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蓄熱槽中の蓄熱要因レンガの表面形状と配列に対する熱伝達および流れ特性の研究

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A Numerical Study on Flow and Heat Transfer Characteristics for Brick's Arrangement and Surface Form in a Rock Bed Heat Storage System

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Abstract

This paper attempts to study numerically heat transfer and fluid flow characteristic for brick(s) element in a rock bed heat storage tank system. The emphasis of this study is to make clear the effect of the brick surfaces and arrangement on the total performance of the heat storage tank. A plain surface brick with two types different positions i.e. incline and parallel with the stream flow were studied. The brick was heated by hot air 50°C and velocity 0.1 m/s from initial condition 20°C. Laminar, transient and two-dimensional governing equations are solved by using SIMPLE algorithm. The calculation results show that the presence of the dimples on brick surfaces did not enhance the heat transfer rate from the air into the brick. The incline position of the brick toward upstream enhances the heat transfer rate significantly. Based on these results a full scale heat storage systems consist of a sets of plain bricks were also studied. As expected, the heat storage tank with inclined positions of bricks reveal the better performance of storing heat from the hot air compared to the parallel position.

Key words: bricks, heat storage, plain surface/discontinuous surface of brick, inclined arrangement

1. Introduction

Solar energy has received big considerations in recent years due to limitation of fossil source energy. Although the solar energy is abundant but there are many problems to be against when using solar energy. Noticeable example, low quality of heat and strongly depend on weather. Based on those problems it has been realized that difficult to do conversion solar energy to the high level energy such as mechanical energy or electrical energy.

From efficiency and effectiveness point of view, using solar energy as a heat is better than transform it to the other energy form. Therefore, use the solar energy as a heat source for room heating in the winter season is a promising application. However, this application still needs an innovation. A heat storage tank is needed because the different of the using time and the available time of the solar energy. A major part of storing energy problem lies in the fluid flow characteristic and heat transfer. Power up performance of the heat storage tank is a most topic in this area. There are several techniques in order to store the heat i.e. using PCM material, porous medium, and sets of brick. In this paper, we focus on using of a set of bricks as a heat storage tank element.

The objective of this research is to study the fluid flow and heat transfer characteristic of the heat storage tank by using a set of the bricks. The emphasis of this research is to make clear the effect of the brick positions and brick surfaces on the fluid flow and heat transfer characteristics. The results can be expected from this study is to supply a necessary information of bricks heat storage tank design and optimization.

2. Problem definition and modeling

In order to acquire these objectives two main parts of numerical calculations were carried out. The first calculation is a basic study on the influence of a brick position and its surfaces individually. Second is calculation for a heat storage tank system which contains a set of bricks. The bricks surfaces and positions in the second calculation are based on the result of the first calculation.

In the first calculation, a brick is heated by hot air 50°C with velocity 0.1 m/s from initial temperature 20°C. A horizontal brick with three different surfaces i.e. plain surface, discontinuous surfaces with square dimples, and

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triangle dimples were studied. Then the plain brick in inclined position (45°) toward to the upstream were also studied. Positions of the bricks are depicted in Figure 1.

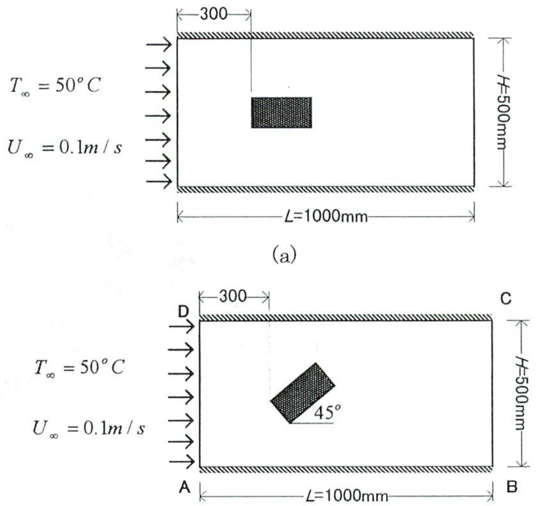


Figure 1 Position of the brick (a) horizontal position and (b) inclined position

In the second part of calculation, a heat storage tank that contains a set of plain bricks is heated by hot air 50°C with velocity 0.1 m/s from initial temperature 20°C. The reason of using the plain surfaces of the bricks will be explained next in the result part of this paper.

