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SIMULATION OF SOLAR AIR HEATING AT CONSTANT TEMPERATURE

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ABSTRACT

Solar space heating with warm air in typical air collectors and rock bed storage systems involves constant air flow rates and varying temperature of supply to rooms and to storage. This practice results in undesirable fluctuations in comfort levels in the living space, excessive storage size, useful but inaccessible heat in storage, and unnecessarily high energy consumption for air circulation and for auxiliary heat. These drawbacks can be avoided by use of a practical controller and variable speed fan to provide heated air from the collector at constant temperature and a continually varying rate.

Collector manufacturer's data, confirmed by seasonal tests on a solar air heating system in Solar House II at Colorado State University, have been used in simulations at constant hot air supply temperatures of 40, 50 and 60°C, and at one typical constant flow rate of 49 kg/hr,m^2 through a 50m^2 collector and rock bed storage unit, providing approximately half the seasonal heating requirements of a residential building.

Auxiliary heat requirements and fan power use in the 40°C and 50°C constant temperature operations were significantly reduced from the levels prevailing under constant flow conditions. Collection efficiency and solar heat supply at constant flow were slightly higher than values at the 60°C constant temperature level.

1. INTRODUCTION

In research on solar air heating systems, and in their commercial design, manufacture, and use, numerous advantages and a few disadvantages compared with liquid systems have been observed. Most of the practical systems have been based on the use of air heating solar collectors and heat storage bins containing small (2-3 cm.) rounded gravel and crushed rock. Air is heated in the collector commonly to maximum temperatures of 60-70°C, circulated by a fan through a vertical rock bin, and returned to the collector. The rocks are heated by the air as the temperature of the air decreases to that of the rocks at the exit of the bin. If heat is needed in the building during such operation, the heated air is diverted from the storage entry to the warm air distribution system, usually via an auxiliary heater employing fuel or electricity if and when required; air returns from the rooms directly to the collector. Stored heat is retrieved, as needed, from the rock bin by circulating room air through it in a direction opposite to that used for storing the heat, the resulting warm air then being supplied to the rooms via the auxiliary heater.

The usual control strategy involves fan operation and heat collection whenever the air temperature at collector outlet exceeds the temperature in the rooms or the temperature in the coolest part of the pebble bed by a pre-set difference. Warm air is supplied to the rooms when a thermostat senses room temperature lower than the thermostat setting by one or two degrees. Auxiliary heat supply is usually controlled by a second set point in the room thermostat, another one to two degrees lower. Solar heated air, either from collector or from storage, passes through the auxiliary heater. If its temperature is too low to meet the heat demand, fuel or electricity is supplied to the auxiliary heater, thereby raising the air temperature to a satisfactory level. None of the auxiliary heat reaches the storage unit, either directly or indirectly, as in some liquid systems.

Certain disadvantages in solar air heating can be reduced or eliminated by supplying air from the solar collector to the heat storage unit (and to the rooms as well) at constant temperature. By varying the collector flow rate, air can be supplied to the heat storage unit at sufficiently uniform temperature to provide two essentially isothermal regions in the bed, a cool zone in the lower portion and a hot zone in the upper portion, with a comparatively small transition zone between them. The size of the rock bed can be substantially reduced because all of the heat is thus stored at a single high temperature rather than over a range of temperatures requiring more volume and mass. Whenever there is heat in storage, useful temperatures are continually available, no auxiliary heat being required.

In conventional, constant flow operation, afternoon solar heat is collected at decreasing temperatures, thereby cooling the upper zones in the rock bed and "pushing" the peak temperature portion downward. At sunset, there is cool rock in the top, a hot zone lower down, and unless the bed is fully heated, a cool zone near the bottom. When heat is being withdrawn from the bed as in the evening, cool air is delivered even though much higher temperatures exist in lower zones of the bed. Auxiliary heating is needed, even though the thermal storage bed is not fully depleted.

Finally, this type of operation assures the lowest possible temperature of air returning to the collector (and therefore maximum collection efficiency) because it is supplied from a uniform cold zone of the rock bed or from the rooms, both at approximately 20°C.

2. METHODOLOGY

Data on a complete solar air heating system operated at two constant air flow rates have been obtained by use of the experimental system in Solar House II at Colorado State University [1]. Continuous monitoring of performance through a full heating season provided the previously published results. Subsequent measurements over a wider range of air rates, and manufacturer's collector efficiency data, have provided further information on the relationships between collection efficiency and air flow rate [2].

