研究論文

Experimental and numerical studies on rock bed heat storage for room heating systems

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Abstract

Solar energy is known as one of the most promising alternative heat energy resources for room heating systems. However, in this area the necessary heat storage utility is needed. This is because solar energy is intermittent by its nature. The basic types of the heat storage techniques can be described as: sensible heat storage and latent heat storage systems. This paper is focused on the sensible heat storage system that uses bricks as storage element. A heat storage system that consists of 20 pieces of common bricks that is made from pit-run clay was studied experimentally and numerically. Five different models with combinations of brick arrangements and baffles inside the heat storage were considered. In the experimental work the heat storage was charged from initial conditions by using heated air 50^{0}C for 5 hours and discharged by using ambient air 15^{0}C for 3.5 hours. In the numerical part, two-dimensional governing equations were solved by using the SIMPLE algorithm during the charge process. Flow and temperature fields were produced and heat transfer was calculated. In spite of the fact that there are slight differences, the experimental and numerical results reveal the same trend and show the good agreement. It was found that for the models without any baffles the performance of the inclined brick positions is better than the horizontal positions and for the models with baffles the staggered brick arrangements with remaining space between the bricks and baffles reveals the best performance for storing the heat.

Keywords: Sensible heat storage, brick, rock bed, baffle, inline, staggered position

1. Introduction

Solar energy is known as one of the most promising renewable energy alternatives. It is free and environmentally clean. There are many technical problems that must be solved before the solar energy is ready to be used. Noticeable examples are: low quality of heat, intermittent and strongly depends on the weather. Employing solar energy as a heat source for room heating systems is a promising application. However, in this application the necessary heat storage utility is needed due to its intermittent. The solar energy can be stored by thermal, electrical, chemical, and mechanical methods. This paper deals with thermal energy stored. The basic types of thermal energy storage techniques can be described as: sensible heat storage and latent heat storage. In the sensible heat storage system, temperature of the storage material(s) varies with the amount of energy stored while the phase does not change. While in the latent heat storage system, the storage material(s) are changed. This storage material is known as the phase change material (PCM). Recently, the sensible heat storage system has received much less consideration than the latent heat storage due to its low density of thermal energy stored. One major drawback of sensible heat storage is the large volume required. However in housing systems where the basement is available, the sensible heat storage systems can be considered as a promisingly alternative. An alternative layout of the sensible heat storage that is heated by solar energy in a housing system is shown in Fig. 1.

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(原稿受付：2006年3月27日)

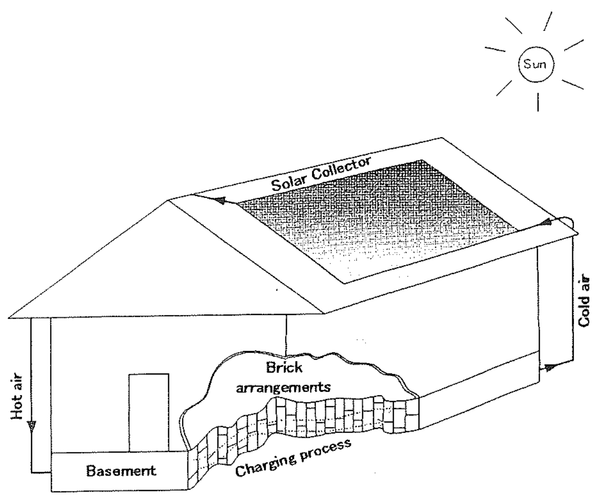

Fig. 1 Layout of the bricks heat storage combined with solar collector for room heating systems

In this paper, we focus on the sensible heat storage system by using bricks as the storage material. The reasons are based on low cost and availability. They also can be kept in an inexpensive container, long life time, and do not require maintenance. A major part of storing energy problem lies in the fluid flow characteristic and heat transfer. The objective of this research is to study the fluid flow and heat transfer characteristics of the rock bed heat storage system. The lack of study on the rock bed heat storage also motivates the present work. The emphasis of this research is to make clear the effect of the brick arrangements and baffles on the fluid flow and heat transfer characteristics. The results can be expected from this study is to supply the necessary information of bricks heat storage designing and optimization. In order to acquire the objective, a scale model of the heat storage has been studied experimentally and numerically.