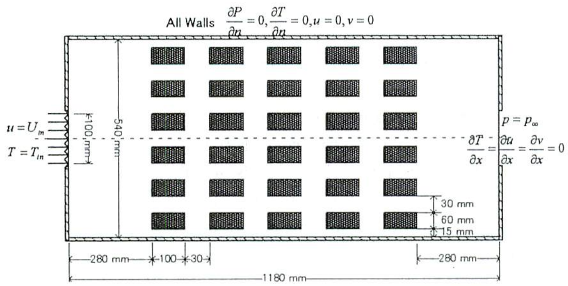


Figure 2 Model 1: In-line horizontal bricks arrangement

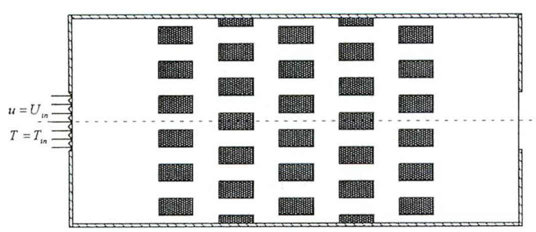


Figure 3 Model-2: Staggered horizontal bricks arrangement

Combination of the in-line and staggered with the horizontal and inclined positions of the bricks were considered. These combinations were divided into four different models and named as follows.

Model-1: Heat storage with in-line horizontal bricks
Model-2: Heat Storage with staggered horizontal bricks
Model-3: Heat Storage with in-line inclined bricks
Model-4: Heat Storage with staggered inclined bricks.

All of the models are depicted in Figure 2, Figure 3, Figure 4, and Figure 5.

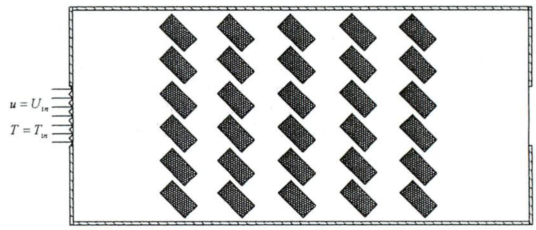


Figure 4 Model-3: In-line inclined bricks arrangement

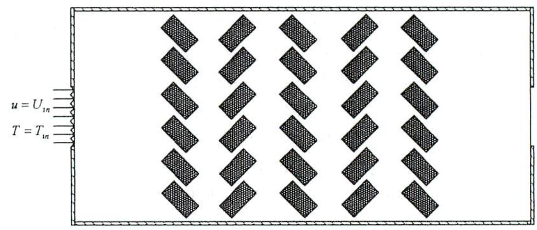


Figure 5 Model-4 Staggered inclined bricks arrangement

3. Mathematical model

The flow is assumed to be transient, laminar, and two-dimensional. The compressibility, radiation heat exchange, buoyancy force, and dissipations are negligible. All of the thermal properties are constant. The governing equations are:

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

X and Y momentum equations

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

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p'}{\partial y} + \upsilon\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

Energy equation

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

Boundary conditions at any time t are:

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

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

The outlet: $\dfrac{\partial u}{\partial x} = 0,\ \dfrac{\partial v}{\partial x} = 0,\ \dfrac{\partial T}{\partial x} = 0$ and $p = p_0$ (7)

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

Total heat stored by bricks is calculated by:

$$Q_{tot} = \Sigma \rho_b.dx.dy.c_b(T_{ij} - T_{in}) \quad (9)$$

The rate of the heat transfer between the brick and the air is calculated by:

$$\dot{q} = \sum k.dx\frac{\partial T}{\partial y}\bigg|_{hor.surf} + \sum k.dy\frac{\partial T}{\partial x}\bigg|_{vert.surf} \quad (10)$$

Equation (10) is used when the particular node of the bricks has both vertical and horizontal contact surfaces to the air. If the node has only one contact surface to the air only one part of the equation (10) is applied, vertical or horizontal only.

Thermal properties, k, c_p, ρ , respectively thermal conductivity (W/m.K), specific heat (kJ/kg.K), and density (kg/m^3) of the materials are listed as follows. The bricks k=0.1, c_p=0.67, ρ =1984, and for air k=0.026, c_p=1.006, ρ =1.165. The interface conductivities due to non uniform conductivities of the material inside the computational domain were handled by harmonic mean conductivities.

