ESTIMATE FOR OPTIMUM VOLUME OF ROCK BED AND AIR FLOW RATE FOR AN AIR-BASED SOLAR HEATING SYSTEM

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ABSTRACT

In this paper, an approach to the optimum volume of rock bed, its charged thermal energy and the optimum air flow rate for an air-based solar heating system in charging mode is presented. The relationship between the optimum volume of rock bed and the air flow rate is approximately obtained as a theoretical solution of the linear approximation equation, and the charged thermal energy in the rock bed is approximately obtained as a function of the air flow rate. And it is found that a sort of the optimum air flow rate is obtained as the air flow rate in which effective charged heat is at maximum value.

INTRODUCTION

Design methods for solar thermal systems (Duffie et al. 1980) can be put in two categories. The first category includes simulation methods. System simulations provide the detailed information and is reliable for new and unique system designs. The second category of design methods includes those that are correlations of the results of a large number of detailed simulations. Examples in this category are the heat table method (Proctor 1975), the f-chart method (Beckman et al. 1977) and so on. The f-chart method has been used for estimating the annual thermal performance of active heating systems for buildings. The results of many simulations are correlated in terms of calculated dimensionless variables in the f-chart method. However, it is necessary to repeat trial and error evaluation in these methods in order to find the optimum system.

Brooks M. and Duchon C. (1982) proposed procedures for optimum sizing of a solar collector from an economic standpoint. Maaliou O. and McCoy B. (1984) proposed a simulation method for optimizing the net economic income for thermal energy storage in packed columns.

In this paper, a theoretical approach to the optimum volume of rock bed from a standpoint of capacity efficiency, its charged thermal energy and the optimum air flow rate for an air-based solar heating system in charging mode are presented. The charged thermal energy in a rock bed for an air-based solar heating system depends on many parameters; air flow rate, collector area, rock bed volume, collector performance, intensity of solar radiation, ambient temperature and so on. The parameters of a solar heating system specified by designers are basically collector area, air flow rate and rock bed volume, and other parameters are given as design conditions.

The ultimate goal of this study is to propose a simple method for the reasonable design of an air-based solar heating system. Although an optimum solar system should be finally designed from the standpoints of energy efficiency and economics, we studied in the first step about an optimum rock bed volume from the standpoint of capacity efficiency.

TARGET SYSTEM AND TYPICAL CONDITIONS

An outline of the target system is illustrated in Fig.1. The system includes flat-plate solar collectors connected in parallel, fans and a rock bed. Heating media air circulates through the collectors and the rock bed in charging mode. The air heated at the collectors flows into the upper part of the rock bed and collected heat transfers from air to solids due to temperature difference, and then air flows into the collectors through the lower part of the rock bed.

A steady state model for the solar collector and the heat transfer model in the rock bed are used for system simulations. These simulations are carried out under the typical conditions shown in Table 1. The incident solar radiation depends on latitude,

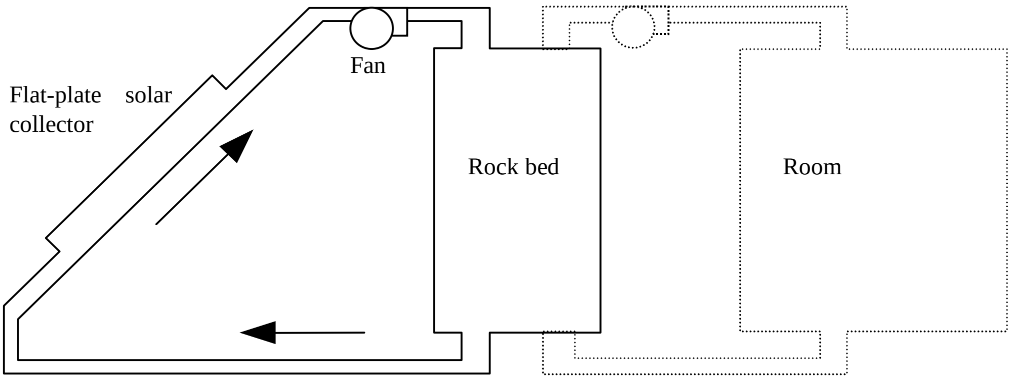

Fig. 1 Outline of the target system

Table 1 Typical conditions for simulations

Latitude	35°41’ N (Tokyo)
Permeability of atmosphere	0.78 [-]
Solar constant	1.37 [W/m^2]
Date	Feb. 1st
Weather	Clear day
Ambient temperature	0 [°C] (constant)
Solar collector (flat-plate)	
Orientation	South
Slope	45 degree
Rock bed	
Initial temperature	20 [°C] (uniform)
Volumetric specific heat of solid	1.92 [MJ/(m^{3}K)]
Void fraction	0.38 [m^3/m^3]

