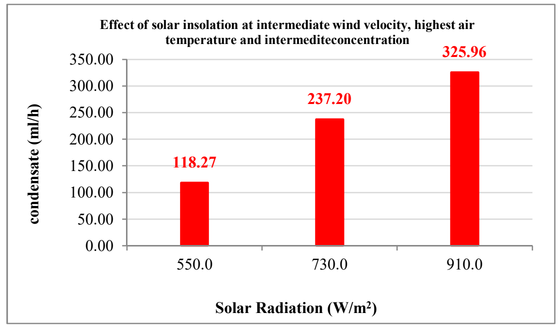
(a)



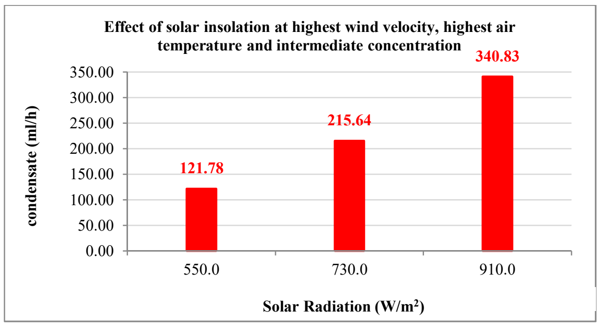
(b)



(c)



(d)



(e)

Figure 2: Effect of Solar insolation on condensate output for varying other parameters

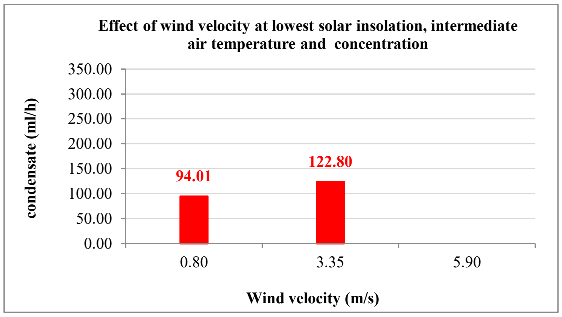
From the charts depicted in figure 1.1 to 1.5 following points can be concluded.

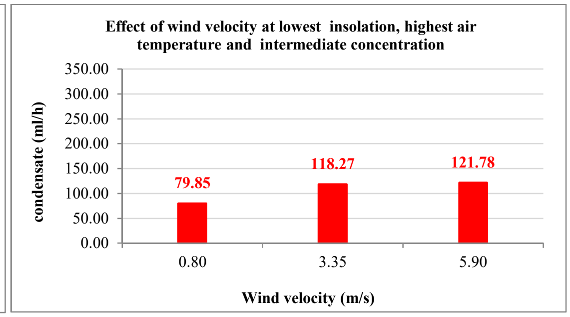
- **i.** Condensate output increases linearly with increase in solar insolation.
- **ii.** Rise in condensate output of the order of 300 % is noted at highest solar insolation, lowest wind velocity and highest air temperature.
- **iii.** Rise in condensate output increases with increase in wind velocity and air temperature. Rise in condensate output is maximum for the case of variation of solar insolation at lowest wind velocity, highest air temperature and average concentration

With increase in solar insolation more energy is available for evaporation of water from LD, so condensate output increases with increase in solar insolation. With increase in wind velocity, convection heat loss from the glass cover increases which reduces the temperature of glass cover increasing temperature difference between glass cover and LD. Temperature difference between glass cover and LD is the driving potential for diffusion of water particles from weak LD solution so condensate output increases with increase in wind velocity.

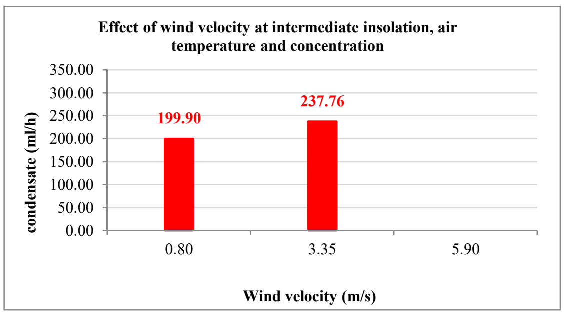
B. *Effect of wind velocity on condensate output*

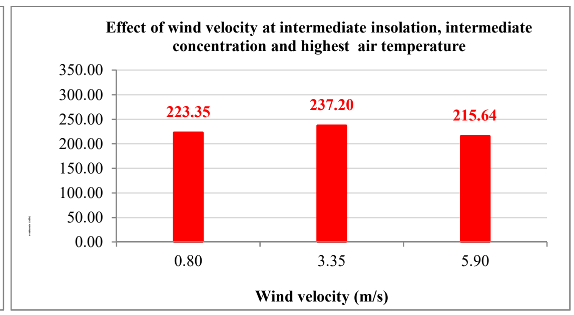
Effects of wind velocity on performance of solar still as LD regenerator is presented here.



