Presented at ISES meeting in Winnipeg, August 15-20 1976

1

CONF-760842--14

A DESIGN PROCEDURE FOR SOLAR AIR HEATING SYSTEMS

By

S. A. Klein, W. A. Beckman and J. A. Duffie
Solar Energy Laboratory
University of Wisconsin-Madison
Madison, Wisconsin 53706, USA

ABSTRACT

A natural extension of the design procedure for liquid-based solar space and water heating systems is a similar analysis for solar heating systems using air as the heat transfer fluid. In this paper, a solar air heating system incorporating a flat-plate air heater and packed bed thermal storage is described and a simulation model for the system is developed.

The results of many simulations of the air heating system are used to establish the relationship between system performance and the system design and meteorological variables. The results are presented in analytic and graphical form, referred to as an f-chart for solar air heating systems. The results of simulations in several widely different climates suggest that the information presented in the f-chart is location independent. Methods of estimating the performance of air heating systems having a collector air capacitance rate and a storage capacity other than those used to generate the f-chart are included.

A comparison of the performance of air and liquid based systems is afforded by a comparison of their respective f-charts. The air system is shown to perform better at high load fractions supplied by solar energy than a liquid-based system with the same collector thermal performance parameters.

INTRODUCTION

A method of estimating the long-term thermal performance of solar space and domestic water heating systems which use liquids as the energy

EB

DISCLAIMER

transfer and storage mediums is available [1,2,3]. This paper is an extension of the design method for solar heating systems which heat air and store the energy in a packed bed. The approach, similar to that used in the previous study, is to identify the important dimensionless variables of the system and to use computer simulations to develop a correlation between these variables and long-term system performance. The correlation, presented in both analytic and graphical form, is referred to as an "f-chart". The f-chart for solar air heating systems is presented and compared to that for the liquid-based systems.

DESCRIPTION OF THE SOLAR AIR HEATING SYSTEM

The solar air heating system chosen for investigation is shown schematically in Fig. 1. Air heating systems of this configuration have been installed in the Denver Solar House [4], in CSU Solar House II [5], and in other solar houses.

This system has three modes of operation. Mode 1 occurs when solar energy is available for collection and there is a space heating load. Then, room temperature air is drawn through the solar collectors, heated, and returned to the building. Mode 2 occurs when solar energy is available for collection at times when there is no space heating load. Air from the bottom of the packed bed is drawn through the solar collectors, heated, and returned to the top of the storage unit. The hot air moving down through the bed heats the pebbles resulting in sensible heat storage. Mode 3 occurs when no solar energy can be collected but there is a space heating load. Hot air is drawn from the top of the packed bed into the house and room temperature air is returned to the bottom of the bed. In modes 1 and 3, auxiliary energy from a conventional furnace may supplement the solar contribution. Energy required for domestic hot water is provided in some systems by heat exchange from the hot air entering or exiting the collector (shown exiting in Fig. 1) to a small domestic water preheat tank. The hot water is further heated to an acceptable temperature, if required, by a conventional water heater.

Models used in the computer simulations for the solar collector, the space and water heating loads, and the auxiliary energy supply are identical to those developed for the liquid-based solar heating system described in Refs. [1,2,3]. The solar air heating system differs from the liquid system primarily because of its packed bed energy storage and the manner in which the system is controlled. Models of the system control strategy and packed bed energy storage are described in the following sections.

CONTROL STRATEGY

The mode of operation of the solar air heating system in Fig. 1 is determined by the position of the motorized dampers. Whenever the collector is operating, damper A is in the position indicated by the solid line; otherwise, its position is indicated by the dotted line. The collector operation is controlled by an on-off differential controller monitoring the temperatures of the air in the collector outlet manifold, T_o, and in the bottom of the pebble bed, T_N, as indicated in Eq. 1.

$$\begin{aligned} T_o - T_N &\leq \Delta T_1 && \text{Collector is operating} \\ T_o - T_N &\leq \Delta T_2 && \text{Collector is off} \end{aligned} \tag{1}$$

ΔT_1 and ΔT_2 are controller deadbands ideally chosen so that the energy collected is at least equivalent to the energy required to operate the blower. Both ΔT_1 and ΔT_2 have been chosen to be 5°C in the examples noted here. Dampers B and C are controlled by the building thermostat. Whenever the building needs heat, the dampers are in the positions indicated by the dotted lines in Fig. 1. Otherwise, their positions are those indicated by the solid lines.