Table 2 Parameters of collector efficiency equation for simulations

	$F'K_{col}$ [W/K]	$F'(\tau\alpha)_e$ [-]
Collector A	3.37	0.76
Collector B	5.42	0.68
Collector C	7.44	0.65

solar constant, permeability of atmosphere, date, weather, orientation and slope of collector. Table 2 shows the efficiency parameters of three different type collectors measured by Tanaka (1982), which are used for simulations in this paper.

OPTIMUM VOLUME OF ROCK BED

SYSTEM SIMULATION

a. Collector Model

The linear definition equation of solar collector efficiency is

$$\eta = F'(\tau\alpha)_e - F'K_{col}\frac{\theta_{col,m} - \theta_{amb}}{I} \quad (1)$$

On the other hand, the collector efficiency can be also described as follows :

$$\eta = \frac{c\rho_{air} F\left(\theta_{col,out} - \theta_{col,in}\right)}{I\, A_{col}} \quad (2)$$

The collector model which gives the air temperature at the collector outlet is derived from Eq.(1) and (2) as follows :

$$\theta_{col,out} = \frac{\left(\frac{c\rho_{air}F}{F'K_{col}A_{col}} - \frac{1}{2}\right)\theta_{col,in} + \frac{(\tau\alpha)_e}{K_{col}} I + \theta_{amb}}{\frac{c\rho_{air}F}{F'K_{col}A_{col}} + \frac{1}{2}} \quad (3)$$

b. Standard Model of Rock Bed

The model presented by Schumann (1928) has been used widely for a heat transfer model of a rock bed in lots of solar simulations. In this study, the Schumann model is also used as the standard model of the rock bed. The basic assumptions leading to the Schumann model are one dimensional plug flow, no axial thermal conduction, constant properties, no heat loss to environment and no temperature gradients within solid particles. In this paper, it is additionally assumed that specific heat of air is neglected. The differential equations for air and solid temperatures are

$$c\rho_{air} F\frac{\partial \theta_{st,air}}{\partial x} = h_v A_{st}\left(\theta_{st,s} - \theta_{st,air}\right) \quad (4)$$

and

$$c\rho_{st,s} A_{st}(1 - f)\frac{\partial \theta_{st,s}}{\partial t} = h_v A_{st}\left(\theta_{st,air} - \theta_{st,s}\right) \quad (5)$$

where, h_v is given by the following equation.

$$h_v = 1.4\left(\frac{F\rho_{air}}{d_e}\right)^{0.76}$$

The charged thermal energy in a day is calculated from temperature distribution in the rock bed at the end time of charging and is derived as follows :

$$Q_s = c\rho_{st,s} A_{st} (1 - f) \int_0^{l_{st}} \left(\theta_{st,s}\big|_{t=t_{end}} - \theta_o \right) dx \qquad (6)$$

The dimensional proportion of the rock bed is fixed in 1:1:2(length of the rock bed, l_{st}) for the standard model simulations.

SIMULATION RESULTS

The simulation results of the standard model under the typical conditions (Table 1 and 2) are shown in Fig. 2 and 3. In these figures, A_{col} is the collector area, Q_s is the charged thermal energy in a day, F is the air flow rate and V is the rock bed volume.

The charged thermal energy increases generally along with the increasing of the rock bed volume, but the charged thermal energy has an upper limit corresponding to each air flow rate. The minimum volume of rock bed in which is charged almost upper limit is regarded as the optimum volume of the rock bed from a capacity efficiency standpoint. Regardless of the air flow rate, the increasing curves of the charged thermal energy overlap each other in the range of smaller rock bed volume than the optimum one.

The temperature distribution in the rock bed is shown in Fig.3 at collector B in the case of V/A_{col}=0.2, 0.4 and 0.8m^3/m^2 at F/A_{col}=40 (m^3/hour)/m^2 shown in Fig.2. In the case of V/A_{col}=0.8 m^3/m^2, the part of non-charged thermal energy remains in the rock bed. And the charged thermal energy at V/A_{col}=0.2 m^3/m^2 is smaller than others because of larger heat loss at the collector. It is found that V/A_{col}=0.4 m^3/m^2 is approximately the optimum volume from a capacity efficiency standpoint.