Until experimental data on system performance at constant temperature can be procured, the results of constant temperature and constant flow operation can best be compared by computer simulation of performance under the two conditions. Relationships between collector efficiency and air flow rate were established and used in detailed simulations based on a TRNSYS computer model [3] of a system employing an array of $50m^2$ of Solaron series 3000 flat plate air collectors providing approximately one-half the seasonal heating requirements of a typical single family residence [4]. Operations at constant air flow rate and at variable flow-constant delivery temperature were simulated for an entire seven-month heating season, employing TMY data for Denver, Colorado. The variable heating requirements of the building were incorporated in the model and computed at hourly intervals. Performances on a sunny day in November and another in January were simulated to provide hourly histories of storage temperatures.

The conditions under which constant temperature operation was simulated are identical with those used in the constant flow examples. During periods when house heating is not required, the total air flow through the collector, whether high or low, is circulated through storage. When space heating is required, hot air is supplied to the rooms at a constant rate, so if solar collection is also occurring, the rate of air supply to the rooms may be greater or smaller than the collector flow rate. The difference in air flows passes through the storage unit; if collector flow rate is higher than the room air supply, a portion is circulated through storage, and when the collector flow rate is low, room air is a mixture of hot air from the collector and from storage. The on-off supply of warm air to the rooms is at constant flow, either from the collector or from storage or from both units.

If air delivered to the rooms from collector or storage in either system is not warm enough to prevent the room temperature from decreasing to the second (lower) setting, auxiliary heat is supplied to the air being delivered from the solar system.

3. SYSTEM DESCRIPTION

The simulated system is shown in Fig. 1. Its design and operation are typical of many residential solar air systems.

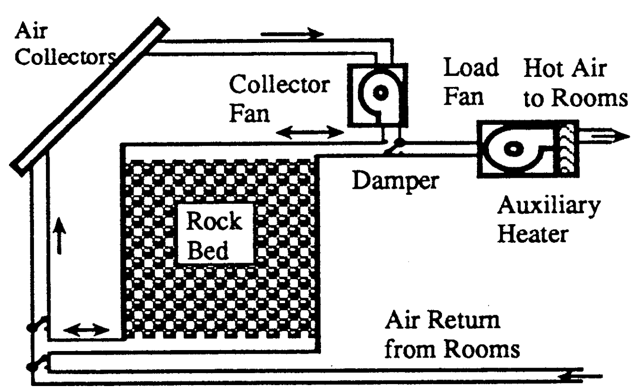

Fig. 1. Solar Air Heating System

3.1 Collector

The internally manifolded Solaron Model 3000 collector has a black chrome absorber and a single, high-transmission glass cover. Manufacturer's tests on two collectors in series at flow rates of 44 kg/m^2hr to 110 kg/m^2hr provided performance data which yielded values of F_R and F_RUL shown in Fig. 2 [4]. The measurements also showed a transmission-absorption product, $\tau\alpha$, of 0.74. At a test flow rate of 66 $kg/hr{\cdot}m^2$, F_RUL is 19 $kJ/hr{\cdot}m^{2\circ}C$ and $F_R\tau\alpha$ = 0.548.

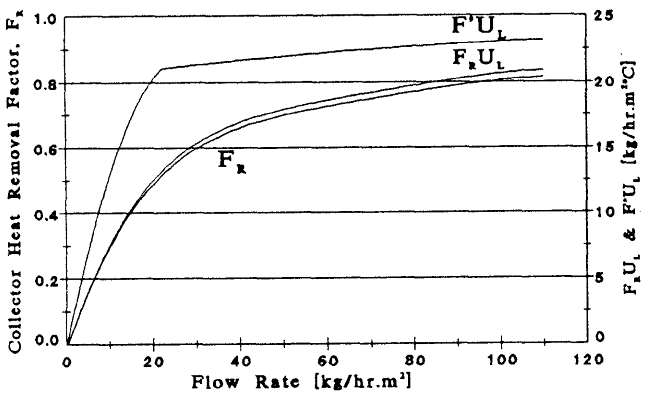

Fig. 2. F'UL and F_RU_L vs. Collector Flow Rate

The useful energy, $\dot{Q}_u$, obtained in constant flow operation was determined by use of the conventional collector efficiency equation at hourly intervals and the computer code outlined in Duffie and Beckman [5].

For constant temperature operation, a method reported by Wuestling, Klein and Duffie [6] was considered. That method is applicable if the collector operates at conditions resulting in a nearly constant value of the $F'U_L$ product. Fig. 2 shows that at flow rates higher than about 20 $kg/hr.m^2$, the $F'U_L$ product is nearly constant, averaging about 0.90. Since the system is operated at hourly flow rates typically in the 20 to 80 kg/m^2 range, the mass flow rate required for maintenance of constant collector outlet temperature was computed by use of the Wuestling model. The TRNSYS component was developed to have a limit in collecting energy, the flow rate being forced to zero when the solar radiation is below the critical threshold level. The component therefore operates by calculating the mass flow rate and heat collection at the constant delivery temperature setting.