The system control strategy could be modelled exactly in the manner just described. However, small time steps (and as a result, excessive computation) would then be required in the simulation, since the system may shift from one mode of operation to another in a period on the order of a few minutes. An alternative method of modelling system performance, suitable for long-term simulations, is not to follow the system mode changes exactly, but rather to assume that during any time period, the system operates in whatever modes necessary to maintain the building temperature at the desired level. Then by comparing energy rates, it is possible to determine the fraction of the time period in which the system operated in each mode.

During each time period, the rate of energy collection is compared with the rate of energy required to meet the heating load using the collector and load models described in Refs. [1,2,3]. If there is zero energy collection, the system is assumed to be in mode 3 operation. If the rate of energy collection is non-zero, but smaller than the rate of energy required by the load, it is assumed that the system is in mode 1 operation. If the rate of energy collection is greater than the rate at which energy is required, the fraction of the time period which the system would have to be in mode 1 operation to just satisty the load is calculated; the system is assumed to be in mode 2 operation during the remainder of the period. This method of calculating system performance allows the simulation to use time steps on the order of an hour without a sacrifice in the accuracy of the calculated long-term system performance.

PACKED BED THERMAL STORAGE

The temperatures of the air and the packing material in the storage unit can be described as a function of axial position in the bed and time by a set of two partial differential equations [6,7]. These equations can be solved by numerical methods; however, small time and distance step sizes are required in order to maintain accuracy which causes this model of packed bed thermal storage to be expensive in terms of computing costs.

A simpler model of packed bed thermal storage, useful for long-term simulations of solar air heating systems, has been developed by Hughes, Klein, and Close [7]. The model was developed by assuming that the volumetric heat transfer coefficient between the bed and the air is infinitely large (infinite NTU model). In this case, the relations governing packed bed thermal performance reduce to a single partial differential equation since the packing material and air temperature at any point in the bed are identical. Using finite difference methods, the bed is divided into a number of segments along the flow direction. The partial differential equation is transformed into a set of ordinary differential equations, one for each segment. It has been found that the finite difference approximation of the infinite NTU model having five segments provides a sufficiently accurate description of thermal storage for long-term simulations of solar air heating systems.

f-CHART FOR SOLAR AIR HEATING SYSTEMS

In a manner identical to that used to develop the f-chart for liquid-based solar heating systems, the fraction, f, of the monthly total heating load supplied by solar energy calculated by the simulation model has been correlated to the dimensionless groups X and Y.

$$X = \frac{AF_R U_L (T_{ref} - \overline{T}_a)}{L} \tag{2}$$

$$Y = \frac{AF_R (\overline{\tau\alpha}) S}{L} \tag{3}$$

where

A is the collector area.

T_{ref} is a reference temperature chosen to be 100°C.

$\overline{T}_a$ is the monthly average ambient temperature.

S	is the monthly total radiation incident on the collector surface (per unit area). A method of estimating S from records of the average daily radiation on a horizontal surface is given in Refs. [1,2,3].
L	is the monthly total space and water heating loads.
$(\overline{\tau\alpha})$	is the weighted average transmittance-absorptance product for the transparent covers and the absorber plate of the collector. For collectors oriented directly towards the equator at a slope from 0 to 15° greater than the latitude, $(\overline{\tau\alpha})$ is approximately 93% and 91% of the transmittance-absorptance product at normal incidence for 1 and 2 glass cover collectors respectively.

The collector design parametes, F_R, U_L and $(\tau\alpha)_n$, can be determined for a specified collector in the manner described in Duffie and Beckman [8] or from collector test results such as those presented by Vernon and Simon [9]. The ranges of the design parameter values examined in the simulations are given in Table 1. The correlation, determined by a least squares fit to the simulation results, is given in Eq. 4. The standard deviation of the simulated system performance from the correlation is 0.033 on a monthly basis and 0.017 when monthly values are used to determine the year average performance. The correlation has been compared with simulation results for heating systems in Madison, Wisconsin, Albuquerque, New Mexico, Blue Hill, Massachusetts, Boulder, Colorado, and Charleston, South Carolina. A graphical representation of Eq. 4, appears in Fig. 2.