OPTIMUM VOLUME ESTIMATION

The increasing curves of the charged thermal energy in rock bed are represented by a model on the assumption of infinite air flow rate. On the other hand, the relationship between the maximum charged thermal energy in rock bed and air flow rate is represented by a model on the assumption of infinite rock bed volume. The relationship between air flow rate and the optimum volume of rock bed is approximately obtained as theoretical solution of simultaneous equations for two models on the assumption of extreme conditions.

Two Models under Extreme Conditions

a. The model of infinite rock bed volume

This model is derived from Eq.(3) under the following assumptions.

(1) The outlet air temperature of the rock bed is identical to initial temperature of the rock bed at all time.

(2) The heat loss is taken account of only at the collector.

Then, the outlet air temperature of the collector is represented as follows :

$$\theta_{col,out} = \frac{\left(\dfrac{c\rho_{air} F}{F' K_{col} A_{col}} - \dfrac{1}{2} \right) \theta_o + \dfrac{(\tau\alpha)_e}{K_{col}} I + \theta_{amb}}{\dfrac{c\rho_{air} F}{F' K_{col} A_{col}} + \dfrac{1}{2}} \qquad (7)$$

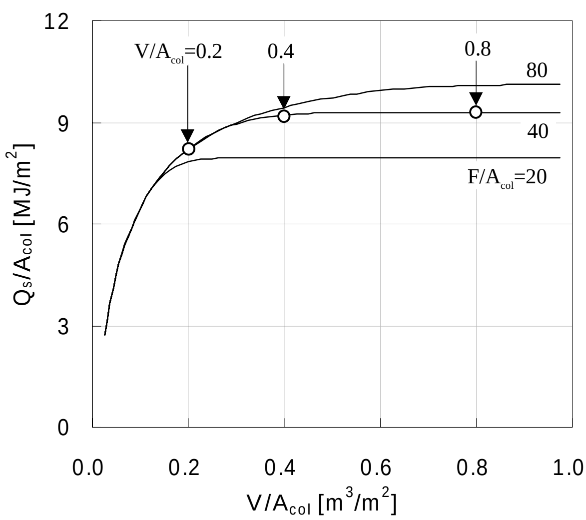

Fig.2 Charged thermal energy in a day along with rock bed volume at collector B in the case of F/A_{col}=20, 40 and 80 (m^3/h)/m^2

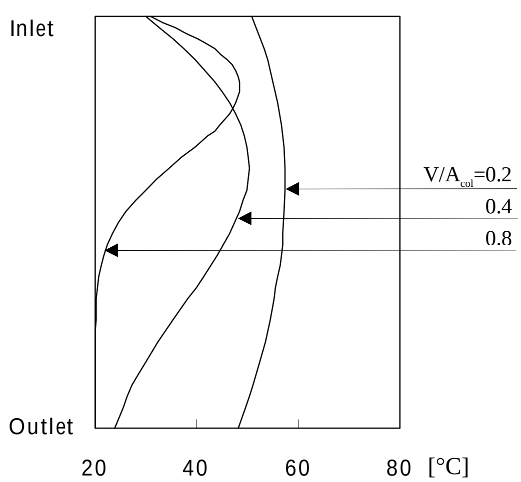

Fig.3 Temperature distribution in rock bed at the end time of charging at collector B in case of V/A_{col}=0.2, 0.4 and 0.8 m at F/A_{col}=15 (m^3/h)/m^2

The thermal energy charged in a day is represented as the following equation.

$$Q_s = c\rho_{air} F \int_{t_{staF}}^{t_{endF}} \left(\theta_{col,out} - \theta_o\right) dt \qquad (8)$$

Substituting Eq.(7) into Eq.(8), the following equation is derived.

$$\frac{Q_s}{A_{col}} = \frac{\dfrac{F}{A_{col}}}{\dfrac{F}{A_{col}} + \dfrac{1}{2}\dfrac{F'K_{col}}{c\rho_{air}}} \times \left\{ F'K_{col}\left(\theta_{air} - \theta_o\right)\left(t_{endF} - t_{staF}\right) + F'(\tau\alpha)_e \int_{t_{staF}}^{t_{endF}} I\, dt \right\} \qquad (9)$$

a. The model of infinite air flow rate

This model is derived from Eq.(3) on the following assumptions.