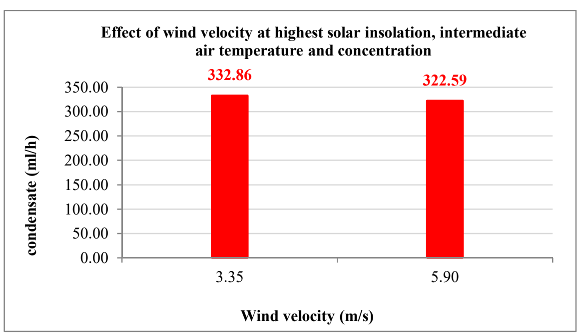


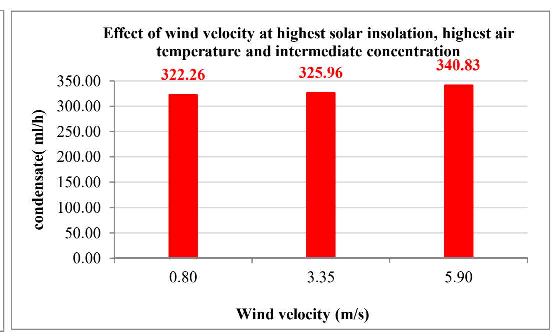
(a) **(b)**





(c) **(d)**





(e) **(f)**

Figure 3: Effect of wind velocity on condensate output for varying other parameters

Following points can be concluded from the charts depicted in figure 2.

- **i.** Condensate output increases with increase in wind velocity in general.
- **ii.** Rise in condensate output increase with increase in air temperature at lower insolation.

iii. Rise in condensate output decreases at intermediate solar insolation.

iv. At intermediate insolation, rise in condensate output decreases with increase in air temperature.

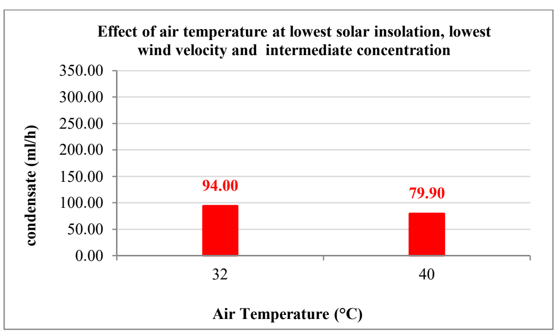
v. At higher insolation effect of wind velocity is very less significant.

vi. Rise in condensate output of the order of 52 % recorded with the increase in wind velocity at lowest insolation and highest air temperature.

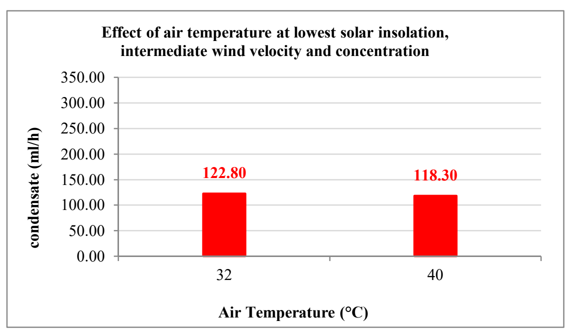
With increase in wind speed, better glass cooling takes place increasing the temperature difference between glass cover and LD which is driving potential for condensate output hence with increase in wind velocity condensate output increases. At intermediate insolation effect of solar insolation on condensate output is predominant which decreases the rise in condensate output by increasing wind speed. At highest insolation, effect of insolation is so predominant that no significant effect of wind velocity is found on condensate output.

C. Effect of air temperature on condensate output

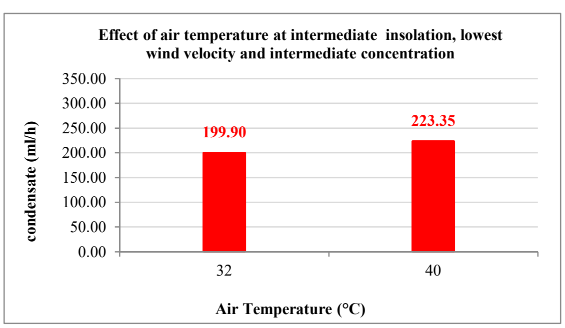
Effects of air temperature on performance of solar still as LD regenerator is presented here.