3.2 Storage

A rectangular rock bed heat storage unit 2m in height (direction of air flow), large enough for storage of all collected energy on a design day of maximum solar radiation in October, was designed. The volume of rock bed storage was estimated as a function of the collector total area and storage temperature range. The amount of useful energy collected during a sunny day with 50 percent collector efficiency is typically:

$$Q_u = (30\ MJ/m^2{\cdot}Day)*(0.5)*A_c = (15000\ kJ/m^2{\cdot}Day)*A_c$$

Energy balance on the rock bed:

$$Q_u = (15000\ kJ/m^2{\cdot}Day) * A_c = \rho_r * C_{pr} * (\Delta T) * V_r$$

where, ρ_r, C_{pr} and k_r are density, specific heat and conductivity of rocks used in the rock bed, respectively, and ΔT is the one-day change in rock temperature. At values of ΔT = 30°C

$$V_r = 15000\ A_c/1533 * 0.88 * 30 = 0.37A_c.$$

For a $50m^2$ collector, storage volume = 18.5 m^3. The height of the rock bed is assumed constant and equal to L_r = 2m.

The area of the base of the rock bed is $A_r = V_r / L_r$ = 0.185 A_cm^2. With a $50m^2$ collector, the rock bed cross section is $9.25m^2$, or approximately 3 m x 3 m square. A constant size rock bed was used at all operating temperatures and flow rates. The number of segments in the rock bed simulation was set equal to 40 nodes.

3.3 Collector Flow Rates

The collector fan operates at constant speed in the usual mode and at variable speed, with maximum flow rate a function of solar supply and collector efficiency when delivering hot air at constant temperature. Maximum useful energy collected with 50% collector efficiency is

$$\dot{Q}_u = (1000\ w/m^2) * 0.5 * A_c = 1800 * A_c\ [kJ/m^2{\cdot}hr]$$

$$\dot{m}_c = (1800 * A_c) / [C_{pa} * (T_o - T_i)]$$

with C_{pa} = 1.012 kJ/kg.°C and when, e.g. $T_o - T_i$ = 21°C

$$\dot{m}_c = 86 * A_c\ [kg/hr] = 4300\ kg/hr$$

The auxiliary furnace energy rate Q_{aux} is estimated with the equation

$$\dot{Q}_{aux} = \dot{m}_{load} * C_{pa} * (T_o - 20)\ \ [kJ/hr]$$

where, $\dot{m}_{load}$ is the mass flow rate of the constant speed load fan, set at 1200 cfm (0.566 m^3/s); T_o is the design outlet collector temperature for the constant temperature control strategy, and 55°C for the constant flow rate control strategy; 20°C is the minimum operating temperature at the bottom of the rock bed.

3.4 Load Strategy

A two-stage thermostat is used for control and selection of the proper source of energy to heat and maintain the temperature in the rooms. When the room temperature drops to 21°C, the first stage turns on the load fan (operating at a constant 1200 cfm rate). Solar heated air from the rock bed or from the solar collectors is supplied to the rooms. Air from the rooms, at room temperature, is returned to the bottom of the rock bed or to the solar collectors. If the room temperature continues to decrease, the second stage, at 20°C, turns on fuel or electric heat in the furnace to increase the air temperature with a constant amount of energy, Q_{aux}, before supplying it to the rooms. Both stages have a deadband of +2°C above their setting.

4. RESULTS AND DISCUSSION

Table 1 contains extensive information on numerous aspects of system performance at constant flow and constant temperature. Solar heat collection, system efficiency, solar fraction, and solar heat usage at 40°C and 50°C constant collection temperature exceed the values obtained with conventional constant flow operation; constant temperature operation at 40°C provides 12 percent more solar heat use (Q_{solar}), and at 50°C, 2 percent more heat than supplied at constant flow. Constant temperature operation at 60°C provides about 5 percent less solar heat than supplied at constant flow.

Solar heat supply in midwinter months is substantially greater at constant temperature (particularly at 40°C) than at constant flow. Auxiliary heat required in December at 40°C constant temperature is 24 percent less than at constant flow, and at 50°C, 11 percent less. For the whole seven-month season, auxiliary heat required at 50°C constant temperature is 6 percent less, and at 40°C, 17 percent less, than at constant flow.

Electric energy for collector fans in constant temperature operation is one-third to two-thirds (at 50° and 40°, respectively) of requirements at constant flow. Load fans use 8 percent to 20 percent less energy.

