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DESIGN, DEVELOPMENT AND TESTING OF MULTIEFFECT DISTILLER/EVAPORATOR USING SCHEFFLER SOLAR CONCENTRATORS

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Abstract

Authors designed and experimented with multistage evaporation system for production of distilled water. Two Scheffler concentrators of 16 sqm each were used for generating steam in the first stage at 8 bar pressure and the pressure is gradually brought down to 1 bar, in four stage distillation unit. Total yield obtained in the project was 2.3 times that of single stage distillation. Temperature drop in every subsequent stage was designed to 25 degree centigrade. Heat of condensation in the last stage and also sensible heat of the condensate in all the stages were used for preheating of water in the next batch. The system has great potential in food processing industry for applications of juice thickening, sauces, jams, salt concentrating systems and distilled water applications, desalination etc. Results of the project are very encouraging for commercial scale application.

Keywords: Solar Multistage distillation; Scheffler concentrator; MED

1. Introduction

As early as in the fourth century B.C., Aristotle described a method to evaporate impure water and then condense it for potable use. However, historically the earliest documented work on solar distillation was by Arab alchemists in the 16th century [1]. Solar stills are very commonly used for low requirements of distilled water. Solar stills are low temperature devices and require large areas. As the evaporation and condensation is done in one single unit, yield is low. Normal output of the still is around 2-3 liters per sqm of area per day, on good sunny day.

Nomenclatures

L	Latent heat of vaporization, kJ
M_d	Rated (design) capacity of distillate, kg
MED	Multi-effect distillation
MSF	Multi-stage flash
N	Number of effects or stages
Q_{ev}	Thermal energy requirement of MED, kJ
PR	Performance Ratio

Because of limited output of solar stills, new designs are done with multistaging of evaporation and condensation stages, which not only improves energy efficiency but also saves lot of space.

2. Multieffect Distillation - Review

To evaporate one kg of water at 1 atm. pressure, 2260 kJ is the net energy requirement. In simple, single stage laboratory evaporators all this 2260 kJ of heat is wasted to atmosphere by way of cooling to get distilled water. Multistage evaporators, also called as multieffect evaporators, use this heat rejected in condenser to evaporate water in the next stage and such battery of condensers-evaporators can be constructed to recycle heat of condensation and increase net yield of distillate. The multi-effect distillation (MED) process is commonly practiced process in desalination for reasons of energy efficiency. References and patents have existed since 1840, more than 170 years ago. Vertical tubes, horizontal tubes and different types of submerged tubes have been commercialized and were used until 1960 when multi-stage flash (MSF) dominated the desalination market. MSF plants are presently the most widely used and are considered as reliable sources for the production of fresh water from the sea in Middle East countries, in general, and in the Gulf region, in particular. Almost all these MEDs are designed for large capacities with conventional fuels and continuous operations. Major features of the MED process are low primary energy consumption, low heat transfer area and high gain ratio [2].

For recycling the heat rejected during condensation of steam different mechanisms are used. Few systems with single stage evaporation use vapor compression heat pumps and mathematical models predict excellent performances. However such systems need external power to drive heat pumps. Contribution of electrical energy for pumping feed water and creating vacuum is high [3].

E1-Nashar [4] has worked on the economics of small solar assisted multiple effect stack distillation plants. He noted that instead of stand alone solar systems, hybrid systems with diesel pumping and solar heating as best option. He noted that the economics depends on the cost of fossil fuels and cost of the collectors. Conventional MES evaporators require energy in two forms, thermal energy for heating and evaporating water and electricity/diesel for running different pumps for feed water, creating vacuum etc [4]. This work was done in 1999 when oil was cheaper. In 2008 the oil cost has become a predominant issue and hence to give up use of any auxiliary power is a good idea. He proposed use of flat plate collectors.

However as the flat plate collectors have capabilities to deliver temperatures up to 90ºC, use of vacuum pump and hence auxiliary power is necessary.

3. Design of New Solar MED Based on Scheffler Solar Concentrators

3.1. Problem definition

Conventional MEDs evaporate water at temperatures below 100ºC in many stages and hence vacuum pump is a must. Also conventional MEDs use continuous feeding system with pumps driven on electricity of diesel. As availability of electrical energy in rural and remote areas is uncertain and cost of diesel is high, authors decided that no external energy source to be used while developing new solar MED application.

As Scheffler concentrators [5] of 16 sqm can generate steam up to 175ºC comfortably, it is possible to deploy multiple stages and gradually reduces the temperature of steam from 175ºC to 100ºC. The new system is not designed to operate below 100ºC and hence vacuum pump is eliminated, as complete system works in positive pressure zone.

