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Experimental Investigation Of Desalination Through Evacuated Tube Collector Type Solar Thermal System

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ABSTRACT - water may be a vital substance for mankind. Approximately 97% of the available water within the world is within the oceans. The Polar Regions contain around 2% of the world's water, and only about 1% of the remaining water is water and should be used by humans, animals and plants. Nowadays, scarcity of unpolluted beverage is one among the most concerns of the many countries so as to provide water in dry regions, several technologies are developed. Among these developments, Reverse Osmosis (RO), Vapor Compression (VP) and Electro dialysis (ED) are the foremost common methods. Fossil fuels are often used for this purpose also . However, air and pollution , and limitation of fuel sources are drawbacks that highlight undeniable importance of the renewable energy technologies within the longer term . solar power is popping to a minimum of one among the important kinds of clean energies, because of its availability, and its potential for big choice of applications. during this work, a replacement passive solar desalination system is introduced, which benefits from excellences of evacuated tube collectors , the evacuated tube collector isn't only used because the solar thermal collector, but also as a basin to heat the water. Hence, the thermal resistance between the collector and basin is virtually eliminated.

I. INTRODUCTION

World's water resources include 97% of sea water and three of water . consistent with predictions by the planet Resources Institute, a minimum of 3.5 billion people within the world will likely experience water shortage by 2025. As most of the world's water resources are covered by sea and oceans, desalination is that the best method for producing beverage . However, most of the desalination technologies are expensive and depend upon fossil fuels. the longer term demand for water may successively deplete the fuel reserves thereby increasing greenhouse gas emissions. Hence, the utilization of renewable energies like solar power for powering desalination plants might be a sustainable solution Water is that the fundamental source of life on earth especially the beverage may be a basic necessity for citizenry along side food and air. Although water is abundant on the world but water is scarce. there's acute shortage of fresh beverage in remote and rural areas of the various countries. Reports state that the quantity of water available per person within the world per person was 4000 m3 a year within the early 1950s. Now, the quantity of water available globally has reduced to 1000 m3 per person per annum , which has resulted in water scarcity. The demand for water is growing steadily and is predicted to be one among the most important problems of the planet during this century thanks to unsustainable consumption rates, increase and increasing trend of the agricultural explosion projects.

The presence of high amount of salts and contamination in water from sources like sea, lakes, rivers and underground water reservoir makes it unsuitable to be used directly. at the most places, enough saline water is out there but it's not suitable for drinking and other domestic, agricultural and industrial applications. additionally to quantity of water, there are many places even in urban areas where water is polluted and isn't completely safe for drinking. Most diseases in these areas are caused by polluted water. consistent with the study made by the planet Health Organization (WHO), polluted water and sanitation deficiency are the explanation for 80% of all the diseases which may make an individual unfit, temporarily or maybe permanent. it's estimated that around 500 million people within the developing countries suffer from diseases produced by water. to unravel these problems, new beverage sources should be discovered

DESALINATION OF WATER

Desalination is the process of removal of salts (Sodium Chloride) and other minerals from the brackish water or sea water to make it suitable for human consumption and / or industrial use. It may also be defined as the process of bringing down the salinity of sea-water or brackish water from a high level of total dissolved solids of 35,000 ppm to an acceptable level of 500 ppm.

CONVENTIONAL METHOD OF DESALINATION PROCESS

Besides the problem of water shortage, process energy constitutes another zone of problem. Desalination processes generally require a significant amount of energy. It was estimated that the production of 1 million m3 of desalinated water per day requires 10 million tons of oil annually. Besides the high expenditure of conventional energy resources, uneven exploitation of fossil fuels results in global warming, climatic changes etc. posing a serious threat to the living conditions of mankind as well as plant kingdom and animal kingdom. On the other hand, people are unable to use the existing popular desalination devices to get fresh water because of limited or even no supply of grid – connected electricity.

NEED FOR ENHANCEMENT OF DESALINATION PROCESS

As most of the desalination technologies require electricity to run these devices, there is a dire need to find some desalination systems operating with locally available renewable energy sources. Concern about harm to the environment, heating and global climate change due to exploitation of fossil fuels has also made it necessary to seek out other ways even for urban areas. Due to high expenses of the conventional energy resources, renewable energy sources like the solar energy have gained much attraction; their use in desalination plants will save conventional energy for doing other applications, reduce environmental pollution and supply a free, continuous and low maintenance energy source. Considering the present circumstances, utilization of solar energy for desalination shall be the promising option and best solution for rural as well as urban areas. There are approximately 16,000 operational desalination plants, located across 177 countries, which generate an estimated 95 million m3 /day of freshwater. Currently, desalination accounts for about one-hundredth of the world's beverage . Desalination is especially prevalent in countries located within the Middle East and North Africa region, like Saudi Arabia , the UAE, and Kuwait. Desalination is also an important source of water in small island developing states. Due to its energy consumption, desalinating sea water is usually more costly than water from surface water or groundwater, water recycling and conservation . However, these alternatives are not always available and depletion of reserves is a critical problem worldwide

SIGNIFICANCE OF SOLAR ENERGY

The direct use of solar energy is indeed a gifted option for eliminating the major operating cost of the desalination plant. The easily available solar power is clean, plentiful and renewable. It has been established as low

– carbon technology, which is technically feasible for fresh water production having large potential of saving high – grade energy.

