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OPTIMIZED OPERATION OF AN INTEGRATED SOLAR DESALINATION AND AIR-CONDITIONING SYSTEM: THEORETICAL STUDY

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Abstract. Integrating the solar distiller with the air-conditioning system can increase the condensate output from the solar stiller while meeting the cooling load needs. The operation of the combined solar distillation and air conditioning system has been modeled and simulated to predict distillate output from the cooling coil for the combined system for a residential space application in the suburbs of Beirut. An optimization problem is formulated to optimize the integrated system operation for minimum energy consumption while meeting the hourly cooling load and the daily fresh water need of 100 liters. The design variable in the optimization study is the fresh air flow rate that passes through the distiller and mixes with return air for the constant volume space supply fan.

The optimization problem is solved for a 10-hour of operation of the combined system for the summer months: June, August and October. It is found that the cost of fresh water production of the combined system is 0.108 kWh/ liter for the month of August and 0.12 kWh/liter of fresh water in October.

Key words

Solar humidification, combined cooling and water production, optimized desalination & air conditioning system operation, solar energy - optimized operation of integrated system

1. Introduction

About 70% of the earth is covered by water, and sea water represents about 97% of the water on the planet and the remaining is fresh water; thus there is a shortage of potable water in many countries around the world. The rural and remote regions in the Middle East countries do not have access to good quality drinking water and as a result they relied on low cost options for producing water from salty aquifers such as solar desalination.

Many researchers have developed mathematical models, and experimentally tried to improve the design of the conventional solar still in order to increase its daily productivity. Tiwari et.al [1] reported that the solar still output can be increased by decreasing the temperature of the glass cover through flowing water over the glass cover. Also Al- Hinai et al [2] reported that the condensate output of a double effect solar still is twice that of a single effect solar stiller when water is passed between the double glass layers and therefore dropping its temperature. Other researchers, Nawayseha et al. [3] focused on the reclamation of the condensing energy by transferring the latent heat of condensation to the feed saline water before it enters the solar stiller. Nawayseha reported that the fresh water output considerably increased in comparison to the water output of a conventional unit. Other researchers considered a simultaneous increase of the evaporator temperature and lowering the temperature of the glass cover, Rahim et.al [4] reported that the enhancement of the efficiency of a conventional solar stiller is related to the temperature difference between the evaporating and condensing zones.

Since the solar stills are not reliable in producing fresh water, other researchers considered combining the air conditioning system with desalination. Yuan et al [5] integrated desalination-air conditioning system utilizing the heat rejected by the condenser and the heat sink of the evaporator to evaporate the sea water and then condense it on the cold surfaces of the evaporator. The water output of the combined system exceeds the output of an improved solar still that harasses the latent heat of condensation and that lowers the temperature of the cover glass. However, the conventional solar still component does not exist in the integrated system of Yuan et al. [5] and it relies on electrical energy to produce fresh water. If the air conditioning system is not running, then no potable water can be produced. The objective of this manuscript is to model and optimize the operation of a combined air conditioning and solar still desalination unit to study the enhancement in distillate output and system performance to meet a specified cooling load and fresh water needs for a residential application with the slightest change in the installed HVAC system.

2. Integrated System Description

The solar distiller unit and air-conditioning integrated system schematic is depicted in Fig. 1. The system is composed of a number of conventional solar stills, a cooling coil heat exchanger and a circulating fan to humidify ambient by passing it over the solar still, mix it adiabatically with return air coming from the air conditioned space and then direct the mixed air to a cooling coil where it gets cooled and dehumidified while simultaneously meeting the air conditioning requirement and potable water needs of a typical house in the rural region without exceeding the cooling capacity of the air-conditioning system. To optimize the operation of the integrated system, it is necessary to model the various components of the system and integrate the simulation models with an optimizer

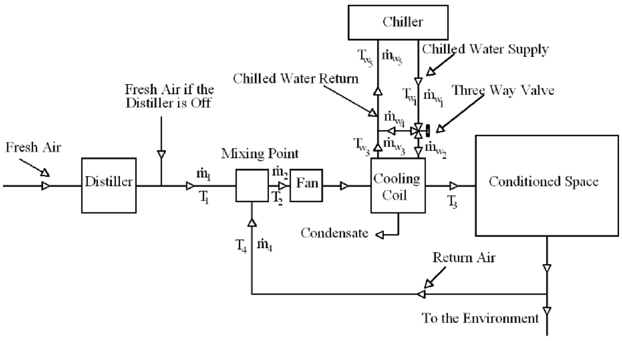

Fig. 1: Schematic of the solar distiller unit and air-conditioning integrated system

3. System Component modeling

Solar Still

The conventional solar still consists of a single pane glass cover and a sea water basin with an absorbing liner. Ambient air enters the stiller from its lower end and leaves the other end after being humidified. Energy balances will be developed for the glass, air flow, and seawater in the basin.

