THERMAL PERFORMANCE OF A SOLAR HYBRID DOMESTIC HOT WATER SYSTEM

C. CHOUHDHURY and H. P. GARG†
Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi-110 016, India

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Abstract—This article describes the results of a simulation study of a forced-circulation solar hybrid domestic hot water system (SHDHW) that circulates air through a rockbed air heater and employs an external air-to-water, transverse fin, shell-and-tube heat exchanger to transfer heat from the air to the water. To satisfy the hot water demand, no auxiliary energy has been supplied to the system. The system performance has been evaluated for a typical cold climate of Delhi, India, and corresponds to the hot water demand of a four-person residential building. In addition to estimating the temperatures of the different components, the study has been extended to compute the pumping power expended in air and water circulation throughout the system in order to estimate the effective energy stored in the water storage tank and the rock bed for reuse during the next instants of operation.

INTRODUCTION

Use of solar hybrid system consisting of an air heater and an air-to-water heat exchanger, in conjunction with a water storage tank, is one of the many ways of protecting the solar water heaters against freezing and corrosion. Additional advantages of the hybrid air-to-water heating systems are their use for multipurpose applications such that the outlet air from the heat exchanger can be used for space heating during late fall, winter and spring and for crop drying during late spring, summer and early fall of the year. In a recent communication, we have made a steady-state analysis of a hybrid air-to-water solar collector consisting of a conventional air heater and a longitudinal fin shell-and-tube heat exchanger, where the effects of the air and the water flow rates, the air collector area and the storage tank volume on the storage tank temperature under no load condition have been studied. In another communication, a transient analysis has been made of a hybrid water-heating system comprising a rock bed air heater and a transverse fin shell-and-tube heat exchanger, where, in addition to the storage tank temperature, the pumping power required for circulation of the air and the water through the system and hence the effective energies stored in or gained by the rock bed and the water storage tank have also been computed. In the system, no hot water is assumed to be withdrawn from the tank to serve the load. The investigation for different flow rates of air and water revealed that although the performance of the system increases with an increase in the flow rates of the fluids, no significant improvement can be achieved by increasing the water flow rate to a value more than twice that of the air flow rate (i.e., for \( \dot{m}_w > 2\dot{m}_a \)) for any fixed value of \( \dot{m}_a \). The present communication deals with the transient analysis of the above system under optimized flow-rate conditions (i.e., \( \dot{m}_w = 2\dot{m}_a \)) for any fixed value of \( \dot{m}_a \) where the load is as proposed in Ref. 7, which is the standard hot water demand for a typical family of two adults and two children in India. In the analysis, no auxiliary energy has been assumed to be used to fulfil the hot water need during the day. This hybrid system performance is evaluated for different lengths of rock-bed collector, rates of fluid flow and volumes of storage tank that would be able to satisfy the daily hot water need during late fall, winter and spring without the use of auxiliary energy in the system.

†To whom all correspondence should be addressed.
DOMESTIC HOT WATER USE PROFILE

The standard draw profile (i.e., rate at which domestic hot water is used up by household) is presented in Fig. 1 for a family of 2 adults and 2 children. Although in real life the actual hot water load is different for different income categories, regions, seasons, etc., the profile in the graph is considered as the standard demand that is to be satisfied by all DHW systems. The temperature at which the DHW is used is 40°C, which can be obtained by diluting, if necessary, the storage-tank hot water with cool water at the supply temperature. Although the supply temperature for most of South India is somewhat warmer than that for some parts of North India, 15°C is assumed to be the representative of the supply temperature in the Indo-Gangatic plain during winter. For these DHW user and supply temperatures, corresponding to the volume of water required, the total energy demand to be satisfied by the DHW system at different time of the day is presented in Fig. 1.

SHDHW SYSTEM DESCRIPTION

The solar hybrid domestic hot water system investigated in the present article is shown schematically in Fig. 2 and comprises (i) a rock-bed air heater; (ii) a transverse fin shell-and-tube heat exchanger; and (iii) a hot-water storage tank, the design features of which are discussed later in detail. The design parameters of each component are summarized in Table 1.

Rock-bed air heater

The rock-bed air heater in the SHDHW system consists of double glass cover and a back wooden plate with insulation on its rear, the air-flow passage between the inner glass cover and the wooden plate being filled with black painted spherical rocks of uniform size which directly absorb the solar insolation transmitted through the cover sheets and transfer the heat to the air flowing through it.
Fig. 2. (a) Schematic view of the solar hybrid domestic hot-water system; (b) tube arrangement in the shell of the transverse fin shell-and-tube heat exchanger.
Table 1. Design details of the hybrid system.