Average temperatures of air supplied to the living space are approximately the same (37°C to 41°C) at constant flow and at the three constant collection temperatures.

Fig. 3 shows, for the constant flow and two constant temperature operations, annual solar fractions of approximately 50 percent, the design basis. Nearly the same solar fractions are obtainable with storage volumes only half the design maximum. The reduction in annual solar fraction suffered by decreasing storage to one-fifth the design maximum ranges from 11 percent to 18 percent.

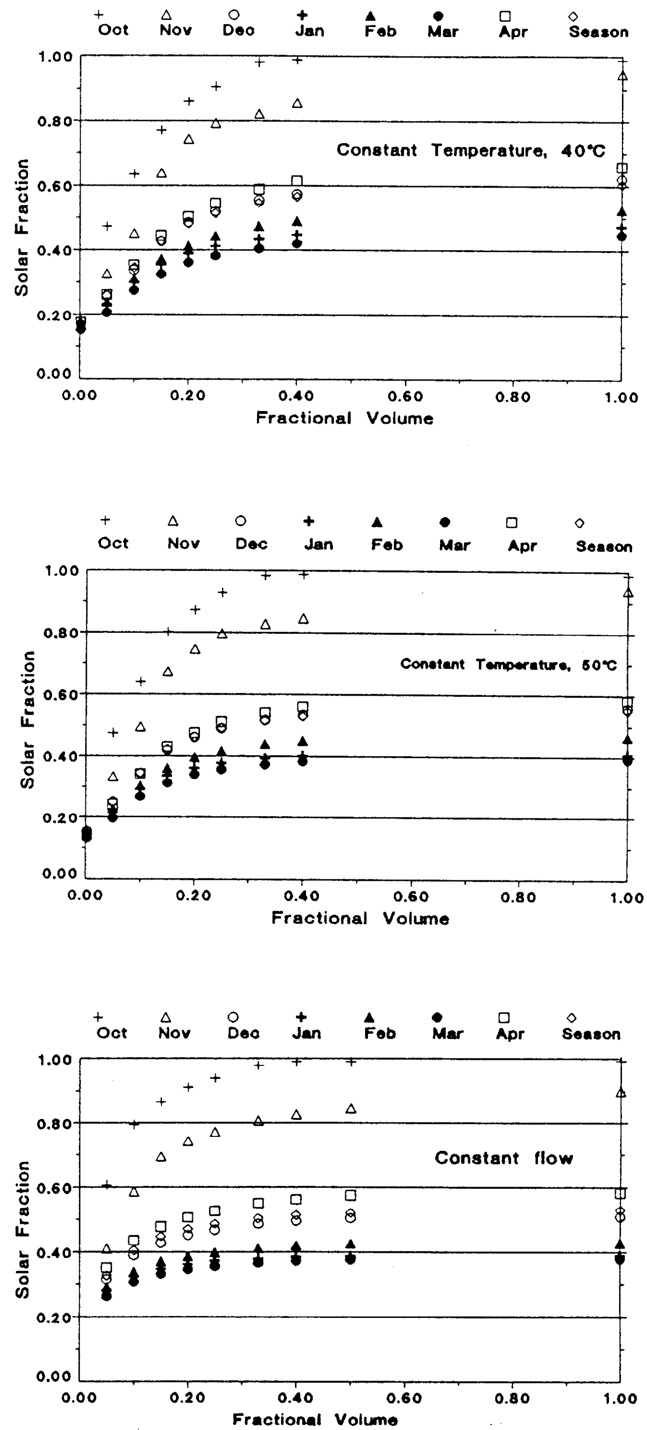

Fig. 3. Solar Fraction in Air Heating Systems

Slightly higher solar fractions are observed for operations at constant temperature than at constant flow; monthly solar fractions range from nearly 100 percent in October to about 40 percent in December, January, and February. Systems without any storage can supply only 15 percent of the monthly and annual heating requirements.

Several examples of the 24-hour time-temperature-position relationship in heat storage rock beds are depicted in Figures 4 - 9. Figs. 4 and 5 show the history on a sunny November day during which no heat was removed from a storage bed initially containing no heated rock. Fig. 4 shows conventional constant flow operation, Fig. 5 constant temperature collector operation at 50°C. Fig. 4 shows that with constant flow, rock temperature at the top of the bed starts to increase at about 0900 hours, rises to 52°C at noon, and decreases to about 27°C at 1700 hours. The location of stored heat between 1700 and 2400 hours is indicated by the bed temperature profile on the left hand "wall" of the diagram--27°C at the top of the bed, rising to 50°C about 0.7 meter from the top, and declining to about 25°C at the bottom. Heated air cannot be obtained from the bed until the high temperature "mound" has been "pushed" toward the top of the bed by air supplied to the bottom. Auxiliary heat would have to be used for several hours until the hot zone had been moved to the top of the bed.

