The effectivity of a hybrid solar distillator directly combined with a solar cell

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Abstract: Solar energy is one of the most promising natural and renewable energy resources. A solar membrane distillator hybridized with a photovoltaic cell supplies with both water and energy which are indispensable for human life and industry and contributes to effective utilization of renewable energy, especially solar energy. The effectivity of a hybrid solar membrane distillator was experimentally and numerically verified. The dependence of cell temperature on conversion efficiency was unrecognized in this work because of an amorphous Si module. However the hybrid solar distillator contributed to the stable standard conversion efficiency of a cell. Relationship between solar intensity and distillate productivity is almost identifiably approximated for the membrane distillator even if with or without a photovoltaic cell. This work indicated of the effectivity of a hybrid solar distillator with a photovoltaic cell.

Keywords: *Hybrid solar distillator, Solar cell, Membrane distillation, PTFE membrane*

Nomenclature

C_P : Specific heat ..... *J/(kg·K)*
D: Distillate productivity..... *kg/(m^2·s)*
e: Porosity of PTFE membrane..... *[-]*
FF: Fill Factor ..... *[-]*
I: Solar intensity..... *W/m^2*
I_{SC} : Short Circuit Current ..... *A*
k: Thermal conductivity..... *W/(m·K)*
l: Thickness of partition..... *m*
L: Length of hybrid distillator..... *m*
P: Saturated vapor pressure..... *Pa*
P_{MAX} : Maximum Power..... *W*
q_I: Heat flux from solar energy..... *W/m^2*
q_L: Latent heat flux ..... *W/m^2*
q_R: Radiative heat flux ..... *W/m^2*
q_S: Sensitive heat flux..... *W/m^2*
q_U: Overall heat flux ..... *W/m^2*
R: Gas constant..... *Pa·m^3/(mol·K)*
T: Temperature ..... *K*
u: Water velocity ..... *m/s*
U: Overall heat transfer coefficient..... *W/(m^2·K)*
V_{OC}: Open Circuit Voltage..... *[V]*
z: Interval ..... *m*
Geek
α: Absorptivity of partition..... *[-]*
Γ: Diffusion coefficient of vapor into air ..... *m/s^2*
δ: Membrane thickness..... *m*
ε: Emissivity of partition ..... *[-]*
ρ: Density ..... *kg/m^3*
σ: Stefan-Boltzmann constant ..... *W/(m^{2}K^4)*
η: Conversion efficiency..... *[%]*

1. Introduction

Water and energy are indispensable for human life and our industry. However arid regions and demand for water sources have been year by year expanding in the world with drastic increases in industrialization. The consumption of natural resources, particularly fossil fuel, for generating the huge energy causes environmental problems such as global warming. Therefore we should aggressively utilize inexhaustible natural resources such as ocean for water and solar energy as one of renewable energy. Utilization of renewable energy for desalination is one of the promising technologies for simultaneously resolving energy and water problems and for the soft global process as reviewed in reference [1].

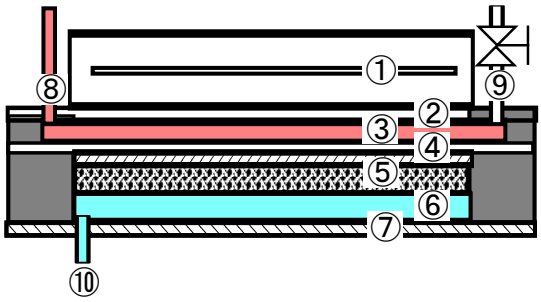
Desalination is one of chemical separation processes which remove salt from seawater or saline or brackish water. Practical desalination processes are classified in thermal and non-thermal processes. Thermal processes utilize phase-change process, evaporation and

condensation, to produce to distillated water such as Multi-stage flash, Vapor compression and solar still. Non-thermal processes are membrane separation processes such as Reverse osmosis and Electrodialysis. Only Membrane Distillation (MD) is classified into both thermal and membrane process. MD has the advantages of high selectivity of separation, lower temperature or pressure operation and the high-mass transfer rate as reviewed in reference [2]. A solar driven membrane distillation is suitable for the combination of desalination process and utilization of renewable energy [3].

On other hands solar energy is one of the most promising and all ranged renewable energy according to the rapid and diverse development of a solar cell. However the maximum conversion efficiency of a cell is below at most 35% in spite of the active research of a new type of solar cell. The low efficiency results from the independent reuse of solar energy that is solar ray or solar heat. Therefore several hybrid photovoltaic–thermal systems have been researched in order to improve the conversion efficiency due to the dependence of cell temperature [4] or recover waste heat [5-7].