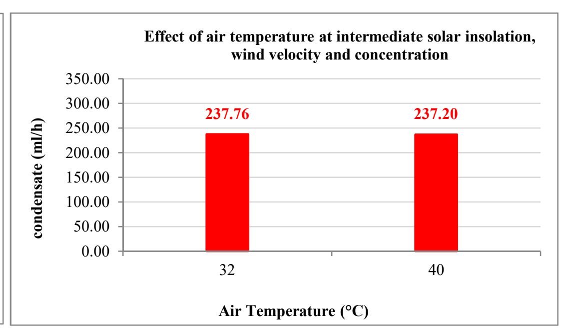
(a)



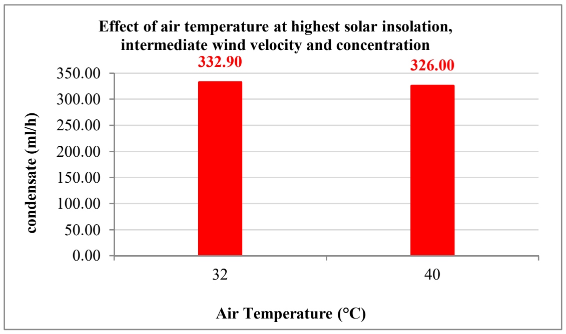
(b)

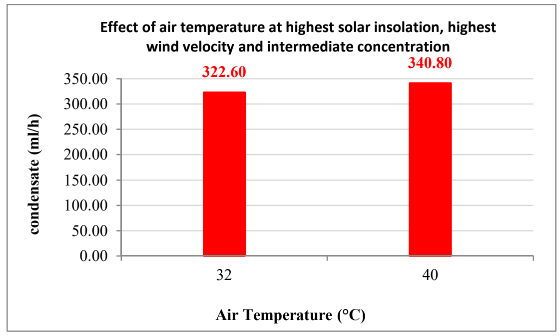


(c)



(d)





(e) **(f)**

Figure 4: Effect of air temperature on condensate output for varying other parameters

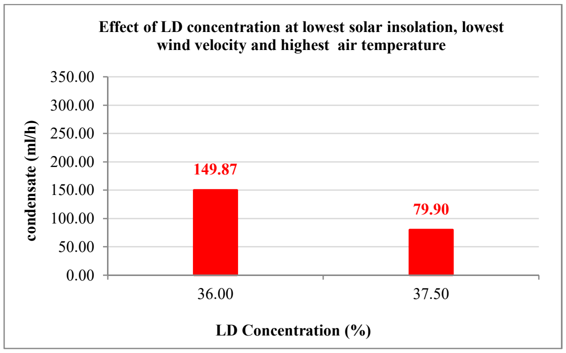
Following points can be concluded from the charts depicted in figure 4.

- **i.** In general, increase in air temperature decreases the condensate output
- **ii.** At lower insolation and lower wind velocity effect of air temperature to reduce condensate output is more but gradually it decreases with increase in wind velocity and insolation and finally at highest insolation and wind velocity it becomes negative. i.e. condensate output increases.
- **iii.** Maximum decrease in condensate output of the order of 15% is found for the case of lowest wind velocity and lowest insolation at intermediate concentration.

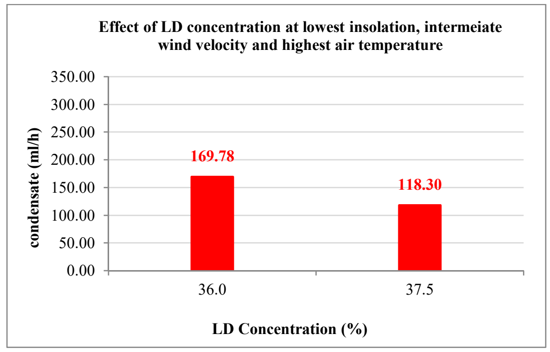
Higher air temperature increases the glass temperature reducing the temperature difference between glass cover and LD which reduces the condensate output. At lower insolation at lower wind speed more time is available for glass heating by increasing air temperature, so effect of reducing condensate output is more at lower insolation and lower wind velocity. At higher insolation and wind speed effect of insolation is more predominant on condensate output. Apart from that higher wind velocity results in more convective heat transfer from glass cover to the ambient reducing its temperature. This combine effect reduces the effect of air temperature to reduce the condensate output and at highest insolation and highest wind velocity effect of air temperature on condensate output becomes negative, i.e. it increases the condensate output.

