Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.794765

51 (2013) 3728–3734
May

Taylor & Francis
Taylor & Francis Group

The research on thermal and economic performance of solar desalination system with evacuated tube collectors

Xiaohua Liu*, Wenbo Chen, Shengqiang Shen, Ming Gu, Guojian Cao

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, PR China
Tel. +86 131 3040 1799; email: lxh723@dlut.edu.cn

Received 15 May 2012; Accepted 19 March 2013

ABSTRACT

In this paper, a solar desalination system with evacuated tube collectors (ETCs) and low-temperature multi-effect distillation (LT-MED) is developed. It solves the problem of shortage of fresh water, while it also avoids the consumption of non-renewable energy resource and environmental pollution. The system configurations designed consist of ETCs, heat storage tank, flash tank, multi-effect distillation, electrical heating and cooling, and so on. Mathematical and economic models are established based on mass and energy conservation, and the thermal and the economic performance of the solar desalination system is analyzed by utilizing MATLAB. In this paper, the fresh water cost reduces with both the increasing of the area of ETCs and collector outlet water temperature. Recommendations given in this paper could be helpful in future initiatives regarding the research and development of this promising solar desalination technology.

Keywords: Solar desalination; Evacuated tube collectors; Low-temperature multi-effect distillation (LT-MED); Heat storage tank; Water cost

1. Introduction

With the growing World population, the scarcity of fresh water sources has become more and more obvious for humans. It is expected that by 2,025, more than 60% of World's population will have water shortage [1]. Desalination of sea or brackish water is the method used currently to produce potable water [2].

There are many methods of desalination which can be mainly classified into membrane methods and distillation methods. Among membrane desalination methods such as reverse osmosis (RO) and membrane distillation (MD), RO is the proven membrane desalination method. Multi-stage flash (MSF) and multi-effect distillation (MED) are the two conventional distillation methods. Essentially, those methods consume fossil fuel and electric power while they discharge a large amount of carbon dioxide which will aggravate energy shortage and environmental pollution.

Although everybody recognizes the strong potential of solar thermal energy for seawater desalination, the process is not yet developed at commercial level. The main reason for this is that the existing technology, although, already demonstrated as technically

*Corresponding author.

Presented at the 2012 Qingdao International Desalination Conference June 26–29, 2012, Qingdao, China

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feasible cannot presently compete, on the produced water cost basis, with conventional thermal distillation and RO technologies [3].

Solar energy is considered to be a renewable energy source. Solar thermal energy is a very convenient source of heating and a technology that does not depend on scarce, finite energy resources [4]. Low-temperature multi-effect distillation (LT-MED) coupled with solar energy is considered as a promising solar desalination technology. In recent years, solar desalination technology has been attracting extensive attention worldwide. In some remote areas where water and electricity infrastructures are currently lacking, solar desalination technology has a very vital significance. For example, in island of Ibzia, Australia, a solar desalination plant with evacuated tube collectors (ETCs) and LT-MED was founded in 1993 [5,6].

Based on this present situation, solar desalination technology is the fundamental way to solve the problem of energy sustainable development and shortage of fresh water. Solar desalination system is studied and some independent parameters which influence the thermal and economic performance of the system are researched in this paper. Recommendations given in this paper could be helpful in future initiatives regarding the research and development of this promising solar desalination technology.

2. Solar desalination system

The solar desalination system in this paper includes ETCs subsystem, thermal storage tank subsystem, flash evaporator subsystem, parallel flow LT-MED subsystem, and assistant electrical heating/cooling subsystem. Fig. 1 shows their coupling.

When solar radiation exists:

(1) ETCs utilize solar radiation to heat the work medium water. If the solar radiation is so weak that the collector outlet water temperature cannot reach the design value, valve 1 closes and valve 2 opens. And, the assistant electrical heating subsystem will supply the heat for the LT-MED subsystem. If the solar radiation is moderate, valve 2 closes and the openings of valve 1, 3, 4, and 5 are controlled to vary the flux of water in collector so as to guarantee the collector outlet water temperature to reach design value. If the solar radiation is too strong that the collector outlet water temperature is higher than the design value, assistant cooling subsystem runs to ensure that it lowers to the design value. During the above process, the flux in valve 3 equals to that in valve 5 which means that the mass of water in storage tank is constant.