2. Experimental Procedure

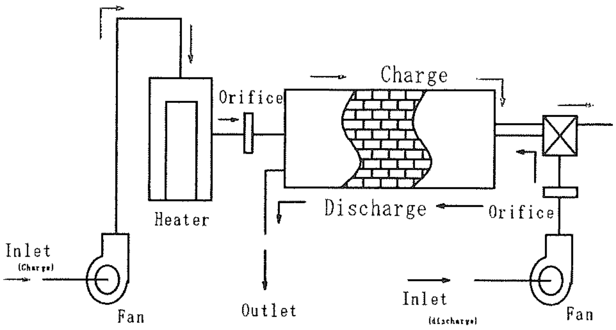

Fig. 2 Flow diagram of the experimental setup

Fig. 2 shows the outline of the present experimental apparatus that was designed to facilitate testing of a variety of brick arrangements and baffles inside the heat storage. The system principally consists of air blowers, heater, velocity anemometer, heat storage, thermocouples and a personal computer as a data acquisition system. During the charge, in order to simulate the air heated by solar collector, ambient air is flowed by fan and heated by using an electric heater. Air flow rate was controlled by fan speed and temperature of the heated air was controlled by power input of the heater. The heat storage was charged by flowing air at temperature 50^0C, a typical temperature for air heated by solar collector. At starting time, the heater needs 30 minutes to reach temperature 50^0C at the inlet. On the other hand, in the experimental work starting temperature was not a constant 50^0C. The heated air flows through the heat storage and increases temperature of the bricks. The bricks store the heat and temperature of the air becomes lower. Temperatures of the inlet, outlet, and inside the bricks were measured by using thermocouple wire and collected every 5 minutes. In this experimental work the charge duration was 5 hours. At discharge, the cold ambient air flowed in opposite direction by using an air blower through the heat storage. Temperature of the cold air was 15^0C. All of the temperatures at inlet, outlet, and inside the bricks were measured and collected every 5 minutes. Total heat storage by all bricks is calculated by using average temperature which is measured by using five points on each brick. The discharge duration was 3.5 hours.

Experimental errors arise from errors in the velocity anemometer and thermocouple. In usual conditions, the velocity anemometer introduced a 3% error and thermocouple a 0.2% error as specified by the makers. The total experimental errors are therefore approximated to be 0.2% error in temperature and 3% in total heat stored by bricks.

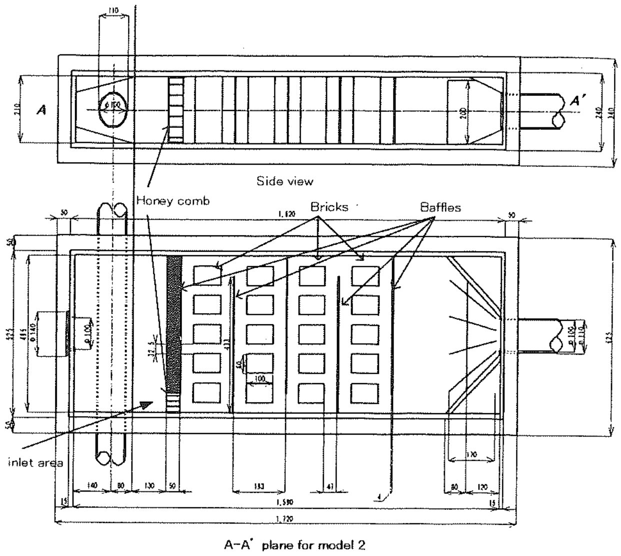

Fig. 3 Dimensions of the heat storage with baffles and the brick arrangements for model 2

The heat storage and brick dimension are depicted in Fig. 3. All of the walls are insulated. The figure consists of side and top view of the heat storage. In this study five different brick arrangements were considered. The schematic diagram of the brick arrangements and the baffles inside the heat storage are shown in Fig. 4. In the figure, the bricks for model 2, 3, and 4 were arranged in four columns and five rows and the columns were separated by attaching a baffle to the left and the right wall. In model 1 and 5 they were arranged in five columns and four rows without any baffles. Brick arrangements of model 2 are shown in Fig.3. The bricks are numbered and shown in the figures. The models are as follows:

1. Model 1 (Fig. 4(a)): all of the bricks are horizontal and inline arrangement without any baffles.
2. Model 2 (Fig. 3): all of the bricks are horizontal and inline arrangement with baffles.
3. Model 3 (Fig. 4(b)): all of the bricks are horizontal, staggered arrangement, and contact with baffles.
4. Model 4 (Fig. 4(c)): all of the bricks are horizontal, staggered, and do not contact with any baffles. There is a remaining space between the bricks and the baffles.
5. Model 5 (Fig. 4(d)): all of the bricks are inclined 45^0 to the horizontal arrangement without any baffles.