(1) The collected heat is entirely charged to solids in rock bed.

(2) The temperature of air and solid in the rock bed is identical to the outlet air temperature of the collector.

(3) The heat loss is taken account of only at the collector.

(4) The heat capacity of air in the rock bed is neglected.

Then, the heat balance equation for the rock bed is represented as follows:

$$c\rho_{st} V \frac{d\theta_{st,s}}{dt} = \left\{ F'(\tau\alpha)_e I - F'K_{CL}\left(\theta_{st,s} - \theta_{amb}\right) \right\} I A_{col} \qquad (10)$$

On the other hand, the charged thermal energy in a day is

$$Q_s = c\rho_{st} V \left(\theta_{st,s}\big|_{t=t_{endV}} - \theta_o \right) \qquad (11)$$

The charged thermal energy is derived from Eq.(10) and (11) as follows :

$$\frac{Q_s}{A_{col}} = F'(\tau\alpha)_e \exp\left[-\frac{F'K_{col}\left(t_{endV} - t_{staV}\right)}{c\rho_{st}} \frac{A_{col}}{V} \right] \times \int_{t_{staV}}^{t_{endV}} I \exp\left[\frac{F'K_{col}\left(t - t_{staV}\right)}{c\rho_{st}} \frac{A_{col}}{V} \right] dt + c\rho_{st} \frac{V}{A_{col}} \left\{ 1 - \exp\left[-\frac{F'K_{col}\left(t_{endV} - t_{staV}\right)}{c\rho_{st}} \frac{A_{col}}{V} \right] \right\} \times \left(\theta_{amb} - \theta_o\right) \qquad (12)$$

Calculation Condition

Solar thermal energy is assumed to be charged on the condition that the heat absorbed at the collector is larger than heat loss from the collector. This condition is derived as the following equation.

$$I > \frac{F'K_{col}}{F'(\tau\alpha)_e}\left(\theta_{col,in} - \theta_{amb}\right) \qquad (13)$$

It is difficult to estimate the end time of charging for the infinite flow rate model beforehand because the inlet air temperature of the collector varies along

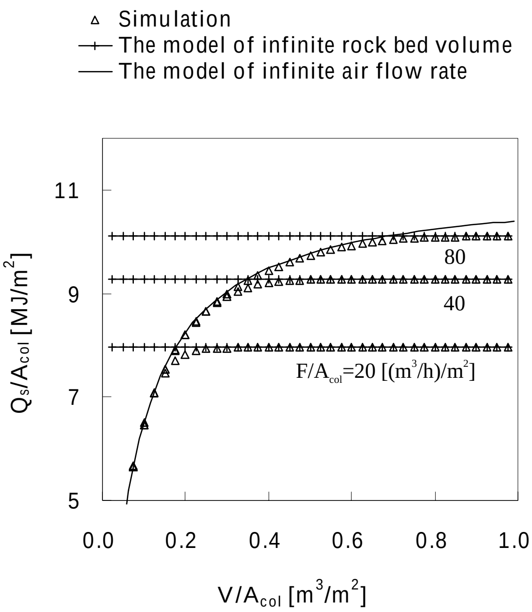

Fig.4 Simulation results of the standard model and two extreme models for the charged thermal energy along with the rock bed volume (Collector B)

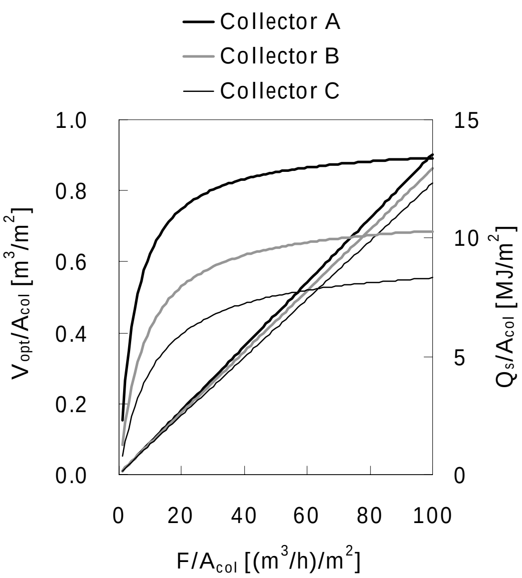

Fig.5 The optimum volume of rock bed and the charged thermal energy along with the air flow rate obtained from simulation results of two extreme models.

with the increase of the charged thermal energy. Eq.(10) is, therefore, solved numerically on the condition of Eq.(13) and then the charged thermal energy is obtained by using Eq.(11).

