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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE WATER DISINFECTING SYSTEM USING SOLAR HOT BOX

Takeo S. Saitoh
Professor of Dept. of Aeronautics and Space Engineering, Tohoku University,
Sendai 980-8579, Japan
Phone : +81-22-217-6974
FAX : +81-22-217-6975
E-mail: saitoh@cc.mech.tohoku.ac.jp

Hamdy H. EL-Ghetany
Doctoral course, Graduate School of Aeronautics and Space Engineering, Tohoku University,
Sendai 980-8579, Japan
Phone : +81-22-217-6976
FAX : +81-22-217-6977
E-mail: ens606@cc.mech.tohoku.ac.jp

ABSTRACT

The Solar Hot Box (SHB) can be used effectively not only in cooking purposes but also in water disinfecting purposes. A mathematical model of the SHB is presented, analyzed, and solved numerically via fourth-order Runge-Kutta method. A solar radiation model is also presented. The effect of environmental conditions (ambient temperature, wind speed, solar radiation and so on) on the SHB performance is clarified. Different heat transfer coefficients among the SHB components are also examined. The presented model can be used to evaluate the SHB performance in water disinfecting process.

I. INTRODUCTION

Thermal application is considered one of the possible solar energy applications. The SHB is the simplest device to convert solar energy into thermal energy. In recent years, many research studies have been conducted in the field of solar disinfection of water. The earlier findings of Acra et al.[2] obtained that the solar radiation has been proven to inactivate and destroy pathogenic bacteria present in drinking water.

David et al.[7] found that, it is not necessary to boil water to make it safe to drink. Heating water to 65 °C for a few minutes or at a higher temperature for a short time will make the water safe from pathogenic activity. This can be easily achieved by using the SHB.

If the internal container (Energy Receiver) is made from a transparent glass, the SHB can be used for water disinfecting system and if it is made from black metal (for ex., iron, copper, or aluminium), the SHB can be used for cooking. In the present study the solar water disinfecting system is only concerned.

The objectives of the present study are i) to theoretically study the water disinfecting system that can be used in any location (because the main heat input, solar radiation, is a function of longitude, latitude, and other parameters) and solving the governing equations numerically. ii) to experimentally verify (thermally and biologically) the present system under the environmental conditions of Sendai city, Japan (38° 15´N latitude, 140° 51´E longitude), and iii) to evaluate the system performance and study its control parameters..

II. EXPERIMENTAL SET-UP

The SHB is placed in the thermally controlled flow solar water disinfecting system presented by Saitoh and EL－Ghetany[12]. It is made from wood of dimensions 0.60 x 0.60 m with a frontal height of 0.30 m while the back is 0.461 m. The inner sides are covered with an aluminum foil to reflect the heat to a transparent glass water container of 0.20x0.20x0.20 m placed inside the SHB. It is insulated with a 0.05 m thick insulation (Styrofoam) to reduce heat loss. The internal absorbing surface is made of thin aluminum sheet with dimensions of 0.50 x 0.50 x 0.10 m with a thickness of 0.5mm and is painted black. The SHB has a double glazed layers spaced 0.04 m apart to reduce the upward heat loss and tilted by an angle of 15° from the horizontal for receiving normal solar radiation through the glass cover. A back reflector with dimensions of 0.621x0.60 m has been fixed to the hood of the SHB to enhance solar radiation on the glazing. The temperature of the SHB components is measured using type T thermocouples of 0.5mm diameter, and a digital temperature logger is used to record the temperature output data. The solar radiation pyranometer is tilted to the same angle as the glass cover of the SHB to measure the solar radiation falling on the tilted surface. A schematic diagram of the SHB is shown in Fig.1.

III. MODELING OF THE SOLAR HOT BOX

To estimate the absorbed energy in the SHB and hence its temperature components, it is necessary to determine first, the amount of solar radiation falling on its tilted surface.