The inlet areas for model 2, 3, and 4 are different from model 1 and 5 due to the presence of the baffle in the inlet area. The inlet area for model 1 and 5 is the whole inlet area of the heat storage. Thus, the input velocity for model 1 and model 5 is smaller than the others since the mass flow rate is the same.

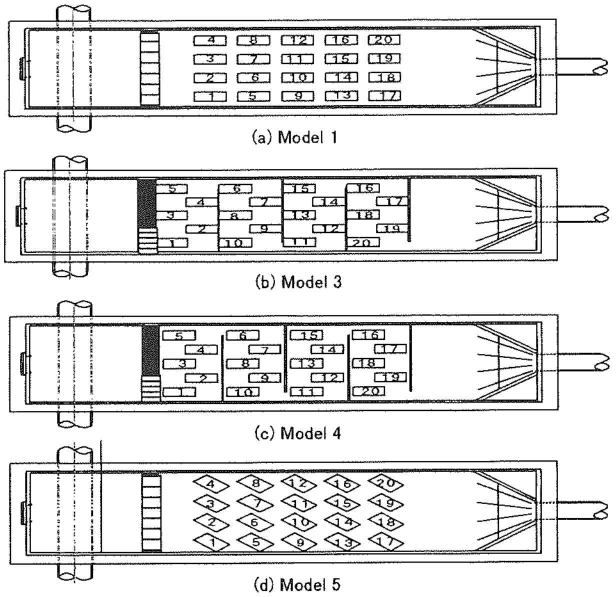

Fig.4 Brick arrangements inside the heat storage

3. Numerical Procedure

In this study a numerically solution to the problems at charge process was carried out also. In order to reduce the computational effort the heat storage tank is modeled as a two-dimensional problem. The flow is assumed to be transient and laminar. The compressibility, radiation heat exchange, buoyancy force, and dissipations are negligible. All of the thermal properties are constant. The heat capacity of the heat storage vessel is also negligible. The governing equations are:

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

X and Y momentum equations

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \qquad (3)$$

Energy equation

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

Boundary conditions at any time t are:

The wall surfaces: $u=v=0\,,\ \frac{\partial T}{\partial n}=0$ (5)

The inlet: $u=U_\infty,\ v=0,\ T=T_\infty$ (6)

The outlet: $\frac{\partial T}{\partial x}=0$ and $p=p_\infty$ (7)

Brick surfaces $u=v=0$ (8)

Total heat stored by bricks is calculated by:

$$Q_{tot}=\Sigma\,\rho_b dxdy c_{pb}(T_{ij}-T_0) \qquad (9)$$

The comparison parameter for flow characteristic is a stream function, and defined as follow.

$$u=-\frac{\partial\psi}{\partial y}\,,\quad v=\frac{\partial\psi}{\partial x} \qquad (10)$$

Thermal properties, k, c_p, ρ, respectively thermal conductivity, specific heat, and density of the materials are listed as follows. The air k=0.026 W/m·K, c_p=1006 J/kg·K, ρ=1.165 kg/m^3. In this study common brick that is made from pit-run clay is used as the storage materials and the thermal properties are: k_b=0.67 W/m·K, c_{pb}=670 J/kg·K, ρ_b=1984 kg/m^3. The interface conductivities due to non uniform conductivities of the material inside the computational domains were handled by harmonic mean conductivities.

All of the governing equations are discretized based on control volume approach on staggered grids system. In order to avoid the physically unrealistic result due to time step of the transient problem the fully implicit scheme is adopted. To handle the convective-diffusion problem, the power law scheme is used. The sets of discreatized linear equations are solved by using line-by-line method which is combined with Thomas algorithm. To couple the pressure distributions and velocities the SIMPLE algorithm is employed.