(2) Thermal storage tank connects with flash evaporator and ETCs, simultaneously. The temperature of water before the flash evaporator is constant, and water partly flashes in the flash evaporator. The flash vapor drives the MED subsystem. The other part of water mixes with the condensed water from the first effect evaporator of MED and is heated by ETCs sequentially.

When solar radiation disappears:

Valves 1, 2, and 4 are closed. The heat driving the MED subsystem comes from the storage tank or assistant heating subsystem. Given the temperature drop

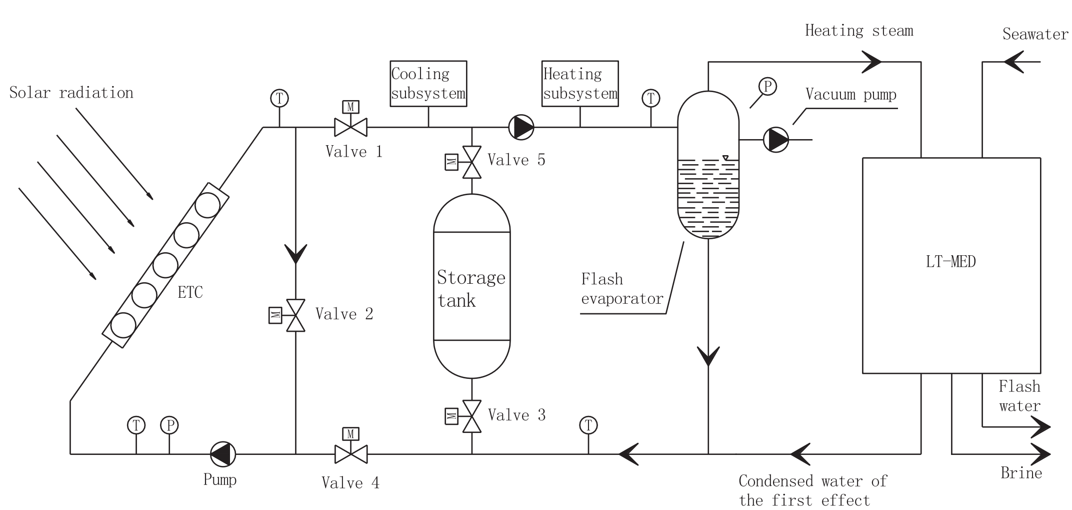

Fig. 1. Flow chart of ETCs seawater desalination system.

of storage tank for heat extraction by MED subsystem and heat dissipation, appropriate storage tank volume should guarantee the lowest temperature of storage tank higher than the heating vapor temperature of the first effect by 1.5℃ [7].

3. Mathematical model

3.1. Evacuated tube collectors

The heat collecting system supposes in Dalian, China, using double-layer all-glass ETCs. Based on "GBT17581-2007", the pressure in it is 10^{-2}Pa. Single collector area is $2.5\,m^2$ and it has 16 collecting pipes. Table 1 shows the dimension and performance parameter of the collector.

The quantity of obtained heat by ETCs can be calculated by formula [8]:

$$Q_y = d \times L \times 16 \times F_R \times [I_{eff} - \pi \times U_L \times (T_{f.i} - T_a)] \quad (1)$$

where d is the external diameter of inside glass tube, m; L is the length of glass tube, m; F_R is the heat removal factor; I_{eff} is the collected heat by tube per unit area per unit time, w/m^2; U_L is the heat-loss coefficient, w/(m^2 ℃); $T_{f.i}$ is the inlet temperature of the collector, ℃; T_a is the monthly mean temperature of the air, ℃.

3.2. Thermal storage tank

3.2.1. Operation in nighttime

Fig. 1 shows the physical model, as the storage tank with intensive mixing single node, the energy equation is:

$$T_s^+ = T_s + \frac{\Delta t}{(mC_p)_s}\{Q_u - Q_{loss} - Q_{load}\} \quad (2)$$

where T_s is the water temperature of storage tank on time t (℃), T_s^+ is the water temperature of storage tank on time $t + \Delta t$ (℃), Δt is the time interval (h), $(mC_p)_s$ is the mass-specific heat product (J/℃), Q_u is the heat in storage tank (J), Q_{loss} is heat loss from the convection of storage tank and environment (J), Q_{load} is the thermal load provided by storage tank (J).

From $t = 16:00$ on, Δt is one hour, the hourly initial temperature is the final temperature in last hour. After 16 h, the water temperature is assumed to be able to drive the MED, which determines the water mass in storage tank and the volume. The volume of storage tank is influenced by two parameters: the initial water temperature and the heat extraction hourly from the storage tank.

