MINIMUM MAINTENANCE SOLAR PUMP

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ABSTRACT

A minimum maintenance solar pump (MMSP), Fig 1, has been simulated for Addis Ababa, taking solar meteorological data of global radiation, diffuse radiation and ambient air temperature as input to a computer program that has been developed. To increase the performance of the solar pump, by trapping the long-wave light rays leaving the absorber - the water tank, two glass covers have been employed. Basic heat transfer equations for double glass glazing and storage tank (absorber plate) along with side and bottom insulations are derived and techniques for the solution of these equations are presented. The minimum quantity of residual water that should remain in the storage tank after the previous day's pumping process, for producing the required maximum vacuum pressure, has been determined. The maximum possible pumping head which depends on the vacuum pressure created within the storage tank and which in turn depends on the quantity of residual water evaporated has then been predicted and presented for representative days of the year.

INTRODUCTION

Search for water resource and its subsequent distribution and utilization for house-hold as well as irrigation purpose have always been important issues.

Use of a conventional pump requires large energy input and this source is unthinkable in the rural areas of developing countries. A minimum maintenance solar-pump can play a major role in meeting the demand despite its low pumping head.

The minimum maintenance solar pump is a solar energy conversion system which operates on a diurnal cycle with solar heating and nocturnal cooling. It consists of a cylindrical drum (storage tank), an insulated box, plain-glass cover, a reflective inner surface, piping systems and valve, Fig. 1.

PRINCIPLE OF OPERATION

The storage tank contains air and residual water from the previous day's operation. The operation of the system starts, in the morning, with both the air-vent pipe and the delivery valve closed. During the day time, as energy is absorbed by the tank which behaves

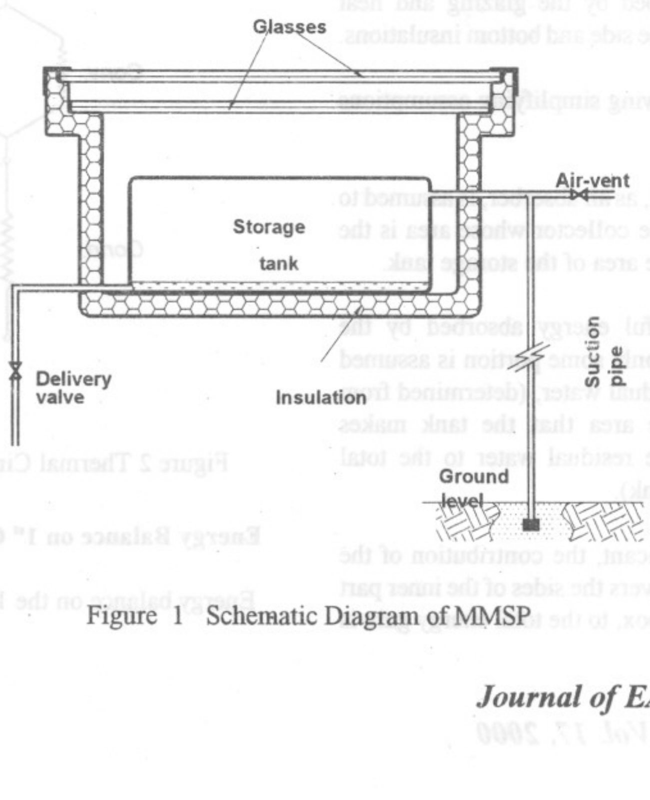

Figure 1 Schematic Diagram of MMSP

as a storage as well as an absorber plate, the air trapped in the tank expands and some of it bubbles out through the suction pipe. As more heat is absorbed from the sun, the residual water in the tank evaporates driving the rest of the air out of the tank.

At the end of the day, when the solar radiation diminishes, the tank cools off, gradually losing the energy it has accumulated during the day. With both the air-vent pipe and the delivery pipe valves still closed, as heat is rejected from the tank, the water vapor condenses causing pressure depression. Water is then slowly charged into the tank from the ground well.

Early in the morning, the air-vent and the delivery-pipe valves are opened and the collected water is removed from the tank, with some residual water left in the tank.

THERMAL ANALYSIS OF THE MMSP

Thermal analysis of the MMSP is evaluated by performing energy balance on:

- The cylindrical storage-tank, to determine the hourly tank surface temperature and the portion of the incoming radiation delivered as useful energy to the air and residual water in the tank, from the hourly insolation data.
- The glass-covers and the insulated box, to determine the portion of the incoming radiation absorbed by the glazing and heat losses through the side and bottom insulations.

In the model, the following simplifying assumptions are made.

- The storage tank, as an absorber, is assumed to act as a flat-plate collector whose area is the projected surface area of the storage tank.
- Out of the useful energy absorbed by the absorber plate, only some portion is assumed to reach the residual water, (determined from the ratio of the area that the tank makes contact with the residual water to the total surface of the tank).
- Although significant, the contribution of the reflector, that covers the sides of the inner part of the insulated box, to the total energy gain is neglected.

The heat exchange processes between the various components of the MMSP and ambient are represented by thermal-resistance network as indicated in Fig. 2. Sets of differential equations are derived from simple energy balances on the glass covers and the storage tank (absorber plate). Due to the transient nature of the radiant and convective heat transfer coefficients, these sets of differential equations are non-linear. An integration scheme which linearises the given set of differential equations within a given time step is applied for solving these equations.