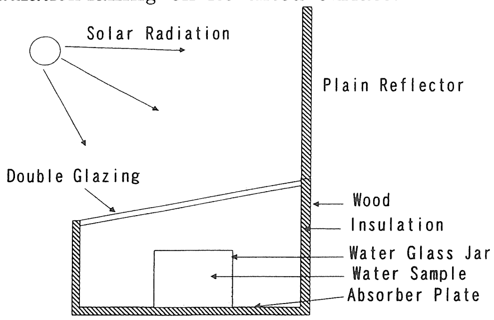

Fig. 1 Schematic diagram of the solar hot box

Calculation of the solar radiation is made for the SHB tilted from the horizontal and facing south using ASHRAE[3] model. But it is found that the parameters used to estimate solar radiation intensity presented by ASHRAE are concerned with one day for each month. So in order to simulate the daily solar radiation intensity throughout the year, the ASHRAE parameters A, B and C are fitted to a fourth-order polynomial equation which is a function of a day number (n) as in the form

$$Y = \sum a_n X^n \qquad (1)$$

where Y related to A, B and C parameters and X related to day number, n (the first of January =1). The ASHRAE data and present equations are shown in Fig. 2.

The components of the SHB for which the energy balance has to be considered are the upper and lower glass cover, absorber plate, stagnant air between lower glass cover and absorber plate, water glass jar (cubic glass container) and water inside the glass container. The heat transfer processes are obtained in Fig.3. To model these processes, the following set of simplifying assumptions are made:

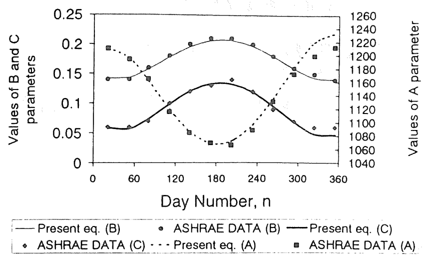

Fig. 2 The ASHRAE data and present equations of A, B and C parameters

1-Various components of the SHB are at different but uniform temperatures at any given time.
2-Solar radiation is incident only on the absorber plate, the water glass jar and the water inside.
3-The SHB has been made from six basic elements.
4- The transparent glass container is full of water.

In the calculations, the glass water container area, A_j, is considered as one side area(square area, 0.20x0.20 m) in both cases of calculating the heat transfer rates between absorber plate and glass water container, and calculating the solar energy absorbed by the glass water container. While for calculating the heat transfer rates between glass water container and internal air, the area is considered as a surface area of the water container except the bottom side.

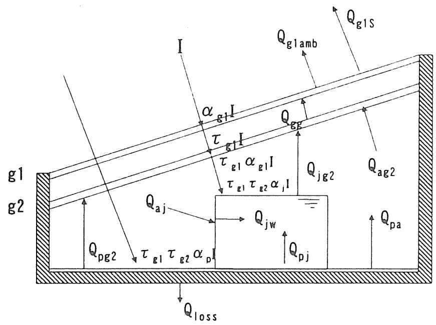

Fig. 3 Heat transfer model for analysis of the solar hot box

The variation of the temperatures of the components with time can be found by solving the energy balance equations given below:

1- Upper Transparent Cover

$$M_{g1}\frac{dT_{g1}}{dt} = A_{g1}\alpha_{g1}I + Q_{gg} - Q_{g1amb} - Q_{g1s} \quad (2)$$

$$M_{g1}\frac{dT_{g1}}{dt} = A_{g1}[\alpha_{g1}I + H_{gg}(T_{g2} - T_{g1}) - H_{g1amb}(T_{g1} - T_{amb}) - H_{g1s}(T_{g1} - T_s)] \quad (3)$$

2- Lower Transparent Cover

$$M_{g2}\frac{dT_{g2}}{dt} = A_{g2}\alpha_{g2}\tau_{g1}I - Q_{gg} + Q_{ag} + Q_{pg} + Q_{jg} \quad (4)$$

$$M_{g2}\frac{dT_{g2}}{dt} = A_{g2}[\alpha_{g2}\tau_{g1}I - H_{gg}(T_{g2} - T_{g1}) + H_{ag}(T_a - T_{g2}) + H_{pg}(T_p - T_{g2}) + H_{jg}(T_j - T_{g2})] \quad (5)$$

