Numerical Simulation for Porous Medium Flat-Plate Solar Collector

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Abstract—A porous medium flat-plate solar collector is analyzed by numerical method to determine its efficiency. Partial differential equations with non-linear boundary conditions are solved by using finite volume method. The temperature distributions of the porous medium, the glass and the air gap are calculated.

Results show that the efficiency of porous medium flat-plate solar collector is increased due to larger heat transfer area. System configuration and a system optimization are studied and simulation results are compared with the measured data in literatures. The analysis indicates that the porous medium flat-plate solar collector is a better choice due to the better efficiency compared to conventional flat plate.

Keywords—Porous medium, solar collector, flat-plate solar collector

1. Introduction

Solar collectors gather the sun's energy, transform its radiation into heat, and then transfer that heat to water, solar fluid, or air. Flat plate solar collector is the most common collector in solar water heater. Recent studies related to increase the efficiency the flat plate solar collector have been concentrated in two areas. A large group of researchers tried to increase the efficiency by treating the surface to maximum the conversion of solar energy. These included: blackening and roughening of the surface, special single or double layer-coating to increase the absorbance and to decrease the plate emittance [1]. Another group of researchers tried to cut the manufacturing cost of the collector by using low-cost material in all-plastic flat-plate solar collector [2], partly plastic collectors to substitute for the expensive glass and metal.

The increase in efficiency of solar collector is achieved by either diminishing the loss from the top surface or by increasing the gain inside the solar collector. The porous medium is proposed to increase in gain inside the solar collector.

Cheung et al. [3,4] analytically and experimental studied the heat transfer in a porous medium solar collector. The typical model of medium flat-plate solar collector is shown in Figure (1). A slab of porous matrix is exposed to solar radiation. The collector matrix is insulated on three sides, and covered by a cover glass with an air gap on the top side. A laboratory model was built and tested. The steady state performance of the collector is analyzed using separation of variable technique. However, due to less than satisfactory workmanship and poor system design, the collector efficiency is lower than expected. It is also interesting to note that the solar collector panel method, where the efficiency is increased with larger surface area, follows a similar principle as the porous medium solar collector. However, the effective surface area for heat transfer is much larger in porous medium flat-plate solar collector. In summary, the use of porous medium has significant advantage over conventional solar collector by increasing the efficiency of heat transfer and decreasing the cost for material in using felt, sand, graphite, ceramic, etc.

Wu [5,6,7] suggested a theoretical model to predicated the efficiency of the porous medium solar collector. Due to the fact that collector are usually tested under quasi-steady-state condition, for which time dependent effects are relatively unimportant in most cases, a steady state model was proposed by Wu.

The first widely used whole solar system simulation model TRNSYS was developed by Klein [8]. The quasi-steady-state model which includes collectors, storage devices, heat exchangers, etc., generates performance values that are independent of system size or locations, or thermal demand profile. Now, TRNSYS is a well-respected energy simulation tool under continual development by a joint team made up of the Solar Energy Laboratory (SEL) at the University of Wisconsin – Madison, The Centre Scientifique et

Technique du Bâtiment (CSTB) in Sophia Antipolis, France, Transsolar Energietechnik GmbH in Stuttgart, Germany and Thermal Energy Systems Specialists (TESS) in Madison, Wisconsin. [9]

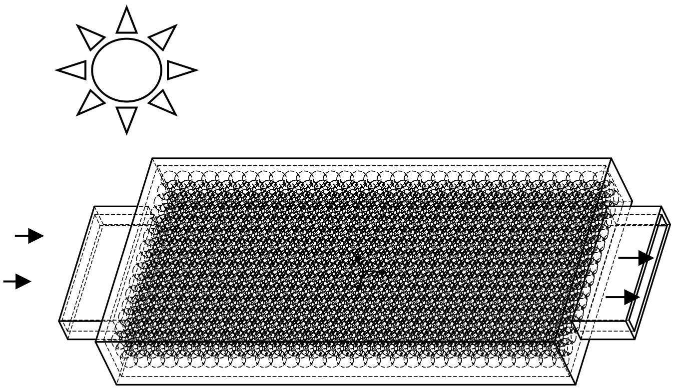

Figure 1 Porous medium solar collector

2. Theoretical Analysis

In order to determine the efficiency of the porous medium solar collector, the fluid and porous medium temperature distributions have to be determined. The purpose of mathematical modeling is to establish a scheme to calculate these temperature distributions and to determine system parameters which optimize the device.