Fig. 5 shows the history of a constant temperature operation at 50°C. It is evident that rock temperature at the top of the bed reaches 50°C at about 1100 hours and stays at that level. The zone of 50°C rock grows in the afternoon to reach downward about one meter at 1600 hours. At any time in the afternoon or evening, heated air can be delivered from the bed at 50°C, thereby reducing or eliminating the need for auxiliary. The temperature - height profile at 2400 hours shows that rock temperature in the upper half of the bed is nearly uniform at 45 to 50°C, indicating that heat is available from storage at high temperature for an extended time period.

Figs. 6 and 7 show storage histories during a November day when solar heat was supplied to and delivered from a rock bed containing heat from the previous day. In the constant temperature operation (Fig. 6), heat is being delivered to the building from storage at 50°C during the period between midnight and 0900 hours. There is no significant decrease in air delivery temperature although the quantity of heat in storage is decreasing. From 0900 to 1600 hours, the zone of hot rocks grows as heat is added to storage at constant temperature. There is only a slight rise in the temperature of cold air supplied to the collector (up to about 32°C between noon and 1700 hours), so high collection efficiency is maintained. After 1700 hours, heat is supplied to the building at 50°C, reducing the volume of heated rock in storage. The amount of stored heat at 2400 hours is slightly lower than at 0100 hours, and the temperature profile is similar.

Fig. 7 shows a storage history on the same November day with constant flow operation. Stored heat from the previous day is shown by the profile on the right hand vertical surface. Until 0700 hours, hot air was supplied to the load from storage at about 80°C. From 0700 to about 0900 hours, delivered air temperatures declined. At 1000 hours, net storage starts to increase, unfortunately, at the bottom of the bed from which air is supplied to the collector. Collection efficiency between noon and 1600 hours is low because of high temperature of air supply to the collector. After sundown, heat is supplied to the building from storage at a nearly constant temperature, and the storage temperature profile is similar to that at 0100 hours.

Figs. 8 and 9 show that on a January day, high building heat requirements have used all the heat stored the previous day and that only the upper third of the rock bed is being effectively used. With constant temperature operation (Fig. 8), rock temperature at the top of the bed rises steeply at 1000 hours to a 50°C maximum prevailing from 1300 to 1800 hours. The zone of rocks heated to at least 45°C extends downward about 0.3 meter at 1600 hours, and temperatures of at least 30°C extend down to the 0.6 meter level. Heat is supplied from the bed at 45 to 50°C until about 2000 hours, and subsequently at temperatures declining to 34°C at midnight.

At constant flow, Fig. 9 shows collection and storage at decreasing temperature after 1400 hours. The temperature of air supplied to the rooms from storage after that time decreases slowly for about 7 hours (until 2100 hours), then steeply to about 30°C at midnight. The perspective view of the temperature profile partially hides the considerable afternoon drop in temperature at the top of the bed.

The examples of heat storage under several conditions clearly show the advantages of solar collection at constant temperature. Whenever heat is in storage, it is available for use at the collection temperature and not "buried" under a mass of colder rock.

5. CONCLUSIONS

Operation of solar air heating systems at constant collector outlet temperature of 50°C and 40°C provides 2 percent to 12 percent more annual solar heat in a residential building than the same system at conventional constant flow rates. Operation at 60°C results in solar heat supply 5 percent less than from the constant flow system.

Operation of solar air collection systems at constant delivery temperatures of 40°C and 50°C results in lower annual auxiliary heat requirements and lower fan energy use than with operation at typical constant flow rates.

The two modes of operation provide air to the living space at approximately the same monthly average temperatures of 37°C to 41°C.

At constant collector delivery temperature, the pattern of heat storage in a rock bed avoids the cold zones and inaccessibility of stored heat commonly encountered with constant flow rate operation.

Constant temperature operation results in better temperature stratification in storage than in constant flow systems.

The annual solar fraction provided by operation at constant 40°C and full-size ($18.53 m^3$) rock bed is 0.60, compared with 0.53 for constant flow operation.

Decreasing storage volumes to one-fifth the full design size reduces solar fractions to the same 0.47 level for constant flow and for 40°C constant temperature operation.