We have been developing a flat type of solar distillator for environmental problem of the global warming by irrigation [8-10]. The flat type of a membrane distillator has the easy combination with other processes due to supporting the water surface with a membrane. In order to effectively utilize solar energy in both energy sources, solar ray and heat, a new solar membrane distillator directly hybridized with a solar cell was set up not in conventional desalination process [11] but in solar distillator unified with a solar cell. A double glass solar cell manufactured by KANEKA Co.LTd and a wide PTFE membrane by NITTO DENKO were selected for the direct hybridization. The effectivity of our hybrid solar membrane distillator was experimentally and numerically investigated. .

2. Experimental set-up



① Double glass solar cell (KANEKA)
② Black coulored PET Sheet
③ Saline water
④ PTFE membrane (NITTO DENKO)
⑤ Polyethylene mesh (fine & Coarce)
⑥ Distillated water
⑦ Stainless plate for radiation
⑧ Feed
⑨ Discharge of air
⑩ Drain of distillated water

Figure 1. A schematic cross section hybrid solar distillator

Figure 1 schematically shows the cross section of a flat-type hybrid solar distillator combined with a solar cell. The double glass solar sell (manufactured by KANEKA Co.Ltd, Amorphous Si, 1.1cm in thickness, 0.98m in length, 0.95m in width) is put on a flat-type membrane distillator. The I-V Curve Tracer (EKO INSTRUMENTS, MP-160) was used to investigate dynamic fundamental characteristics of a cel l, the Open Circuit Voltage, Short Circuit Current, Conversion Efficiency and Fill Factor of solar cell. A flat-type of membrane distillator composed of a solar absorber of black colored PET sheet (1.88mm in thickness), saline water (2mm in thickness), PTFE (Poly Tera Fluoro Ethylene) membrane (NITTO-DENKO Co.Ltd,NTF-5200,1μm in porε diαmεtεr,85μm in thickness and 80% in void fraction), diffusion gap of water vapor supported with fine and coarse types of polyethylene meshes (5mm in thickness)and radiator of stainless plate(2.2mm in thickness). The hybrid distillator was tilted at the lower angle, 2 deg., for the stable water flow and set up a t the outdoor situation in JAPAN. The intensity of solar energy measured with a pyranometer (EKO Instruments Co. Ltd. Model MS-42). Distillate productivity and

partitions temperatures obtained with cupper-constantan thermocouples were respectively recorded per one hour and one minute. The water volume heated through the cell was keeping at the constant value without the outlet of water. Each dynamic characteristics of separately solar cell, membrane distillator and the hybrid membrane distillator was independently measured in order to estimate the effectivity of the hybridization at the different weather conditions during the summer season in Japan

The Photovoltaic performance, particularly Conversion efficiency (η), was evaluated by I-V curve tracer (EKO Instruments Co. Ltd. Model MP-160) on the basis of experimental data of Open Circuit Voltage (V_{OC}), Short Circuit Current (I_{SC}), Maximum Power (P_{MAX}), Fill Factor (FF).

3. Numerical simulation

3.1. Heat and mass balances

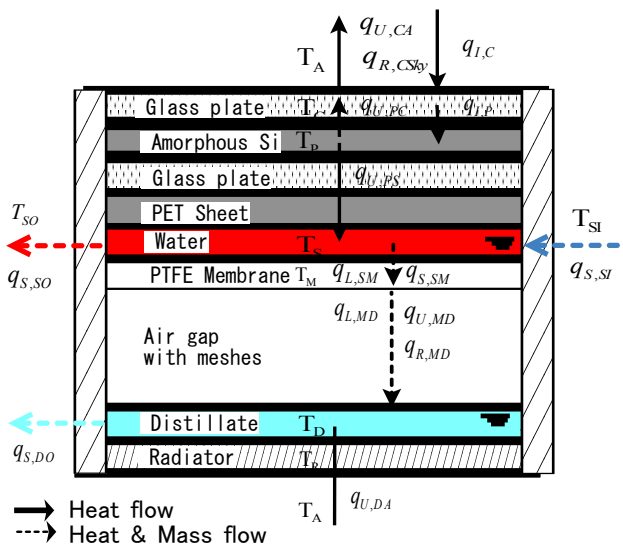


Figure 2. Heat and mass flow of a hybrid distillator

Figure 2 s hows flows of heat and mass transfer for the simulation model of a hybrid solar distillator. This model was constituted on the following assumptions ;

1. Temperature gradients in the flow direction are negligible.
2. Heat transfers with respect to PET sheet, PTFE membrane and radiator are approximated as overall heat transfer coefficients due to only heat conduction.
3. Temperature polarization across the PTFE membrane is negligible.
4. The mesh spacer within the air gap between the PTFE membrane and the radiator has no effect on the heat and mass transfer.