SOLAR DESALINATION

Solar Desalination is a process of separation of pure water from saline water by using solar energy. It is a technique to produce potable water at a lower cost than the other available desalination processes for a certain amount of water produced. It is very costly to create and operate desalination plants. Depending on their location, building a plant can cost from $300 million to $2.9 billion. Once operational, plants require huge amounts of energy. Energy costs account for one-third to one-half of the entire cost of manufacturing desalinated water. Because energy is such an outsized portion of the entire cost, the value is additionally greatly suffering from changes within the price of energy. It is estimated that a 1 cent increase within the cost of a kilowatt- hour of energy raises the value of of 1 acre- foot of desalinated water by $50. Solar desalination is primarily a zero-carbon emission process and the advancements in solar technology enables overcoming previously existing problems like dust and high temperatures, which affected the efficiency of previously used solar panels. In 2011, the Environment Agency-Abu Dhabi (EAD) tested cutting-edge solar technologies for desalinating water in the desert. The trial conducted at 30 sites in the Emirate of Abu Dhabi was said to be the largest across the globe. Each unit set at the solar desalination facilities in Sweihan and Hameem could generate 35 kW/h of energy on the average and thus produce 1050 kW/h of energy on the entire . This shows that the negative impact of desalination process on the environment also because the cost of manufacturing water are often reduced using the solar desalination technology.cannot cross a vacuum, it forms an efficient isolation mechanism to remain heat inside the collector pipes. Since two flat sheets of glass are normally not strong enough to confront to a vacuum, the vacuum is sort of created between two concentric tubes. ETCs are able to do temperatures above 200°C. The air between the 2 glass tubes is removed (or evacuated) to make a vacuum, which reduces conductive and convective heat

ADVANTAGES OF SOLAR DESALINATION

- Solar Desalination is a cheap , effective and environment friendly method over all the traditional distillation methods for getting pure water through the utilization of solar power . • it's one among the technologies with better solution to the matter of energy security and climatic change with almost negligible running cost. • The plants are often found out easily either onshore or offshore. • Low maintenance costs. • Any sort of water are often purified into potable water by means of this process and also the produced water are going to be of top quality

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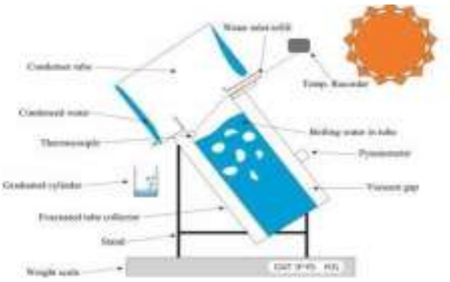
II. LITERATURE SURVEY

1. Solar desalination and up to date developments - Isha Ullah Mohammed G Rasul (2018) water resources are depleting rapidly because the water demand round the world continues to extend . water resources are also not equally distributed geographically worldwide. the simplest because of tackle this instance is to use solar energy for desalination to not only caters for the water needs of humanity, but also to offset some detrimental environmental effects of desalination. A comprehensive review of the most recent literature on various desalination technologies utilizing solar energy is presented here. This paper also highlights the environmental impacts of desalination technologies in conjunction with an economic analysis and price comparison of conventional desalination methods with different solar energy based technologies. the simplest thanks to grapple with this example for humanity is to seek out some alternative means of water production.
2. Literature review on Evacuated Tube Collectors by S.C. Bhatia, in Advanced Renewable Energy Systems, 2014 Evacuated tube collectors are how during which heat loss to the environment, inherent in flat-plates, has been reduced. Since heat loss because of convectionloss.
3. Literature review on current and potential uses of effluents by Jesus Alberto Garcia-Nunez Manuel Garcia-Perez, 2016 Expansion of urban populations and increased coverage of domestic water system and sewerage produce to greater quantities of municipal wastewater. With this emphasis on environmental health and pollution issues, there's an increasing awareness of the need to eliminate these wastewaters safely and beneficially. Use of wastewater in agriculture might be a crucial consideration when its disposal is being planned in arid and semi-arid regions. However it should be realized that the amount of wastewater available in most countries will account for fewer than alittle fraction of the whole irrigation water requirements. Nevertheless, wastewater use will end within the conservation of upper quality water and its use for purposes apart from irrigation. because the marginal cost of other supplies of fantastic quality water will usually be higher in water-short areas, it makes sense to incorporate agricultural reuse into water resources and land use planning.
4. Literature review on Solar ChimneyPower Generation System was presented by a German Professor Schlarich in 1978. A pilot solar chimney power station was constructed at Manzanares, Spain, in 1981. Since then, more and more researchers have shown strong interest in such solar chimney power systems. Moreover, solar chimney may be a promising large-scale power technology that absorbs direct and diffused radiation and produces power without releasing greenhouse gasses.
5. Literature review on The concept of combination of solar chimney and seawater

desalination was proposed by B. A. Kashiwa and C.B. Kas hiwa in 2008 They introduced a theoretical basis for the feasibility of the solar cyclone, suggesting that an experimental study of the separation device would be worthwhile. Akbarzadeh et al. suggested the utilization of a solar pond instead of collector within the solar chimney and built alittle model of that. The thermal energy that's stored at the lowest of the solar pond is used during a tool to heat up the air. Kalogirou did sea water desalination using renewable sources of energy. Nawayseh et al. , Alhazmy , and Zhou et al. did their add getting water production by humidification and dehumidification of sea water. initially Niroomand and Amidpour integrated solar chimney for power generation and seawater desalination.