Air heater: duct length = 2 m, 4 m; duct depth = 0.1 m; duct width = 1 m; rock size = 0.03 m; packing porosity = 0.5.

Heat exchanger: duct size of the shell = 1.25 m x 1.25 m; no. of tube banks = 12; no. of tubes per one bank = 24 and 20 alternately (in triangular pitch); tube O.D. = 0.025 m; tube I.D. = 0.02 m; no. of fins = 8/0.025 m⁻¹; fin thickness = 0.0009 m; fin height = 0.0009 m.

Water storage tank: volume = 100 lt, 200 lt, 300 lt.

Transverse fin shell-and-tube heat exchanger

The transverse fin shell-and-tube heat exchanger comprises several banks of tubes (with transverse fins) such that the tubes are arranged in triangular pitch in the shell. Since the water in the tube passes from one bank to the next, the number of passes of water flow is considered to be the same as the number of tube banks in the shell. The air in the shell flows in a direction at right angles (cross flow pattern) to the direction of water flow in the tubes.

Hot-water storage tank

The domestic hot water storage tank in the hybrid system is assumed to be made up of steel with glass wool insulation on its outer walls. The water in the tank is assumed to be non-stratified, i.e., fully mixed with uniform temperature throughout.

MODE OF OPERATION

The SHDHW system is assumed to operate during the bright sunshine hours only during the day. The air flow in the system starts only when \( T_R - T_{wa} = 5^\circ C \) and the water flow starts when \( T_o > T_{wa} \) (since the tank is non-stratified, \( T_{wa} = T_{aw} \)). Both the water and air flow through the heat exchanger in a cross-flow pattern. The outlet air from the heat exchanger enters the air-heater provided its temperature is higher than that of ambient air at that particular instant (i.e., if \( T_{oa} > T_A \)). Provision is assumed to be made such that if \( T_{oa} < T_A \), then the ambient air enters the air-heater, receives heat from the black painted rocks and recirculates through the heat exchanger to transfer its heat to the relatively cool water circulating through it from the water storage-tank. The cold water, after receiving heat from the hot air in the heat exchanger, enters the water storage-tank, gets mixed with the stored water and then re-enters the heat exchanger. These flow cycles are repeated until the storage-tank water temperature becomes the same as the rock-bed temperature in the air-heater. In addition, at different times of the day, hot water from the storage-tank is extracted at the required temperature as shown in Fig. 1 to serve the DHW requirement and cold water at the supply temperature is refilled in the storage-tank.

THEORETICAL MODEL

Energy-balance equations

The time-dependent energy-balance equations for the different components of SHDHW system assuming the losses through the connecting pipes and the edge losses from the air heater to be negligible are as presented overleaf.
(a) Air heater

\[ M_1C_1(\partial T_1/\partial t) = \alpha_1 I + h_{21}(T_2 - T_1) - h_{1A}(T_1 - T_A), \]

\[ M_2C_2(\partial T_2/\partial t) = \alpha_2 I + h_{R1}(T_R - T_2) - h_{21}(T_2 - T_1) - h_{2A}(T_2 - T_A), \]

\[ M_RC_R(\partial T_R/\partial t) = \alpha R I - h_{R1}(T_R - T_2) - h_{R2}(T_R - T_2) - h_{R3}(T_R - T_3), \]

\[ M_sC_s(\partial T_s/\partial t) = -\dot{m}_sC_s(T_s - T_{in}) + h_{R1}(T_R - T_s) + h_{21}(T_2 - T_s) + h_{3A}(T_3 - T_s). \]

\[ M_RC_s(\partial T_s/\partial t) = h_{R3}(T_R - T_s) - h_{3A}(T_3 - T_A). \]

(b) Heat exchanger

\[ M_{wh}C_{wh}(\partial T_{wh}/\partial t) = \dot{M}_wC_s(T_w - T_{wh}) - A_{sw}h_{sw}T_{LG} - A_hU_{wh}(T_{wh} - T_A), \]

\[ M_{wL}C_w(\partial T_{wL}/\partial t) = A_{sw}h_{sw}T_{LG} - \dot{M}_wC_w(T_w - T_{wl}). \]

\[ \Delta T_{LG} = C(\Delta T_1 + \Delta T_2)/2, \]

where \( C = 0.95 \) (Ref. 2), \( \Delta T_1 = T_o - T_{wo} \) and \( \Delta T_2 = T_{ho} - T_{wl} \).