In the SIMPLE algorithm under-relaxation factor is an essential problem and there is no special rule in determining the proper under-relaxation factor. The big under-relaxation factor, especially for velocities, will lead the calculation into divergence otherwise a very small under-relaxation factor leads to a lengthy calculation. Considering both computational cost and convergence the under-relaxations factor for momentums is about 0.01 and for pressure it is 0.2 were used. The solution is considered to be converged when the normalized residual of the algebraic equation is less than a prescribed value of 10^{-4}. Based on this procedure the FORTRAN codes have been developed.

In the present numerical study a uniform grid spacing system was employed. In order to reduce the numerical errors the proper grid number test was conducted. The number grids 200 × 160 and 400 × 320 were tested and no obvious difference of the total heat stored was observed, less than 1%. The 200 × 160 grids are used.

4. Results and Discussion

In order to solve the problem the experimental and numerical works were carried out. In the experimental work mass flow rate of the air is kept constant at 0.007 kg/s for all models. In order to get the uniform velocity profile, a honey comb was attached in the inlet area. This mass flow rate is equivalent to inlet velocity 0.72 m/s for model 2, 3, and model 4 and 0.09 m/s for model 1 and model 5. In the numerical work, the inlet velocities from the experimental are employed as such. Although temperature of the air heated in the inlet was not constant in the experimental work, especially in the first 30 minutes, while in the numerical calculations inlet temperature was fixed at 50^0C. Flow and temperature fields were produced and total heat absorbed was calculated. Time step in the numerical solutions is 5 minutes.

4.1. Comparison between calculations and experiments

A particular experimental and numerical result during charge process of model 3 is presented in Fig. 5. The time variations in measured and calculated temperatures of brick 6, brick 18, and brick 20 were plotted and the inlet temperature during experiment is also presented as a reference. The figure shows that there are slight differences between the experimental and numerical results. This is because in the experimental part the inlet temperature at the beginning was not a constant 50^0C especially in the first 30 minutes due to no by-pass line in the inlet-side for charging inlet air at uniform temperature. The other reason might include the heat capacity of the heat storage vessel was not considered in the numerical ones. However, after 2 hours of the charging process the discrepancies between those results become smaller. Assuming the problems in the two-dimensional case might be causing these discrepancies also. However, the experimental and numerical data reveal the same trend and show good agreement.

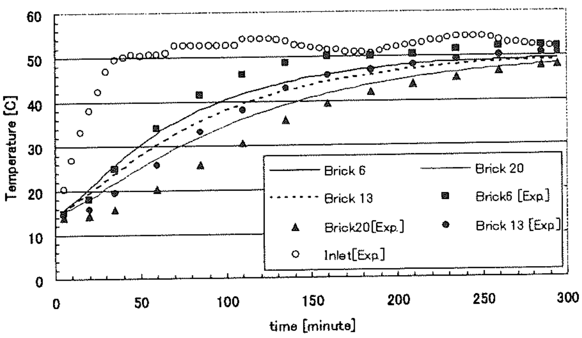

Fig. 5 Time variations in the inlet and the brick temperatures during the charge process for model 2

4.2. Flow and temperature fields

In order to make clear the effect of the brick arrangements and the baffles flow fields (streamlines) are presented in Fig. 6. The figure shows that in model 1 there are many stagnant fluids inside the heat storage which take place among the bricks. These stagnant fluids correlated to the poor convective heat transfer rate and results in a low heat absorbed amount. Attaching baffles in model 2, 3, and 4 reduces the stagnant fluids. The stagnant fluids in model 2 are still significant due to inline positions of the bricks. Thus, the presence of the baffles in this model is not effective. In model 3 the brick arrangements were changed becoming staggered but one surface of each brick does contact with its nearest baffle. It can be seen that this model reduces the stagnant fluids inside the heat storage but the contact surfaces switched off the flow from this surface. This related to less convective heat transfer areas.