6. **Khoo and Lee developed the complete solar desalination system consisting of solar collector, chimney, desalination system, and passive condenser system**. The air inside the solar collector is heated up as the solar radiation strikes the solar collector. Hence, the hot air moves from the solar collector to the chimney and rises to the top due to stack effect. Inside the chimney, a sprinkler (mistifier) sprays a fine mist of saline water downwards. The hot air rising up the chimney would then transfer heat by convection into fine water droplets, causing evaporation of the saline water. The water vapour produced will then be carried up and out of the chimney by the air flow from where it will come into contact with a passive condenser and condenses to form fresh liquid water droplets which are collected in an external reservoir. Alvarez et al. designed solar collectors using recycled aluminium cans at an affordable cost

III. 3. PRINCIPLE

In this study, evacuated tube collector (ETC) is employed as a basin. The present system can be classified as a passive solar desalination system. However, the conventional basin is eliminated from the setup and the ETC itself serves as a basins. The ETC absorbs the incoming solar radiation, converting it into heat at the inner absorbing surface, and transfers this heat directly to water inside it by means of natural convection and causes it to evaporate. Hence, there is no thermal resistance between the collector and the conventional basin as proposed by previous researchers. Therefore, a higher rate of production is expected.

IV. PROCESS OPERATION

The Process involves all three modes of heat transfer. The solar radiations falling on the evacuated tube collectors, In this experiment as we have mentioned, the evacuated tube collectors not only act as the solar thermal collector but also as the basin, where the effluent (unpotable water) is stored. This leads to rise in temperature of the effluent and the effluent begins to evaporate. The combination of reduction in density and surface tension causes effluent vapor (steam) to flow upwards and get collected in the condenser tank, the condenser thereby causes condensation and breaks down the evaporated effluent into tiny droplets of potable water. The collecting jar fixed adjacent to the condenser collects the tiny water droplets dripping from the condenser. This methodology signifies the difference in having the thermal resistance between the collector and basin in conventional solar desalination process like flat – plate method and the evacuated tube collector method of solar desalination where the collectors and the basin are one and the same, thus virtually eliminating the thermal resistance

V. ECONOMICS

Compared to purchasing comparable quantities of bottled water, the average return on investment on a Evacuated Tube collector set – up (ETC) for a family is typically a couple of years. Factoring in the health costs of contaminated water, payback for a ETC can be immediate. Solar distillation is the cheapest way to clean water for a household and is quite economical as compared to reverse osmosis and electric distillation. A square meter for a ETC set – up as on today costs about Rs.30,000/-. Many families often spend around Rs.500/- per week on bottled water and Rs.300/- per week on purified water. This represents an investment on anywhere from Rs.10,000/- to Rs.40,000/- per year for bottled water. Thus Simple Pay-back Period on a Solar Still strictly compared to purchasing bottled water is typically within 2 to 3 years.

The presented high performance solar desalination device can be a very economical, cost effective, minimum maintenance and the zero energy cost option. Moreover there is no pollution involved.

VI. DIMENSIONS OF THE SET – UP

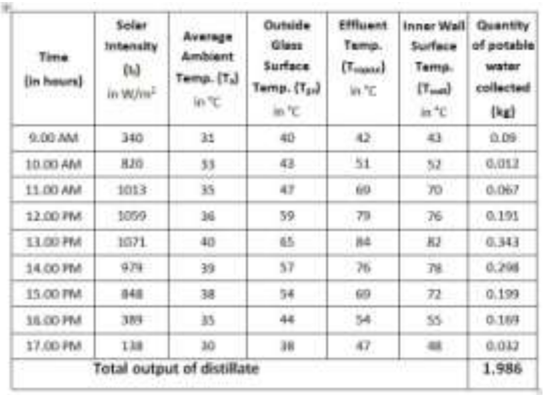
1. Length of the evacuated tubes 1820 mm
2. Inner diameter of the glass tube 47 mm
3. Outer diameter of the glass tube 57 mm
4. Condenser zone Outer diameter 58 mm
5. Condenser zone Inner diameter 48 mm
6. Condenser zone length 650 mm

