Multiple Effect Vertical Diffusion Stills – AReview

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***Abstract*- Availability of good quality drinking water is becoming a serious global problem. The situation is worse in electricity deficient and non-electrified areas. Therefore, economical and indigenous technologies are required to suit local conditions. Solar distillation is the earliest water purification technique that produces ultrapure water. However, due to the low productivity of solar stills, potable water is far from the reach of the common man. With the advent of Multiple Effect Diffusion Still (MEDS), researchers have been able to solve this problem to an extent. MEDS is not only capable of producing high yield but it also produces distillate efficiently. This paper presents a critical review of various designs of Multiple Effect Diffusion Stills.**

Keywords: Multiple Effect Diffusion, Solar Distillation, Vertical Solar Still.

Nomenclature:

D_i = Rate of distillate per unit area produced in i-th effect, kg/m^2-h

F = feed to the still (kg/m^2 h)

$L_{i,e}$ = latent heat of water at the evaporating temperature of i-th effect, J/kg

M_B = molecular weight of binary (two component) system

M_w = molecular weight of water

P_T = total pressure, psi

P_w = partial pressure of water vapour, psi

Q_{ei} = rate of heat transfer by evaporation (per unit area) in the i-th effect, W/m^2

R = gas constant

T = Temperature, R

T_H = temperature of the hot water supply to the still,

V_B = molecular volume of binary (two component) system

V_w = molecular volume of water

W_w = rate of diffusion of water vapour (lb/hr ft^2)

I. INTRODUCTION

The water consumption is doubling every 20 years, worldwide, outpacing by two times the rate of population growth. While the availability of potable water is on the decline, the demand for water is on the rise. Shortages of water and unreliable water quality are considered major obstacles to achieving sustainable development and improvement in the quality of a healthy life. The demand for water is increasing rapidly due to continuously increase in demand for water for irrigation, rapid industrialization and civilization, improving living standards and population growth whereas the existing resources of water are depleting. Major reasons for this shortage are

- Insufficient rain and occasional drought due to deforestation.
- Excessive tapping of groundwater sources and its irregular &incomplete replenishment by rainwater.
- Deterioration in quality of water due to the pollution of water caused by domestic and industrial effluents.

This is resulting in deep shortages of water or era of famine. Desalination is recognized as one of the best possible means to enhance the water supply using natural resources for meeting the rapidly increasing demand for water.

The quality of water is measured in terms of TDS, i.e. total dissolved solids. Seawater, saline water and healthy potable water have a different TDS/salinity level. Water containing TDS concentration of less than 500 mg/L is considered as good quality drinkable water. An average TDS concentration of seawater is around 35,000 mg/L whereas any water having TDS concentration between the two is considered as saline water.

Saline water of having low TDS, i.e. salinity between 500 to 1000 mg/L is categorized as wastewater. The reclaimed water from wastewater can be used for irrigation, as cooling water and for industrial purposes and for some domestic applications. Since the projected industrial and irrigation requirements would be far exceeding that of domestic requirements, recycle and reuse of wastewater apart from desalination make enormous sense for future water management.

Therefore, a universal approach is required to be considered to confront with the scarcity of fresh water. It includes wastewater treatment as well as:

- Seawater desalination in coastal areas
- Saline water desalination in remote locations,
- Purification of water,
- Wastewater reuse,
- Rainwater harvesting, and
- Water supply schemes.

Purification of water, desalination, and wastewater reuse schemes are destined to play a major role. Therefore, commercially viable indigenous technologies are required to suit local conditions. Distillation produces ultrapure water which is superior in quality among all water produced by other desalination processes. Multiple Effect Diffusion Still is the new panacea to produce distilled water at a much faster rate than conventional stills using solar energy but without electricity. The recycling of latent heat of condensation makes this device very efficient.

II. Working of Multiple-Effect Diffusion Still

Fig. 1 shows the working of Multiple Effect Diffusion Still. The setup of a typical MEDS includes a number of parallel plates placed vertically between two plates. The first plate of the Multiple Effect Diffusion Still, called heating plate, is exposed to Sun and gets heated by solar radiation. The last plate of the Multiple Effect Diffusion Still, also known as a cooling plate, is cooled by cold water, atmospheric air or otherwise. A porous wick material is attached to the back side of each plate except the last plate. Hot water from the solar collectors or normal saline water is supplied to the wick attached to the plates except the cooling plate. The saline water in the first wick attached to the first plate gets heated and evaporates as it is in contact with the hot plate. The water vapours thus formed start diffusing towards the second plate through a small gap between wick and plates. This vapour gets condensed on the second plate. This evaporation and condensation pair is known as one stage of Multiple-Effect Diffusion Still. The second plate gets heated by taking the latent heat of condensation from the vapours and transfers it to the saline water flowing in the wick attached to itself. The heated water evaporates again and condenses on the next plate.