The proposed model is based on the following assumptions:

1. Performance is in pseudo transient state, i.e., solar radiation is considered as a constant for a given small time interval.
2. The heat transfer coefficients are variable.
3. The sky temperature is same as the ambient temperature.
4. There is a negligible absorbance and temperature drop through the cover.
5. The headers of solar collector provide uniform flow through the porous medium.
6. Only average air gap temperatures in the y-direction are computed.
7. The headers cover a small area of the collector and the effects can be neglected.
8. Energy loss through the bottom insulation is considered.
9. All heat transport phenomena are taken independent of the z-direction.
10. No evaporation and condensation of working fluid.

Governing equations

<u>Porous medium</u>

The porous medium temperature distribution is determined by the energy conservation equation; refer to Figure (2), heat is transferred to the fluid by heat convection.

$$\rho_m C_{pm} V_m \frac{\partial T_m}{\partial \tau} = V_m\left[\frac{\partial}{\partial x}\left(k_{m,x}\frac{\partial T_m}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{m,y}\frac{\partial T_m}{\partial y}\right)\right]+h_v A_w (T_f - T_m) \quad (1)$$

The boundary conditions are

$$Q(x=0)=0 \quad (2)$$

$$Q(L_x=0)=0 \quad (3)$$

$$Q(y=0) = -\frac{k_i}{L_{bi}} A (T_m - T_b)|_{y=0} \quad (4)$$

$$Q(y=L_y) = A\left[\alpha_m \tau_G I + h_{ai}(T_{ai}-T_m) - \frac{\sigma(T_m^4 - T_G^4)}{\left(\frac{1}{\varepsilon_m}+\frac{1}{\varepsilon_G}-1\right)}\right] \quad (5)$$

<u>Glass</u>

The cover glass gains energy by convection and radiation from the porous medium through the air gap and loses energy via radiation and convection to the ambient. The energy balance is

$$\rho_G C_{pG} V_G \frac{\partial T_G}{\partial \tau} = L_z L_x\left[\alpha_G I + \varepsilon_G \sigma\left(T_{sky}^4 - T_G^4\right) + h_a(T_a - T_G) + h_{ai}(T_{ai} - T_G) + \frac{\sigma(T_m^4 - T_G^4)}{\left(\frac{1}{\varepsilon_m}+\frac{1}{\varepsilon_G}-1\right)}\right] \quad (6)$$

Where h_a=1.004+0.24v [9]

<u>Air Gap</u>

The air gap transfers energy between the cover glass and the porous medium by heat convection. Base on the conversation of energy the governing equation is written as

$$\rho_a C_{pa} V_a \frac{\partial T_{ai}}{\partial \tau} = L_z L_x[h_{ai}(T_G - T_{ai}) + h_{ai}(T_m - T_{ai}) \quad (7)$$

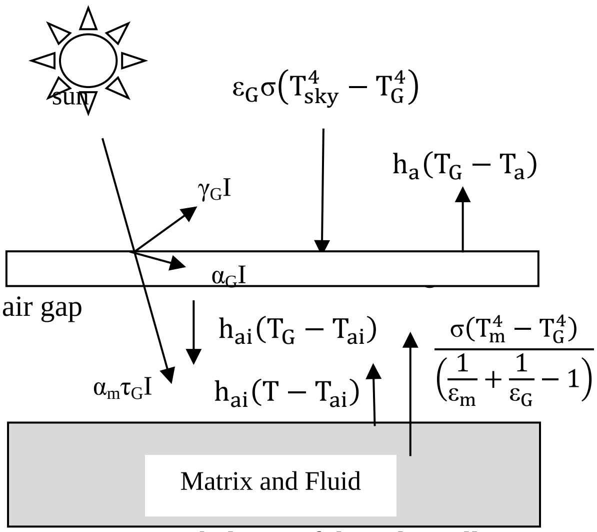

Figure 2 Energy balance of the solar collector

<u>Fluid</u>

The energy of fluid is transported from porous medium by heat convection. The energy balance is

$$\rho_f C_{pf} V_f \frac{\partial T_f}{\partial \tau} = \rho_f C_{pf} V_f \bar{u} \frac{\partial T_f}{\partial x} + V_f \frac{\partial}{\partial y} k_f \frac{\partial T_f}{\partial y} + h_v A_w (T_m - T_f) \quad (8)$$