The differential equations are evaluated for the various components of the MMSP at time $(t + \Delta\tau)$ based on available data at time t, with the time interval $\Delta\tau$ set to 60 seconds.

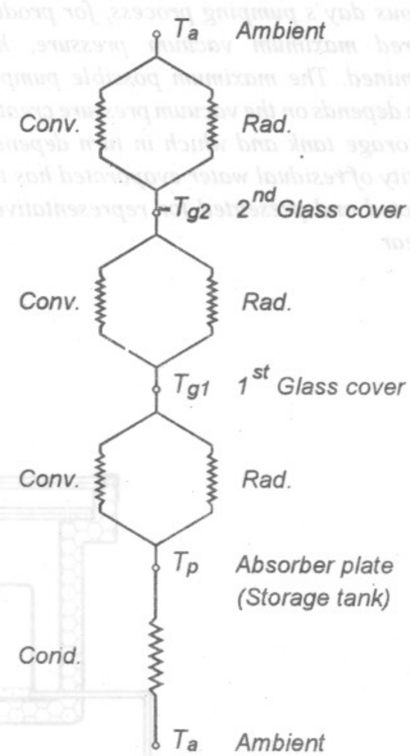

Figure 2 Thermal Circuit for Energy Balance

Energy Balance on 1st Glass Cover

Energy balance on the 1 st glass cover gives:

$$(m\ c_p)_g \frac{dT_{g1}}{dt} = A_g\ I_{N1} + A_g\ h_{g12}\ (T_{g1} - T_{g2}) - A_c\ h_{pg1}\ (T_p - T_{g1}) \qquad (1)$$

The temperature of the first glass cover at time (t $+\Delta\tau$) in terms of the absorbed incident radiation on the surface of the glass, heat losses from the first glass cover to the second glass cover and heat losses from the storage tank (absorber plate) to the glazing at time t is given by:

$$T_{g11} = \frac{A_g\ I_{N1}}{(m\ c_p)_g}\ \Delta t + \left\{ 1.0 - \frac{(A_g\ h_{g12} + A_c\ h_{pg1})}{(m\ c_p)_g}\ \Delta\tau \right\} T_{g10} + \left\{ \frac{A_g\ h_{g12}}{(m\ c_p)_g}\ \Delta\tau \right\} T_{g20} + \left\{ \frac{A_c\ h_{pg1}}{(m\ c_p)_g}\ \Delta\tau \right\} T_{p0} \qquad (2)$$

where:

$$h_{g12} = (h_{g12})_{Conv} + (h_{g12})_{Rad} = (0.06 - 0.017\ \frac{\theta}{90})\ \frac{\lambda_a}{x_{12}}\ G_{r1}^{\frac{1}{3}} + \epsilon_{g12}\ \sigma \left\{ T_{g10}^{\ 2} + T_{g20}^{\ 2} \right\} (T_{g10} + T_{g20}) \qquad (3)$$

$$h_{pg1} = (h_{pg1})_{Conv} + (h_{pg1})_{Rad} = (0.06 - 0.017\ \frac{\theta}{90})\ \frac{\lambda_a}{x_{pg1}}\ G_{r2}^{\frac{1}{3}} + \epsilon_{pg1}\ \sigma \left\{ T_{p0}^{\ 2} + T_{g10}^{\ 2} \right\} (T_{p0} + T_{g10}) \qquad (4)$$

Energy Balance on 2 Nd Glass Cover

Energy balance on the 2 nd glass cover yields:

$$(m\ c_p)_g \frac{dT_{g2}}{dt} = A_g\ I_{N2} + A_g\ h_{g12}\ (T_{g1} - T_{g2}) - A_g\ h_{g2a}\ (T_{g2} - T_a) \qquad (5)$$

The temperature of the second glass cover at time (t + $\Delta\tau$) in terms of the absorbed incident radiation on the surface of the glass, heat absorbed by the first glass cover and heat losses from the second glass cover to the ambient at time t is given by:

$$T_{g21} = \frac{A_g\ I_{N2}}{(m\ c_p)_g}\ \Delta t + \left\{ 1.0 - \frac{(A_g\ h_{g21} + A_g\ h_{g2a})}{(m\ c_p)_g}\ \Delta t \right\} T_{g20} + \left\{ \frac{A_g\ h_{g12}}{(m\ c_p)_g}\ \Delta\tau \right\} T_{g10} + \left\{ \frac{A_g\ h_{g2a}}{(m\ c_p)_g}\ \Delta\tau \right\} T_a \qquad (6)$$

where:

$$h_{g2a} = (h_{g2a})_{Conv} + (h_{g2a})_{Rad} = 5.7 + 3.8\ .\ V + \epsilon_{g2a}\ \sigma \left\{ T_{g20}^{\ 2} + T_{a0}^{\ 2} \right\} (T_{g20} + T_{a0}) \qquad (7)$$

and

$$h_{g21} = h_{g12} \qquad (8)$$

Energy Balance on Storage Tank

The cylindrical tank is considered to be painted with selective black coating. For the thermal analysis, the storage tank is replaced with a flat-plate collector at a depth of x_{pg1} from the first glass cover with its area assumed to be the projected surface area of the storage tank. From energy balance on the absorber plate:

$$(m\ c_p)_p \frac{dT_p}{dt} = A_c\ I_{N3} - A_c\ h_{pg1}\ (T_p - T_{g1}) - A_c\ h_{pab}\ (T_p - T_a) - A_1\ h_{pae}\ (T_p - T_a) \qquad (9)$$