RESULTS OF EXTREME MODELS

Fig. 4 shows simulation results of the standard model and two extreme models at collector B. It is considered that the intersection point of two extreme models shows the optimum volume of rock bed in a given air flow rate.

Fig.5 shows the relationship among the optimum volume of rock bed, V_{opt} and the air flow rates, and the charged thermal energy. The optimum volume of the rock bed is larger at higher collector performance, but not so much sensitive to collector performance. And the relationship between the optimum volume and the air flow rate is approximately linear.

LINEAR MODEL FOR OPTIMUM VOLUME OF ROCK BED

The previous results of extreme models suggest that the relationship between the optimum volume from a capacity efficiency standpoint and the air flow rate is presented in a form of appeerent linear equation. The following linear equation is, therefore, derived from Eq.(9) and (12).

$$\frac{V_{opt}}{A_{col}} = P\,\frac{F}{A_{col}} \tag{14}$$

where

$$\begin{aligned} P = \frac{2\,c\rho_{air}}{F'K_{col}\,D_{(V_{opt})}} \Bigg\{ & F'(\tau\alpha)_e \frac{V_{opt}}{A_{col}} \int_{t_{staV}}^{t_{endV}} I\,dt \\ & - F'K_{col}\frac{V_{opt}}{A_{col}}\left(\theta_o - \theta_{amb}\right)\left(t_{endV} - t_{staV}\right) \\ & - D_{(V_{opt})}\frac{V_{opt}}{A_{col}} \Bigg\} \end{aligned} \tag{15}$$

and

$$\begin{aligned} D_{(V_{opt})} = {} & F'(\tau\alpha)_e \int_{t_{staF}}^{t_{endF}} I\,\exp\left[\frac{F'K_{col}}{c\rho_{st}}\frac{A_{col}}{V_{opt}}\left(t - t_{endF}\right)\right] dt \\ & - c\rho_{st}\frac{V_{opt}}{A_{col}}\left(\theta_o - \theta_{amb}\right) \\ & \times\left(1 - \exp\left[-\frac{F'K_{col}}{c\rho_{st}}\frac{A_{col}}{V_{opt}}\left(t_{endF} - t_{staF}\right)\right]\right). \end{aligned}$$

It is considered that P is nearly constant for the optimum volume in Eq.(14). When exponential parts are expanded in a series, higher order are neglected, and t_{staF} is identical to t_{staV} and t_{endF} is identical to t_{endV}, and then Eq.(16) is derived as follows :

$$P = \frac{c\rho_{air}}{c\rho_{st}} \frac{2(\tau\alpha)_e \int\int_{t_{staV}}^{t_{ensV}} I\,dt - K_{col}\left(\theta_o - \theta_{amb}\right)\left(t_{endV} - t_{staV}\right)^2}{(\tau\alpha)_e \int_{t_{staV}}^{t_{endV}} I\,dt - K_{col}\left(\theta_o - \theta_{amb}\right)\left(t_{endV} - t_{staV}\right)} \tag{16}$$

The orientation of collector is set at due south so that solar radiation is symmetrical with respect to true solar time at 12:00, therefore double integration of solar radiation I is

$$\int\int_{t_{staV}}^{t_{endV}} I\,dt = \frac{t_{endV} - t_{staV}}{2}\int_{t_{staV}}^{t_{endV}} I\,dt \tag{17}$$

Therefore, Eq.(14) can be transformed to the following equation as the linear approximation model.

$$\frac{V_{opt}}{A_{col}} = \frac{c\rho_{air}\left(t_{endV} - t_{staV}\right)}{c\rho_{st}}\frac{F}{A_{col}} \tag{18}$$

Equation (18) shows that the optimum volume of rock bed has heat capacity which is identical to the heat capacity of air which has passed through the rock bed during the charging period.

The relationship between the optimum volume of rock bed and the air flow rate obtained from two extreme models and the linear approximation model is shown in Fig.6. The linear approximation model agrees well with the extreme models.