VII. COST ANALYSIS

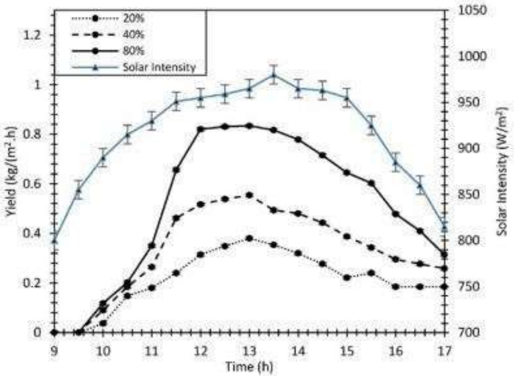
The overall cost of the Evacuated tube collector set – up at an inclination angle of 35 ° came to about 30,000 INR, the set – up at usual times would have costed about 20 – 25,000 INR but due to the coronavirus pandemic which resulted in shortage of parts and to have the work time squeezed between the curfew due to the lockdown, the production and labor cost for the proposed set – up was higher but higher as expected , the fabrication of the solar evacuated tube collector set – up was done by Chennai Solar energy systems , No. 121 – c , SIDCO Women industrial park , Kattur , Chennai –62

VIII. PERFOMANCE ANALYSIS

The experimental observation was carried out for a period of 3 days continuously i.e. (26.03.2021 , 27.03.2021, 28.03.2021) On all the days of experimentation, recordings were carried out for a frequency of every one hour from morning 9:00 AM till evening 5:00 PM. In the beginning at 9:00 AM, the solar intensity is low and temperature of glass cover started rising above atmospheric temperature. In the evening towards 5:00 PM, the temperature of inner surface of the glass cover will approach atmospheric temperature. Experimental observation of solar desalination using Evacuated tube collector type solar thermal system on (26.03.2021)



Time (in hours)	Solar Intensity (I_t) in W/m²	Average Ambient Temp. (T_a) in °C	Outside Glass Surface Temp. (T_{go}) in °C	Effluent Temp. (T_{output}) in °C	Inner Wall Surface Temp. (T_{wall}) in °C	Quantity of potable water collected (kg)
9.00 AM	340	31	40	42	43	0.09
10.00 AM	820	33	43	51	52	0.012
11.00 AM	1013	35	47	69	70	0.067
12.00 PM	1059	36	59	79	76	0.191
13.00 PM	1071	40	65	84	82	0.343
14.00 PM	979	39	57	76	78	0.298
15.00 PM	848	38	54	69	72	0.199
16.00 PM	389	35	44	54	55	0.169
17.00 PM	138	30	38	47	48	0.032
Total output of distillate						1.986



IX. HEAT TRANSFER CALCULATIONS

The heat transfer in solar distillation systems can be classified in terms of external and internal modes. The external heat transfer mode is primarily governed by conduction, convection and radiation processes which are independent on one another. This heat transfer occurs outside of the solar still from the glass cover, bottom and side surfaces of the still through insulation. Heat transfer within the solar still is referred as internal heat transfer mode which consists of radiation, convection and evaporation (diffusion). In this case, convective heat transfer occurs simultaneously with evaporative heat transfer and these two heat transfer processes are independent on radiation heat transfer. Heat transfer between the evaporating surface and the glass cover is controlled by free convection, evaporation, and radiation. Hence the understanding of these modes of heat transfer is essential for the prediction of the performance of any solar still.

HEAT TRANSFER COEFFICIENTS BY DUNKLE'S MODEL

It is very important to know accurately the heat and mass transfer processes in basin type solar stills for improving their performance. Dunkle (1961) proposed a group of complete heat and mass transfer correlations based on a modified Grashoff number to express the operating processes of basin type solar stills. Most of the work done on solar stills has used the expressions for internal heat transfer coefficients as developed by Dunkle under simulated conditions.

$$Nu = \frac{h_{cw} d_f}{K_f} = C\, Gr.Pr()^{n}$$

$$Nu = C\, Ra^{n} = 0.075 Ra^{1/3} \qquad (10.1)$$

In the above said free convection correlation, Dunkle used coefficients as C = 0.075 and n = 0.33. The main drawback of the analysis developed by Dunkle and used by other investigators is due to two assumptions:

1. Free convection in the still may be described by equation (10.1) originally developed for free convection of air without evaporation.
2. The use of the constant 0.0163 in the relationship between $h_{c\ w\text{-}gl}$ and $h_{eva\ w\text{-}gl}$ is valid only at the operating temperature of the saline in the still is less than 50° C (T_w< 50°C).
3. It is valid for the temperature difference of 2°C between evaporative and condensing surfaces.

Internal Heat Transfer Coefficients

The convection heat transfer occurs from the airvapour mixture to the glass. Evaporation occurs from the water to the air-vapour mixture. The condensation heat transfer occurs from the air-vapour mixture to the glass. At the steady state, the evaporation rate and the condensation rate are supposed to be equal. Thus, there are three modes by which the internal heat transfer within the still is governed. The heat exchange between evaporative surfaces i.e., water and inner surface of the glass cover inside the distillation unit is known as internal heat transfer.

The internal heat transfer that is heat exchange from the water surface to the glass cover is governed by three modes viz., radiation, convection and evaporation and hence the total internal heat transfer coefficient from water to glass will be the sum of all these heat transfer coefficients by each mode. These heat transfer modes are discussed separately.