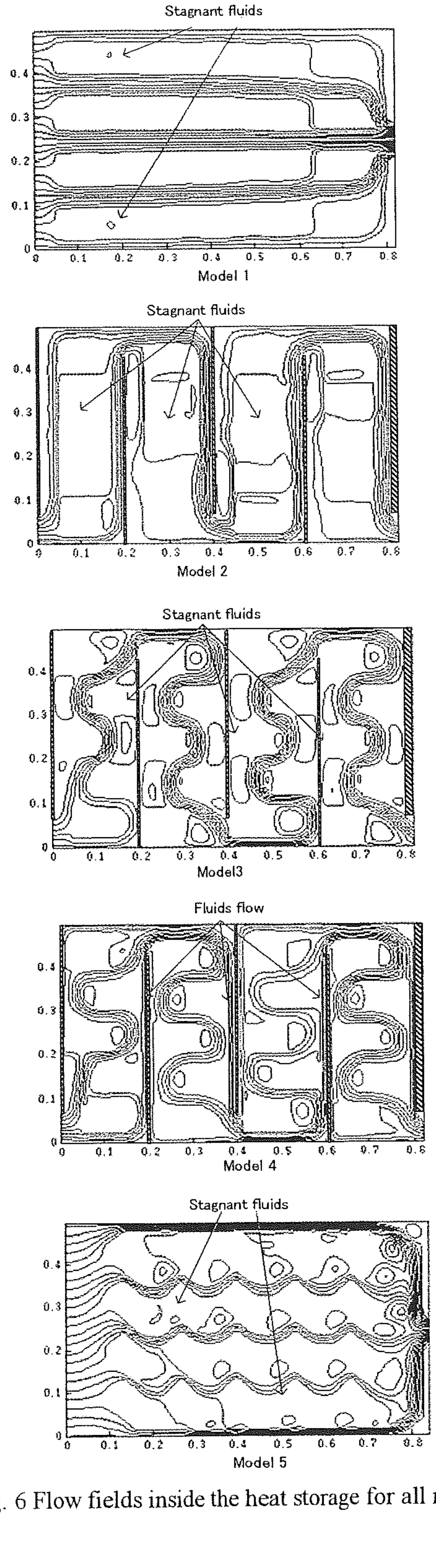

Fig. 6 Flow fields inside the heat storage for all models

In model 4 the brick positions are staggered but there is a remaining space between the bricks and the baffles. The fluids flow through the space and increase the convective heat transfer areas. In model 5 there are some stagnant fluids also. Based on these discussions a conclusion can be drawn that model 4 decreases the stagnant fluids significantly. This model will increase the convective heat transfer areas and results in a good heat absorb rate.

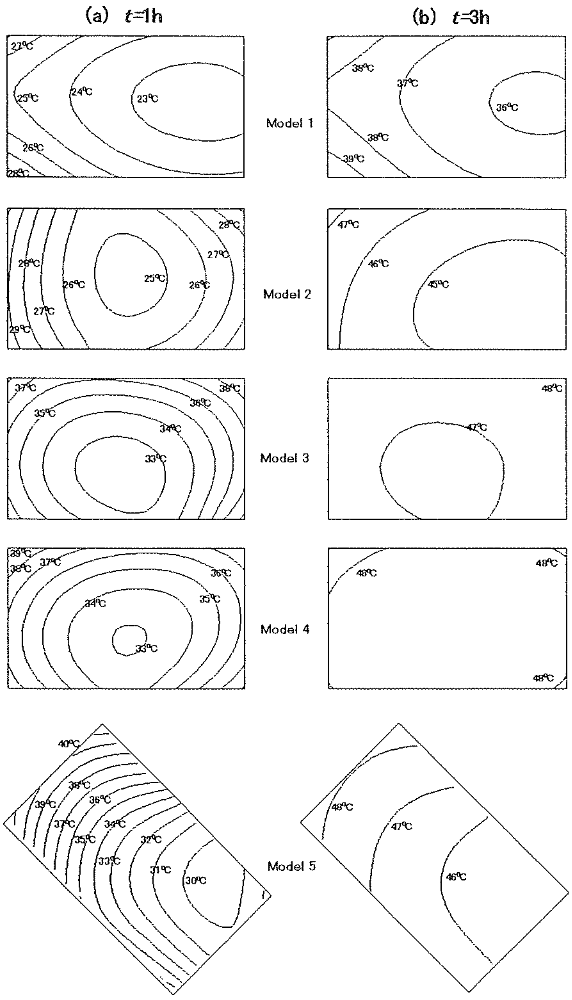

Fig. 7 Isotherms in brick number 8 (model 2, 3, 4) and number 6 (model 1, 5) at (a) t=1 hour and t=3 hours