The temperature of the storage-tank (absorber plate) at time (t $+\Delta\tau$) in terms of the absorbed incident radiation on its surface, heat loss to the first glass cover and heat losses through the back-insulation and the side-edge-insulation to the ambient at time t is given by:

$$T_{p1} = \frac{A_c\ I_{N3}}{(m\ c_p)_p}\ \Delta t + \left\{ 1.0 - \frac{(A_c\ h_{pg1} + A_c\ h_{pab} + A_1\ h_{pae})}{(m\ c_p)_p}\ \Delta\tau \right\} . T_{p0} + \left\{ \frac{A_c\ h_{pg1}}{(m\ c_p)_p}\ \Delta\tau \right\} T_{g10} + \left\{ \frac{(A_c\ h_{pab} + A_1\ h_{pae})}{(m\ c_p)_p}\ \Delta\tau \right\} T \qquad (10)$$

In Eq. (10).

$$h_{pab} = \frac{\lambda_i}{t_b} \quad (11)$$

$$h_{pae} = \frac{\lambda_i}{t_e} \quad (12)$$

and

$$A_1 = P \cdot d_e \quad (13)$$

A flow-chart of the developed transient simulation program for the prediction of thermal parameters of the MMSP system is presented in Fig. 3.

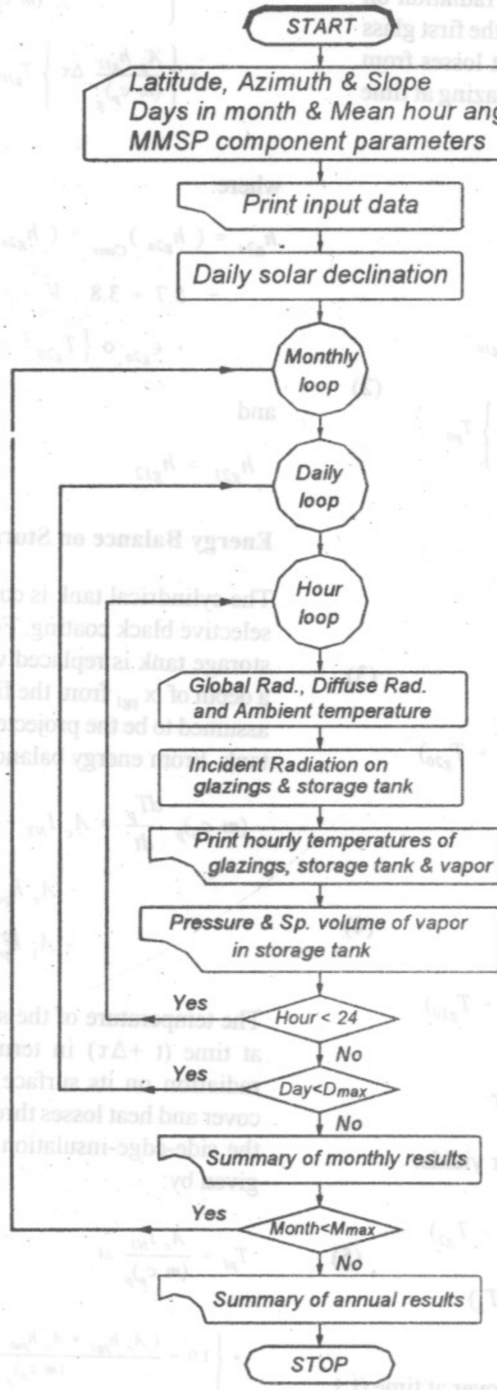

Figure 3 Flowchart of MMSP Simulation Program

The quantity of residual water that must be left in the tank after the previous day's operation must be just enough to be all evaporated at the end of the day. An optimum quantity, for a year round operation, has been determined for the volume of tank considered in this study.

The mass of water that is evaporated and which varies with the hourly intensity of the solar radiation and thus with the prevailing temperature in the tank, neglecting the specific volume of the water in the tank, is determined from the relation:

$$m_{wev} = \frac{V_T}{v_v} \tag{14}$$

The specific volume of the vapor and the prevailing vapor pressure in the tank, at time $(t + \Delta\tau)$, are determined at the mean temperature of the water in the tank and the plate temperature at the same time, using steam table values. The temperature of water vapor in the tank at time $(t + \Delta\tau)$ is:

$$T_{v1} = \frac{T_{p1} + T_{v0}}{2} \tag{15}$$

The pumping head of water is determined from Eq. (16) after choosing an optimum pipe diameter for an acceptable head loss due to pipe friction.

$$\Delta H = \left\{ \frac{\Delta p - \Delta p_f}{\rho\, g} \right\} \tag{16}$$

DISCUSSION OF RESULTS

The absence of recorded hourly values of climatic data has made it necessary to generate hourly global radiation, diffuse radiation and ambient temperature, respectively, from available daily global radiation, daily diffuse radiation and daily maximum and minimum temperatures of average values of seven and more years [1].

The relevant state variables and geometric data used in the MMSP model simulation are given in the following table.