Radiation heat transfer: In this case, the water surface and the glass cover are considered as infinite parallel plane under the assumption of small inclination of the glass cover. The rate of radiation heat transfer from the water surface to the glass cover is given by qr w-gl eff (Tw

$$+273)^4 - \left(T_{gl} + 273\right)^4 □□□ \qquad (10.2)$$

$$q_{r\,w\text{-}gl} = h_{r\,w\text{-}gl}\left(T\ T_w - {}_{gl}\right)$$

(10.3)

For conventional still: average saline water temperature

$$h_{r\,w\text{-}gl} = □\ □_{eff}□□□\left(T\ 273_w + \right)^2 + \left(T\ 273_{gl} + \right)^2 □□□\left(T\ T\ 546_w + {}_{gl} + \right)$$

(10.4)

For conventional still: average saline water temperature $= 61^\circ C$

Average basin temperature $= 63^\circ C$; Average ambient temperature $= 35^\circ C$ and

Average glass cover inner surface temperature $=$

$$56.8^\circ C \quad {}_{r\,w\text{-}gl} \qquad {}^{-8}□□\left(61 + 273\right)^2 + \left(56.8 + 273\right)^2$$

$$□□\left(61+56.8+546\right) = 7.4\ \mathrm{m\ KW}_2$$

$$h = 1\ 5.6\ 10\ □ \qquad □$$

Convective heat transfer: Heat transfer occurs across humid air in the still from the water surface to the glass cover by free convection, which is caused by the effect of buoyancy due to density variation in the humid fluid which occurs due to the temperature gradient in the fluid. Hence the rate of heat transfer from the water surface to the glass cover by convection in the upward direction can be calculated as

$$q_{c\,w\text{-}gl} = h_{c\,w\text{-}gl} \left(T\ T_w - {}_{gl} \right)$$

(10.5)

$h_{c\,w\text{-}gl} d_f$ $\quad {}_n \quad Nu \quad =$

$\underline{\qquad\qquad} = C\ \ Gr\ \ Pr\Big($

$\Big)$

K_f

(10.6)

$$Gr = g\square\square\ \square_2 d\ T_{23f}$$

$\square_f$

(10.7)

$$Pr = \square C_{Pf}$$

K_f

(10.8)

$\square \left(P_w - P_{gl}\right)\left(T_w + 273\right)\square \quad \square = T\ \square\square\square\left(T_w\right.$

$\left. - T_{gl}\right) + \underline{\qquad\qquad\qquad} 268.9\ 10\square - P_w \quad \square\square\square$

(10.9)

Grashoff number depends on the average spacing between the water and the glass cover. In equation (12.6), C and n are constants depending on the Grashoff number. For the normal operating temperature range of 50°C and d$_f$ = 0.25 m, Dunkle had taken C = 0.075 and n = 0.33 and Dunkle derived the following expression for convection heat transfer coefficient hc w-gl.

Grashoff number can be calculated using equation (3). The physical properties of the humid air are calculated from the average film temperature of the air vapour mixture, T$_f$.

$$T_f = \frac{T\ T_w + {}_{gl}}{2}$$

(10.10)

$$C_P = 999.2 + 0.1434\ T_f + 1.101\ 10\square{-}_4 T_{2f} - 6.7581\ 10\ \square\ {}_{-8}T_{f3}$$

(10.11)

Thermal conductivity $= = K \quad 0.0244 + 0.7673\ 10\,\square T_f$

(10.12)

Viscosity $= \square = 1.718\ 10\square^{5} + 4.62\ 10^{-8}\square T_f$

(10.13)

353.44 Density $= \square =$

$$\frac{}{T_f + 273.15}$$

(10.14)

1 Expansion

factor $= \square = \dfrac{}{T_f + 273.15}$

(10.15)

Grashoff number depends on the average spacing between the water and the glass cover. In equation (12.6), C and n are constants depending on the Grashoff number. For the normal operating temperature range of 50°C and $d_f = 0.25$ m, Dunkle had taken C = 0.075 and n = 0.33 and Dunkle derived the following expression for convection heat transfer coefficient $h_{c\,w\text{-}gl}$.

$$h_{c\,w\text{-}gl} = 0.884\left[(T_w - T_g) + \frac{(P_w - P_{gl})(T_w + 273)}{268.9\ 10^3 - P_w}\right]^{1/3} \tag{10.16}$$

Evaporative heat transfer: Evaporation of water from the water surface is the function of convection heat transfer. So the evaporation heat transfer coefficient (mass transfer coefficient) heva w-gl from the water surface to the glass cover is derived in terms of convection heat transfer coefficient h_c w-gl by Baum (1963).

$$\frac{h_{c\,w\text{-}gl}}{h_{eva\,w\text{-}gl}} = \frac{h\,M\,1_{fg}\ _w}{C\,M\,P_{Pa}\ _a\ _T} \tag{10.17}$$