3.2. New solar MED design

The thermal energy requirement of the MES evaporator, Q_{ev} depends essentially on its rated capacity as well as its performance ratio. The performance ratio for MES evaporators depends essentially on the number of effects, N, according to the following relation:

$$PR = -0.809 + 0.932N - 0.0091N^2 \tag{1}$$

and Q_{ev} can be obtained by the following equation

$$Q_{ev} = M_d \frac{L}{PR} \tag{2}$$

where M_d is the rated (design) capacity and L is the latent heat of vaporization [4].

El-Wakil [6] has provided monograms for overall heat transfer coefficient for evaporators. From the monograms it can be seen that the heat head of 25ºC provides maximum heat transfer coefficient and hence the same was adopted for first three stages and 15ºC was adopted for last stage. First evaporation takes place at 175ºC and further evaporations at 150ºC, 125ºC and in the last stage at 110ºC. Using four-stage evaporator and Eq. (1), the performance ratio can be calculated as 2.77. This will serve as a benchmark for the actual test rig.

New MED design is planned for the areas with bad or no power and hence the designs of all components were amended to incorporate intermittent and manual operations. These included hand pumps for feeding water intermittently, condensers with storage capacity of 20 liters, anticipating two hours of storage and evaporators for 20 liters storage as well. Evaporator design was changed from coil type to storage tanks. Schematic diagram is shown in Fig. 1. Design philosophy was adopted as per guidelines given by Kern [7] and Bell et. al [8] in their handbooks. Component sizing is done by calculating heat transfer areas as specified.

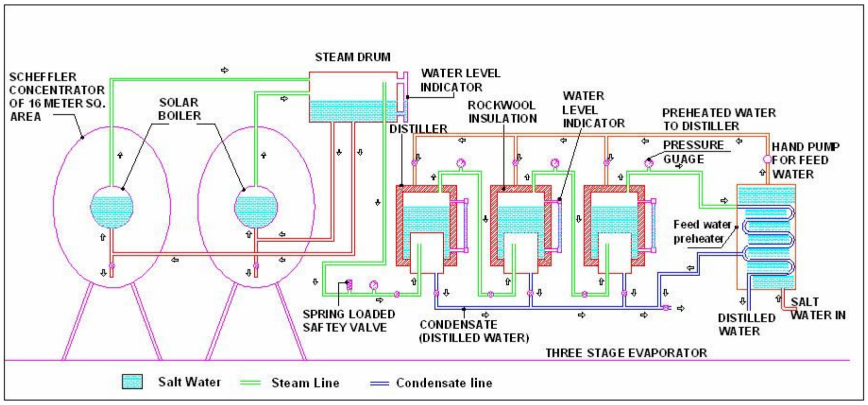

Fig. 1. Schematic Layout of MED with Scheffler Concentrators and Heat Recovery Unit.

4. System Components

System primarily included two major components, Scheffler steam system and multistage evaporators. A heat exchanger was added later on to the system to preheat feed water from last stage of steam condensation and from the sensible heat loss of the condensate.

4.1. Scheffler steam system

Scheffler steam system consisted of two Scheffler concentrators [5] of 16 sqm each, facing south, also referred as standing dishes. Solar radiation is concentrated within 500 mm diameter of receivers delivering concentration ratio in the range of 80 [9]. Both the receivers are connected to a water-steam storage tank with inlet and outlet connections. All piping and storage systems are insulated with rock wool insulation of 70 mm thick. System is provided with safety features like pressure relief valve, fusible plug etc. System can be seen in Fig. 2.

Fig. 2. Photograph of Solar Steam Generator with Multistage Evaporators.

4.2. Multeffect evaporator-condenser unit

First stage boiling is carried out in the water-steam drum of the system and further three stages of evaporator were manufactured as per design discussed above, making it four stage system. First three stages of evaporators-condensers were designed with temperature drop of 25 degree centigrade and last stage with 15 degree centigrade. As the system used all manual operation, continuous drainage of condensate was not possible. Hence the system is designed with storage for condensate which can be drained every two hours. Similarly evaporator sections were designed and constructed large enough to accommodate feed water storage for at least 2 hours. Feed water is also introduced in all stages with hand operated piston pump. All MED components were designed as pressure vessels and tested for pressure of 15 bar.

4.3. Heat recovery unit

First few trials were taken without a heat recovery unit, and feed water was introduced at room temperature. Authors realised that heat of condensation of steam in the last stage of evaporation and sensible heat of condensed water in early stages can be used for preheating feed water. Hence a heat recovery unit was added later on to the system.