Parameters	*Specification*
Collector area	0.98 m ^{2}
Collector perimeter	2.80 m
Back insulation thickness	0.05 m
Edge insulation thickness	0.05 m
Depth of edge	0.725 m
Emissivity of collector panel	0.09
Emissivity of glass	0.90
Space between panel and glass	0.415 m
Space between glasses	0.04 m
Thermal conductivity of insulation	0.045 W/m K
Absorptivity of panel	0.95
Transmissivity of glass	0.90
Volume of tank	0.202 m ^{3}

The MMSP simulation results for representative days of only some of the months (Jan. 17, Mar. 15, May 16, Jul. 13, Sep. 14 and Nov. 14) are presented in Fig. 4 to Fig. 9, respectively. The useful solar energy incident on the tank Q_{in}, the tank (plate) temperature T_p, the water vapor temperature in the tank T_v, the glazing temperatures T_{g1} and T_{g2} are also indicated in these figures.

As expected, for higher useful solar energy intercepted by the system, the higher is the water vapor temperature in the storage tank, Fig. 4, Fig. 5, Fig. 6 and Fig. 9. In the months of July and September, however, the water vapor temperatures in the storage tank are low for the useful solar energy intercepted during these months are lower, Fig. 7 and Fig. 8.

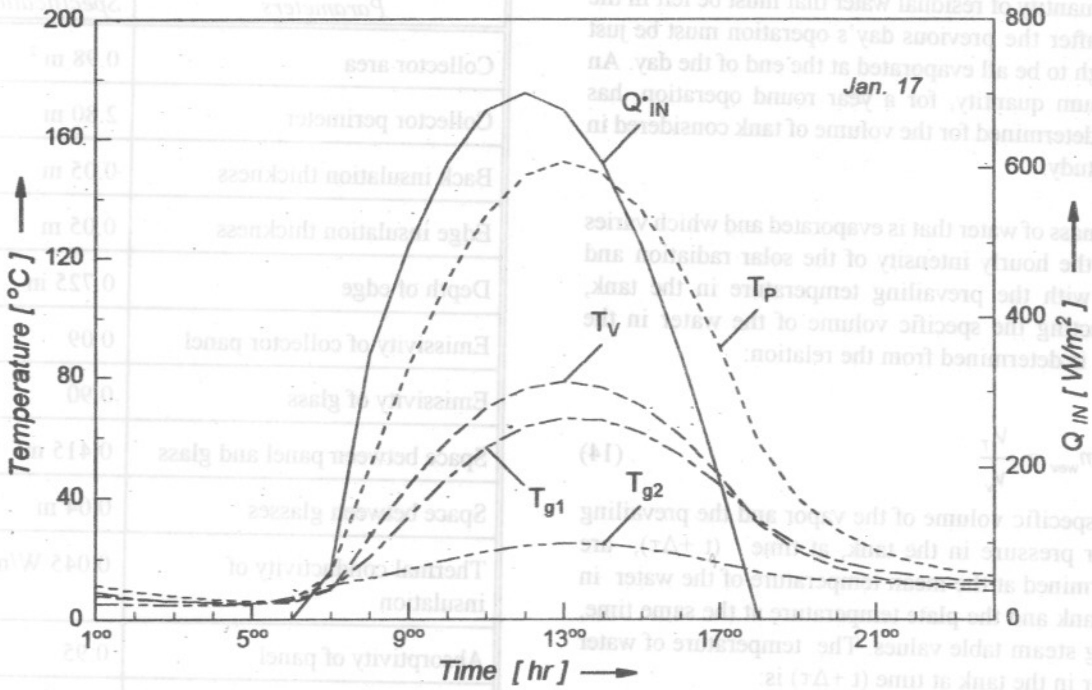

Figure 4 Useful Solar Insolation & Temperature Variations on Jan. 17

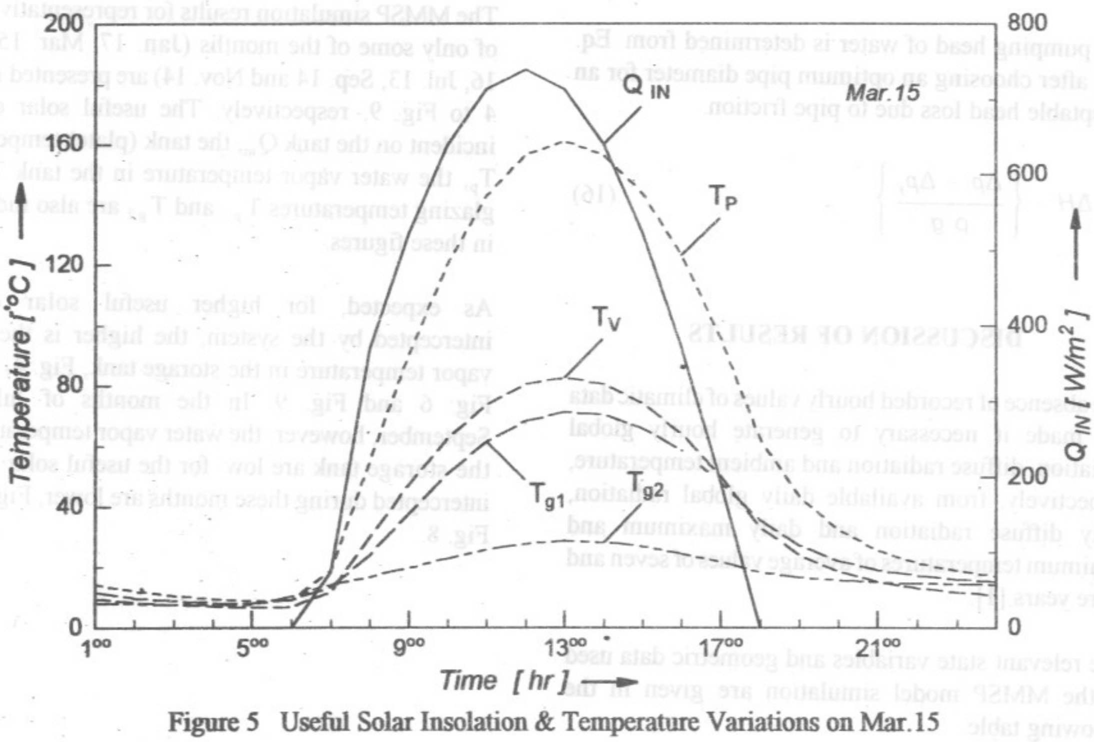

Figure 5 Useful Solar Insolation & Temperature Variations on Mar.15

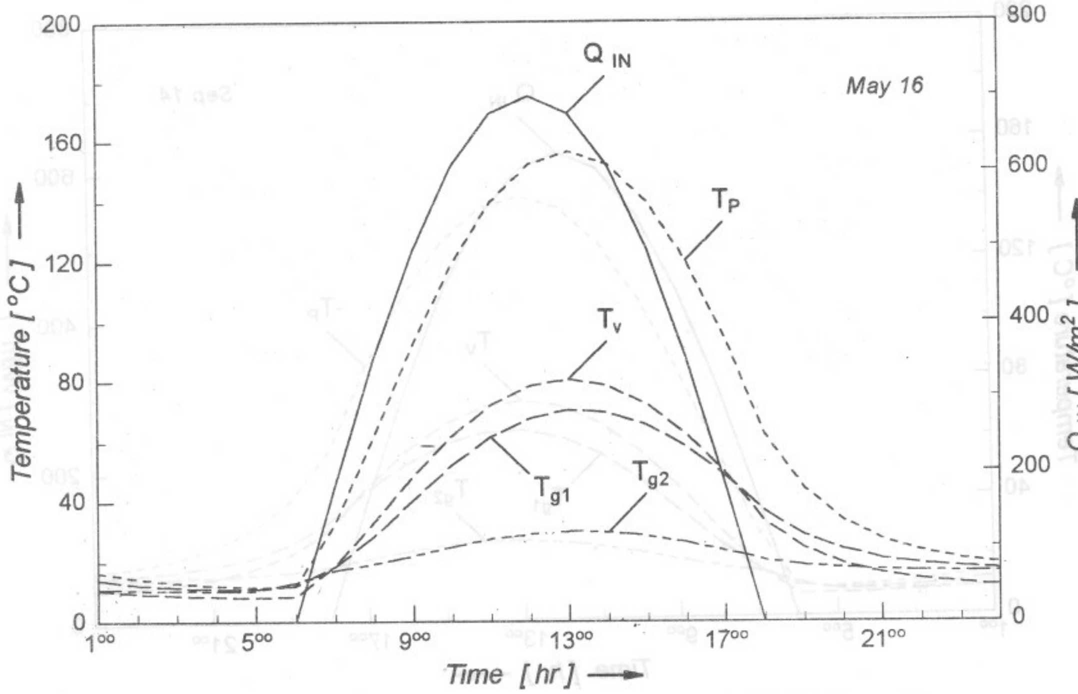

Figure 6 Useful Solar Insolation & Temperature Variations on May 16

