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Energy and exergy analysis of conventional and modified solar still integrated with sand bed earth: Study of heat and mass transfer

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ABSTRACT

Experimental and theoretical evaluation of solar-earth water still suitable for coastal areas or swamps has been investigated. Relative analysis of energy and exergy of MSSIE and CSS have been done by using Dunkle, Clark, Kumar & Tiwari, Tsilingiris and modified Spalding's mass transfer theory reported in this paper. Clark model overestimates theoretical yield throughout the experimentation and it gives 285.02% and 82.4% higher distillate output as compared to experimental result in case of MSSIE and CSS respectively during peak hours. It has been observed that internal efficiency gradually increases till 16:00 h and reaches a value of 25.55% & 25.29% for MSSIE and CSS respectively. For MSSIE the maximum value of exergy as predicted by Clark model is 5.015% at 15:00 h which is 141.1% and 64.9% higher than Kumar & Tiwari and Dunkle models respectively. For CSS maximum exergy efficiency as predicted by Clark is 1.656% at 15:30 h which is 26.9% and 66.53% higher than Kumar & Tiwari and Dunkle models respectively. Numerical results obtained from Kumar & Tiwari model gives good agreement with the experimental result as it predicts only 11.9% higher value in case of MSSIE and 12.31% higher in case of CSS.

1. Introduction

The demandfor potable water is increasing day by day due to population growth and a huge amount of wastewater being produced by industries. As per world water council (WWC) estimation,the population growth expected during 2000–2025 the global average annual per capita availability of renewable water resource is projected to fall from 6600 m^3 to 4800 m^3 [1]. For sustainable water production method suitable for remote areas, solar stills continue to attract wide research attention that has targeted to enhance the productivity of distiller unit. Numerous experimental works have been reported for enhancing the productivity of conventional single slope solar still (CSS) [2–9]. A comprehensive review for enhancing the distillate yield using fin, energy storage materials and multi-basin solar still have been discussed by Panchal and Mohan [10]. Experimental and numerical investigations on single and double effect solar desalination systems are reported by Kalbasi et al. [11]. A detailed review of the effect of various heat exchange mechanisms adopted by researchers to augment the water production from different solar still designs has been reported by Kabeel et al. [12]. Different ways to enhance the distillate output using wicks, internal and external condensers, internal and external reflectors, phase change materials, Stepped solar still and a new method to improve the solar still yield by using nano-particles have also been reported by various researchers [13,14]. Effect of the number of stages on the distillate yield of a multi-effect active solar still has been investigated by Karimi et al. [15]. Effect of climatic parameters on single slope solar still has been reported by Afrand and Karimipour [16]. Performance and enviro-economic analysis of active multi-effect vertical solar still has been reported by Reddy and Sharon [17]. Influence of Parameters affecting the accuracy of Dunkle's model at elevated temperatures has been reported by Tsilingiris [18]. For enhancing the productivity of solar distiller units use of flat plate reflectors are reported by Tanaka [19]. Chilton and Colburn analogy model for prediction of heat and mass transfer in solar distiller units have been reported by Tsilingiris [20]. A comparative study on effect of climatic condition for a simple basin solar still have been investigated and reported by Boukar and Harmim [21]. Solar earth water still is a device which produces distilled water by condensation of moisture in the ground. The pioneering experiments on solar earth water still were conducted by Kobayashi in the suburbs of Tokyo [22]. The highest daily yield of 1.1 lit/m^2 and 0.2 lit/$m^2$was recorded during sunny and nocturnal hours respectively. Ahmadzadeh has been reported the output of the solar still at the agriculture school of Pahlavi university Iran [23] as follows:

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Nomenclatures

A_s	basin area (m^2)
C	constant
c_p	specific heat at constant pressure (J/kg-K)
d	characteristic length of solar still (m)
$\dot{E}x_{dest,basin}$	exergy destruction in basin (W)
$\dot{E}x_{dest,glass}$	exergy destruction in glass (W)
$\dot{E}x_{dest,water}$	exergy destruction in water (W)
$\dot{E}x_{evap}$	exergy output of soar still (W)
$\dot{E}x_{in}$	radiation exergy input (W)
$\dot{E}x_{insu}$	exergy loss through insulation (W)
$\dot{E}x_{trans(glass\rightarrow air)}$	exergy transfer from glass to ambient (W)
$\dot{E}x_{trans(water\rightarrow glass)}$	exergy transfer from water to glass (W)
$\dot{E}x_{water}$	exergy utilized to raise the temperature of saline water (W)
F_{cw}	convective heat transfer fraction
F_{ew}	evaporative heat transfer fraction
F_{rw}	radiative heat transfer fraction
F_{12}	view factor
g	acceleration due to gravity (m^2/s)
g^*	mass transfer conductance (kg/m^2 hr)
Gr	Grashof number
h_{cw}	convective heat transfer rate (W/m^2 K)
h_{ew}	evaporative heat transfer coefficient (W/m^2 K)
h_{rw}	radiative heat transfer coefficient (W/m^2 K)
h_{1w}	total internal heat transfer coefficient (W/m^2-K)
$I(t)$	incident solar radiation on inclined cover surface (W/m^2)
k	thermal conductivity of humid air (W/m K)
L	latent heat of vaporization (J/kg)
Le	Lewis number
$\dot{m}_{ew}$	distillate output (kg/m^2 hr)
$m_{H_2}o, ci$	mass fraction of water at glass (kg of water/kg of moist air)
$m_{H_2}o, w$	mass fraction of water over water surface (kg of water/kg of moist air)
M_a	molar mass of air (kg/kmol)
M_w	molar mass of water (kg/kmol)
n	constant
Nu	Nusselt number
P_{ci}	saturated vapor pressure on inner glass surface (Pa)
P_t	total atmospheric pressure (Pa)
P_w	saturated vapor pressure on water surface (Pa)
Pr	Prandtl number
P_{LM}	logarithmic mean pressure (Pa)
$\dot{q}_{cw}$	convective heat transfer rate from water to glass cover (W/m^2)
$\dot{q}_{ew}$	evaporative heat transfer rate from water to glass cover (W/m^2)
$\dot{q}_{rw}$	radiative heat transfer rate from water to glass cover (W/m^2)
$\dot{q}_1$	total internal heat transfer rate from water to glass cover (W/m^2)
$\mathfrak{R}$	universal gas constant ($\mathfrak{R}$ = 8.314 kJ/kmol K)
T_{ci}	inner glass cover temperature (°C)
T_w	temperature of water surface (°C)

Greek

α	thermal diffusivity (m^2/s)
α_b	absorptivity of basin
α_g	absorptivity of glass
α_w	absorptivity of water
β	expansion factor (K^{-1})
σ	Stefan Boltzmann constant (W/m^{2}K^4)
ρ	density of humid air (kg/m^3)
μ	dynamic viscosity of humid air (Ns/m^2)
ε_{eff}	effective emissivity
η_i	instantaneous thermal efficiency
η_{Ex}	exergy efficiency of solar still
τ_g	transmissivity of glass cover
τ_w	transmissivity of water

Depth of placement (m)	Daily output (l/m^2)
0.00	0.00
0.08	0.74
0.28	1.00

Experimental evaluation of solar-earth water still has been reported by Sodha et al. [2]. Effect of covering the nearby surface of sand bed solar still by black polythene sheet and coal powder have been reported by Tiwari and Mishra [4]. The effect of different type of sand(black and yellow), sand bed heights from 0.01 to 0.05 m, and the height of water above the sand bed level from 0.0 to 0.03 m on the solar still performance have been reported by Omara and Kabeel [24]. It is observed that the potential of earth water solar still has not been explored extensively although many explanations and observations are available since a long time. This paper reports a study of energy and exergy evaluation of laboratory experiments on the solar-earth water still which simulates the conditions in areas where the soil is rich in moisture. A comparison of different influencing parameters using Dunkle, Clark, Kumar & Tiwari and modified Spalding's mass transfer theory have been reported.

2. Experimental setup

A modified single slope solar still integrated with earth (MSSIE) and conventional solar still (CSS) are shown in Fig. 1a & b respectively. Seventeen circular holes of 20 *mm* diameter and four circular holes of 10 *mm* diameter have been made in basin area of $1m \times 1m$. Inner surface of basin area has been covered with 2.5 *cm* thick layer of silica sand. Top surface of this layer were covered with thin layer of black coal dust. Still has kept in tray made of GI sheet of size 1.5 $m \times$ 1.5 $m \times$ 0.6 m containing silica sand and water. Following measurements were made:

- Distillate yield at half hour interval for continuous 10 h.
- Incident solar radiation on inclined glass cover surface with the help of SP light silicon Pyranometer.
- Ambient temperature (in shade), basin, inner and outer glass cover surface temperatures bya k-type thermocouple and MDTI039T digital temperature indicator.

3. Theoretical background

The convective heat transfer rate from water to glass surface is described as:

$$\dot{q}_{cw} = h_{cw}.\,(T_w - T_{ci}) \tag{1}$$

In natural convection where heat transfer is caused due to density difference of fluid, the Nu can be written as:

$$Nu = \frac{h_{cw} d}{k} = \mathrm{C}(\mathrm{Gr}{\cdot}\mathrm{Pr})^n \tag{2}$$