3.2.2. Operation in daytime

Fig. 2 shows the physical model of thermal storage tank for operation in daytime. The condensing water outflow from MED and the mixed water from storage tank flow into the collector together, the flux of mixing water is controlled so as to guarantee the collector outlet water temperature to reach the design value. The collected heat and the water temperature of storage tank changes with time, so it is necessary to change the flux in valve 3 based on the variation of solar radiation in order to meet the mass and energy balance. The equation is given as follows:

$$C_{p,ts} \times m_1 \times ts + C_{p,txl(i)} \times m_2 \times t_{xl}(i) + Q = C_{p,tfo} \times (m_1 + m_2) \times t_{fo} \quad (3)$$

Table 1
Dimension and performance parameter of ETCs

Dimension	Diameter of inside glass tube	d	47 (mm)
	Diameter of outside glass tube	D	58 (mm)
	Interval space between tubes	B	116 (mm)
	Length of tube	L	1.8 (m)
Performance	Normal projective factor of collector	τ	0.92
	Normal absorption factor of collector	α	0.86
	Heat loss coefficient	U_L	2w/(m^2 ℃)
	Heat removal factor	F_R	0.95

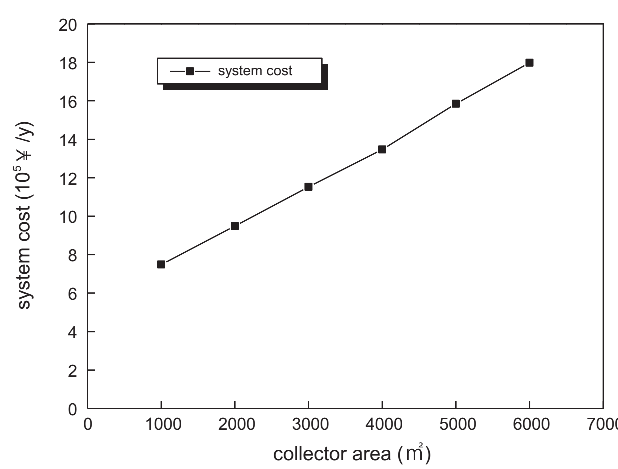

Fig. 2. Effect of collector area on system cost.

$$C_{p,txl(i)} \times M \times t_{xl(i)} + m_2 \times (C_{p,tfo} \times t_{fo} - C_{p,txl(i)} \times t_{xl(i)}) - Q_l = C_{p,txl(i+1)} \times M \times t_{xl(i+1)} \quad (4)$$

where Q is the collected heat per unit of time, M is the water mass of storage tank, Q_l is the heat loss in daytime. Given an initial value $t_{xl(1)}$, time interval is one hour, the maximum flux m_2 and the water temperature $t_{xl,(i)}$ can be calculated at different times initiating in daytime.

3.3. Mathematical model of parallel flow LT-MED system

LT-MED means the desalination technology that when the highest temperature of the first-effect heating steam cannot exceed 70℃, and it concludes two basic flows, namely serial flow, parallel flow. In the parallel feed system, the feed water leaving the condenser is divided and distributed almost equally to each effect. Because of pressure difference between the evaporators, the brine that enters into the bottom of the next evaporator flashes out some steam, and the condensed water of the former evaporator also flashes out some steam at the steam entrance of the next evaporator.

Take evaporator as example, the mathematical model for it is listed as follows and mathematics of other parts can be found in [9].

The heat balance in evaporator of effect i:

$$(M_{v(i-1)} - M_{p(i-1)}) \times \lambda_{i-1} + M_{b.out(i-1)} \times C_{pb.out(i-1)} \times t_{b.out(i-1)} - M_{b.in} \times C_{pb.in} \times t_{b.in} = (M_{vi} \times \lambda_i)/\eta \quad (5)$$

where M, λ, h, η, C_p are the mass flow rate of steam (kg/s), latent heat (J/kg), specific enthalpy (J/kg), adiabatic efficiency of evaporator, and specific heat (J/(kg·K), respectively; subscript b, v, p, i, in and out represent the brine, steam, preheater, number of effects, inlet, and outlet, respectively.

Thermal storage tank and flash evaporator mathematical model can be found in [10,11].

4. Economic model of solar desalination system

4.1. The cost of evacuated tube collector

The economic model of ETCs is performed as:

$$J_{a1} = F_c \times A \times C_{col} \quad (6)$$

where F_c is the annual depreciation and maintenance rate, 0.05; A is the area of ETCs (m^2); C_{col} is the price of ETCs and is estimated to be 1,900 ¥/m^2.