3- Internal Air

$$M_a\frac{dT_a}{dt} = Q_{pa} - Q_{aj} - Q_{ag} \quad (6)$$

$$M_a\frac{dT_a}{dt} = (A_p - A_j)H_{pa}(T_p - T_a) - A_jH_{aj}(T_j - T_a) - A_{g2}H_{ag}(T_a - T_{g2}) \quad (7)$$

4- Water Glass Jar

$$M_j\frac{dT_j}{dt} = A_j\alpha_j\tau_{g1}\tau_{g2}I + Q_{pj} - Q_{jg2} + Q_{aj} - Q_{jw} \quad (8)$$

$$M_j\frac{dT_j}{dt} = A_j[\alpha_j\tau_{g1}\tau_{g2}I + H_{pj}(T_p - T_j) - H_{jg}(T_j - T_{g2}) + H_{aj}(T_a - T_j) - H_{jw}(T_j - T_w)] \quad (9)$$

5- Absorber Plate

The absorber plate that causes the heating of the solar hot box components absorbs most of the solar radiation. Then the approximate uniform transient temperature of the plate is given by

$$M_p\frac{dT_p}{dt} = (A_p - A_j)\alpha_p\tau_{g1}\tau_{g2}I - Q_{pj} - Q_{pa} - Q_{loss} - Q_{pg} \quad (10)$$

$$M_p\frac{dT_p}{dt} = (A_p - A_j)\alpha_p\tau_{g1}\tau_{g2}I - A_jH_{pj}(T_p - T_j) - (A_p - A_j)H_{pa}(T_p - T_a) - A_pH_{pamb}(T_p - T_{amb}) - A_{g2}H_{pg}(T_p - T_{g2}) \quad (11)$$

6- Water Inside Glass Container

$$M_w\frac{dT_w}{dt} = A_j\tau_{g1}\tau_{g2}\tau_jI + Q_{jw} \quad (12)$$

$$M_w\frac{dT_w}{dt} = A_j\tau_{g1}\tau_{g2}\tau_jI + A_jH_{jw}(T_j - T_w) \quad (13)$$

The above differential equations can be solved numerically using the fourth-order Runge-Kutta method to find the temperature relations of the SHB components with time.

IV HEAT TRANSFER MODES

To solve the energy balance equations, the convective, conductive and radiative heat transfer coefficients should be estimated first. Some of them are described below:

H_{g1amb} is the convective heat transfer coefficient between upper glass cover and ambient which can be estimated from the relation given by[9]

$$H_{g1amb} = 5.7 + 3.8\,U \quad (14)$$

H_{g1s} is the radiative heat transfer coefficient between upper glass cover and sky that can be obtained as

$$H_{r,g1s} = \varepsilon_g\sigma(T_{g1}^2 + T_s^2)(T_{g1} + T_s) \quad (15)$$

Several relations for clear skies have been proposed to relate T_s to other measured meterological variables. As an example, the sky temperature can be related to the local air temperature in a simple relationship[9] :

$$T_s = 0.0552\,T_{amb}^{1.5} \quad (16)$$

where T_s and T_{amb} are both in degree Kelven.

H_{gg} is the convective heat transfer coefficient across a rectangular enclosure formed between two inclined glass covers. It can be estimated using the Holland correlation[10]

$$N_u = 1 + 1.44\left(1 - \frac{1708}{Ra\cos\beta}\right)^{*}\left[1 - \frac{1708(\sin(1.8\beta))^{1.6}}{Ra\cos\beta}\right] + \left(\left(\frac{Ra\cos\beta}{5830}\right)^{1/3} - 1\right)^{*} \quad (17)$$

where

$(\ )^{*}$ = means brackets go to be zero when negative i.e. if the quantity inside the brackets is negative, it is considered as zero.