Fig. 7 shows temperature fields inside the bricks. There are many temperature fields produced but in the figure only one brick from each model at t =1and t =3 hours is presented. In the figure bricks with the same position in the heat storage tank were chosen. Those bricks are number 8 of model 2, 3, and 4 and number 6 for model 1 and 5. The contour level increments for each brick are kept constant at 1^{0}C. The more packed isotherms related to a high heat transfer rate. Temperature fields of model 1 show that in the front side of the brick it is more packed. This is because the fluid flows from this side. In model 2, the baffles make the fluids flow from the front and back side of the brick but stagnant on its top and bottom. This flow results in a high heat transfer rate from the front and back sides but poor from its top and bottom, shown by more packed isotherms in the front and back sides. The staggered positions in model 3 and 4 make the fluids flow from the top of the bricks also. This enhances the heat transfer rate from the top also, in the figure shown by the more packed isotherms in the top area. In model 5, inclined position enhances heat transfer rate from the front and bottom of the bricks but much less from its top and back sides. The same isotherms pattern can be seen for t =3 hours but the isotherms are more rare.

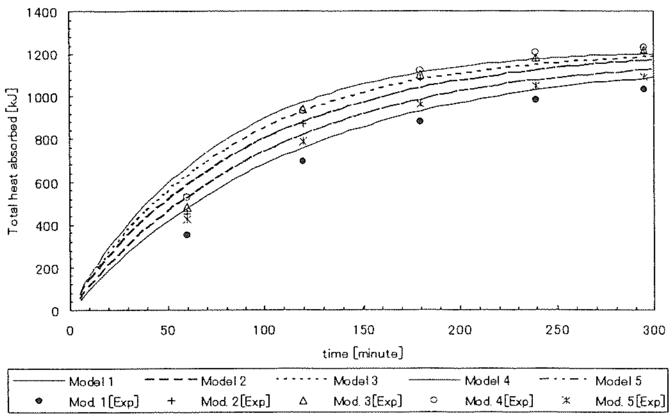

Fig. 8 Total heat stored during charge process for all models

4.3. Total heat absorbed

Total heat absorbed by all bricks for all models is presented in Fig. 8. The experimental results are presented in the figure also. In the experimental ones the total heat stored by all bricks is calculated based on the average temperature of the bricks. In spite of the fact that there are some discrepancies, the experimental and numerical results reveal the same trend and show good agreement. The figure shows that the lowest performance is model 1 followed by model 5, 2, and 3, but as expected model 4 provides the best performance. The conclusions can be drawn from the figure are as follows: for cases without any baffles the inclined position (model 5) is better than horizontal position (model 1). Furthermore, if the presence of the baffles are considered model 4 is the best.

Furthermore the discussion here is the heat absorb rate of the heat storage. In this study the maximum amount of heat which can be stored by each model is the same due to the same number of bricks. However, the heat absorb rate of each model is different due to the difference of heat transfer rate from the bricks surfaces. The total heat released by heated air is constant due to the constant temperature in the inlet. The ideal heat storage is the heat storage which is able to absorb all of the heat from the heated air, or the output temperature of the air is equal to the initial condition of the bricks.

Based on the aforementioned ideal heat storage and in order to compare the heat absorb rate of the typical heat storage, a parameter which is named as *heat absorb efficiency* is proposed. The heat absorb efficiency is defined by total heat stored rate by the heat storage divided by total heat stored rate by ideal heat storage. In this study the total heat stored by the heat storage is calculated based on the stored total thermal energy in the bricks. The heat absorb efficiency at any time is calculated by using equation (11).

$$\eta = \frac{Q_{tot}|_n - Q_{tot}|_{n-1}}{\dot{m}_a c_p (T_{in} - T_0)\Delta t} \quad (11)$$

Q_{tot} is the total heat absorbed by bricks and calculated by using equation (9).

The total heat absorbed by bricks Q_{abs} can be defined by using heat absorb efficiency η, and calculated as follow.

$$Q_{abs} = \dot{m}_a c_p (T_{in} - T_0) \int_0^t \eta \, dt \quad (12)$$

Furthermore, in case of time $t \to \infty$, Q_{abs} is constant or equal to the maximum heat can be absorbed by all bricks. Since the number of the bricks for all models is the same, Q_{abs} is the same regardless of the models.