4. Solution methods

All of the governing equations are discretized based on control volume approach on staggered grid 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. Iterations process will be stopped if the continuity equation is satisfied (total mass residual compared to total mass from inlet area is $\leq 10^{-3}$). Based on this procedure the FORTRAN codes have been developed

5. Result and discussion

Calculations for all cases with time step 10 second, 1 minute, and 10 minute for total 6.5 hours were carried out.

5.1. Effect of the brick surfaces

The isotherm lines inside the brick for Δt = 1h, 2h, 3h, and 6h for horizontal plain brick are shown in Figure 6. The blue color indicates the lower temperature and the red color higher temperature. The increment in the figure is 10% of the highest and lowest temperature. The figure shows that at the left side of the brick (upstream) the isotherm lines are closely due to the higher heat transfer rate. Based on the density of the isotherm lines inside the brick, the figures show that the heat transfer rate through the left and right sides (upstream and downstream) of the brick are higher than that of the top and the bottom sides. The isotherm lines are smooth due to plain surface. There is no significant different of isotherm lines form of the discontinuous surface bricks and the plain bricks (the isotherm lines for discontinuous bricks are not shown).

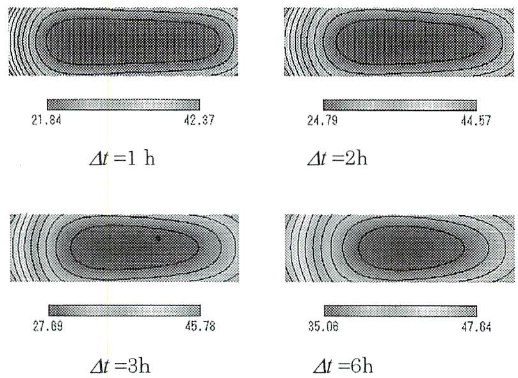


Figure 6 Isotherm lines inside the brick for horizontal plain brick

In order to make clear the effect of the brick surface, total heat absorbed by plain surface brick and discontinuous brick, square and triangle dimples, are shown in Figure 7.

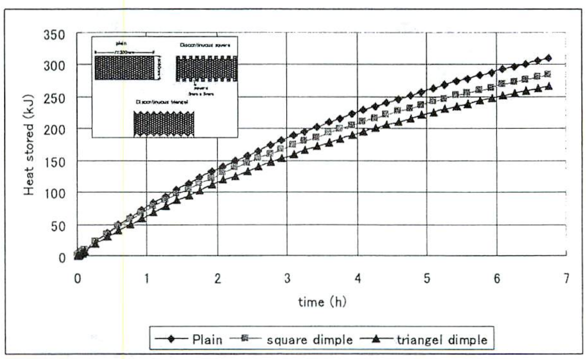


Figure 7 Total heat stored by plain brick and discontinuous brick

It can be seen from the graph that the brick with plain surfaces stores the highest heat compared to the discontinuous bricks. It is known that the element of the brick adjacent to the flowing air stores bigger heat, compared to the element inside the brick, caused by this element has the higher temperature due to higher heat transfer rate. Since the plain brick has no reduced element the total heat stored by this brick is the highest. In the discontinuous bricks because of the element of the bricks adjacent to the flowing air is reduced due to presence of the dimples, the total heat stored by this bricks are lower than the plain brick. On the other way can be said that total heat stored in the plain brick is bigger compared to the discontinuous bricks because of the total mass of the brick discontinuous bricks are lower than total mass of the brick in case-1.

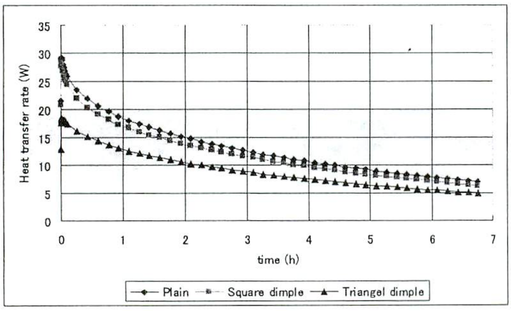
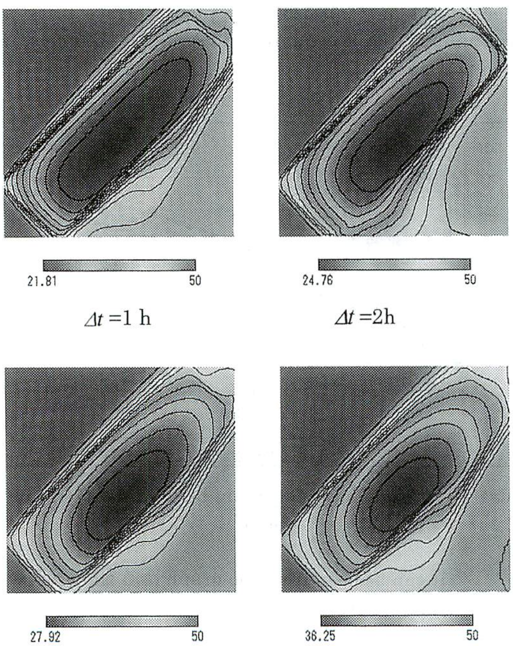