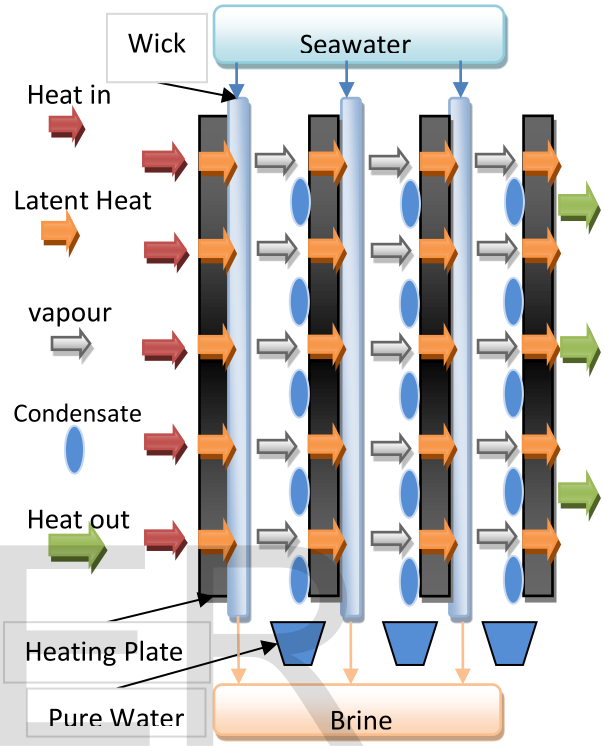

Fig. 1- Schematic diagram of Working of Simple Multiple-Effect Diffusion Still

This evaporation-condensation process is repeated several times. The condensed water from each condensing plate is collected at the bottom of the plate. The recycling of heat through multi-effect distillation leads to high distillate efficiently.

III. Various Designs of MEDS

Due to high distillate output and simplicity of design of Multiple-Effect Diffusion Still, solar distillation has moved to the next generation. A MEDS setup consists of a solar collector, manually operated casters for solar tracking and a multi-effect diffusion unit which includes some vertically placed parallel plates having a wick fixed on one side. Researchers have designed different designs of multi-effect diffusion unit by varying different parameters such as, diffusion gaps between two plates, no. of stages (effects), the design of plate, different solar collectors etc. Various types of MEDS are -

- Simple MEDS [1-2]
- Basin type MEDS [3-4]
- MEDS with flat plate reflector [9-12]
- Vertical MEDS with heat-pipe solar collector [6-8]
- MEDS with heat pipe and vacuum tube solar collector [13]
- Bended-plate MEDS with heat pipe and vacuum tube solar collector [14]
- Spiral MEDS with heat pipe and vacuum tube solar collector [15]

a. Simple MEDS

The concept of diffusion type solar still was first introduced by R.V. Dunkle in 1961 [1]. A small five-stage (five effects) diffusion still operating with air and hydrogen atmosphere was experimented. Dunkle pointed out the advantages as well as some operating and design problems of MEDS. It was indicated by the equation for the rate of diffusion (1) that to get a high diffusion rate, a diluent gas of low molecular weight should be selected. Dunkle also proved his claim by experimentation on small five-stage (five effects) diffusion still operating with air and hydrogen atmosphere.