The Boundary conditions are

$$\frac{\partial T_f}{\partial y}(y=0)=0 \quad (9)$$

$$\frac{\partial T_f}{\partial y}(y=L_y)=0 \quad (10)$$

$$T_f(x=0)=T_{f,in} \quad (11)$$

The average of fluid velocity within the porous medium is determined by Darcy's law, i.e.

$$\bar{u}=\frac{Q}{A\varepsilon} \quad (12)$$

Where εis the porosity of porous medium and A is the cross-sectional area of the solar collector.

The useful energy gain from the solar collector at a given time is the difference between the amount of solar energy absorbed by the absorber plate and the energy loss to the ambient. The equation that applies to the flat-plate solar collector is:

$$Q_u=F_RA_c\left[I(\tau_G\alpha_m)-U_L\left(T_{f,in}-T_a\right)\right] \quad (13)$$

Where the heat removal factor FR is defined as the rate of heat transfer to the working fluid divided by the rate of heat transfer at the minimum temperature difference between the absorber and the surroundings.

The useful energy gain by the fluid in steady state at a give time can be written as

$$Q_u=Q_wA_cC_p(T_{f,out}-T_{f,in}) \quad (14)$$

The efficiency of solar collector is defined as the heat transferred from the porous medium to the fluid per area of collector surface divided by the solar radiation, which is

$$\eta=\frac{Q_u}{A} \quad (15)$$

Putting equations (13) and (14) into equation (15), the efficiency of solar collector can be expressed as

$$\eta=F_R(\tau_G\alpha_m)-\frac{U_LF_R(T_{f,in}-T_a)}{I} \quad (16)$$

Alternatively, this can be expressed as

$$\eta=\frac{Q_wC_p(T_e-T_{in})}{I} \quad (17)$$

3. Finite Volume Method

The governing equations, 1, 6, 7 and 8, are a system of coupled partial differential equations. For simplification, steady state was studies. These equations were written as

$$\Delta y_i\Delta z\frac{k_{m,x}}{\Delta x_j}\left(T_{i,j-1}-T_{i,j}\right)-\Delta y_i\Delta z\frac{k_{m,x}}{\Delta x_{j+1}}\left(T_{i,j}-T_{i,j+1}\right)+\Delta x_j\Delta z\frac{k_{m,y}}{\Delta y_{i+1}}\left(T_{i+1,j}-T_{i,j}\right)-\Delta x_j\Delta z\frac{k_{m,y}}{\Delta y_i}\left(T_{i,j}-T_{i-1,j}\right)+h_vA_w\left(t_{i,j}-T_{i,j}\right)=0 \quad (18)$$

$$\Delta x_j\Delta z\frac{k_f}{\Delta y_i}\left(t_{i+1,j}-t_{i,j}\right)-\Delta x_j\Delta z\frac{k_f}{\Delta y_{i+1}}\left(t_{i,j}-t_{i-1,j}\right)+\rho_fC_{pf}\Delta y_i\Delta z\epsilon(t_{i,j-1}-t_{i,j+1})+h_vA_w\left(T_{i,j}-t_{i,j}\right)=0 \quad (19)$$

$$h_{ai}\left(T_{Gj}-2h_{ai}T_{aj}+h_{ai}T_{nj}\right)=0 \quad (20)$$

$$\alpha_GI+\epsilon_G\sigma\left(T_{sky}^4-T_{Gj}^4\right)+h_a\left(T_a-T_{Gj}\right)+h_{ai}\left(T_{ai}-T_{Gj}\right)+\frac{\sigma(T_{nj}^4-T_G^4)}{(\frac{1}{\varepsilon_m}+\frac{1}{\varepsilon_G}-1)}=0 \quad (21)$$

The modeling equations, (18)-(21), together with appropriate non-linear boundary conditions, form a large sparse matrix. The set of modeling equations were programmed by FORTRAN. The system of equations (18)-(21) can be expressed in matrix form as

$$[A]\bar{x}=\bar{b} \quad (22)$$

Where [A] is the coefficient matrix, $\bar{x}$ is the vector of unknown temperature, and $\bar{b}$ is the vector which is defined according to the initial conditions. Equation (22) represents the quasi steady-state of the system, i.e. (22) is solved for small time interval, during which the input data approximately constant.