6. NOMENCLATURE

A_c	collector area [m^2]
C_p	specific heat [kJ/kg.°C]
F'	collector efficiency factor
F_R	heat removal factor
$F_R U_L$	negative of the slope of the collector efficiency versus $(T_i - T_a)/G_T$ curve
$F_R(\tau\alpha)$	intercept of the collector efficiency versus $(T_i - T_a)/G_T$ curve (corrected for non-normal solar incident)
G_T	solar radiation per unit area incident on collector plane [$kJ/m^2.hr$]
$G_{T,op}$	solar radiation per unit area incident on collector plane in operation [$kJ/m^2.hr$]
k	effective thermal conductivity in axial direction [kJ/hr.m.°C]
$\dot{m}_c$	collector mass flow rate [kg/hr]
$\dot{m}_{load}$	load mass flow rate [kg/hr]
NTU	number of transfer units
Q_{aux}	total auxiliary energy used by furnace [Mj]
Q_{cf}	total electric energy to operate the collector fan [Mj]
Q_{lf}	total electric energy to operate the load fan [Mj]
Q_{solar}	total solar energy used [Mj]
Q_u	total useful energy gain [Mj]
$\dot{Q}_u$	rate of useful energy gain [kJ/hr]
r	non-test flow rate correction ratio
$\overline{SF}$	average solar fraction [%]
$\overline{SCE}$	average solar collector efficiency [%]
$\overline{SSE}$	average solar system efficiency [%]
T_a	ambient temperature [°C]
$\bar{T}_{Elf}$	average air temperature entering load fan [°C]
T_i	collector inlet temperature [°C]
$\bar{T}_i$	average collector inlet temperature [°C]
TimeC	total time the collector fan operated [Hours]
TimeL	total time the load fan operated [Hours]
$\bar{T}_{rs}$	room supply average air temperature [°C]
T_o	collector outlet temperature [°C]
$\bar{T}_o$	average collector outlet temperature [°C]
UA	overall building loss coefficient area product [kJ/hr.°C]
ρ	effective density [kg/m^3]

7. REFERENCES

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8. DESIGN DATA

UA of building = 1200 kJ/hr.°C

Collectors

$A_c = 50 m^2$

Tilt = latitude + 10°
number of Collectors in series = 2
orientation - South
Single glazing
test data

$\dot{m}_{c,test}$ = 66.07 kg/hr.m^2
$F_R U_L$ = 19 kJ/hr.m^2.°C
$F_R(\tau\alpha)$ = 0.5476

C_p of air = 1.012 kJ/kg.°C
Constant flow collector, collector mass flow rate = 2450 kg/hr
Constant temperature collector, maximum collector mass flow rate = 4644 kg/hr

Heat Storage Rock Bin

C_{pr} of pebbles = 0.88 kJ/kg.°C
effective density (including voids), ρ_r = 1533 kg/m^3
effective thermal conductivity in axial direction, k_r = 0.45 kJ/hr.m.°C
volume = 18.5 m^3
shape 2 m high with (3.04 x 3.04 m) square cross section
storage/collector ratio = 0.37 m^3/m$_2$
thermal loss coefficient, U = 1 kJ/m^2.hr.°C
storage is modeled with an "infinite" NTU model.

Power Requirements

Collector fan power
constant flow 900 kJ/hr
constant temperature 30 kJ/hr to 1700 kJ/hr
Load fan power 900 kJ/hr

