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# Active multi-effect vertical solar still: Mathematical modeling, performance investigation and enviro-economic analyses

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## HIGHLIGHTS

- Optimization and distillate yield enhancement of multi effect vertical solar still.
- Year round performance analysis of active multi-effect vertical solar still
- Economic feasibility and environmental benefits of the proposed distillation unit
- High distillate yield, low distillate production cost, minimal environmental impact

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## ABSTRACT

In this paper, year round performance and enviro-economic analyses of active multi-effect vertical solar still were carried out using the developed comprehensive mathematical model. The optimum number of effects, mass flow rate of feed water and gap between the effects were found to be five, 7.20 kg/h and 0.05 m, respectively. Maximum annual average distillate yield of 6.78 and 21.29 kg/m$^2$-d was noticed for the optimized unit under normal mode and low pressure mode operation. Maximum annual average Performance ratio (PR) and Solar energy Coefficient of Performance (SCP) of 5.59 and 3.03 was noticed under evacuated mode operation. Energy payback time and distilled water production cost of the evacuated unit treating 5 wt% saline water was around 1.37 yrs and Rs.2272.00/m$^3$ (33.00 USD/m$^3$), respectively and it can effectively mitigate at least 81.81 tons of $CO_2$ emission during its life time of 20 yrs. Distilled water production cost of the evacuated unit was found to reduce from Rs.2270.00/m$^3$ (33.00 USD/m$^3$) to Rs.1310.00/m$^3$ (19.00 USD/m$^3$) by decreasing the interest rate from 12% to 5%. Salinity of feed water and interest rate at which the unit was financed played a major role in distilled water production cost.



## 1. Introduction

Alarming pollution of limited fresh water reserves, rapid rise in human population and climate change have increased the demand for fresh water around the globe. Mostly, arid and semi-arid regions are severely affected by the increasing scarcity of fresh water. Fresh water demand is increasing nearly by two folds for every two decades. [1]. Desalination of saline water to produce fresh water is an energy consuming process. According to thermodynamic limits, nearly 0.71 kWh of energy is required for desalination process to produce 1.0 m$^3$ of fresh water [2]. However, in current situation desalination of saline water using large scale matured technologies like multi-stage flash and multi-effect distillation systems requires combustion of at least one ton of oil to produce twenty tons of fresh water [3,4]. Desalination can be made sustainable by operating distillation units with renewable energy such that the environmental pollution and depletion of non-renewable fossil fuel reserves can be minimized [4]. Generally, arid and semi-arid regions are blessed with abundant solar radiation and brackish water which paves the way for setting up solar energy operated community scale distillation units to meet the fresh water demands in those regions [5].

Solar still has been considered as a simple and cost effective device to provide clean drinking water to rural, arid and remote communities. However, its drawbacks are mainly lower yield and large area occupancy [6,7]. One of the most efficient ways to enhance its yield is by providing additional stages or basins for utilizing the latent heat of condensation for further evaporation [8]. Both passive mode and active mode operation of multi stage still has been studied by researches around the globe. In passive mode operation, distillation basin is directly heated by solar radiation. In case of active mode operation, heat energy from sun is harvested using solar collectors and is used for evaporation of water in the basin [9,10]. The yield from passive triple basin still was nearly 62% higher than conventional single basin still [11]. Kumar and