A Three effect diffusion solar still was studied by Elsayed, Fathalah, Shams, and Sabbagh [2]. A diffusion unit with 10-mm diffusion gap and cotton as wick material was used for experimentation in which hot water at 90°C was supplied directly to the wick. The author developed a mathematical model for MEDS, empirical relations for *i*-th effect distillate and heat transfer are given from (2) to (4).

$$W_w = -\frac{14.6 * t^{\frac{1}{2}} * M_w}{\left\{R * \left(V_w^{\frac{1}{3}} + V_b^{\frac{1}{3}}\right)^2\right\}} * \left(\frac{1}{M_w} + \frac{1}{M_b}\right)^{\frac{1}{2}} * \frac{1}{P_T - P_w} * \frac{dP_w}{dx} \tag{1}$$

$$D_1 = (0.8 + 0.015\,F)\left(\frac{T_H}{75}\right)^{1.63 + 0.032F} \tag{2}$$

$$D_2 = (0.65\ 0.0025\,F)\left(\frac{T_H}{75}\right)^{1.88 + 0.039F} \tag{3}$$

$$D_3 = (0.45 - 0.005\,F)\left(\frac{T_H}{75}\right)^{2 + 0.035F} \tag{4}$$

Equation (5) gives evaporative heat transfer rate per unit area for the *i*-th effect of the diffusion unit

$$Q_{ei} = D_i * L_{i,e} \tag{5}$$

Performance ratio was given as

$$PR = 2.31 - 0.0516\,F + 4.9 * 10^{-4} F^2 \tag{6}$$

b. Basin type MEDS

Tanaka, Nosoko and Nagata [3,4] constructed a basin type MEDS having a basin covered with tilted double glass. The sun-facing wall of the basin was made of several vertical parallel plates having small diffusion-gap between them. The wicks were attached to the cooler sides of the vertical plates and supplied with saline water. Theoretical analysis and an outdoor experiment was performed in winter and fall conditions in Japan.

The theoretical prediction of distillate of the proposed still having 10 effects with 5-mm diffusion gap was 15.4 kg/m^{2}d when average solar irradiation on glass cover was 22.4 MJ/m^{2}d. It was found that cumulative efficiency of proposed still was about 3.5 times higher than the experimental result of horizontal basin type conventional solar still by Cooper [16]. Experimentation of a diffusion still having 11 effects with 5-mm diffusion gap gives daily distillate of 14.8-18.7 kg per unit glass cover area. It was also found that the distillate output increased by decreasing the diffusion gap and by providing small spacers between the condensing plate and the wick. Productivity also increased when the number of spacers between every gap was increased.

c. MEDS with Flat Plate Reflector

Tanaka and Nakatake [9-12] proposed a newly designed, vertical multiple effect diffusion solar still coupled with flat plate mirror. The dependency of absorption of solar radiation on the first plate on the inclination angle of flat-plate-mirror and azimuth angle of solar still was theoretically predicted [9]. The experimental results [12] have shown that

- Optimum results were obtained when the inclination angle of the mirror was 8° and 15° at the equator on the winter solstice and the spring equinox, respectively.

- For spring equinox, results were found optimum when azimuth angle of MEDS was kept at +90° during the afternoon and -90° during morning whereas for winter solstice, the azimuth angle was +45° during the afternoon and -45° during the morning.

The theoretical study predicted the distillate output of 34.5 kg/m^2d on the winter solstice and 29.2 kg/m^2d on spring equinox at the equator when the diffusion unit had 10 effects with 10 mm diffusion gap between partitions.

An outdoor experimental study [11] also showed that experimental outcomes were in good agreement with the theoretical predictions. This equality between theoretical and experimental results shows that all type of irradiation i.e. diffused, direct and reflected, on the first heating plate can give quite a right estimate according to the geometrical model.

A little anomaly was also found between theoretical and experimental results because of the air-bubble formation between the plate and the wick. Another reason for the discrepancy was the absorption of condensed vapour back to the wick due to bends in the wick.

Tanaka and Nakatake [12] also experimented on the MEDS coupled with flat plate reflector at Fukuoka, Japan. The results of this study showed that the proposed MEDS having 6 partitions with 5-mm diffusion gap gave overall daily distillate of about 13.3 kg/m^2 when maximum insolation on the glass cover was 20.2 to 22.9 MJ/m^2-day.

d. Vertical MEDS with Heat Pipe Solar Collector

Tanaka and Natakate [6] proposed a simple vertical MEDS which can be folded or dismantled when shipping. It consists of a heat pipe solar collector having a glass cover and a selective-film coated collector plate. The theoretical prediction of the proposed still having 10-effects with 3-mm and 5-mm diffusion gap between the wick and condensing plates showed that daily distillate output was 21.8 and 19.2 kg/m^2d, respectively when solar irradiation was 24.4 MJ/m^2d which is 13% larger than that of basin type MEDS [4].

e. MEDS with Vacuum Tube Solar Collector and Heat Pipe

Researchers faced the problem of low convective heat transfer in previous designs of MEDS. Low-temperature gradient also leads to low vapour diffusion capacity. Chong, Huang, Po- Wu and Kao [13] proposed a new solar still coupled with heat pipe & vacuum tube solar collector to solve this issue. Vacuum Tube Solar Collector (VTSC) produces a high-temperature gradient which gives high distillate output whereas heat pipe efficiently transfers the solar heat to multi-effect diffusion unit.