TABLE 1. System Performance

Collector strategy	Constant 40°C Temperature	Constant 50°C Temperature	Constant 60°C Temperature	Constant 2450kg/hr Flow rate
Q_u (TimeC)	68460(1331)	61380(1199)	56770(1053)	57240(1445)
Oct	10270(242)	9625(223)	9581(204)	7946(227)
Nov	10050(202)	9646(193)	9427(180)	9027(213)
Dec	10140(175)	9062(157)	8177(131)	8354(192)
Jan	9586(181)	8213(162)	7193(139)	7911(200)
Feb	9411(166)	8269(151)	7427(131)	7671(182)
Mar	9027(164)	7856(146)	6998(125)	7579(195)
Apr	9987(201)	8710(168)	7971(144)	8751(237)
SSE (SCE)	32.5(36.3)	29.2(34.5)	25.0(32.0)	27.2(29.5)
Oct	25.9(27.5)	24.3(26.7)	22.4(25.7)	20.0(22.6)
Nov	29.2(31.2)	28.0(30.6)	25.4(28.8)	26.2(27.7)
Dec	37.6(41.6)	33.6(39.5)	28.1(37.1)	31.0(33.0)
Jan	36.1(39.6)	30.9(36.5)	25.1(33.0)	30.0(31.1)
Feb	36.3(40.9)	31.9(38.2)	26.5(35.0)	30.0(32.0)
Mar	33.4(40.5)	29.1(37.9)	24.0(34.7)	28.0(31.3)
Apr	33.4(39.7)	29.1(38.4)	24.7(36.2)	29.3(32.1)
SF (TimeL)	60.5(2592)	55.0(2178)	51.1(2003)	53.0(2816)
Oct	98.9(48)	98.7(39)	98.6(28)	99.2(72)
Nov	94.7(120)	94.1(103)	95.1(90)	90.0(142)
Dec	62.3(456)	55.9(376)	50.6(371)	51.0(384)
Jan	47.3(557)	40.7(492)	35.8(436)	38.8(442)
Feb	52.7(474)	46.5(403)	41.8(377)	42.8(399)
Mar	44.8(545)	39.2(458)	35.1(389)	37.8(421)
Apr	66.0(393)	58.4(307)	52.9(312)	58.3(364)
Q_{solar} (Q_{aux})	63890(41800)	58030(47430)	53770(51470)	56810(50460)
Oct	6034(70)	6058(79)	6115(87)	6604(56)
Nov	10210(573)	10210(636)	10290(534)	10150(1125)
Dec	10140(6148)	9068(7157)	8183(8007)	8356(8041)
Jan	9612(10700)	8230(12010)	7205(12950)	7915(12470)
Feb	9387(8427)	8255(9519)	7418(10310)	7669(10260)
Mar	8873(10920)	7741(11990)	6900(12760)	7525(12360)
Apr	9636(4963)	8472(6039)	7657(6823)	8588(6152)
Q_{cf} (Q_{lf})	930(2331)	448(1959)	278(1801)	1299(2532)
Oct	138(43)	130(35)	117(25)	204(69)
Nov	133(108)	116(93)	95(81)	192(146)
Dec	127(410)	49(338)	16(333)	172(438)
Jan	133(501)	32(422)	9(392)	180(527)
Feb	132(426)	37(362)	12(339)	163(457)
Mar	124(490)	34(412)	11(350)	175(515)
Apr	143(353)	50(276)	18(281)	213(380)
T_o (T_i)	51.66(34.6)	58.8(35.5)	67.31(36.6)	45.7(29.7)
Oct	74.6(65.1)	79.0(67.9)	83.9(69.7)	69.0(55.0)
Nov	66.7(51.8)	69.9(52.6)	75.7(54.8)	57.7(40.7)
Dec	42.6(21.6)	50.0(21.4)	60.0(21.3)	39.0(21.4)
Jan	40.7(21.4)	50.0(21.3)	60.0(21.3)	37.4(21.4)
Feb	41.4(21.4)	50.0(21.4)	60.0(21.3)	38.5(21.4)
Mar	41.3(21.3)	50.0(21.3)	60.0(21.2)	37.0(21.3)
Apr	43.7(25.3)	51.1(24.4)	60.1(22.7)	37.6(22.7)
T_{Elf} (T_{rs})	30.9(37.4)	31.6(40.4)	31.1(41.4)	29.3(36.5)
Oct	65.5(66.0)	74.8(75.6)	80.7(81.9)	53.9(53.2)
Nov	53.4(55.3)	58.6(61.1)	59.4(61.8)	45.6(48.4)
Dec	30.2(35.6)	30.9(38.6)	29.2(38.6)	28.2(34.9)
Jan	28.2(36.0)	27.9(37.8)	27.7(39.6)	26.7(35.3)
Feb	29.2(36.4)	29.5(39.0)	29.0(40.0)	27.4(35.5)
Mar	27.8(35.8)	28.0(38.5)	28.1(41.4)	26.5(35.2)
Apr	31.1(36.2)	32.2(40.2)	30.6(39.4)	29.5(35.4)

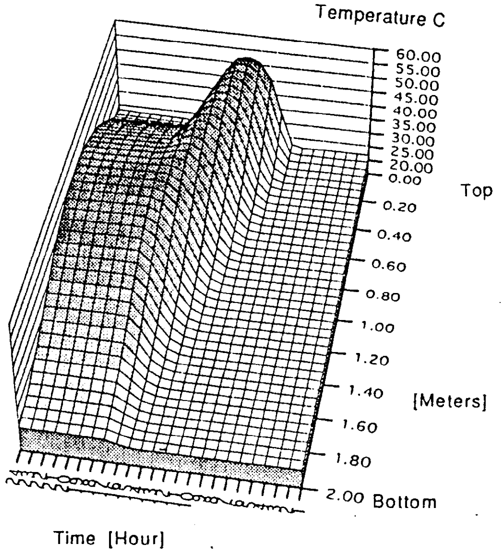

Fig. 4. Temperature Distribution in a Rock Bed (November, constant flow, no load)