D. Effect of LD concentration on condensate output

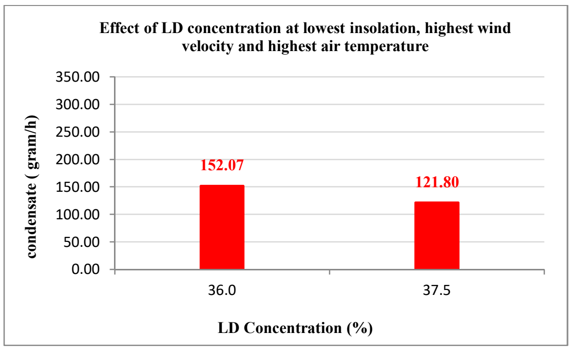
Effects of LD concentration on performance of solar still as LD regenerator is presented here.


Effect of LD concentration at lowest solar insolation, lowest wind velocity and highest air temperature
condensate (ml/h)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
149.87
79.90
36.00
37.50
LD Concentration (%)

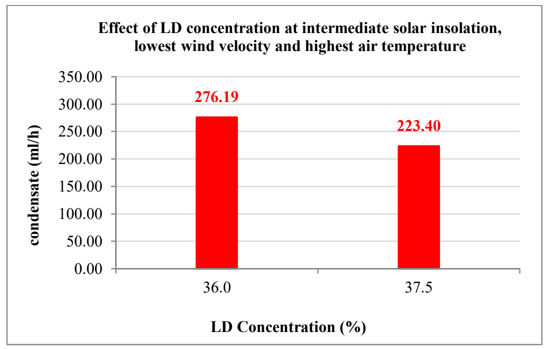
(a)


Effect of LD concentration at lowest insolation, intermeiate wind velocity and highest air temperature
condensate (ml/h)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
169.78
118.30
36.0
37.5
LD Concentration (%)

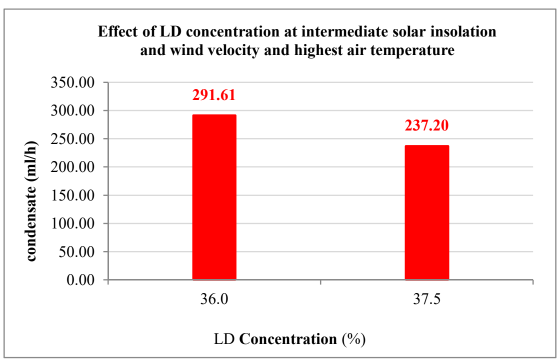
(b)


Effect of LD concentration at lowest insolation, highest wind velocity and highest air temperature
condensate (gram/h)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
152.07
121.80
36.0
37.5
LD Concentration (%)

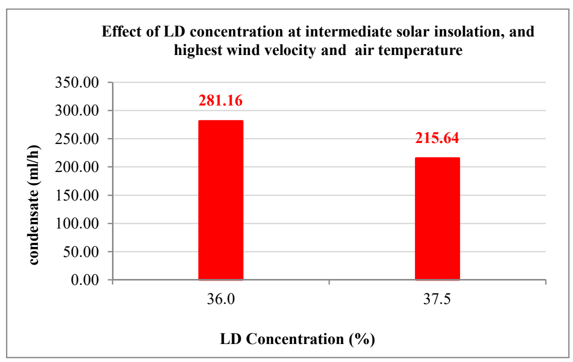
(c)


Effect of LD concentration at intermediate solar insolation, lowest wind velocity and highest air temperature
condensate (ml/h)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
276.19
223.40
36.0
37.5
LD Concentration (%)

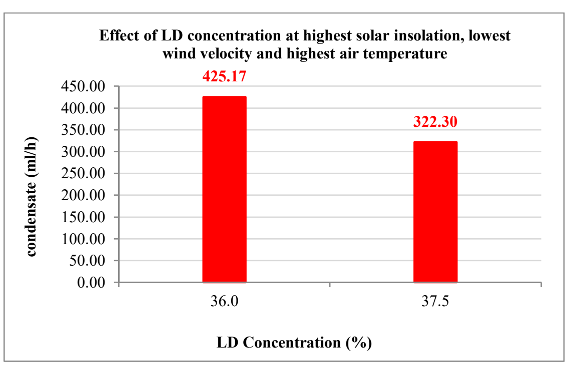
(d)


Effect of LD concentration at intermediate solar insolation and wind velocity and highest air temperature
condensate (ml/h)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
291.61
237.20
36.0
37.5
LD Concentration (%)