$$f = 1.040Y - 0.065X - 0.159Y^2 + 0.00187X^2 - 0.0095Y^3 \qquad (4)$$

$$\text{for} \left\{ \begin{array}{l} 0 \leq Y \leq 3.0 \\ 0 \leq x \leq 18.0 \quad \text{and } 0 < f < 1 \\ Y > 0.07X \end{array} \right.$$

The collector overall efficiency factor, F_R, which appears in the dimensionless groups X and Y is a function of the collector fluid capacitance rate as discussed in Duffie and Beckman [8]. Aside from affecting the value of F_R, a change in capacitance rate affects the thermal stratification in the packed bed. An increase in air flowrate tends to improve system performance by increasing the value of F_R, but it also tends to decrease performance somewhat by reducing the degree of thermal stratification in the packed bed.

TABLE 1

Ranges of Design Parameter Values Examined
for Solar Air Heating Systems

$0.6 \leq (\tau\alpha)_n \leq 0.9$	
$5.0 \leq F_R A \leq 120.0$	m^2
$7.5 \leq U_L \leq 30.0$	kJ $hr^{-1} m^{-2}$ °C^{-1}
$30.0 \leq s \leq 90.0$	degrees
$300.0 \leq UA \leq 2400.0$	kJ hr^{-1} °C^{-1}
$(\dot{m}C_p)_c/F_R A = 58.7$	kJ $hr^{-1} m^{-2}$ °C^{-1}
$V\rho_{app}C_r/F_R A = 400.00$	kJ m^{-2} °C^{-1}

The f-chart for air heating systems was generated for a collector air capacitance rate per equivalent collector area of 58.7 kJ hr^{-1} m^{-2} °C^{-1}. The performance of systems having collector capacitance rates between 30 and 120 kJ hr^{-1} m^{-2} °C^{-1} can be estimated by multiplying the values of X by $\left[[(\dot{m}C_p)_c/F_R A]/58.7 \right]^{0.28}$

The results of many simulations in which the packed bed storage capacity per equivalent collector area was varied from 200 to 1600 kJ m^{-2} °C^{-1} indicate that the performance of air heating systems is slightly less sensitive to storage capacity than liquid-based systems. One explanation for the reduced sensitivity is that the air heating system can operate in the collector-load mode, in which storage is not used. The f-chart for air heating systems was generated for a storage capacity per equivalent area of 400 kJ m^{-2} °C^{-1}. The performance of systems with other storage capacities can be determined by multiplying the dimensionless group X by $[V\rho_{app}C_r/F_R A)/400]^{-0.3}$.

COMPARISON OF THE LIQUID AND AIR HEATING SYSTEMS

A comparison of the f-charts for the liquid and air systems indicates that, for the same values of X and Y, the air system outperforms the liquid system, particularly for systems designed to supply a large fraction of the heating load. There are several reasons for this behavior. First, the average collector fluid inlet temperature is lower for the air system (and thus the collector efficiency is higher) than that for the liquid system at times when there is a space heating load, since in this case, room temperature air is circulated through the air heater and returned to the building. Second, the thermal stratification is ordinarily maintained at a higher level in pebble beds than in water tanks primarily because of the smaller fluid capacitance rates normally used in air heaters. A third reason is that a heat exchanger between the storage unit and the heating load is not required in an air heating system and thus the penalties associated with heat exchange are avoided. Fourth, air systems do not "dump" energy as liquid systems do when the fluid temperature reaches its boiling point, and fifth, the storage capacity used to generate the f-chart for the air systems is slightly larger than that used for the liquid systems. It cannot be concluded, however, that air heating systems perform better than liquid systems. The overall collector efficiency factor, F_R, is ordinarily lower for air heaters. As a result X and Y are ordinarily lower and thus the performance of an air system may be equivalent to or lower than that of a liquid system, all else being the same.

REFERENCES

1. Klein, S. A., Beckman, W. A. and Duffie, J. A., "A Design Procedure for Solar Heating Systems", Solar Energy, Vol. 18, pp. 113 (1976).

2. Beckman, W. A., Duffie, J. A. and Klein, S. A., "Simulation of Solar Heating Systems", to be published as Chapter 9 in the ASHRAE book, Applications of Solar Energy for Heating and Cooling a Building, (1976).