H_{ag} is the convective heat transfer coefficient between internal air and lower glass cover which can be estimated from the relation[1]

$$Nu = 0.033\,Ra^{0.343} \quad (18)$$

where the representative length of *Ra* is considered as the average hight of the enclosure.

H_{pg} is the radiative transfer coefficent between absorber plate and lower glass cover which is found from the relation

$$H_{pg} = \frac{\sigma(T_p + T_{g2})(T_p^2 + T_{g2}^2)}{\frac{1-\varepsilon_p}{\varepsilon_p} + \frac{1}{F_{pg}} + \frac{A_p(1-\varepsilon_{g2})}{A_{g2}\varepsilon_{g2}}} \qquad (19)$$

H_{jg} is the radiative transfer coefficent between water glass container and lower glass cover which is found from the relation

$$H_{jg} = \frac{\sigma(T_j + T_{g2})(T_j^2 + T_{g2}^2)}{\frac{1-\varepsilon_j}{\varepsilon_j} + \frac{1}{F_{jg}} + \frac{A_j(1-\varepsilon_{g2})}{A_{g2}\varepsilon_{g2}}} \qquad (20)$$

where $F_{pg}=A_p/A_g$ and $F_{jg}=A_j/A_g$

H_{pa} is the convective heat transfer coefficient between absorber plate and internal air which can be estimated using the Holland correlation[10]

$$Nu = 1 + 1.44\left(1 - \frac{1708}{Ra}\right)^* + \left(\left(\frac{Ra}{5830}\right)^{1/3} - 1\right)^* \qquad (21)$$

where

( )* = means brackets go to be zero when negative

H_{aj} is the convective heat transfer coefficient between internal air and water glass container which is influenced by the air convection in the enclosure. Assuming that this convection is very close to vertical plate being heated in hot air, the H_{aj} can be estimated using the Churchill and Chu correlation[6]

$$Nu = \left[0.825 + \frac{0.387\,Ra^{1/6}}{\left[1 + \left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{8/27}}\right]^2 \qquad (22)$$

H_{pj} is the conductive heat transfer coefficient between absorber plate and water glass container which can be estimated from the relation

$$H_{pj} = \frac{k_j}{\delta_j} \qquad (23)$$

H_{jw} is the convective heat transfer coefficient between water glass container and water inside it which can be estimated using the Dropkin and Somerscale correlation[8]

$$Nu = 0.069\,Ra_{jw}^{1/3}\,\Pr^{0.074} \qquad (24)$$

H_{pamb} is the conductive heat transfer coefficient between absorber plate and ambient which can be estimated from the relation

$$H_{pamb} = \frac{k_i}{\delta_i} \qquad (25)$$

V. RESULTS AND DISCUSSION

From the simulation model, it is found that some parameters affect the performance of the SHB such as :

Absorber plate thickness It is found that there is no big difference of absorber plate temperature values with a thickness of 0.1, 0.5 , and 1mm. While using larger than 1mm thickness will increase the amount of heat stored and decrease the output temperature values.

Glass container height and thickness It is found that the lower the glass container's height the shorter the time that is needed for heating the contaminated water with the same cross sectional area. From theoretical calculations, it is found that for clear sky conditions, 8 lieters of water can be heated to the end of simulation within 3.5 hours. While 10 liters need 4.5 hours under the same weather conditions. The effect of glass container thickness on water temperature of the SHB is also studied. It is found that the smaller thickness gives a higher amount of conductive heat between the absorber plate and the water which consequently increases the water temperature. Also the thinner the glass the shorter the time is needed for heating the contaminated water inside the SHB .

Insulation type and thickness It is found that using larger thickness and lower thermal conductivity give higher output water temperature.It is found also that the SHB is affected by the environmental conditions like ambient temperature, wind speed and solar radiation. As an example, the water temperature variation's calculations for the 0.5 m/s wind speed and 8 liters water content is obtained in Fig. 4.