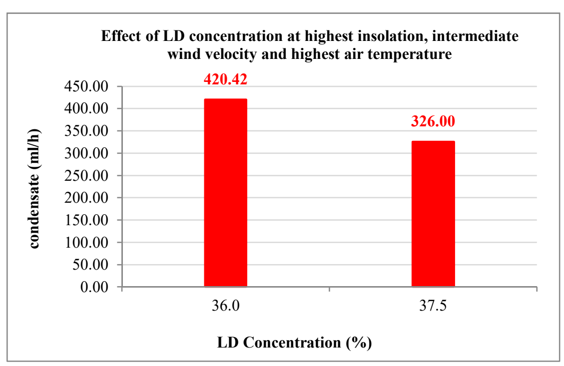
(e)


Effect of LD concentration at intermediate solar insolation, and highest wind velocity and air temperature
condensate (ml/h)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
281.16
215.64
36.0
37.5
LD Concentration (%)

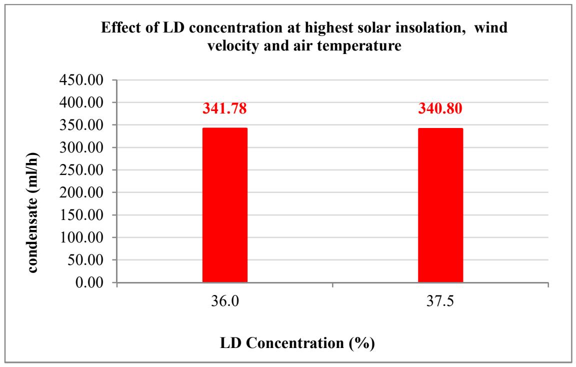
(f)


Effect of LD concentration at highest solar insolation, lowest wind velocity and highest air temperature
condensate (ml/h)
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
425.17
322.30
36.0
37.5
LD Concentration (%)

(g)


Effect of LD concentration at highest insolation, intermediate wind velocity and highest air temperature
condensate (ml/h)
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
420.42
326.00
36.0
37.5
LD Concentration (%)

(h)



(i)

Figure 5: Effect of LD concentration on condensate output for varying other parameters

Following points can be concluded from figure 5

i. In general condensate output decreases with increase in concentration of LD.
ii. Effect of concentration on condensate output decrease at higher solar insolation
iii. At lower insolation, as the wind velocity increases, decease in condensate output decreases.
iv. At intermediate insolation, percentage decrease in condensate remains almost constant with increase in wind velocity.
v. At higher insolation also, percentage decrease in condensate remains almost constant with increase in wind velocity.

As concentration of LD increases vapour pressure of water in LD increases so less amount of diffusion of water particles from LD to glass takes place. Thus, with increase in concentration condensate output decreases. At lower insolation effect of concentration of LD is more, however as insolation increases effect of concentration decreases as effect of solar insolation is more predominant. Wind velocity and concentration of LD has opposite effect on condensate output, hence at lowest insolation when effect of solar insolation is less predominant, effect of concentration to decrease the condensate output decreases with increase in wind speed. However, at intermediate and higher insolation, effect of solar insolation is more predominant hence effect of concentration remains constant with increase in wind speed.

5. Results of parametric investigation reported in literature for solar still as a desalinator:

G N Tiwari et al (2009) developed a mathematical model to carryout parametric study to understand the effect of wind velocity on daily yield of active and passive solar still used as a desalinator. They noted that daily yield increases with increase in wind velocity, reaches a peak value at certain velocity and remains constant. So these results are in confirmation with the results obtained in this work. Garg and Mann (1975) concluded that productivity of solar still increases with increase of total solar radiation, Ambient Temperature and wind speed. A A El. Sebaii (2011) carried out simulation study for a single basin single slopping solar still to understand the effect of wind velocity on daily productivity of solar still. He claimed that yield of solar still increases with increase in wind velocity beyond certain critical mass of water in the basin up to certain specific velocity, beyond this; effect of wind speed is insignificant. For mass of water lower than the critical mass, productivity decreases with increase in wind speed. Cooper (1967) carried out simulation study for a double slopping single basin solar still using FEA to study the effects of parameters: wind speed, ambient temperature, depth of water in the basin. He found that the productivity of the still increases with increase in wind speed and air temperature. Soliman (1972) carried out theoretical and experimental analysis of double sloped single basin solar still to study the effect of wind speed on the performance of the still. He found that yield increases with increase in wind velocity.

6. Conclusion

From the parametric study made following points can be concluded.

- **i.** In general condensate output increases with increase in solar insolation and wind speed and decrease in concentration and air temperature
- **ii.** Effect of solar insolation on condensate output is the most significant than any other parameters.
- **iii.** At higher insolation effect of other parameters decreases.
- **iv.** Effect of air temperature on condensate output is least significant

__________________________End of report_____________________________