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## Nomenclature

| | |
|---|---|
| $A_c$ | Area of flat plate solar collector ($m^2$) |
| $A_p$ | Area of evaporating or condensing surface of each effect ($m^2$) |
| AOMC | Annual operation and maintenance cost (USD) |
| ASV | Annual salvage value (USD) |
| $B_i$ | Volumetric expansion coefficient corresponding to the average temperature of ith effect ($K^{-1}$) |
| $c_{av(i)}$ | Specific heat capacity of humid air in ith effect (J/kg-K) |
| CC | Capital cost of the distillation unit (USD) |
| $C_{p(i)}$ | Specific heat capacity of the ith vertical chamber (J/kg-K) |
| $C_{pb}$ | Specific heat capacity of brine (J/kg-K) |
| $C_{pf}$ | Specific heat capacity of the feed water (J/kg-K) |
| CPL | Distilled water production cost (USD/L) |
| $D_{(i)}$ | Diffusion coefficient of humid air in ith effect ($m^2/s$) |
| $E_{in}$ | Embodied energy (kWh) |
| $E_{out}$ | Annual energy output of the unit (kWh) |
| EPBT | Energy payback time (yrs) |
| F′ | Collector efficiency factor |
| FAC | Fixed annual cost (USD) |
| g | Acceleration due to gravity ($m/s^2$) |
| $Gr_i$ | Grashof number of ith effect |
| h | Hour angle (degree) |
| $h_{c(i)}$ | Convective heat transfer coefficient ($W/m^2$-K) |
| $h_{fg}$ | Latent heat of vaporization (J/kg) |
| H | Length of each effect (or) vertical chamber (m) |
| $I_b$ | Beam radiation ($W/m^2$) |
| $I_d$ | Diffuse radiation ($W/m^2$) |
| $I_t$ | Global solar radiation reaching the tilted surface ($W/m^2$) |
| IR | Interest rate (%) |
| $K_{(i)}$ | Thermal conductivity of humid air in ith effect (W/m-K) |
| L | Latitude (degree) |
| $Le_{(i)}$ | Lewis number of humid air in ith effect |
| LH | Latent heat (kJ/kg) |
| LT | Life time of the distillation unit (yrs) |
| $M_a$ | Molecular weight of air (kg/kmol) |
| $m_{b(i)}^{\bullet}$ | Mass flow rate of brine leaving the ith effect (kg/s) |
| $m_c^{\bullet}$ | Mass flow rate of feed water circulated through the collector (kg/s) |
| $m_{d(i)}^{\bullet}$ | Distillate yield of ith effect (kg/s) |
| $m_d$ | Cumulative distillate yield (kg) |
| $m_{f(i)}^{\bullet}$ | Mass flow rate of heated feed water entering ith effect (kg/s) |
| $M_{p(i)}$ | Mass of the ith vertical chamber (kg) |
| $M_v$ | Molecular weight of water vapor (kg/kmol) |
| $M_Y$ | Annual average distilled water production (kg) |
| $n_p$ | Payback period (yrs) |
| NCEM | Net $CO_2$ emission mitigated over the life time of the distillation unit (tons) |
| $P_{LM(i)}$ | Logarithmic mean pressure of ith effect |
| $P_o$ | Operating pressure (bar) |
| PPD | Distilled water production per USD (L/USD) |
| PR | Performance ratio |
| $Pr_i$ | Prandtl number of ith effect |
| $P_{s(i)}$ | Partial vapor pressure of saline water at the evaporating surface of ith effect (Pa) |
| $P_t$ | Total pressure (Pa) |
| $P_{T_a}$ | Partial vapor pressure corresponding to the ambient temperature (Pa) |
| $P_{T_{p(i)}}$ | Partial vapor pressure corresponding to the temperature of ith effect (Pa) |
| $P_{T_{p(i+1)}}$ | Partial vapor pressure corresponding to the temperature of (i + 1)th effect (Pa) |
| $P_{T_{p(N)}}$ | Partial vapor pressure corresponding to the temperature of Nth effect (Pa) |
| $Q_{c((i-1)-i)}$ | Convection heat transfer between (i-1)th and ith effect (W) |
| $Q_{c(N-a)}$ | Convection heat transfer between Nth effect and ambient (W) |
| $Q_{r((i-1)-i)}$ | Radiation heat transfer between (i-1)th and ith effect (W) |
| $Q_{r(N-a)}$ | Radiation heat transfer between Nth effect and ambient (W) |
| $Q_{e((i-1)-i)}$ | Evaporation heat transfer between (i-1)th and ith effect (W) |
| $Q_{e(N-a)}$ | Evaporation heat transfer between Nth effect and ambient (W) |
| $Q_u$ | Useful heat energy supplied by the solar collector (W) |
| R | Universal gas constant (J/kmol-K) |
| SCP | Solar energy Coefficient of Performance |
| Sa | Salinity of feed water (wt%) |
| $S_p$ | Selling price of distillate (USD/L) |
| $T_a$ | Ambient temperature (°C) |
| $T_{av}$ | Average temperature of ith and (i + 1)th effect (°C) |
| $T_{b(i)}$ | Temperature of brine leaving the ith effect (°C) |
| $T_{ci}$ | Inlet temperature of the feed water entering the flat plate solar collector (°C) |
| $T_{co}$ | Outlet temperature of the flat plate collector (°C) |
| $T_{p(i)}$ | Temperature of the ith effect (°C) |
| TAC | Total annualized cost (USD) |
| $U_l$ | Overall heat loss coefficient of solar collector ($W/m^2$-K) |
| W | Gap between evaporating and condensing surface (m) |
| $X_{H_2O}$ | Mole fraction of water in saline water |
| $\Delta t$ | Time step size (s) |
| $\Delta T_i'$ | Modified temperature difference between evaporating and condensing surface of ith effect (°C) |
| $\Delta T_N'$ | Modified temperature difference between evaporating and condensing surface of Nth effect (°C) |
| $\alpha_p$ | Absorptivity of absorber plate of solar collector |
| $\beta$ | Tilt angle of flat plate collector (degree) |
| $\varepsilon_p$ | Emissivity of metal surface |
| $\varepsilon_w$ | Emissivity of water |
| $\delta$ | Declination (degree) |
| $\upsilon_{(i)}$ | Kinematic viscosity of humid air in ith effect ($m^2/s$) |
| $\rho_{av(i)}$ | Density of humid air in ith effect ($kg/m^3$) |
| $\rho_g$ | Ground reflectance |
| $\theta$ | Inclination angle of the still (degree) |
| $\theta_i$ | Angle incidence of solar radiation (degree) |
| $\tau_g$ | Transmissivity of glass cover of solar collector |
| $\sigma$ | Stefan-Boltzmann constant ($W/m^2$-$K^4$) |

Tiwari [12] estimated that the operation of multi stage solar still with number of collectors beyond three would not be economical. The distillate productivity with optimum solar collectors for triple effect active basin still was estimated to be 12.0 kg/$m^2$-d [12]. Multi stage stacked tray solar still integrated with solar collector (3.0 $m^2$) was found to produce nearly 6.7 kg/$m^2$-d of distillate under the simulated climatic conditions of Delhi, India [13]. Four stage solar still integrated with evacuated tube collector (1.7 $m^2$) was found to produce nearly 11.0 kg/$m^2$-d distillate under the simulated Middle East climatic conditions [14]. Real time investigation on seven stage solar still integrated with solar collector (2 $m^2$) was carried out under the climatic conditions of Brazil and the unit was able to produce nearly 25.0 kg/$m^2$-d of distillate free from microbiological contaminants [15]. Triple effect solar still with enhanced condensation surface integrated with evacuated tube