The heat absorb efficiency for all models are presented in Fig. 9. The figure shows that η decreases as charge time increases. This is because the temperatures of the bricks increase and reduce the ability of the bricks to absorb the heat. Model 4 reveals the most efficient heat storage is before 100 minutes but much less efficient after that. The conclusion can be drawn that for the typical heat storage its better to charge the heat storage model 4 until 100 minutes otherwise it will not be efficient anymore compared to the other models. The time of 100 minutes is not a fixed limitation time for the problems and it depends on the dimensions and heat capacity of the heat storage. Indeed, this conclusion shows that for typical heat storage there is always a time limit for when the efficiency will reverse.

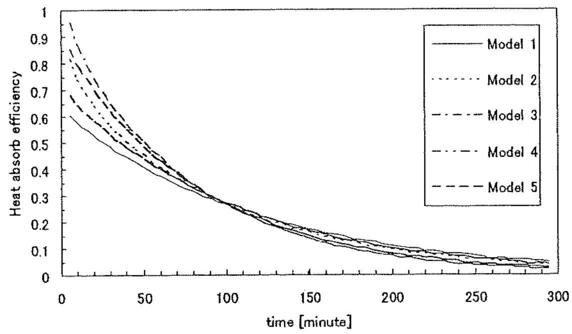

Fig. 9 Time variations of the heat absorb efficiency for all models

4.4. Pressure drop

Pressure drop between the inlet and the outlet of the heat storage for all models is presented in Fig. 10. The figure shows that the pressure drop of model 3 is the highest. Comparing pressure drop of model 3 and model 4, it can be seen that for the same staggered positions but remaining space between the brick and baffle will give a lower pressure drop but the highest performance.

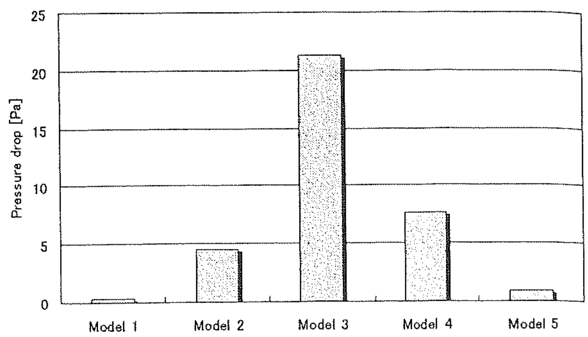

Fig. 10 Pressure drop during charge process for all models

4.5. Discharge process

After the charge process, discharge was carried out experimentally. The discharge time is about 3.5 hours. The results and the ratio between the total energy stored and released are presented in Table 1. The data shows that model 5 has the best performance in releasing the heat already stored. However based on the total heat able to be released by heat storage, model 4 is the best.

Table 1 Total heat stored, discharged, and the ratio for 5 hours charge and 3.5 hours discharge

	$Q_{charg.}$[kJ] (a)	$Q_{disc.}$[kJ] (b)	Ratio (b)/(a)
Model 1	1103.4	891.0	0.7853
Model 2	1206.9	916.8	0.6680
Model 3	1218.0	1000.9	0.7230
Model 4	1229.4	1087.4	0.7771
Model 5	1093.4	891.0	0.8149

5. Conclusions

In this paper the convective heat transfer and flow characteristics of a heat storage system by using bricks as a storage element was investigated experimentally and numerically, considering the effect of the brick arrangements and baffle plates on it performance.

The conclusions are as follows:

1. If the presence of the baffles is not considered the inclined brick arrangements is better than horizontal in storing the heat performance.
2. Attaching baffles reduces the stagnant fluid and enhance the heat transfer rate compared to the corresponding case without any baffles.
3. Combination of attaching baffles and staggered positions of the bricks with remaining space between the brick and the baffle reveal the best performance.

4. For the typical heat storages there is always a time limit during the charge process which will eventually reverse the heat absorb efficiency in comparison with other models.

Nomenclature

c_p	Specific heat (J/kg· K)
k	Thermal conductivity (W/m· K)
$\dot{m}$	mass flow rate (kg/s)
n	normal direction
p	Pressure (N/m^2)
Q	Heat stored (J)
t	time (s)
Δt	time step (s)
T	Temperature (^{0}C, K)
u, v	Velocity component in x and y-directions (m/s)
x, y	Horizontal and vertical coordinate (m)

Greek symbols

η	Heat absorb efficiency
υ	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
ψ	Stream function

Subscript

a	Related to the air
abs	Related to absorb
b	Related to the brick
in	Related to the inlet area
n	Related to the present time
tot	Related to the total
∞	Related to the ambient
0	Related to the initial condition

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