The transient temperature of the glass cover can be represented by:

$$m_g c_{pg} \frac{dT_g}{dt} = I_{(t)}\alpha_g A_g + h_{r1}(T_w - T_g)A_w - h_{c-g}(T_g - T_{air})A_g - h_{r2}(T_w - T_{sky})A_g - h_{c-a}(T_g - T_\infty)A_g \quad (1)$$

Where m_g is the mass of the glass cover, C_{pg} is the glass heat capacity, T_g is the glass temperature, $I_{(t)}$ is the incident solar radiation on the glass surface, T_w is the water temperature, T_{air} is the air temperature inside the still, and T_∞ is the ambient air temperature, A_g is the glass cover area, h_{c-g} is the convective coefficient between glass and air flow in the still, h_{c-a} is the convective coefficient between glass and ambient and h_{r1} and h_{r2} are the inner and outer radiative heat transfer coefficients. The term on the right hand side represents: 1) the energy absorbed by the glass, 2) the radiative heat exchange of the glass with water, 3) the convective heat exchange with the flowing air, 4) the radiative heat loss with the sky and 5) the convective heat loss with the ambient air.

The transient water basin temperature is written as a balance between the solar energy absorbed by the water and the energy losses by convection to the flowing air, radiation to the glass and evaporation.

$$m_w \times c_{p_w} \frac{dT_w}{dt} = I_{(t)}\tau_g \alpha_w A_w - h_1(T_w - T_g)A_w - h_{c-w}(T_w - T_{air})A_w - \dot{m}_w h_{fg} \quad (2)$$

Where m_w is the mass of water in the basin, C_{pw} is the specific heat of water; τ_g is the glass and $\dot{m}_w$ is the water evaporation rate. The lumped energy balance for the moving air can be written as:

$$h_{c-w}(T_w - T_{air})A_w + h_{c-g}(T_g - T_{air})A_g + \dot{m}_{air} c_{p_{air1}} T_{air1} + \dot{m}_w h_{fg} + \dot{m}_{air} w_1 c_{p_v} T_{air1} - \dot{m}_{air} c_{p_{air2}} T_{air2} - \dot{m}_{air} w_2 c_{pv} T_{air2} = 0 \quad (3)$$

Where A_w is the water basin surface area, C_{pv} is water vapor specific heat; T_{air1} and T_{air2} are the inlet and exit air flow temperatures. The rate at which water is evaporated can be obtained from the correlation developed Al-Shamiri et al. [6] that take into account the water salinity

Knowing the solar radiation, the four transient variables: T_{air}, T_w, Tg and $\dot{m}_w$ are coupled and their simulations is performed by the classical fourth-order Runge–Kutta method for a time step of ten seconds.

Cooling Coil

The modeling of cooling and dehumidification of the coil operation is adopted from the quasi-static model of Zhou and Braun [7] to predict outlet air temperature and humidity conditions for known air inlet conditions leaving the solar still. The model utilizes effectiveness relationships for heat and mass transfer using a lumped formulation approach.

The optimization of the operation of the integrated system requires the minimization of the energy consumption of the following function:

$$J_{operational} = \int_{t_o}^{t_f} \{J_{chiller} + J_{fan} + J_{pump}\} dt \quad (3)$$

Where $J_{operational}$ is the total energy used by the combined system and $J_{chiller}$, J_{fan} and J_{pump} are the energy consumed by the chiller, fan and pump respectively. The operational energy consumption can be calculated for a typical summer day using the free derivative genetic algorithm optimizer.

4. Case Study

A case study of a typical residential house (120 m^2) of an overall convective heat transfer coefficient, $U_{overall}$ = 2.85W/m^2-K in the suburbs of Beirut is selected for the optimization operation problem of the integrated air-conditioning-desalination study. The peak load of the air-conditioning system is 5.4 kW and the house daily need of fresh water is 100 liters. To insure the daily delivery of 100 liters during the summer season, four distillers, each of area 1.2 m^2, are needed as determined by the operation of the system in the month of October (the summer month of the least solar radiation) for Beirut weather. The standalone operation of the four solar desalination units and the air-conditioning system cannot produce more than 50 liters per day and the condensate from the HVAC system for the case study operating alone does not exceed 30-35 liters/day for the peak August month. Combining the operation of both the distiller and the HVAC system can meet the daily fresh water need of 100 liters.