If the ambient temperature is fixed (i.e. 20°C) and the wind speed is varied as shown in Fig.5, it is found that the worst conditions for causing heat loss to be maximum is when the ambient temperature is decreased and the wind speed increased. The instantaneous temperature distribution of the SHB components for a test

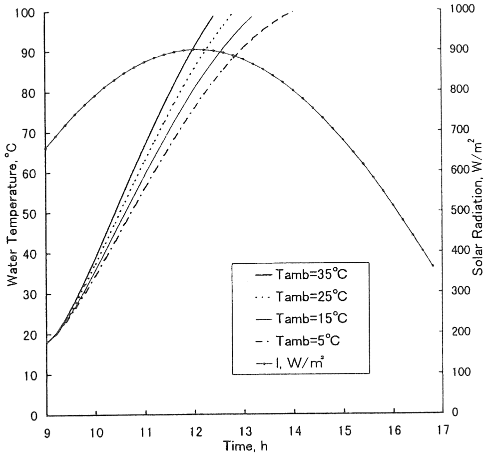

Fig.4 Water temperature variation under different ambient temperatures on 21st Dec. 1997 (wind speed =0.5 m/s)

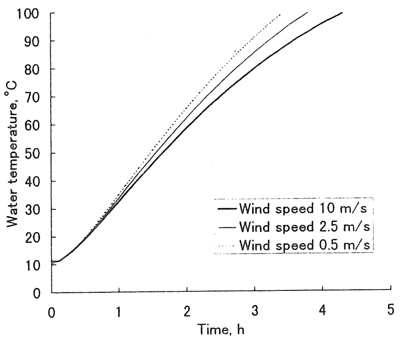

Fig.5 Effect of wind speed on the water temperature of the solar hot box

run on May 6,1997 is shown in Fig.6. It is found that the glass water container temperature, T_j, and plate temperature, T_p, are nearly equal. This is because the bottom of the water container is in good contact with the absorber plate and regarding to the first simplifying assumption it is considered that the glass container has a uniform temperature from its all sides due to its small thickness. The upper glass cover temperature, T_{g1}, is affected by the ambient temperature and wind speed while the lower glass cover temperature, T_{g2}, and internal air temperature, T_a, are affected by the heat exchanges between the SHB components. Considering the horizontal line in the figure represent the disinfecting temperature of the water (65°C) which is higher than the milk pasteurization temperature (62. 8 °C). It is obvious that the water temperature reached the disinfection temperature theoretically within 2 hours.

As a verification, the experimental temperature distribution is made as shown in Fig. 7. The internal air temperature, T_a, is measured at the mid of the average hight of SHB. The water temperature, T_w, is measured as the average temperature between the top and bottom temperatures of the glass water container because it is found that it has stratification of some extent. It is found that experimentally, the water temperature reached the disinfecting temperature within 2.5 hours. The time difference between experimental and theoretical data is due to the assumptions in the calculations of temperatures and solar radiation.

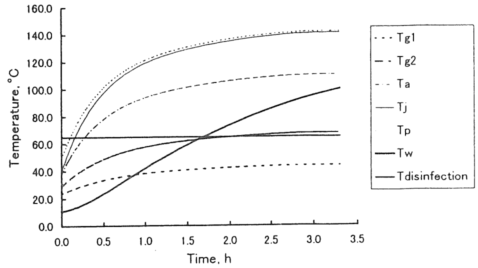

Fig.6 The theoretical instantaneous temperature distribution of the solar hot box on May 6,1998

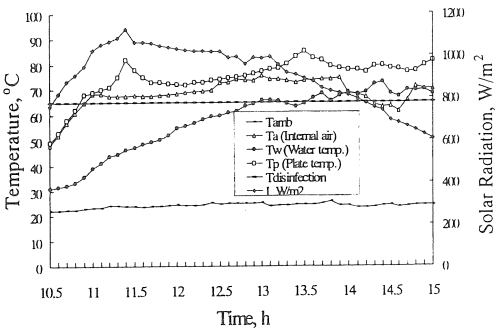

Fig. 7 The experimental temperature distribution of the solar hot box on May 6,1998

It is clear also from Fig. 7 that the water temperature reached maximum value of 72 °C only even the radiation is good due to windy weather condition that increased the heat loss and decreased the output temperature.