A schematic layout of the system with all three main components as above and is shown in Fig. 1 showing all system components as well as instrumentation. Water and steam flows are marked with arrows.

5. System Operation

A schematic layout of the system is shown in Fig. 1 and actual photograph is shown in Fig. 2. Steam is generated by solar boiler comprising of Scheffler solar concentrators, receivers and steam tank. Steam tank is half filled with water. Water circulation to the receivers is by gravity and steam comes back in the top of the tank and is stored there [10]. This pressurised steam is fed to the condensing tank of first evaporator. Condensing tanks are designed in place of coils to accommodate two hours of condensate so that the tanks can be manually drained. Heat of condensation in the earlier stage is used for evaporating water which is further condensed in following stage. Heat transfer areas are calculated taking 25ºC temperature drop, which gives optimal overall heat transfer coefficient. In current project steam generated in water-steam drum is the first stage of evaporation and there are further three stages added, making it a four stage evaporation-condensation system.

6. Results and Discussion

Trials were taken on the test unit for a month. Typical data sheet for a day is shown in the Table 1.

Table 1. Typical Data Sheet.

Time (Hour)	T1 (° C)	Pressure P1 Bar	Yield gms	T2 (° C)	Pressure P2 Bar	Yield gms	T3 (° C)	Pressure P3 Bar	Yield gms	T4 (° C)	Press. P4 Bar	Yield gms
7:00 AM	28	-	-	28	-	-	28	-	-	28	-	-
8:00 AM	69	-	-	29	-	-	29	-	-	29	-	-
9:00 AM	101	1	-	29	-	-	29	-	-	30	-	-
10:00 AM	146	4	-	29	-	-	29	-	-	29	-	-
11:00 AM	172	7.8	-	30	-	-	29	-	-	29	-	-
12:00 PM	169	7.6	12600	129	2.7	2800	66	-	-	30	-	-
1:00 PM	171	7.6	14300	146	4.1	10700	128	2.5	5800	46	-	-
2:00 PM	167	7.2	16300	147	4.1	12100	127	2.4	8600	89	-	350
3:00 PM	171	7.8	14800	149	4.5	11000	123	2.2	7800	94	-	4900
4:00 PM	164	7	14600	144	4	10400	123	2.1	7600	95	-	4300
5:00 PM	148	4.6	9800	131	2.7	7500	116	1.7	4600	94	-	3800
6:00 PM	121	2.2	5600	108	1.1	4400	100	1	3200	93	-	2300
7:00 PM	94	1	2300	97	1	2200	91	1	1500	67	-	200
8:00 PM	66	-	900	64	-	100	58	1	100	55	-	-

Readings for the days with more than one hour cloud cover were discarded. Average performance for valid readings was computed. Net Yield per square meter per day and Performance ratio were important parameters. Average figures for these parameters are mentioned below.

a. Net yield per sqm of concentrator: 6.5 liters/sqm

b. Average Performance ratio: 2.3.

These parameters can be used as basis for design and scale up the system for customer's requirements of higher magnitudes.

7. Conclusion

Experimental set up used only two 16 sqm Scheffler concentrators and ended up with larger fixed losses as can be seen from the observation table. This has been the experience with all steam generation systems using solar concentrators. Bigger systems with large number of Scheffler concentrators are likely to improve Performance ratio. Last stage of evaporator in current system generates steam at atmospheric pressure. Design used by Wolfgang Scheffler uses steam at atmospheric pressure and delivers yield of 2.5 to 3 times. If this steam generated in last stage of pressurised multistage evaporator is used as primary source in Wolfgang Scheffler's MED7, then it is possible to increase the overall performance ratio to above five.

It is observed that the system takes time to heat up itself and practical steam generation starts only after 11.00 a.m. Also all stored heat in the system is wasted overnight and one has to have a fresh start next morning. Authors recommend having some other renewable energy back up system like biogas or biomass for overnight operation. This will not only increase yield because of added operating hours, but also will reduce overnight system losses to a large extent, increasing overall performance ratio.

Results of the project demonstrated that there exists huge potential for applications like generating distilled water for food processing, pharmaceutical and other industries on moderate scale. Same design will be useful as chemical evaporators without any amendments for utilisation in food processing and can cater applications like salt concentration systems, thickening of salt fruit juices, jams, pulps, sauces and similar applications where water is evaporated on large scale. Evaporating water for thickening of effluent of industries is other promising area.

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