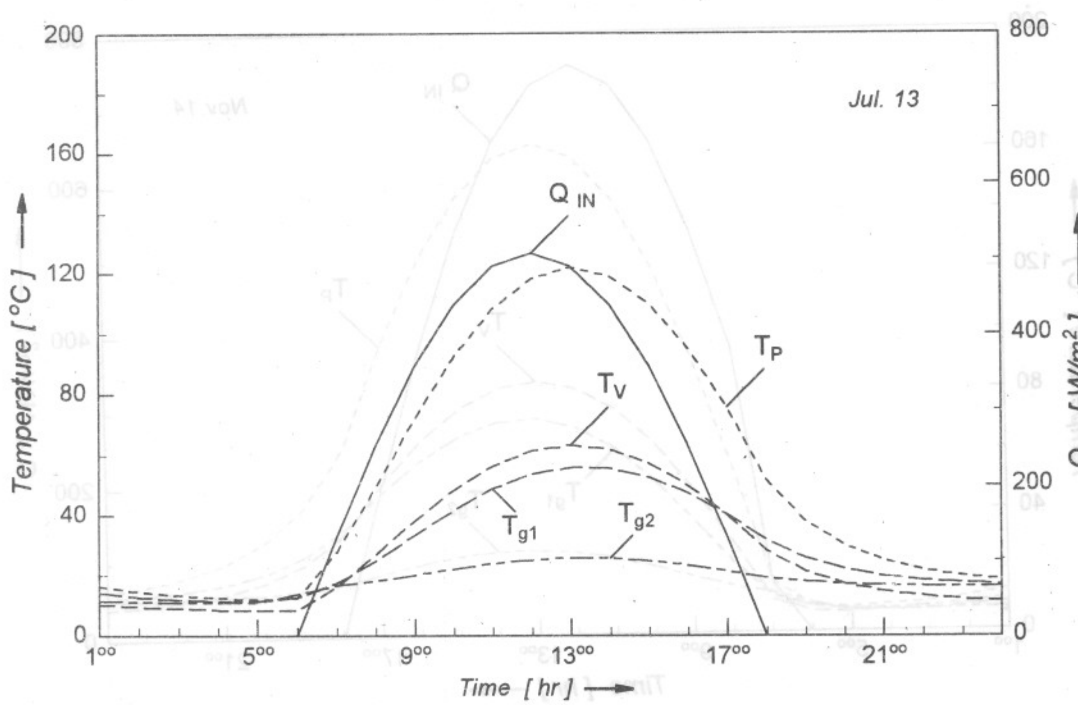

Figure 7 Useful Solar Insolation & Temperature Variations on July 13

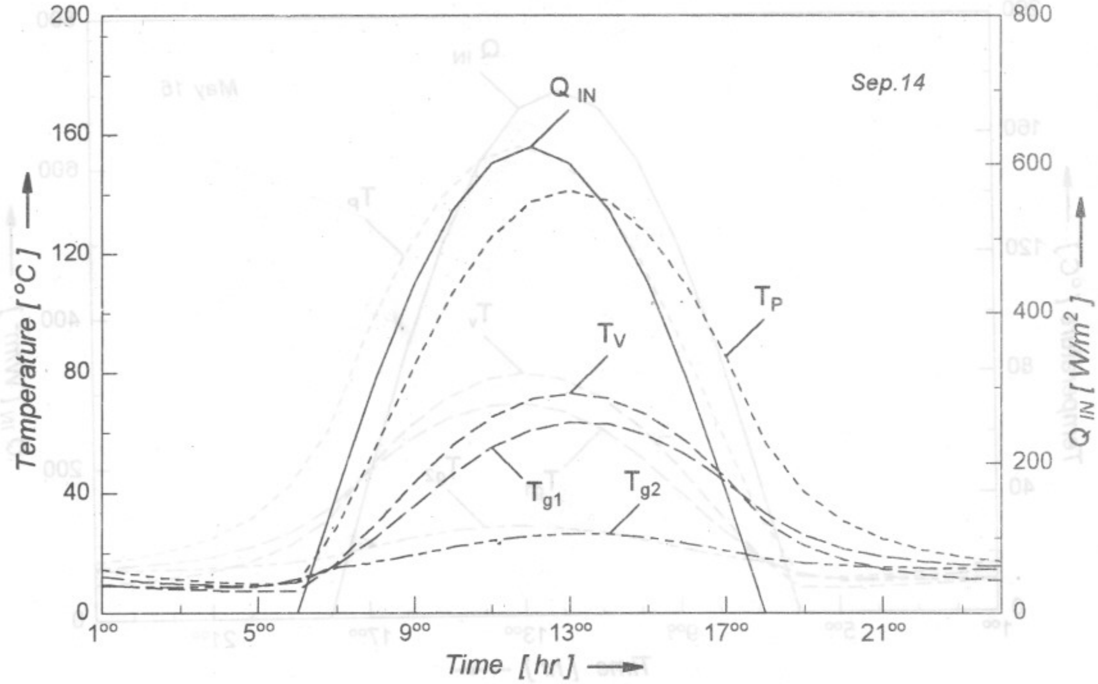

Figure 8 :Useful Solar Insolation & Temperature Variations on Sep. 14

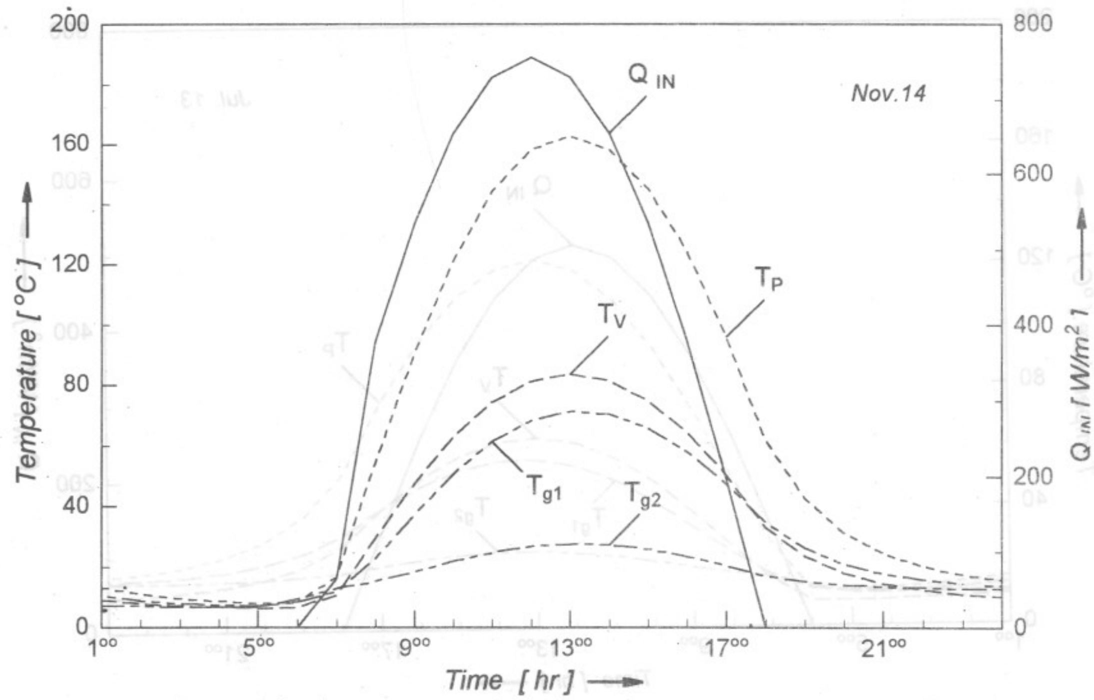

Figure 9 Useful-Solar Insolation & Temperature Variations on Nov. 14

The same effects are reflected on the pumping head, Fig. 10. Maximum pumping head of approximately 5.6 m is achieved in the month of November while a minimum head of nearly 2.35 m is observed in July. Since July is a rainy month in Addis Ababa, the lower pumping head may be compensated by rain water itself.

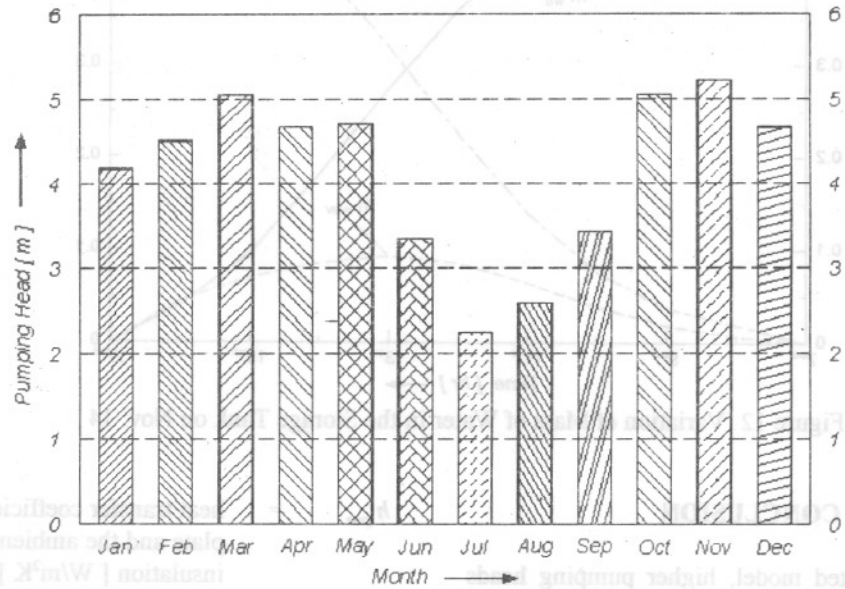

Figure 10 Pumping Head of the MMSP

For a year round operation, the minimum quantity of residual water that should remain in the storage tank after the previous day's pumping operation, for the storage tank considered in this study, is 0.50 kg. Variation of the quantity of residual water in the tank for the month of minimum solar radiation (July) and the month of maximum solar radiation (November) are presented in Fig. 11 and Fig. 12, respectively.

The mass of water evaporated each hour m_{wev}, the cumulative mass of water evaporated over the day m_{Sum_ev} and the mass of water in the tank at the beginning of each hour m_{wo} are indicated. In the month of July, Fig. 11, only nearly half the mass of the residual water in the tank evaporates while the whole quantity is observed to be evaporated in the month of November, Fig. 12.