Designers will easily obtain the rock bed volume from a linear approximation equation, Eq(18) and its charged thermal energy from the equation, Eq(9) when air flow rate and collector operating time are

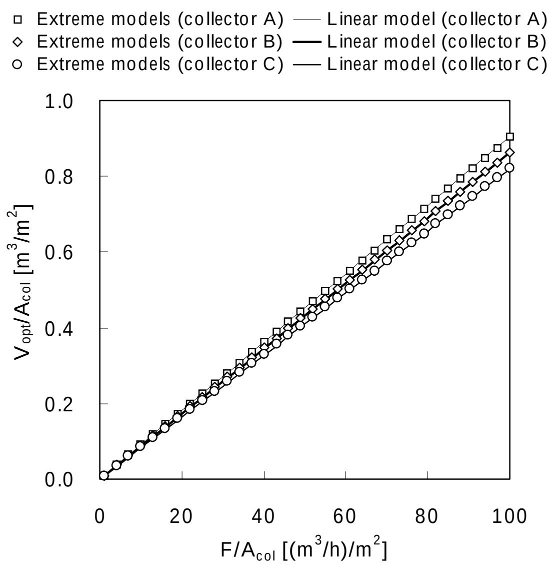

Fig.6 Relationship between the optimum volume of rock bed and the air flow rate obtained from two extreme models and the linear approximation model

given.

OPTIMUM AIR FLOW RATE

In the next place, the equivalent thermal energy are used in order to specify the optimum air flow rate. In this paper, the result of subtracting the equivalent heat of consumed energy at fan from the charged thermal energy is defined as the effective charged heat. And the air flow rate in the case that the effective charged heat is at maximum is considered the optimum air flow rate.

In this paper, it is assumed that the rate of consumed energy at fan is calculated by the following equation.

$$W_{fan} = \frac{P_T F}{\eta_{fan}} \tag{19}$$

The total pressure loss is expressed by the following equation as the sum of pressure loss in the duct, collector and rock bed.

$$P_T = P_d + P_{col} + P_{st} \tag{20}$$

Each pressure loss is based on the following assumptions; (1) in the duct, local loss and friction loss of the straight duct are considered, and the diameter of the duct is fixed regardless of the air flow rate, (2) in the collector, only local loss was considered, because friction loss is significantly smaller than local loss, and the length of the collector is fixed at 3.6 m, (3) the pressure loss of the rock bed is calculated using the empirical formula of Chandra (1981). Adding Eq.18 as the condition on the relationship between the air flow rate and the rock bed volume at collector B, the total pressure loss is

$$P_T = \left(6{,}015 + \frac{139{,}784}{A_{col}^{\ 4}} + \frac{25{,}920}{A_{col}^{\ 2}}\right) F^2 + 34.25 F^{\frac{2}{3}} + 162.9\,F \tag{20}$$

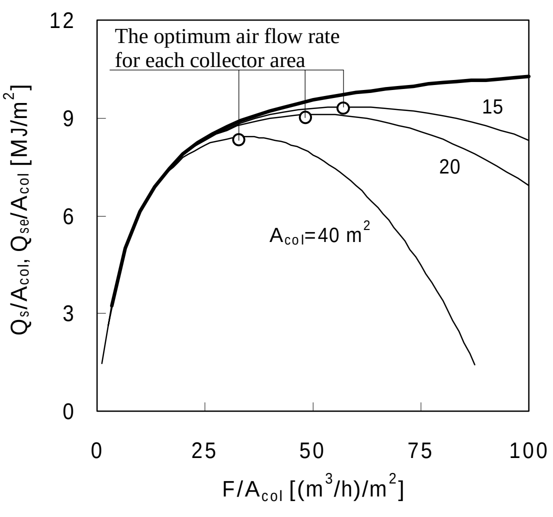

Fig.7 The charged heat and the effective charged heat along with the air flow rate at collector B in the case of A_{col}=15, 20 and 40 m^2.

In this equation, the total pressure loss becomes about 139 Pa when the collector area is 20 m^2 and the air flow rate is 500 m^3/h.

CONSIDERATION OF THE AIR OPTIMUM FLOW RATE

FIg.7 shows the relationships between the rock bed volume and the effective charged heat per collector area when the collector area is 15, 20 or 40 (m^3/h)/m^2 is shown.

When the maximum of effective charged heat exists, it is considered that the air flow rate in which the effective charged heat has the maximum value is the optimum air flow rate. This optimum air flow rate, collector area and rock bed volume along with the effective charged heat are shown in Fig.8. And the results are also shown in this figure when the pressure loss is a half or double of the reference pressure loss calculated in Eq.20.