4.2. The cost of evaporator

The economic model of evaporator in this paper adopts that in [12]:

$$J_{a2} = F_c \times \sum_{i=1}^{n} \{[4,400 + (B - 620)] \times 1.2 \times (0.667 + 0.0287 \times A) \times h \quad (7)$$

where F_c is the annual depreciation and maintenance rate, 0.05; B is the material price of evaporator, 85,000 ¥/t; h is the gain coefficient which equal 1, 1.2, 1.5 depending on the area of evaporator; A is the area of evaporator (m^2).

4.3. The cost of condenser and preheater

The economic model of condenser and preheater can be written as follows:

$$J_{a3} = F_c \times A_{con} \times a \quad (8)$$

$$J_{a4} = F_c \times A_{pre} \times a \quad (9)$$

where J_{a3} is the cost of condenser and preheater; F_c is the annual depreciation and maintenance rate, 0.05; A_{con} is heat transfer area of condenser (m^2) and A_{pre} is heat transfer area of preheater (m^2); a is the price of per condenser and preheater area and is estimated to be 3,500 ¥/m^2.

4.4. The cost of thermal storage tank

The economic model of thermal storage tank in this paper is [13]:

$$J_2 = F_c \times 456.6 \times \left(\frac{M_{st}}{300}\right)^{-0.46} \times M_{st} \quad 100 \leqslant M_{st} \leqslant 600 \quad (10)$$

where F_c is the annual depreciation and maintenance rate, 0.05; M_{st} is the volume of thermal storage tank (m^3).

4.5. The cost of electrical heating and cooling

The economic model of electrical heating and cooling is given as follows:

$$J_{a7} = F_c \times \alpha \times P_{ele} \tag{11}$$

$$J_{a8} = F_c \times \delta \times A_{coo} \tag{12}$$

where J_{a7} is the cost of electric heater (¥/*y*), and J_{a8} is the cost of cooler (¥/*y*); F_c is the annual depreciation and maintenance rate, 0.05; P_{ele} denotes the power of double-pipe electric heater (kw); α is the price per unit of electric heater power and is estimated to be 300 ¥/*kw*; A_{coo} is the heat transfer area of cooler (m^2); δ is the price per unit of cooler area and is estimated to be 1,600 ¥/m^2.

4.6. The cost of land

The economic model of land is written as follows:

$$J_{a9} = 0.02 \times 1.1 \times A \times C_{land} \tag{13}$$

where J_{a9} is land cost (¥); C_{land} is the cost per unit of land area and is estimated to be 200 ¥/m^2.

4.7. The operating cost of pump

The economic model of pump is defined as follows:

$$J_{b1} = \frac{60 \times 60 \times 24 \times 365 \times \sum N_i}{3,600,000} \times \psi \tag{14}$$

where J_{b1} denotes the operating cost of pump (¥); ψ is the price per unit of electricity (¥/kWh).

4.8. The cost of manpower

Calculation in accordance with a day in three shifts, two people per class, the annual salary is 30,000 ¥/py.

4.9. The cost of seawater pretreatment

The cost of drug seawater pretreatment is estimated to be 0.2 ¥/(td).

4.10. The cost of electricity in heating subsystem

The economic model of electricity is as follows:

$$J_{b4} = (Q_D/3,600,000) \times 0.5 \tag{15}$$

where Q_D is total heat of the whole year (*J*); 3,600,000 is the heat per unit of electricity (*J*); 0.5 is price per unit of electricity (¥/kWh).

4.11. The cost of fresh water

The economic model of fresh water is as follows:

$$J = 1,000 \times \frac{\sum J_{ai} + \sum J_{bj}}{DD \times \theta} \tag{16}$$

where J is fresh water cost per unit of fresh water production (¥/t); $\sum J_{ai}$ and $\sum J_{bj}$ are, respectively, investment cost and operating cost (¥/y); θ is the operating time annually and is estimated to be 7,200 h; *DD* is fresh water production (kg/h). System cost includes $\sum J_{ai}$ and $\sum J_{bj}$.

The cost of flash evaporator, pump investment, civil installation, and auxiliary equipment, etc can be found in [14–16].

5. The thermal and economic performance

According to the solar desalination system, two independent parameters are analyzed: collector area (*A*), collector outlet water temperature (T_{fo}), which have influence on the thermal and economic performance of system.