The rate of evaporation heat transfer per unit area from the water surface to the glass cover can be obtained by substituting the appropriate values for the parameters in equation (12.11) as follows:

$$q_{eva\ w\text{-}gl} = 0.0163 h_{c\ w\text{-}gl} \left(P_w - P_{gl}\right) \qquad (10.18)$$

Equation (10.12) can be rearranged as

$$q_{eva\ w\text{-}gl} = h_{eva\ w\text{-}gl} \left(T_w - T_{gl}\right) \qquad (10.19)$$

From equations (12.12) and (10.13)

$$h_{eva\ w\text{-}gl} = 0.0163 h_{c\ w\text{-}gl} \frac{\left(P_w - P_{gl}\right)}{\left(T_w - T_{gl}\right)} \qquad (10.20)$$

$$h_{eva\ w\text{-}gl} = 0.0163 \times 1.957 \times \frac{\left(0.2086 - 0.16511\right) \times 10^5}{\left(61 - 56.8\right)} = 27.71 \frac{W}{m^2 K}$$

The value of $h_{eva\ w\text{-}gl}$ can be more realistic for larger values of $(T_w - T_{gl})$. The values of P_w and P_{gl} can be obtained from the expression

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273}\right] \qquad (10.21)$$

Thus total internal heat transfer coefficient obtained by combining the equations (10.4), (10.10) and (10.14), called overall heat transfer coefficient from the water surface and the glass cover due to the combined effect of convection, evaporation and radiation is given as

$$U_{o\ w\text{-}gl} = \left(h_{c\ w\text{-}gl} + h_{eva\ w\text{-}gl} + h_{r\ w\text{-}gl}\right)$$

(10.22)

$$U_{o\ w\text{-}gl} = \left(1.957 + 27.71 + 7.4\right) = 37.1 \frac{W}{m^2 K}$$

(10.23)

$$\frac{h_{c\ b\text{-}w} X}{K_w} = Nu = 0.54\left(Gr\ Pr\right)^{0.25}$$

(10.24)

For mean film temperature of water and basin liner T_{fw} is calculated to find the physical properties of water

$$T_{fw} = \frac{T_b + T_w}{2} = \frac{63 + 61}{2} = 62C$$

Physical properties of water at 62˚C are:

$\rho = 983.9\ kg/m^3$; $\nu = 0.466 \times 10^{-6}\ m^2/sec$; $K_w = 6.53 \times 10^{-3}$ W/m K; Pr = 2.94

$C_{p\,w} = 4184.2$ J/kg K; $\beta = 1/T_{fw} = 1/335 = 2.985 \times 10^{-3}$ X = 1m; $\Delta T = 2$˚C From equation (6.24), Gr. Pr $= 7.9 \times 10^{11}$

$$h_{c\ b\text{-}w} = 0.54\left(7.9 \times 10^{11}\right)^{0.25} \frac{0.653}{1} = 332 \frac{W}{m^2 K}$$

Similar to the above said procedure, internal heat transfer coefficients for the modified regenerative still with gravel are also calculated and given below

Convection heat transfer coefficient of water with glass cover $h_{c\ w\text{-}gl} = 1.79\ W/m^2\ K$

Evaporation coefficient of water with glass cover heva w-gl = 23.85 W/m2K

Radiation heat transfer coefficient of water with glass cover $h_{r\ w\text{-}gl} = 6.6\ W/m^2\ K$

Overall heat transfer coefficient of water with the glass cover $U_{o\ w\text{-}gl}$ is given as

$$U_{o\ w\text{-}gl} = \left(1.79 + 23.85 + 6.6\right) = 32.24 \frac{W}{m K_2}$$

Similarly convection coefficient of gravel to water hcg- w is calculated for the average temperatures of gravel and water. For mean film temperature of water and gravel Tf g-w is calculated to find the physical properties of water

$$T_{fwg} = \frac{T_g + T_w}{2} = \frac{61 + 59}{2} = 60C$$

Physical properties of water at 60˚C are:

$\rho = 985$ kg/m³ ; $\nu = 0.478 \times 10^{-6}$ m²/sec; $K_w = 651 \times 10^{-3}$ W/m K; Pr = 3.02

$C_{p\,w} = 4183.2$ J/kg K; $\beta = 1/T_{fwg} = 1/333 = 3 \times 10^{-3}$ X = 1m; $\Delta T = 2$˚C From equation (12.24), Gr Pr = 7.7×10^{11}

$$h_{gw} = 0.54\,(7.7 \times 10^{11})^{0.25}\; 0.651 = 300\ \frac{W}{m^2 K}$$

External Heat Transfer Coefficients

External heat transfer occurs outside of the solar still from the glass cover, bottom and side surfaces of the still through insulation. From the glass cover heat loss occurs by convection and radiation independently to the ambient air. Latent heat of condensation released due to condensation of water vapour tends to heat the glass cover. As heat capacity of the glass cover is less than the air (CP gl = 800 J/kg K), the glass cover is heated reducing the condensation. Therefore to improve the efficiency of the still that latent heat of condensation has to be reused for additional evaporation of saline water.