On the other hand, the relationship between the collector area and the air flow rate in which charged thermal energy is 100 and 250 MJ are shown in Fig.9. In this figure, the relationship between the collector area and the optimum air flow rate in which the effective charged heat has the maximum value, is shown in the round seal, and W_{fan} is the rate of consumed energy at fan. The air flow rate, rock bed volume and collector area can be decided from the charged heat. Though the optimum air flow rate is estimated in this manner, the air flow rate in which the effective charged heat is at maximum, seems to be too large from an economical standpoint. When the air flow rate decreases, the collector area doesn’t increases so much at the air flow rate more than 400 m^3/h, while the rate of the consumed energy at fan greatly decrease.

Because of the above reason, it is considered that the air flow rate is difficult to estimate its optimum value by the consumed energy at fan during the charging period and the charged heat.

In the next place, the temperature distribution of the rock bed at the end time of charging is shown in Fig. 10 when the charged heat is 100 MJ in the case of five kinds of air flow rate ; 100, 200, 400, 721 (the optimum air flow rate with the maximum effective charged heat) and 1000 m^3/h. In the case of smaller flow rate, heat loss at the rock bed and radiation heat loss at the collector increase because the temperature of the collector is higher. Generally, about 30 - 50 °C is good for the temperature in a direct solar heating system; therefore, it seems that about 400 m^3/h is better for the air flow rate when the thermal energy of 100 MJ is charged under the condition shown in

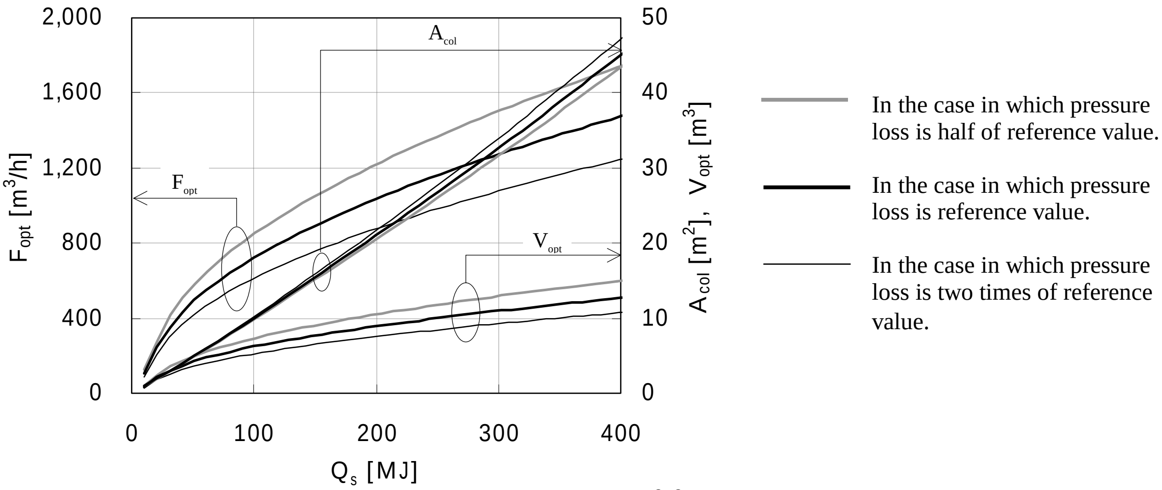

Fig.8 The optimum volume of rock bed, the collector area and the optimum air flow rate along with the charged thermal energy, in the case in which pressure loss is half, one and tow times of reference pressure value.

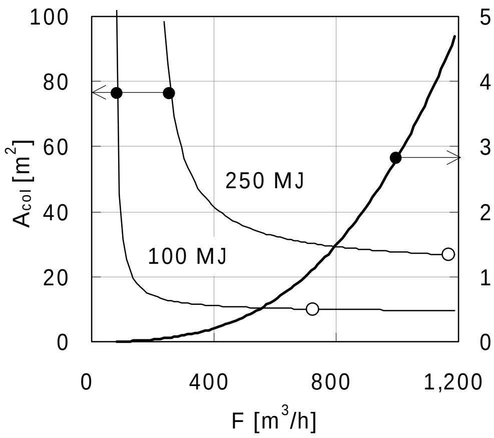

Fig.9 relationship among collector area, air flow rate and power consumption of fan in case of charged heat *Qs*=100 and 250 MJ