(c) Water storage tank

\[ MC(\partial T_{wL}/\partial t) = \dot{M}_wC_w(T_w - T_{wL}) - U_{sw}A_s(T_{wL} - T_A) - M_{wL}C_w[T_{wL} - T_{wL}(1)]. \]

where \( MC = M_wC_w + M_{wL}C_{wL}, T_{wL} = T_{wl} \) and \( T_{wL}(1) = 15^\circ C. \)

On the rhs of the above equation, the load factor, i.e., the factor three, is assumed to be zero on the first day of operation of the system.

The differential Eqs. (1)–(9) were converted into difference equations by replacing \( dT/dt \) by \( (T_i - T_{i-1})/\Delta t \), where \( T_i \) and \( T_{i-1} \) are the temperatures of a particular component of the system just after and before the time interval \( \Delta t \). The simultaneous difference equations thus obtained were solved by using a finite difference technique to obtain the temperatures of the different components of the system.

**Effective energy stored (E.E.S.)**

By obtaining the temperatures of the water (W) in the storage tank and the rock bed (R) in the air heater, the effective energy stored in the storage tank and the rock bed at different time (t) for reuse at the next instant are obtained as

\[ \text{E.E.S.}(W) = M_wC_w(T_w(t) - T_{wL}(1)) - \int_0^t M_w\Delta \rho_w dt/\rho_w - \int_0^t M_s\Delta \rho_w dt/\rho_s. \]

\[ \text{E.E.S.}(R) = M_RC_R(T_R(t) - T_{wl}(1)) - \int_0^t M_s\Delta \rho_w dt/\rho_s. \]

To compute the temperature of the different components and the energy stored in the water storage-tank and rock-bed of the SHDHWS system, the different heat transfer coefficients and the pressure drop experienced by the fluids in completing the flow cycles in the system are obtained by using the standard empirical relations summarized in Refs. 6, 8, 9.

**RESULTS AND DISCUSSION**

The hourly values of the solar insolation and the ambient temperature for a typical winter day in Delhi, for which the SHDHWS system has been evaluated, are presented in Fig. 3. The system evaluation has been carried out for different flow rates of air and water with \( \dot{m}_w = 2\dot{m}_a \). We chose this constraint because it has been observed in our earlier investigation\(^6\) that although the system performance increases with an increase in the flow rate of water for a particular flow rate of air, no significant improvement in the performance was observed when \( \dot{m}_w > 2\dot{m}_a \).
Typical values of the variation of the storage-tank water temperature with load (as per the profile shown in Fig. 1) on the second and the third days of operation of the SHDHW system are plotted in Fig. 4 for collector areas of 2 and 4 m² and an air-flow rate of $m_a = 60$ kg/h-m². For obvious reasons, in the case of the 4 m² collector area, the maximum storage temperature is observed to be about 14°C higher than for the 2 m² area of the rock-bed collector. On the second day of operation, when hot water is extracted from the storage tank in the morning and cold water is fed into it at the supply temperature, a sudden fall in the tank temperature is observed which then rises as the intensity of the solar flux increases. Hot water is again assumed to be extracted from 12 noon and 1 p.m. during the day and from 6 to 7 p.m. in the evening at the temperature of 40°C from the storage tank. This process is repeated on the third and subsequent days as well.

A similar study of the 2 m² collector area with lower flow rates of air ($m_a < 60$ kg/hm²) and a larger volume of the storage tank ($M_{sw} > 100$ kg) resulted in a lower temperature of the storage-tank water, even on the third day of operation, suggesting that it is not possible to extract hot water at 40°C from the SHDHW system for a collector area of 2 m² (length = 2 m)
and width = 1 m) with $m_a > 60 \text{ kg/h-m}^2$. This point is revealed by the fact that on the second and third days of operation of the SHDHW system, the storage-tank temperature for the 2 m$^2$ collector area in Fig. 4 at 12 noon is exactly 40°C, which would certainly be decreased at lower values of the air-flow rate and higher values of the water mass in the storage-tank.

The effective thermal energies stored in the storage-tank water and the rock bed, which are obtained by subtracting the energy expended in the water and the air flow through the heat exchanger and the rock bed from the total energy stored in these components, for collector lengths of 2 and 4 m, $m_a = 60 \text{ kg/h-m}^2$ and $M_a = 100 \text{ kg}$ are presented in Fig. 5. As expected, the energy stored in the water and the rock bed is observed to be much greater for the 4 m$^2$ area than that for the 2 m$^2$ area of the rock-bed air heating collector.