Energy balances for each partition are presented as follow:

Glass cover [T_C] : : $$\rho_C C_{P,C} \ell_C \frac{dT_C}{dt} = q_{I,C} + q_{U,PC} - q_{U,CA} - q_{R,CSky} \quad (1)$$

Amorphous Si [T_P] : : $$\rho_P C_{P,P} \ell_P \frac{dT_P}{dt} = q_{I,P} - q_{U,PC} - q_{U,PS} \quad (2)$$

Saline Water [T_S] : $$\rho_S C_{P,S} \ell_S \left(\frac{dT_S}{dt} + u_S \frac{dT_S}{dx} \right) = q_{U,PS} - q_{S,SM} + q_{S,SI} - q_{S,SO} \quad (3)$$

PTFE Membrane [T_M] : $$\rho_M C_{P,M} \ell_M \frac{dT_M}{dt} = q_{S,SM} - q_{L,MD} - q_{U,MD} - q_{R,MD} \quad (4)$$

Distillated Water [T_D] : $$\rho_D C_{P,D} \ell_D \left(\frac{dT_D}{dt} + u_D \frac{dT_D}{dx} \right) = q_{L,MD} + q_{U,MD} + q_{R,MD} - q_{U,DR} \quad (5)$$

Radiator [T_R] : $$\rho_R C_{P,R} \ell_R \frac{dT_R}{dt} = q_{U,MR} - q_{U,RA} \quad (6)$$

Distillate productivity is evaluated the following expression [12]

$$D = \Gamma \frac{\pi}{RT_{av}} \frac{1}{\left(\delta / e^{3.6} + z\right)} \frac{P_S - P_D}{P_{BM}}$$

3.2. Numerical analysis

Heat and mass transfer Equations.(1)-(7) were numerically simulated by Runge-Kutta method for estimating dynamic characteristics during one day and compared with experimental data in the open air situation. The temperature gradients along the flow direction may be negligible due to some partitions with high thermal conductivities. The initial or static conditions were estimated by simulated data at the steady state.

4. Results and discussion

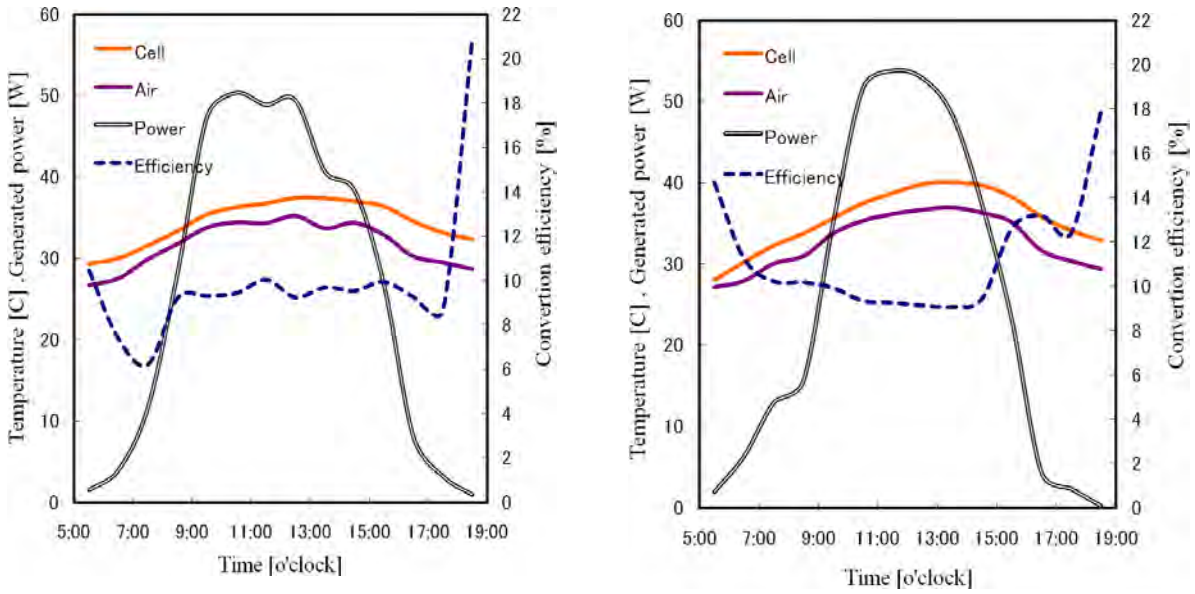
4.1. Dynamic characteristics of solar cell

4.1.1. Effect of hybridization on conversion efficiency (η)

Conversion efficiency of photovoltaic cell (η) can βe estimated by the following expression.