The air-conditioning is characterized by a constant flow fan and chilled water pump. The hours of operation of the combined solar still/air-conditioning are limited to the 10 hours of the air-conditioning system operating time from 10:00 am to 8:00 pm. During each hour of operation, the amount of fresh air passing through the solar still can be optimized to obtain at the end of the combined system operating time the daily required 100 liters of water.

Since a constant air volume fan and constant chilled water pump are used, the objective function for minimizing the operational cost can be written as:

$$J_{operational} = \int_{to}^{tf} J_{chiller}\, dt \qquad (4)$$

The chiller cost is calculated from the instantaneous cooling load and the chiller coefficient of performance (COP). The COP is related to the part load ratio (*PLR*) defined as the ratio of the instantaneous load on the chiller divided by the capacity load of the chiller, $P_{chiller}$. Mathematically, *PLR* can be calculated from the following equation:

$$PLR = \frac{\dot{m}_{w,chiller} c_{pw} (\Delta T_{w,chiller})}{P_{chiller}} \qquad (5)$$

Knowing *PLR*, then the *COP* can be calculated from the following equation using Visual-DOE 4.0 Program Library (2005) for chillers with *PLR* between 0.2 and 0.9:

$$\begin{aligned} COP = {} & 7.927\,PLR^3 - 21.194 PLR^2 \\ & +16.485 PLR + 2.214 \\ & +0.1(T_{chiller} - 6) \end{aligned} \qquad (6)$$

The objective function is subject to the following constraints associated with the system physical model and the bounds on system variables.

1) The cooling coil capacity is less than the capacity of the air conditioning system.

2) The total amount of condensate water is equal to 100 liters.

3) The amount of fresh air entering the distiller should be greater than the required fresh air but less than the fan capacity, 0.5 kg/s

4. Optimization Procedure

For each interval of the specified operation (starting at 10:00 am with a maximum of 10-hour intervals) of the combined desalination and air conditioning system, the genetic algorithm seeds simultaneously the 10 hourly values of fresh air flow rate, $\dot{m}_1$, for each operating interval. Knowing the amount of fresh air passing through the distiller, the psychometric conditions of the fresh air leaving the distiller can be calculated using the solar still model and the amount of return air is computed since a constant air volume fan is used. To meet the cooling load and fresh water requirements of the space, the amount of chilled water supplied to the cooling coil and the condensate drain are determined from the cooling coil model that requires the following inputs: condition of air entering cooling coil and the chilled supply water temperature as well as the physical dimensions and characteristics of the cooling coil. Finally, the energy consumed of the chiller is determined. This procedure is repeated with new values of $\dot{m}_1$ to determine the best values that would provide the amount of fresh water and cooling with the least chiller consumed electrical energy.

5. Results and Discussion

The annual energy consumption is calculated for the combined solar still/air conditioning system over the cooling demand months of June, August, and October while collecting the 100 daily liters of fresh water.

Figure 2 shows the (a) optimized fresh air flow rate design variable for the 10 hours of operation for the three selected summer months and (b) the optimized hourly energy consumption bar chart in kWh for the three months as a function of the operating hour of the day. The hourly optimized fresh air flow rate starts high at 10:00 in the morning and then decreases as the ambient temperature increases to reach a minimum at the peak hour and then starts to increase again. The variation in the hourly energy consumption operation of the combined system is small and the combined system hourly energy need is close to the maximum energy demand at the peak.