These results are confirmed also micro-biologically by taking a water samples and count its bacterial contents. It is found that the coliform bacteria which is considered as an indicator of fecal pollution are eliminated within 3 hours due to expose to solar radiation and the water temperature is higher than the dis-infecting temperature.

Some of the instantaneous heat transfer coefficients variations of the SHB are obtained in Fig.8. It is found that some of the heat transfer coefficients are affected by the environmental conditions such as:

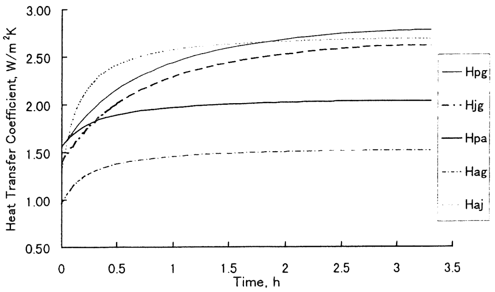

Fig. 8 The instantaneous heat transfer coefficient variation of the solar hot box

H_{g1s} is affected by ambient temperature and H_{g1amb} is affected by wind speed. While H_{gg} is affected by the temperature difference between upper and lower glass cover.

V CONCLUSION

Solar radiation has been shown to inactivate and destroy pathogenic bacteria present in water. The presented solar radiation model obtained good agreement with experimental measurements when a clear sky condition is available. It is found that the SHB is affected by some parameters such as glass container height and thickness, insulation type and thickness, clarity of the contaminated water and environmental conditions (ambient temperature, wind speed and solar radiation intensity). It is found also that the coliform bacteria which is considered as an indicator of infectious bacteria are eliminated after exposing to solar radiation intensity within three hours (as it is thermally confirmed theoretically, experimentally and micro-biologically) when the contaminated water temperature reached the disinfecting temperature.

NOMENCLATURE

A = area , m^2
c_p = specific heat at constant pressure, J/ K
H = heat transfer coefficient , W/ m^2 K
I = solar radiation , W/m^2
M = heat capacity ($M=\rho V c_p$), J/K
Q = heat transfer rate, W
S = bacterial survival ratio, %
T = temperature , K
t = time , h
V = volume , m^3
Nu = Nusselt number, (HL/k),dimensionless
Ra = Rayleigh number, $(g\beta_a^{'}\Delta TL^3/\nu\alpha)$ dimensionless
Pr = Prandtl number,$(c_{pw}\mu_w/k_w)$ dimensionless
U = wind speed, m/s
k = thermal conductivity, W/mK
L = width of air layer

Greek letters

α = absorptivity
β = tilt angle
β' = coefficient of thermal expansion of air
ρ = density
τ = transmissivity
σ = Stefan-Boltzmann Constant
δ = thickness
ν = kinematic viscosity of air, m^2/s
μ = dynamic viscosity, Pa s

Subscripts

a = internal air
ag = between internal air to transparent cover
aj = between internal air and glass jar
amb = ambient
$g1$ = upper transparent cover
$g2$ = lower transparent cover
gg = between transparent covers
$g1amb$ = between upper transparent cover and ambient
$g1s$ = between upper transparent cover and sky
j = jar
jg = between glass jar and transparent cover
jw = between glass jar and water
$loss$ = losses to surroundings
p = absorber plate
pa = between absorber plate and internal air
pg = between absorber plate and transparent cover
pj = between plate and glass jar
$pamb$ = between absorber plate and ambient

s = sky
w = water
i = insulating material

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