5.1. The influence of collector area

If the collector outlet water temperature is 88℃, the heating steam temperature of the first effect is 66℃

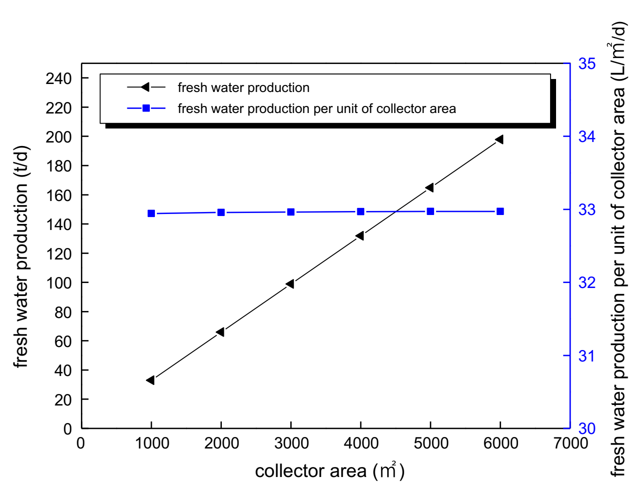

Fig. 3. Effect of collector area on fresh water cost and fresh water production per unit of collector area.

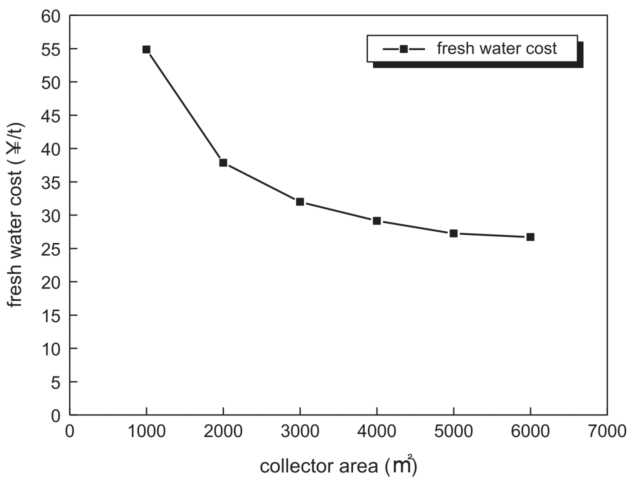

Fig. 4. Effect of collector area on fresh water cost.

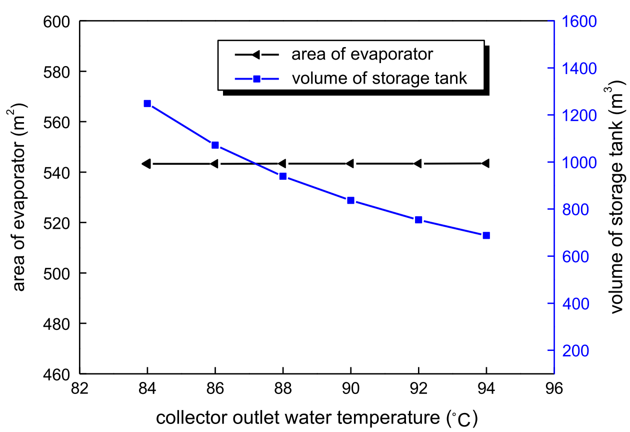

Fig. 5. Effect of collector outlet water temperature on the area of evaporator and the volume of storage tank.

and the number of effects is 8. When collector area changes, the variations of the performance of system are shown in Figs. 3–5.

With the increasing of collector area, the system cost and fresh water production increase gradually, but fresh water production per unit of collector area changes slightly, the fresh water cost declines all the way. The heat of the system required is noticed to be greater with the increasing of collector area, therefore, fresh water production increases. Meanwhile, the increasing of fresh water production and collector area leads fresh water production per unit of collector area to change slightly. On the other hand, the equipments cost and operating cost matched with collector area increase which leads to increased system cost. As a result, fresh water cost reduces greatly.