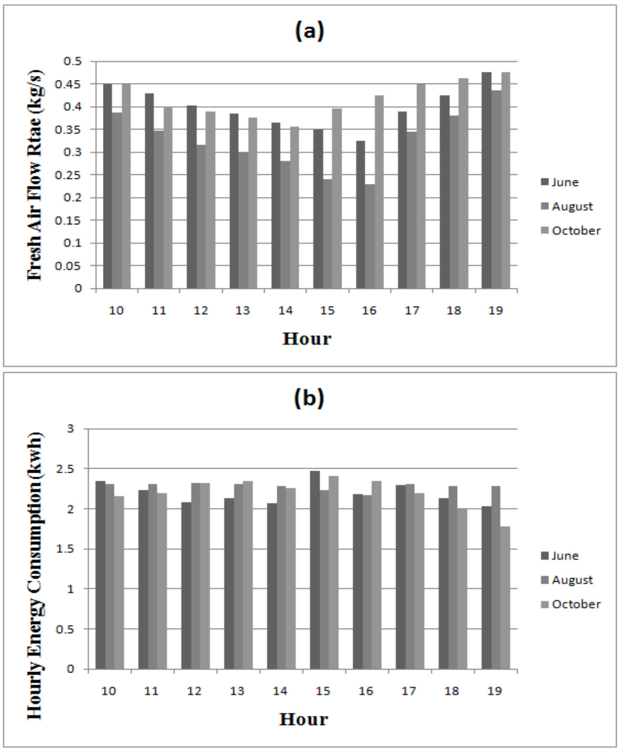

Fig. 2: (a) optimized fresh air flow rate design variable for the hours of operation for the studied months (June, August & October) and (b) the optimized hourly energy consumption bar chart in kWh for the different three months as a function of the hour of the day.

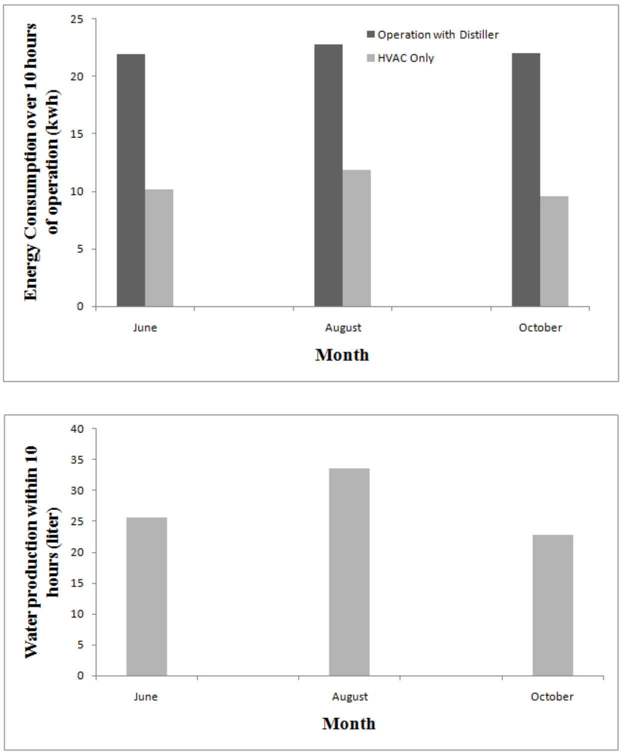

Fig. 3: (a) the optimized total energy consumption bar chart in kWh for the 10 hours of operation when the distiller is operated and when it is not operated for the different months and (b) The amount of water condensate over 10 hours when the distiller is not operated with the HVAC system.

Figure 3a shows the optimized total energy consumption bar chart in kWh for the 10 hours of operation for the three selected months. On the same plot the energy consumption of the cooling system is shown when the distiller is not operated. Figure 3b shows the amount of water condensate over 10 hours when the HVAC system is operated without the solar still. The figures show that the month of October consumes the least combined energy but it uses more energy to produce the 100 liters compared to the rest cooling months. Because of the lower solar insolation required to evaporate the sea water, the amount of the hourly fresh air has to be increased which causes an increase in the chiller energy consumption. The operation of the distiller doubles the electric energy consumption of the cooling system. The excess electrical energy consumption varied from a minimum value of 10.94 kWh in August and maximum value of 12.4 kWh in October for the operation of the distiller with the HVAC system. Using 0.12 $/kWh as energy cost, the cost of producing 100 liters of fresh water per day is less than 1.5 USD over the consumption when the cooling system is run alone. It is found that the cost of fresh water production of the combined system is 0.108 kWh/ liter for the month of August and 0.12 kWh/liter of fresh water in October.

6. Conclusion

The operation of the combined solar distillation and air conditioning system has been modeled and simulated to predict distillate output from the cooling coil for the combined system. An optimization problem is formulated to optimize the integrated system operation for minimum energy consumption while meeting the cooling and fresh water need of a residential space in the suburbs of Beirut. The design variable in the optimization study is the fresh air flow rate that passes through the distiller and mixes with return air for the constant volume space supply fan.

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7. Acknowledgment

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