3. Klein, S. A., "A Design Procedure for Solar Heating Systems", Ph.D. Thesis, University of Wisconsin, (1976).

4. Löf, G. O. G., El-Wakil, M., and Chou, J. P., "Design and Performance of Domestic Heating Systems Employing Solar Heated Air--The Colorado Solar House", Proceedings of the UN Conference on New Sources of Energy, Vol. 5, UN, New York, p. 185 (1964).

5. Ward, D. S., Löf, G. O. G. and Smith, C. C., "Design of a Solar Heating and Cooling System for CSU Solar House II, paper presented at the International Solar Energy Congress and Exposition, UCLA, July 28-August 1, (1975).

6. Hughes, P.J., "The Design and Predicted Performance of Arlington House," M.S., Dept. of Mech. Engr., University of Wisconsin, Madison (1975).

7. Hughes, P.J., Klein, S.A., and Close, D.J., "Packed Bed Thermal Storage Models for Solar Air Heating and Cooling Systems," ASME Journal of Heat Transfer, Vol 98, Series C, 2, May 1976.

8. Duffie, J.A. and Beckman, W.A., *Solar Energy Thermal Processes*, Wiley Interscience, New York (1974).

9. Vernon, R.W. and Simon, F.F., "Flat-Plate Collector Performance Determined Experimentally with a Solar Simulator," NASA paper #TMS-71602.

FIGURE 1 SCHEMATIC DIAGRAM OF A SOLAR AIR HEATING SYSTEM

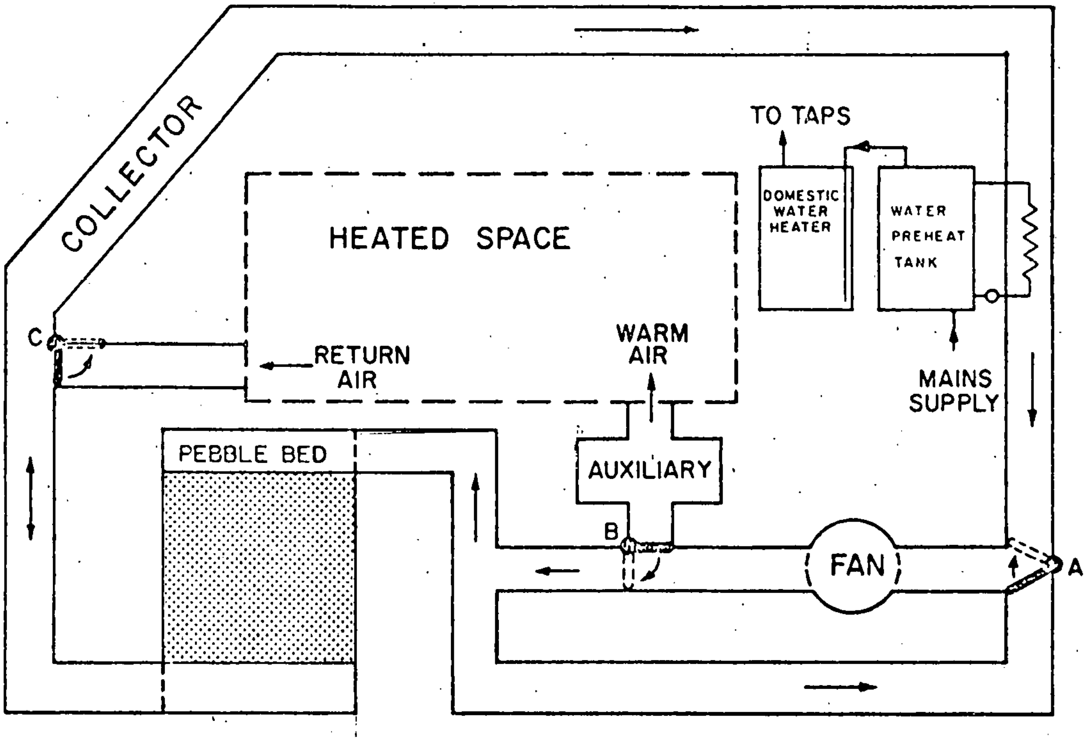

FIGURE 2 f -CHART FOR SOLAR AIR HEATING SYSTEMS