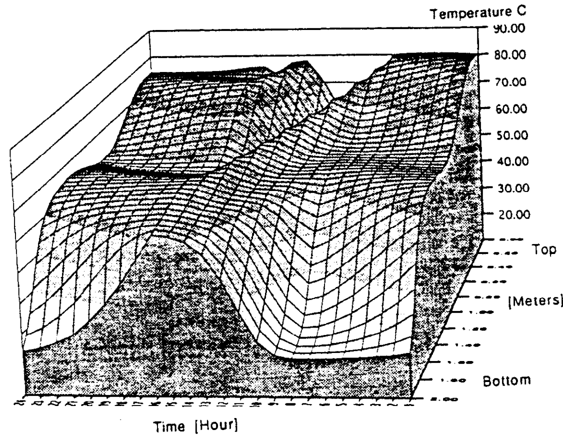

Fig. 7. Temperature Distribution in a Rock Bed (November, constant flow)

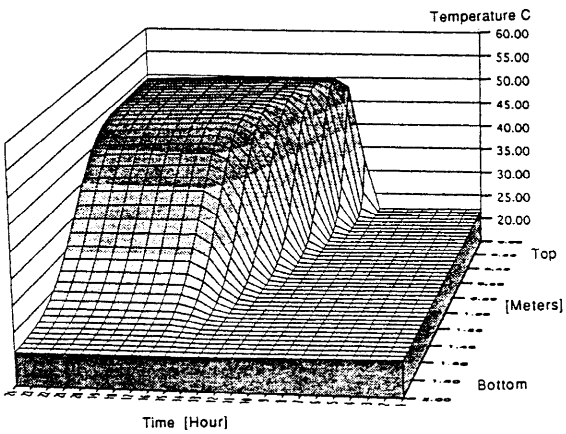

Fig. 5. Temperature Distribution in a Rock Bed (November, 50°C, no load)

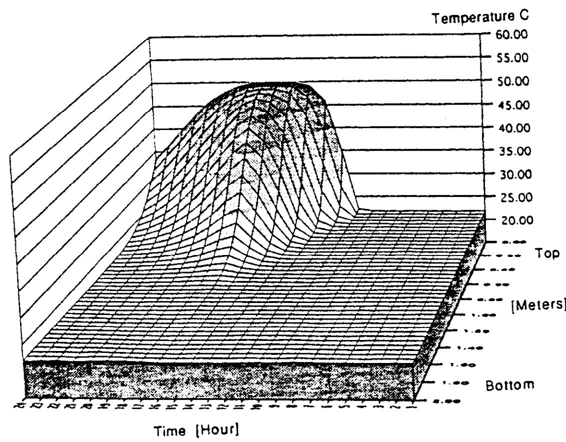

Fig. 8. Temperature Distribution in a Rock Bed (January, 50°C, constant temperature)

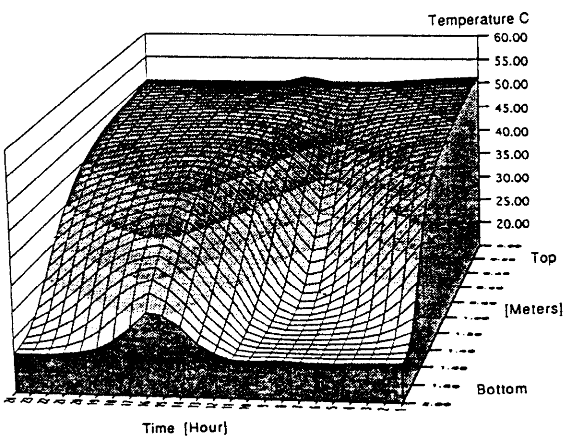

Fig. 6. Temperature Distribution in a Rock Bed (November, 50°, constant temperature)

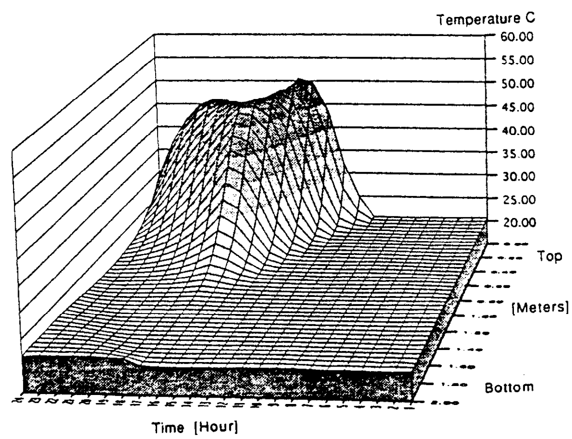

Fig. 9. Temperature Distribution in a Rock Bed (January, constant flow)