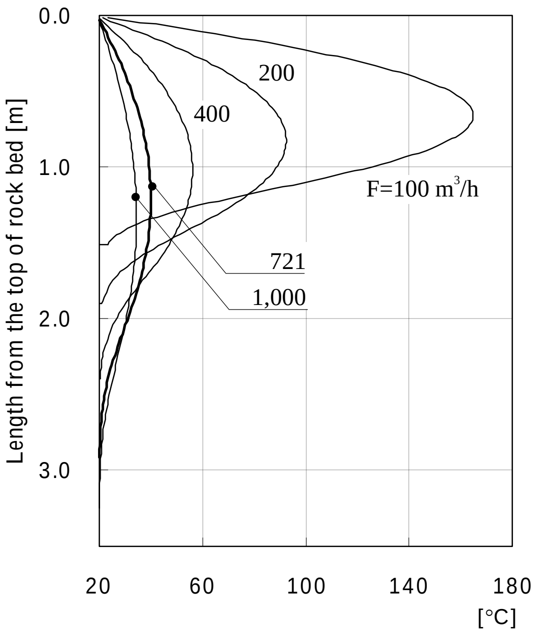

Fig.10 The temperature distribution in a rock bed on completion of charging heat on the conditions for five kinds of air flow rate; *F*=100, 200, 400, 721 and 1,000 m^3/h

table 1.

CONCLUSIONS

A theoretical approach to the optimum volume of rock bed from a standpoint of capacity efficiency and its charged thermal energy for the air-based solar heating system in charging mode is presented, and the optimum air flow rate is discussed. The following results are obtained;

(1) As a result of the standard model simulation, the charged thermal energy increases generally with the increasing of the rock bed volume, but the energy has an upper limit corresponding to the air flow rate. The minimum volume of the rock bed which can be charged almost upper limit is regarded as the optimum volume from a standpoint of capacity efficiency.

(2) The relationship between the optimum volume of rock bed and the air flow rates is approximately obtained as a solution of simultaneous equations for two models on the assumption of extreme conditions and this theoretical solution is found to be linear approximately. It is found that the linear approximation model which can be simply solved, is derived from the extreme models.

(3) The result of the linear approximation model agrees well with the one of the extreme models.

(4) We attempted to obtain the optimum flow rate by the consumed energy at fan and the charged thermal energy. A sort of the optimum air flow

rate was estimated as the air flow rate in which effective charged heat is the maximum value.

In our study, we present a simple method for the optimum volume of rock bed from the standpoint of capacity efficiency and discuss the optimum air flow rate from the standpoint of energy. We are afraid that our study has not yet reached to the stage of comparing with F-Chart method and so on because we just began by studying only on charging mode,.

We would like to study on a simple method for the optimum volume of rock bed from the standpoint of energy, economics or other measures at the next step.

NOMENCLATURE

A_{col}	collector area
A_{st}	cross-sectional area of rock bed
$c\rho_{air}$	volumetric specific heat of air
$c\rho_{st}$	volumetric specific heat of rock bed $(= c\rho_{st,s}(1-f))$
$c\rho_{st,s}$	volumetric specific heat of solids in the rock bed
d_e	equivalent diameter of solids in the rock bed (=0.04)
f	volumetric bed void fraction
F	air flow rate
F'	collector efficiency factor
F_{opt}	optimum flow rate of air
h_v	the volumetric heat transfer coefficient between the air and solids
I	solar radiation intensity
K_{col}	collector overall heat loss coefficient of a collector
l_{st}	length of the rock bed along with air flow direction
P_{col}	pressure loss at collector
P_d	pressure loss at duct
P_{st}	pressure loss at rock bed
P_T	total pressure loss
Q_s	charged heat in the rock bed
Q_{se}	effective charged heat in the rock bed
t	time
t_{sta}	the start time of charging
t_{end}	the end time of charging
V_{st}	Volume of rock bed
V_{opt}	optimum volume of rock bed from a standpoint of capacity efficiency
η_{fan}	efficiency of fan
θ_{amb}	ambient temperature
$\theta_{st,air}$	air temperature in the rock bed
$\theta_{col,m}$	the average temperature of the air at the collector inlet and outlet
$\theta_{col,out}$	outlet air temperature of collector
$\theta_{st,s}$	solids temperature in the rock bed
$(\tau\alpha)_e$	transmittance-absorptance product

SUBSCRIPT

air	air
amb	ambient
col	collector
F	the infinite flow rate model
opt	optimum
s	solid in the rock bed
st	rock bed
V	the infinite volume model
fan	fan

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