Overall heat transfer coefficient from basin to ambient air through bottom and sides of the basin due to combined effect of conduction and convection can written as

$$U_{oba} = \left[\frac{1}{h_{cbw}} + \frac{L_{ins}}{K_{ins}} + \frac{L_w}{K_w} + \frac{1}{h_{cba}}\right]^{-1} \qquad (10.25)$$

$$U_{oba} = \left[\frac{1}{3321} + \frac{0.0125}{0.052} + \frac{0.037}{0.04} + \frac{1}{1.51}\right]^{-1} = 0.504\ \frac{W}{m^2 K}$$

Convective heat transfer coefficient:

Heat transfer from the glass cover to ambient air by convection is considered as forced convection if air is blown over the glass cover with velocity of V m/sec. Then the empirical relation is

Top Loss Coefficient: Due to small thickness of the glass cover, the temperature in the glass may be assumed to be uniform. The external heat transfer by radiation and convection losses from the glass cover to outside ambient air can be expressed as

$$q_{gl\,a} = q_{r\,gl\,a} + q_{c\,gl\,a}$$

(10.26)

$$_{r\,gl\text{-}a} = □\ □_{eff}□□(T_{gl} + 273)_4 - \left(T_a + 273\right)_4 □□$$

q

(10.27)

$$q_{r\,gl\,a} = h_{r\,gl\text{-}a}\left(T\,T_{gl} - {}_a\right)$$

(10.28)

$h_{r\,gl\text{-}a}$ is the radiation heat transfer coefficient from the glass cover and ambient air given as

$h_{r\,gl\text{-}a} = □$	$□_{eff}□□□$	$\left(T\ 273_{gl} +\right.$	$\left.\right)_2 + \left(T\ 273_a +\right.$	$\left.\right)_2 □□□$	$\left(T\,T\ 546_{gl}\right.$
$+\ _a +$	$\left.\right)$		(10.29)		

It is noted that as the glass cover radiates heat to the atmosphere, the effective shape factor from a small object to a large enclosure is 1. $_{10^{4}}\ ^{-8}\ □□(56.8+273)^2 + (35+273)^2$

$□□(56.8+35+546) = 0.736_{m}\ KW_2$

$h \quad = 1\ 5.67\ 10□ \qquad □$

Convective heat transfer coefficient: Heat transfer from the glass cover to ambient air by convection is considered as forced convection if air is blown over the glass cover with velocity of V m/sec. Then the empirical relation is

$$h_{c\,gl\text{-}a} = +2.8 \qquad 3.0^{V}$$

(10.30)

Hence the rate of heat transfer from the water surface to the glass cover by convection in the upward direction can be calculated as

$$q_{c\,gl\text{-}a} = h_{c\,gl\text{-}a}\left(T_{gl} - T_{a}\right)$$

(10.31)

The convection coefficient can be obtained from the convection correlation

$$h^{c}{}^{gl\text{-}a}X \qquad {}_{a}Nu =$$

$$\underline{\qquad\qquad} = C\,Gr$$

$$Pr\Big(\qquad\Big)$$

$$K_{a}$$

(10.32)

$$Gr = \frac{g^{\square\square}\ \square_{2\,3} X\ T}{\square}{}^{2}$$

(10.33)

$$Pr = \frac{\square C_{pa}}{K_{a}}$$

(10.34)

Convection correlation for the upward direction from a horizontal surface to air is given a

$$Nu = 0.15(Gr\ Pr)^{0.33}\ \text{for} 8\ 10\ □\ □^{6} \qquad GrPr$$

$$□10^{11} \qquad (10.35)$$

Grashoff number can be calculated using equation (12.33). The physical properties of the ambient air are calculated from the average film temperature between the glass cover temperature and ambient temperature $T_{f\ amb.}$

$$T_{f\,a} = \frac{T_{gl} + T_{ava\,a}}{2} = \frac{56+35}{2} = 45.5\,C$$

(10.36)

Mean film air temperature between glass cover and ambient air $T_{f\,a}$ can be calculated from the glass cover temperature T_{gl} and average ambient temperature $T_{ava\ a}$

Physical properties of air are taken from Tables for the mean film temperature as $\rho = 1.107$ kg/m^3; $\upsilon = 17.56 \times 10^{-6}$ m^2/sec; Pr = 0.698; $K_a = 27.58 \times 10^{-3}$ W/m K; $\beta = 1/T_{f\,a} = 1/319 = 3.13 \times 10^{-3}$ 1/K; X= 1 m; $\Delta T = 20^{\circ}$C

From equations (12.33) and (12.34), Gr. Pr = 1.39 × 10^9

$$h_{c\ gl\text{-}a} = 0.15\ 1.39\ 10(□\ _{9})_{0.333}\ 27.58\ 10□\ _{-3} = 4.58\ \underline{\qquad} m$$

KW$_2$

Total top loss coefficient or Overall heat transfer coefficient of glass cover to ambient air is the combination of convection and radiation heat transfer coefficients.

$$U_{o\ gl\text{-}a} = h_{c\ gl\text{-}a} + h_{r\ gl\text{-}a} = 4.58 + 0.736 = 5.316\frac{W}{m\,K^{2}}$$