4. Results and Discussions

Data comparison was done by using input data given in Table 1 which were from reference (4).

Table 1 Input Data

System parameter	reference (4)
Effective length of collector	170 cm
Effective width of collector	80 cm
Effective depth of collector	11 cm
Wind speed	1.5 m/s
Diameter of particles	0.25 cm
Mass flow rate Q_w	90 kg/hr
Thickness of air gap	0.3 cm
Thickness of bottom insulation	8 cm
Absorbance of matrix	0.96
Emittance of matrix	0.95
Emittance of glass	0.9
Transmittance of glass	0.75
Porosity of matrix	0.325
Solar radiation (W/m^2)	100-1000
Inlet fluid temperature	37--60℃
Ambient air temperature	25℃
Insulation thermal conductivity	0.5 W/m-K
Porous medium	Wet felt
Working fluid	water

The comparison of collector efficiency between experimental data and the results in this numerical analysis is shown in Figure 3. The matching between the numerical predication and experiments is excellent.

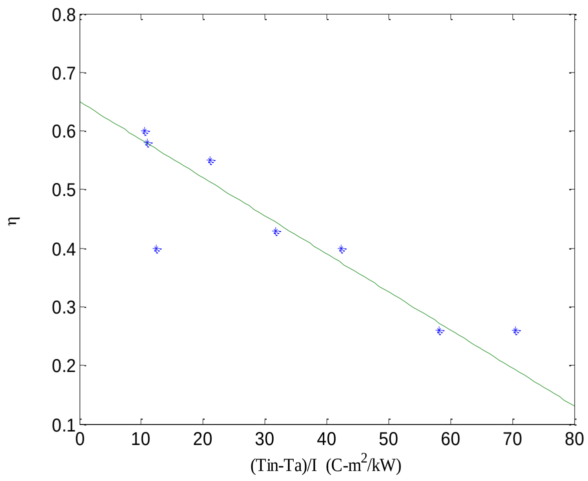

Figure 3 Comparison of collector efficiency between experimental data[4] and numerical analysis results

Utilizing the sets of system parameters shown in Table 1, the efficiency curves of this porous medium flat-plate solar collector and a conventional collector are shown as a function of $(T_{in}-T_a)/I$ in Figure 4. Based on the data, the porous medium flat-plate solar collector is more efficient than the convectional flat-plate solar collector.

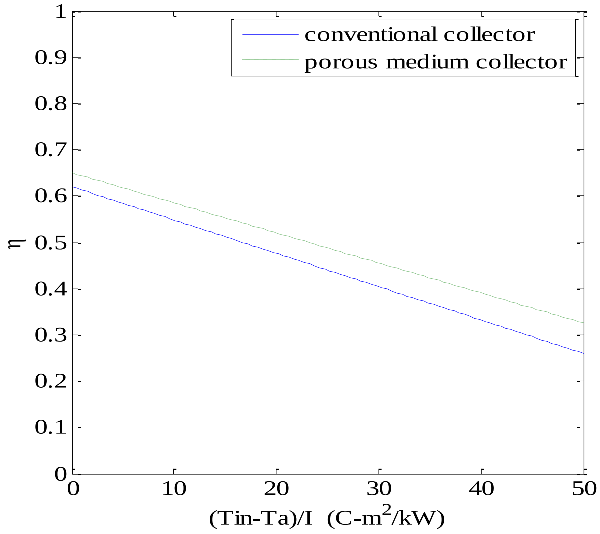

Figure 4 Comparison of efficiency of flat-plate solar collector and porous medium solar collector

A study of the thickness of porous medium has been done. The results, shown in Figure 5, suggest a narrow thickness is an effective design. The 3cm thickness of porous medium solar collector was used for the following numerical analysis. Systemic parametric studies have been done.