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{V_{OC} I_{SC} FF}{P_{in}} \times 100[\%] \quad (8)$$

Figures 3-(a),(b) show profiles of generated power by a photovoltaic cell and conversion efficiency (η) averaged for one hour in case of (a) exclusive solar cell (11.Augus.2010) and (b) hybridized cell (26.August.2010). In spite of the lower solar intensity per a day Fig. 3(b) shows the higher peak power and average conversion efficiency as shown in Table 1, which is list up each averaged values from 7:00 to 18:00.



(a) Exclusive solar cell
[I=20.4MJ/(m^2·d),11.August.2010]

(b) Hybridized cell
[I=19.0MJ/(m^2·d), 26.August.2010]

Figures 3. Profiles of generated power and conversion efficiency for one day

Table 1 Each characteristic value averaged for 10 hours from 7:00 to 18:00

	Efficiency(η)	Power(P)	$T_{Cell\text{-}terminal}$	T_{Air}
(a) Exclusive solar cell	9.13	32.13	35.36	32.76
(b) Hybridized cell	10.42	30.7	36.85	33.96

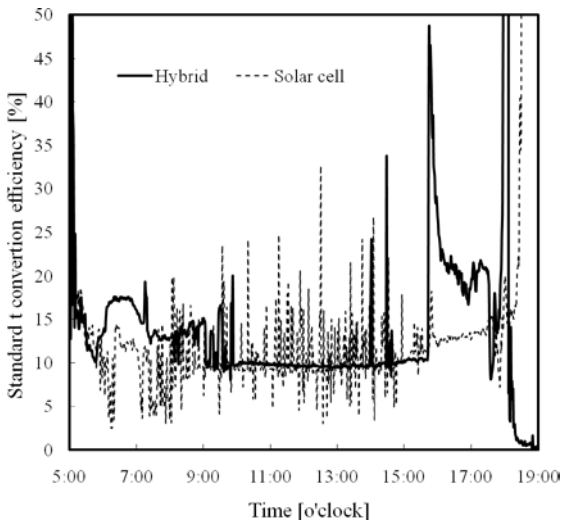


Figure 4. Detailed profiles of standard conversion efficiency

The conversion efficiency at the standard condition of solar irradiation (1kW/m^2) and of cell temperature (25C) is generally available for the public evaluation due to the free dependency of cell temperature. Figure 4 shows detailed profiles of standard conversion efficiency in two cases. Hybridization compresses fluctuation of standard conversion efficiency due to the steady water. In this work water has no flow along the PET sheet and was supplied only for the volume of evaporated water vapor due to the closed outlet of water. Solar intensity inherently has a fluctuated profile due to the presence of variable weather conditions such as cloud, indirect intensity, wind and so on.