Proposed still of 10 effects with 6-mm diffusion gap produced distillate of around 13.7 L/m^2d and 19.7 L/m^2d at solar irradiation of 600 W/m^2 and 800 W/m^2 respectively. Whereas MEDS with 20-effects produced 17.9 L/m^2/day which was higher by 32% compared to 10-effect still.

f. Bended-plate MEDS with Vacuum Tube Solar Collector and Heat Pipe

Conventionally designed MEDS having flat vertical plates attached with wick material were facing a typical problem of wicks separating from the surface of the flat plates. This problem increased the re-absorption process of condensate and reduced daily distillate productivity. Huang, Chong, Chang, Wu and Kao [14] solved this problem to an extent with a new bended-plate-design in which wick- attached plates were kept slightly curved instead of keeping them straight. The highest productivity of proposed still obtained was 23.9 kg m^2/d which was about 29% larger than that of the simple MEDS with basin [3-4]. COP of the new still was 1.5-2.44 that was higher than the COP of MEDS with basin, which had a COP of 1.45-1.88 [3].

g. Spiral MEDS with Vacuum Tube Solar Collector and Heat Pipe

Huang, Chong, Wu, Dai and Kao [15] developed a modern solar still with a new design in which the diffusion unit was shaped spirally. The measured productivity was 40.6 kg/d for 1.08 m^2 absorber plate area which was the highest ever achieved as reported literature so far. The measured COP of this still was in between 2.0-3.5 which was around 44% higher than that of MEDS with bended shape (1.5-2.44). These highly favourable results were obtained because of the phenomenon of lateral diffusion. The spiral shape of the diffusion unit amplifies the diffusion process. The heat transfer in the outmost cell also increased due to the larger surface area for evaporation and condensation at the outermost cell.

IV. Factors influencing the Productivity of MEDS

The productivity of MEDS depends on solar irradiation as well as design and operational parameters. Design parameters include thickness of diffusion gap, emissivity of the front surface, no. of partitions, absorptivity of the absorber, etc. Whereas operational parameters include saline water flow rate to wick, azimuth angle of the still, angle of the collector from the horizontal surface, temperature of saline water feed, etc. Many researchers have worked on MEDS [1–12]. Tanaka and Nakatake performed a theoretical study to find the dependency of various factors affecting the productivity of the flat plate reflector coupled MEDS [10]. Tanaka, Nakatake and Watanabe also performed a parametric study on heat pipe solar collector coupled MEDS [8]. They concluded that the daily yield of MEDS depends primarily upon the diffusion gap between the partitions, the number of partitions and the mass flow rate of brackish water to wick material.

V. Conclusion

On the basis of experimental and theoretical results of different designs of multiple effect diffusion still under various climatic conditions, it was felt that multiple effect diffusion still is a promising thermal desalination device which produces distilled water efficiently and faster than conventional solar stills. Among all the variants, spiral MEDS with vacuum tube solar collector & heat pipe by Huang, Chong, Wu, Dai and Kao [15] have provided the maximum productivity of 40.6 kg/m^2d with maximum COP of 2.0-3.5. Vacuum Tube Solar Collector produces high-temperature gradient whereas heat pipe efficiently transfers the solar heat to diffusion unit which leads to high yield. The flat mirror is an economic and simplest alternative to the solar collector. Bended shape of partitions solves the peel-off problem of wick material whereas the spiral design of the diffusion unit enhances the diffusion rate and increases heat and mass transfer at an outer cell. The productivity of MEDS majorly depends on the number of partitions, diffusion gap between partitions and mass flow rate of brackish water to wick material.

Based on the specific conclusions drawn from the examination of MEDS by several authors, previous designs provide a solid platform for the researchers to modify the device using more commonly available materials to produces pure water at a lower cost so that no-one is deprived of the essential need of pure water.

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