As discussed above, since it is not possible to extract water at 40°C from the SHDHW system with a 2 m$^2$ collector area with lower fluid-flow rates and larger storage-tank volumes, efforts were made to obtain the storage-tank water temperature and the effective energy stored in the

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**Fig. 5.** Hourly variations of the effective energy stored in the water (W) and rock-bed (R) for three consecutive days; $M_a = 100 \text{ kg}$, $m_a = 60 \text{ kg/h-m}^2$.

**Fig. 6.** Hourly variations of the storage-tank water temperature; $L = 4 \text{ m}$, $m_a = 20 \text{ kg/h-m}^2$. 
water and the rock bed for air-flow rates \( \dot{m}_a = 60 \text{ kg/h-m}^2 \) and storage-tank water masses \( M_{sw} = 100 \text{ kg} \) for a 4 m\(^2\) area of the rock-bed air heater.

The hourly values of the storage-tank water temperature at an air-flow rate of \( \dot{m}_a = 20 \text{ kg/h-m}^2 \) with \( \dot{m}_a = 2\dot{m}_a \) and an air-heater area of 4 m\(^2\) for different storage-tank volumes are depicted in Fig. 6. The curves clearly show the lower values of the storage-tank temperatures at larger volumes of the storage-tank. This difference in the storage-tank temperature for different storage-tank volumes decreases with an increase in the number of hours of operation, i.e., on the second and the third days of operation of the SHDHW system.

Similar computations for higher air-flow rates resulted in higher storage-tank temperatures for any fixed storage-tank volume. In addition, the differences in the storage-tank temperatures for different storage-tank volumes were observed to decrease with an increase in the number of days of operation.

The hourly values of the effective energies stored in the storage-tank water and the rock bed for a 20 kg/h-m\(^2\) air-flow rate for different storage-tank volumes are presented in Fig. 7. The effective energy stored in the water is observed to be higher for a larger volume of the hot-water storage tank, whereas the reverse is the case for the effective energy stored in the rock bed. The difference in the E.E.S. for different storage-tank volumes are observed to increase for water and decrease for the rock bed with an increase in the number of hours of days of operation of the system. With an increase in the fluid-flow rates, the effective energy stored in the water was observed to increase, whereas that in the rock bed was observed to decrease. This result may be attributed to the fact that at larger air-flow rates, more heat is transferred from the rock bed to the flowing air which, in turn, is received by the water in the heat exchanger and is stored in the water tank.

CONCLUSIONS

From the results of our simulation studies of the solar hybrid domestic hot water (SHDHW) system, we conclude that to satisfy the hot-water requirement of a family of 2 adults and 2 children, without the use of auxiliary energy, the SHDHW system with a 4 m\(^2\) heater area is ideally suited. The SHDHW system with a 2 m\(^2\) air-heater area will only be suitable at air-flow rates \( \geq 60 \text{ kg/h-m}^2 \) (with \( \dot{m}_a = 2\dot{m}_a \)) and hot water storage-tank volumes \( \leq 100 \text{l} \). To satisfy the hot-water need of a residential building of more than four persons, larger air-heater areas with higher air and water flow rates should be employed.
REFERENCES


NOMENCLATURE

$A =$ Surface area (m$^2$)

$C =$ Specific heat capacity (J/kg·°C)

$h =$ Heat transfer coefficient (W/m$^2$·°C)

$L =$ Length (m)

$\dot{m} =$ Specific mass flow rate (kg/h·m$^3$)

$\dot{M} =$ Mass flow rate (kg/h)

$M =$ Mass (kg) and (kg/m$^3$)

$\Delta p =$ Pressure drop (Pa)

$\Delta t =$ Time difference (sec)

$T =$ Temperature (°C)

$T(1)$ = Temperature at the starting of the system operation (°C)

$\Delta T =$ Temperature difference (°C)

$\alpha =$ Solar absorptance

$\tau =$ Solar transmittance

Subscripts

1 = Outer cover
2 = Inner cover
3 = Back plate
$A =$ Ambient
$a =$ Air
$h =$ Heat exchanger
$I =$ Inlet to heat exchanger
IN = Inlet to air-heater
$L =$ Load
LG = Logarithmic
$O =$ Outlet
$R =$ Rocks
$s =$ Storage tank
$st =$ Stainless steel
$w =$ Water