4.2. Dynamic characteristics of membrane distillation

4.2.1. Effect of hybridization on temperature profiles of each partition

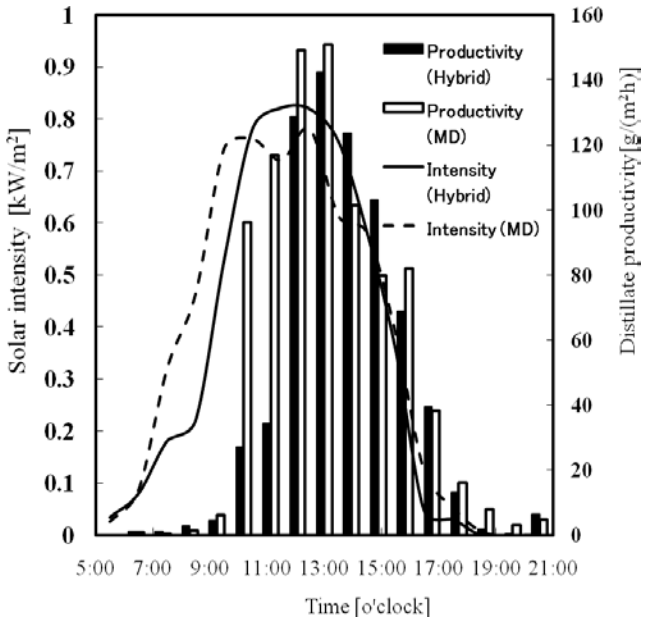


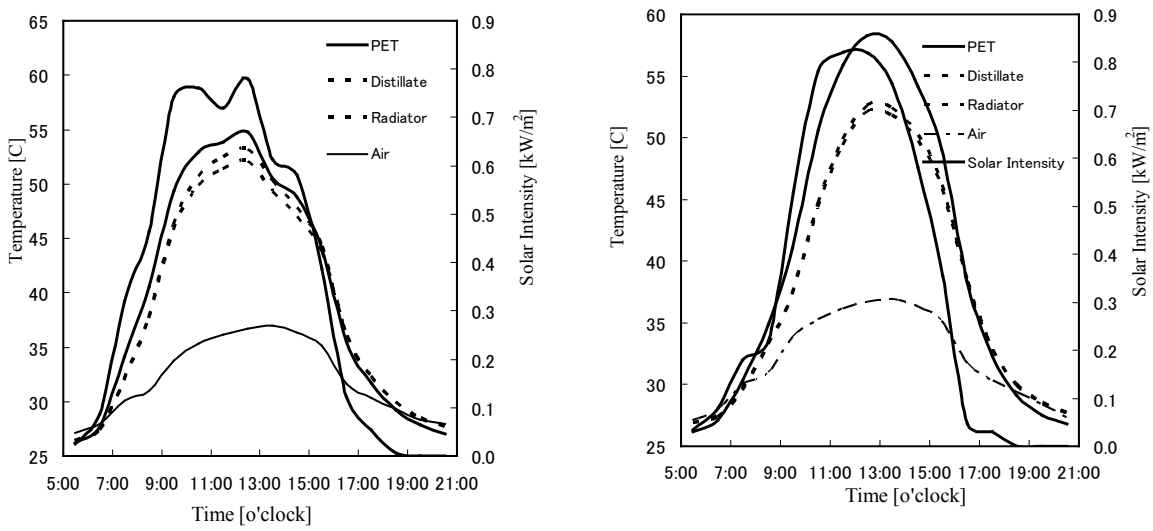
Figure 5. Effect of hybridization on distillate productivity for one hour

Figure 5 shows profiles of distillate productivity per one hour in two cases of hybrid distillator and membrane distillator without a photovoltaic cell. Table 2 lists up experimental data with total distillate productivity per a day in cases of MD with and without a cell. In spite of the less solar intensity by 20% i, the decrease of distillate productivity n case of the hybridized MD was settled within the less range of 7%.

Figures 6-(a),(b) indicate that hybridization increases the temperature difference between PET sheet and distillate partition. The temperature on PET sheet almost equals to that of evaporated water. The distillate productivity only depends on t he temperature difference between evaporated vapor and condensed water .

Table 2 Total distillate productivity per a day in cases of MD with and without a cell

	Solar intensity [MJ/(m^2・d)]	Distillate productivity[kg/(m^2・d)
MD without a cell	20.4	0.855
Hybridized cell	19.0	0.691