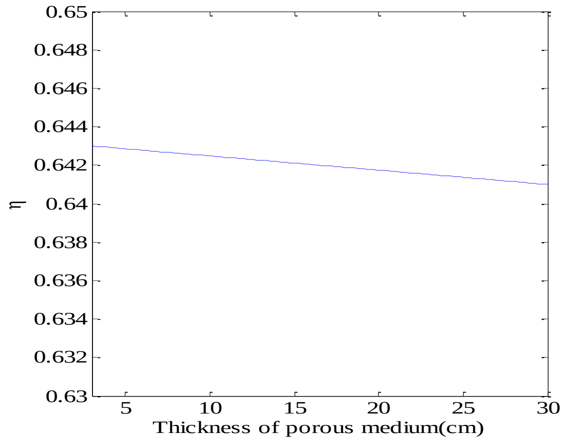

Figure 5 Collector efficiency versus thickness of porous medium

Higher flow rate will result in a high efficiency; refer to Figure 6. However, higher flow rate will also result in high energy costs and lower temperature gains, i.e. temperature difference between the outlet flow and inlet flow.

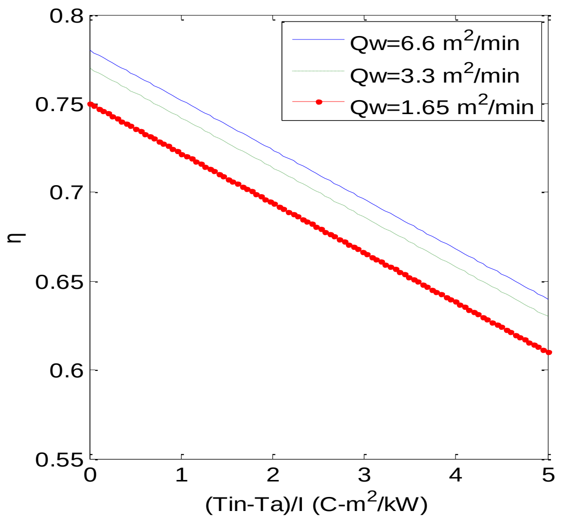

Figure 6 Comparison of collector efficiency at different volume flow rates

The air gap heat transfer coefficient shows the sensitivities of solar collector efficiency, as shown in Figure 7. When the air gap heat transfer coefficient is zero means that the air gap is evacuated and there is no heat loss from the air gap.

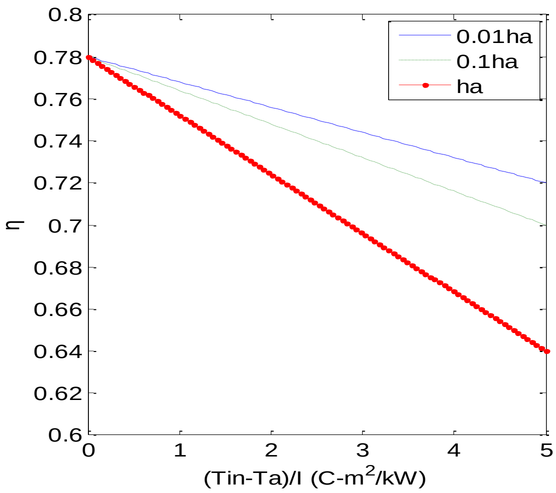

Figure 7 Collector efficiency at different air gap heat transfer coefficients

The matrix wetted area (heat transfer area) can be changed by altering the particle diameter and the porosity of the matrix material. Figure 8 shows the efficiency versus the change of the matrix wetted area. The results show that the efficiency is increased rapidly in the lower matrix heat transfer area region. In general, an increase in the matrix heat transfer area also increases the value of the internal heat transfer coefficient approximately to the 0.51-power [9].
The heat loss through the boundary is proportional to the thermal conductivity of the insulation material. Figure 9 shows the efficiency curves at different thermal conductivities of insulation material. The results indicate insulation material is a very important factor in the design the solar collector.