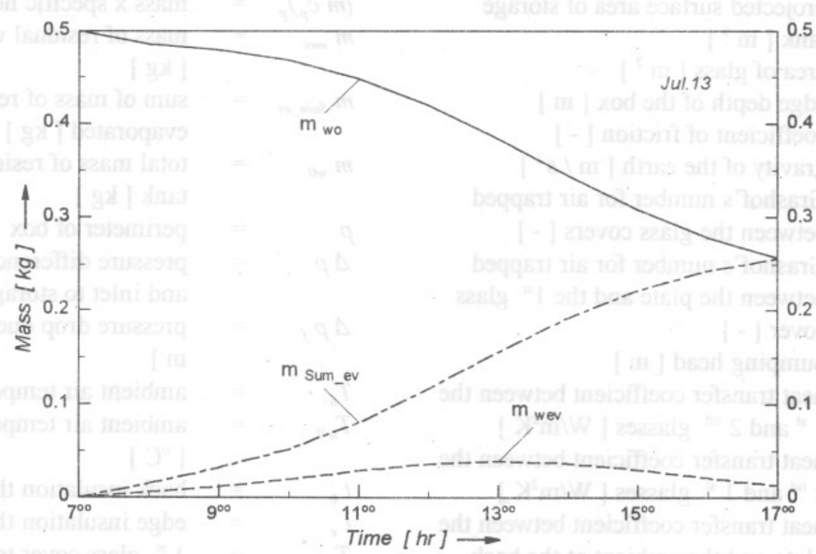

Figure 11 Variation of Mass of Water in the Storage Tank on Jul. 13

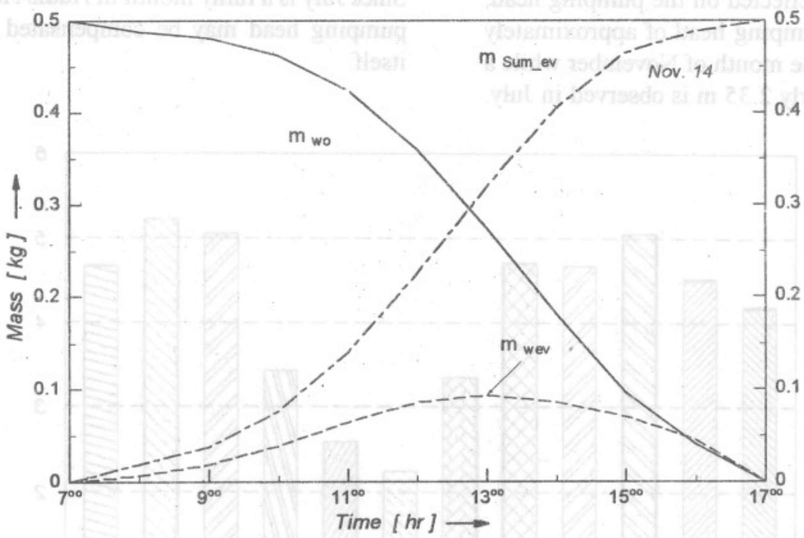

Figure 12 Variation of Mass of Water in the Storage Tank on Nov. 14

CONCLUSION

With the presented model, higher pumping heads could have been obtained, had the MMSP operated at areas of higher solar-intensity and ambient temperatures than the study site, Addis Ababa. Moreover, it would be of practical interest if a series of minimum maintenance solar pumps are built to increase the capacity.

NOMENCLATURE

A_1	=	area of inner sides of the box [m ^{2}]
A_c	=	projected surface area of storage tank [m ^{2}]
A_g	=	area of glass [m ^{2}]
d_e	=	edge depth of the box [m]
f	=	coefficient of friction [-]
g	=	gravity of the earth [m / s ^{2}]
G_{r1}	=	Grashof's number for air trapped between the glass covers [-]
G_{r2}	=	Grashof's number for air trapped between the plate and the 1st glass cover [-]
ΔH	=	pumping head [m]
h_{g12}	=	heat transfer coefficient between the 1 st and 2 nd glasses [W/m^{2}K]
h_{g21}	=	heat transfer coefficient between the 2 nd and 1 st glasses [W/m^{2}K]
h_{pab}	=	heat transfer coefficient between the plate and the ambient at the back insulation [W/m^{2}K]
h_{pae}	=	heat transfer coefficient between the plate and the ambient at the edge insulation [W/m^{2}K]
h_{pg1}	=	heat transfer coefficient between the plate and the 1 st glass [W/m^{2}K]
h_{g12}	=	heat transfer coefficient between the 1 st and the 2 nd glasses [W/m^{2}K]
I_{N1}	=	solar radiation intensity on the 1 st glass cover [W/m^2]
I_{N2}	=	solar radiation intensity on the 2 nd glass cover [W/m^2]
I_{N3}	=	solar radiation intensity on the storage tank [W/m^2]
$(m\, c_p)_g$	=	mass x specific heat of glass [J/K]
$(m\, c_p)_p$	=	mass x specific heat of plate [J/K]
m_{wev}	=	mass of residual water evaporated [kg]
m_{Sum_ev}	=	sum of mass of residual water evaporated [kg]
m_{w0}	=	total mass of residual water in the tank [kg]
p	=	perimeter of box [m]
Δp	=	pressure difference b/n suction poir and inlet to storage tank [N/ m ^{2}]
Δp_f	=	pressure drop due to pipe friction [m]
T_a	=	ambient air temperature [°C]
T_{a0}	=	ambient air temperature at time t [°C]
t_b	=	back insulation thickness [m]
t_e	=	edge insulation thickness [m]
T_{g1}	=	1 st glass cover temperature [°C]
T_{g2}	=	2 nd glass cover temperature [°C]

T_{g10} = 1^{st} glass cover temperature at time t [°C]

T_{g20} = 2^{nd} glass cover temperature at time t [°C]

T_{g11} = 1^{st} glass cover temperature at time $(t + \Delta\tau)$ [°C]

T_{g21} = 2^{nd} glass cover temperature at time $(t + \Delta\tau)$ [°C]

T_p = plate temperature [°C]

T_{p0} = plate temperature at time t [°C]

T_{p1} = plate temperature at time $(t + \Delta\tau)$ [°C]

T_{v0} = temperature of water in storage tank at time t [°C]

T_{v1} = temperature of water in storage tank at time $(t + \Delta\tau)$ [°C]

x_{12} = spacing between the 1^{st} and 2^{nd} glass covers [m]

x_{pg1} = spacing between the plate and the 1^{st} glass cover [m]

V = wind velocity [m / s]

V_T = volume of storage tank [m^3]

v_v = specific volume of water vapor in the storage tank at the prevailing temperature [m^3 / kg]

ϵ_{g12} = overall emittance between the glass covers [-]

ϵ_{pg1} = overall emittance between the plate and the 1^{st} glass cover [-]

λ_a = thermal conductivity of air [W / m^2 K]

λ_i = thermal conductivity of insulation material [W / m^2 K]

ρ = density of water [kg / m^3]

σ = Stefan Boltzman's constant [5.67×10^{-8} W / m^2 K^4]

θ = inclination of the solar collector [degree]

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