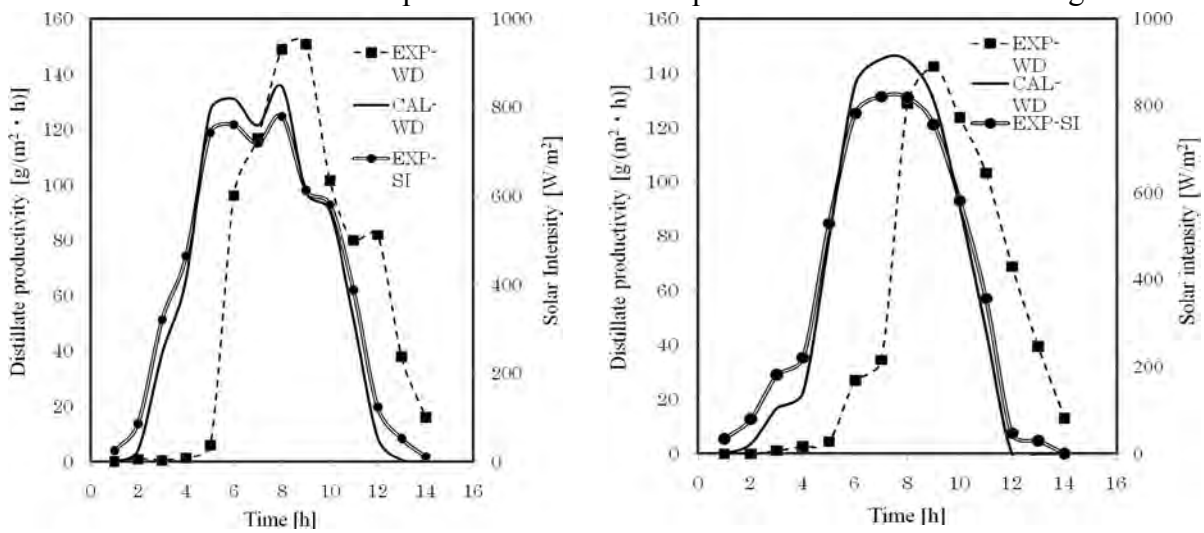


(a) MD without a cell *(b) MD with a cell (Hybrid)*

Figures 6. Temperature distributions in two types of Membrane Distillators (MD)

4.2.2. Numerical results

Figures 7-(a),(b) show profiles of dynamic distillate productivity by numerical simulation in two cases of membrane distillator with and without a photovoltaic cell. Experimental solar intensity and air temperature were used as the weather parameters. The peak value of distillate productivity is underestimated because productivity in Fig.7-(a) was calculated by the hybrid simulation model. Both profiles of productivity in Figs.7-(a),(b) were correspondingly traced by the model. However experimental times at the peak productivity were shifted by two hours from that of solar intensity. The calculated productivity has a response of no time lags for solar intensity due to the negligible temperature gradient along the water flow. The assumption will be invalid in case of operational conditions of water flow. The larger specific heat of water and thickness of spacer mesh than other partitions result in the time lag.



(a) MD without a cell *(b) MD with a cell (Hybrid)*

Figures 7. Numerical prediction of distillate productivity

4.2.3. Effect of hybridization on distillate productivity

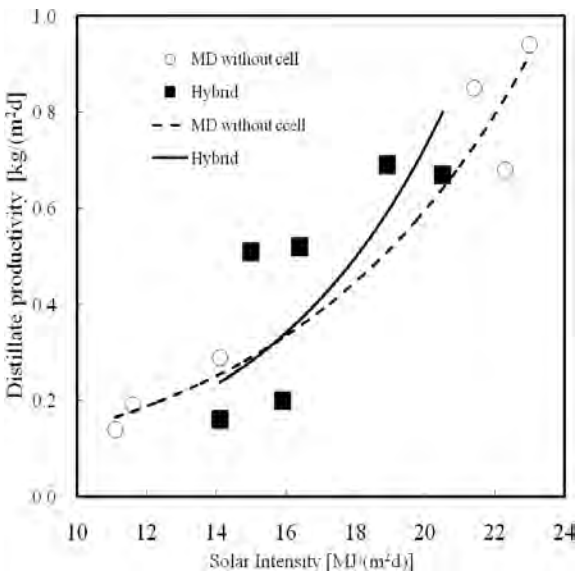


Figure 8. Effect of solar intensity on distillate productivity

Figure 8 shows the effect of solar intensity on distillate productivity for one day. Experimental data were intensively obtained at the summer season in Japan due to the less solar intensity than other arid lands. Approximated curves with experimental relationship between solar intensity and distillate productivity for membrane distillators even if with or without a photovoltaic cell were almost identifiable. The results indicate the effectivity of a hybrid solar membrane distillator directly with a photovoltaic cell even if for the increasing thermal resistances. The productivity is not necessarily desirable in comparison with our previous report [8]. The improvements of hybridization and process flow of water are required.

5. Conclusions

A solar membrane distillator hybridized with a photovoltaic cell supplies with both water and energy which are indispensable for human life and industry and contribute to effective utilization of renewable energy. The effectivity of a hybrid solar membrane distillator was experimentally and numerically verified.

The dependence of cell temperature on conversion efficiency was unrecognized in this work because of an amorphous Si module. However the hybrid solar distillator contributed to the stable standard conversion efficiency of a cell. An amorphous Si module is suitable for the comparatively higher temperature condition.

Relationship between solar intensity and distillate productivity is almost identifiably approximated for the membrane distillator even if with or without a photovoltaic cell. .The performance of distillate productivity is not necessarily desirable. The improvements of hybridization and process flow of water should be required.

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