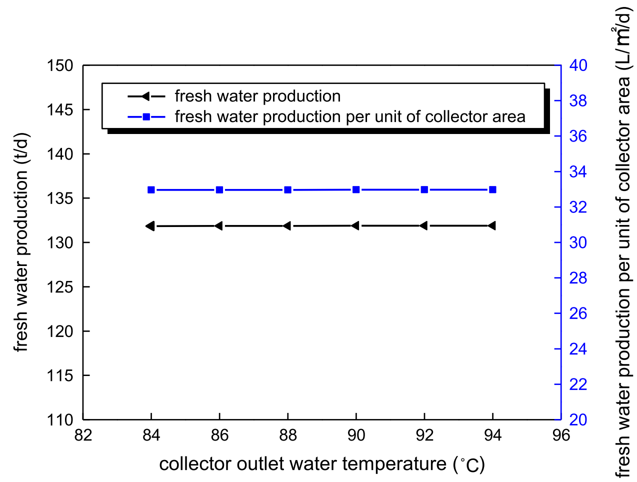

Fig. 6. Effect of collector outlet water temperature on fresh water cost and fresh water production per unit of collector area.

5.2. *The influence of collector outlet water temperature*

If the collector area is 4000 m^2, the heating steam temperature of the first effect is 66℃ and the number of effects is 8. The effect of collector outlet water temperature on the performance of system is analyzed in Figs. 6 and 7.

As illustrated in Figs. 6 and 7, with the increasing of collector outlet water temperature, the area of evaporator, fresh water production, and fresh water production per unit of collector area changes slightly, but the volume of storage tank and fresh water cost reduces gradually because the increasing of collector outlet water temperature leads to the increasing of initial temperature of storage tank for operation in nighttime.

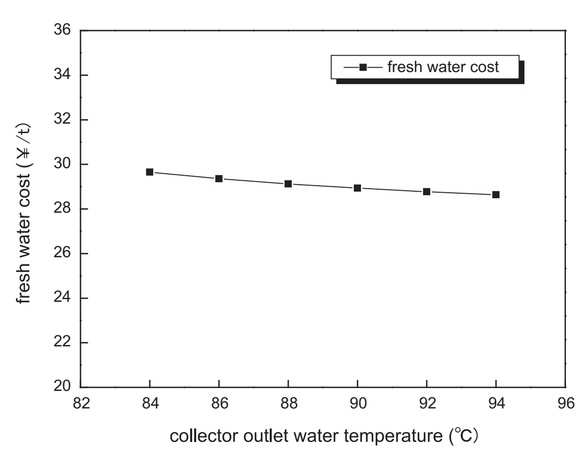

Fig. 7. Effect of collector outlet water temperature on fresh water cost.

6. Conclusion

The thermal and economic performance on solar desalination system with ETCs and LT-MED is presented in this paper. Taking the actual project into account, the collector area and collector outlet water temperature impacting on the system performance are analyzed. Under the calculation conditions of this paper, the following conclusions can be drawn:

(1) With the increasing of the collector area, the system cost and fresh water production increases, the fresh water production per unit of collector area changes slightly, but fresh water cost reduces greatly.
(2) With the increasing of collector outlet water temperature, the volume of storage tank decreases gradually, but the area of evaporator, fresh water production, and fresh water production per unit of collector area change slightly, fresh water cost reduces gradually.

Acknowledgments

This work is supported by the Fundamental Research Funds for the Central Universities (DUT10ZD109), the Technology Fund of Dalian Construction Commission, the Foundation of Key Laboratory of Liaoning Province for Desalination and the Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education.

Nomenclature

I_{eff} — collected heat by tube per unit area per unit time, w/m^2
$T_{f.i}$ — inlet temperature of collector
T_a — monthly mean temperature of the air, ℃
M — mass flow rate of steam, kg/s
λ — latent heat, J/kg
h — specific enthalpy, J/kg
η — adiabatic efficiency of evaporator
C_p — specific heat, J/(kg K)
F_c — annual depreciation and maintenance rate
A — area, m^2
C — price, ¥/m^2
B — material price
M_{st} — volume of thermal storage tank, m^3
P_{ele} — power of double-pipe electric heater, kw
a — price of per condenser and preheater area, ¥/kw
α — price per unit of electric heater power, ¥/kw
δ — price per unit of cooler area, ¥/m^2
ψ — price per unit of electricity, ¥/kWh
Q_D — total heat of the whole year, J
$\sum J_{ai}$ — Investment cost, ¥/y
$\sum J_{bj}$ — operating cost, ¥/y
DD — fresh water production, kg/h
θ — Operating time annually

Subscript

b — brine
v — steam
p — preheater
i — number of effects
in — inlet
out — outlet
col — evacuated tube collector
con — condenser
coo — cooler
pre — preheater
$land$ — land

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