X. CONCLUSION

A new simple, still efficient solar desalination system was presented. The innovation of using evacuated tube collector (ETC) to directly transfer the heat to the salty water improves the performance of the desalination system. A remarkable increase in the hourly yield of the current study in comparison with previous studies was seen. Implementing ETCs for direct heat transfer to the water and eliminating a need for separate basin, reduce the heat loss to the surroundings and enhance the efficiency of the absorbed solar radiation. The present study showed that the highest rate of production is obtainable when the tube is 80% filled with water and lower filling ratios of the tube adversely affect the heat transfer in the tube. The effect of the inclination angle of the ETC on the performance of the present system was also investigated. It was shown that decreasing the inclination angle decreases the performance of the system and the optimum inclination angle is 35°, which is the latitude of the location of experiments. However, it was demonstrated that deviations from the optimum angle rapidly decreases the yield. In situations in which the angle is smaller than the optimum angle, bubble migration is decelerated, and therefore bubbles migration to the surface and rate of evaporation decreases. Finally, proposed theoretical results were compared to the experimental data obtained around solar noon. This comparison presented a good agreement, indicating that the model is suitable for the proposed analysis.

REFERENCES

[1] K.V. Kumar, R.K. Bai, Performance study on solar still with enhanced condensation, Desalination 230 (2008) 51–61.
[2] G. Tiwari, A.K. Tiwari, Solar Distillation Practice for Water Desalination Systems, Anshan Pub, 2008.
[3] M. Thirugnanasambandam, S. Iniyan, R. Goic, A review of solar thermal technologies, Renew. Sust. Energ. Rev. 14 (2010) 312–322.
[4] A. Kabeel, S. El-Agouz, Review of researches and developments on solar stills, Desalination 276 (2011) 1–12.
[5] A. Singh, G. Tiwari, P. Sharma, E. Khan, Optimization of orientation for higher yield of solar still for a given location, Energy Convers. Manag. 36 (1995) 175–181.
[6] S. Rai, G. Tiwari, Single basin solar still coupled with flat plate collector, Energy Convers. Manag. 23 (1983) 145–149.
[7] O. Badran, H. Al-Tahaineh, The effect of coupling a flat-plate collector on the solar still productivity, Desalination 183 (2005) 137–142.
[8] S. Kumar, G. Tiwari, H. Singh, Annual performance of an active solar distillation system, Desalination 127 (2000) 79–88.
[9] K. Sanjeev, G. Tiwari, Optimization of daily yield for an active double effect distillation with water flow, Energy Convers. Manag. 40 (1999) 703–715.
[10] A. Singh, G. Tiwari, Thermal evaluation of regenerative active solar distillation under thermosyphon mode, Energy Convers. Manag. 34 (1993) 697– 706.
[11] S. Kumar, A. Tiwari, Design, fabrication and performance of a hybrid photovoltaic/ thermal (PV/T) active solar still, Energy Convers. Manag. 51 (2010) 1219–1229.
[12] L. García-Rodríguez, C. Gómez-Camacho, Design parameter selection for a distillation system coupled to a solar parabolic trough collector, Desalination 122 (1999) 195–204.
[13] H. Tanaka, Y. Nakatake, A vertical multipleeffect diffusion-type solar still coupled with a heatpipe solar collector, Desalination 160 (2004) 195– 205.
[14] R. Dev, S.A. Abdul-Wahab, G. Tiwari, Performance study of the inverted absorber solar still with water depth and total dissolved solid, Appl. Energy 88 (2011) 252–264.
[15] K.K. Murugavel, K. Srithar, Performance study on basin type double slope solar still with different wick materials and minimum mass of water, Renew. Energy 36 (2011) 612–620.
[16] R. Dev, G. Tiwari, Annual performance of evacuated tubular collector integrated solar still, Desalin. Water Treat. 41 (2012) 204–223.
[17] K. Sampathkumar, T. Arjunan, P. Senthilkumar, The experimental investigation of a solar still coupled with an evacuated tube collector, Energy Sources, Part A 35 (2013) 261–270.
[18] H.K.S. Abad, M. Ghiasi, S.J. Mamouri, M. Shafii, A novel integrated solar desalination system with a pulsating heat pipe, Desalination 311 (2013) 206– 210.
[19] H. Kargarsharifabad, S.J. Mamouri, M. Shafii, M.T. Rahni, Experimental investigation of the effect of using closed-loop pulsating heat pipe on the performance of a flat plate solar collector, J. Renewable Sustainable Energy 5 (2013) 013106.
[20] S.J. Mamouri, H.G. Derami, M. Ghiasi, M.

Shafii, Z. Shiee, Experimental investigation of the effect of using thermosyphon heat pipes and vacuum glass on the performance of solar still, Energy 75 (2014) 501–507.

[21] K. Sampathkumar, T. Arjunan, P. Pitchandi, P. Senthilkumar, Active solar distillation—a detailed review, Renew. Sust. Energ. Rev. 14 (2010) 1503– 1526.)