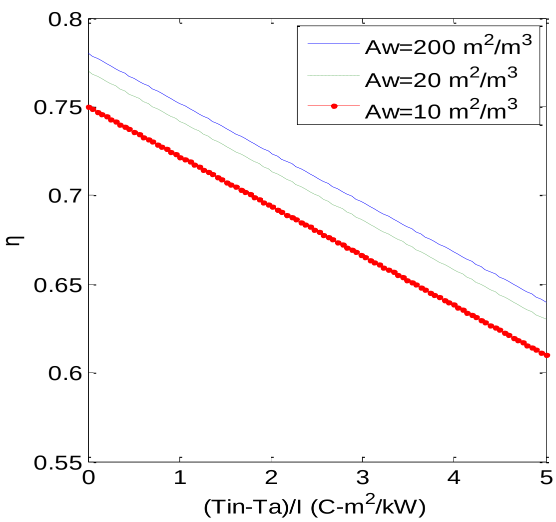

Figure 8 Comparison of collector performance at different matrix heat transfer area

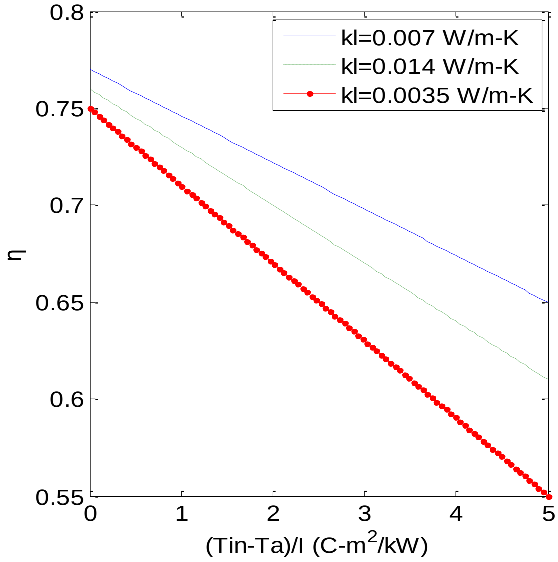

Figure 9 Comparison of collector efficiency at different thermal conductivities of insulation material

5. Conclusions

1. A porous medium flat-plate solar collector has been analyzed to determine its efficiency for collecting solar energy and transmitting this energy to the fluid.
2. Coupled partial differential equations with a non-linear boundary condition are solved by using a finite volume method. The effects of system parameter for the porous medium flat-plate solar collector are studied.
3. The results appear to offer the development of an efficient and low-cost solar collector.
4. This computer program can be used to predict the performance of the porous medium flat-plate solar collector.

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Nomenclature

A_c: cross sectional area of the solar collector
A_w: wetted area of the matrix (heat transfer area)
C_p: specific heat of the fluid
C_{pm}: specific heat of the matrix
C: intrinsic permeability
F_R: collector heat removal efficiency factor
h_v: heat transfer coefficient between the matrix and the fluid
h_a: heat transfer coefficient between the glass and the ambient
h_{ai}: air gap heat transfer coefficient
I: solar radiation
k_f: thermal conductivity of the fluid
k_i: thermal conductivity of the insulation material
k_m: thermal conductivity of the matrix
L_x: length of the solar collector
L_y: height of the solar collector
L_{bi}: thickness of bottom insulation
L_{ei}: thickness of edge insulation
P: pressure
Q: mass flow rate
Q_u: rate of useful energy collection
S_i: sources or sinks of energy in volume i
T: local matrix temperature
T_a: ambient temperature
T_{ai}: local air gap temperature
T_G: local glass temperature
T_{sky}: apparent sky temperature
t: local fluid temperature
t_{in}: fluid entrance temperature
t_e: fluid exit temperature
U: fluid velocity in x-direction
U_L: collector energy loss coefficient
V_F: volume of the fluid
V_m: volume of the matrix
X: horizontal coordinate of the system
Y: vertical coordinate of the system

Greek Symbols

α_G: glass absorbance
α_m: matrix absorbance
γ_G: glass reflectance
ε: porosity of porous medium
ε_G: emittance of the glass
μ: viscosity of the fluid
ν: kinematic viscosity of the fluid
ρ_F: density of the fluid
ρ_m: density of the matix
σ: Stephan Boltzman constant
τ: time
τ_G: transmissivity of the glass
η: efficiency

Subscripts

i: y-direction
j: x-direction