Figure 8 Total heat transfer rate from the air into the brick

The total heat transfer rate from air into the brick for plain brick and discontinuous bricks are shown in Figure 8. For all bricks, as expected, the rate of the heat transfer is decreasing with time elapse. The graph shows that for plain brick the total transfer heat rate is the biggest. Based on those analysis cited above, it is clear that employ plain surface brick is better.



Δt =1 h　Δt =2h

Δt =3h　Δt =6h

Figure 9 Isotherm lines inside the inclined brick

5.2. Effect of the brick position

In order to make clear effect of the brick position to the stream flow, calculation a brick with horizontal and inclined positions were carried out and result is presented in Figure 9 and Figure 10.

Figure 9 show that for almost all sides of the brick isotherm lines are closely. It does mean that the heat transfer rates from these sides are bigger. This result already expected. Since the position of the brick is inclined towards to the upstream, the surfaces close to the accelerated flow is larger. The accelerated flow results the bigger temperature gradient consequently heat transfer rate is enhanced.

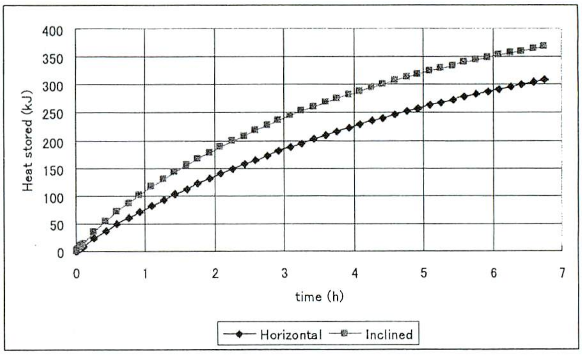
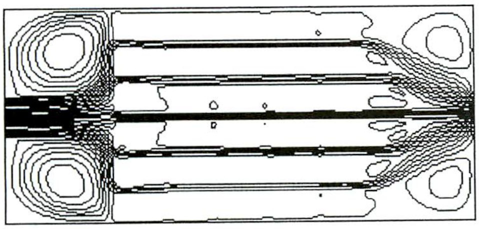


Figure 10 Total heat stored by brick for horizontal brick and inclined brick

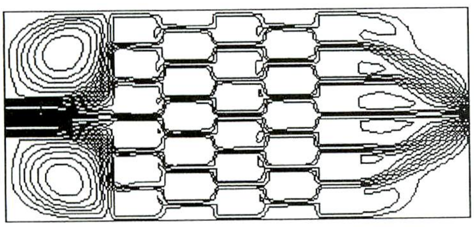
Figure 10 shows that total heat stored by brick for horizontal and inclined brick. Since the heat transfer rate for inclined brick is bigger than horizontal brick the total heat stored for inclined brick is bigger. Based on this discussion is better to employ the plain brick with inclined position.

5.3. Application to the heat storage system

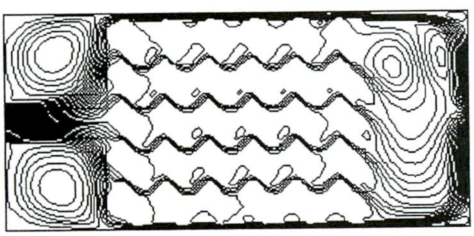
Calculation for heat storage tank consist of 24 pieces of plain bricks with four different arrangements were carried out. Streamlines and temperature distributions inside the heat storage at Δt=1 h 6 minute for all models are shown in Figure 11 and Figure 12. It can be seen clearly that inclined and staggered position has strongly influence to the flow characteristic inside the heat storage. In addition the flow characteristic influences the heat transfer rate from the air into the bricks. The influence can be seen in Figure 16. The figure shows that for horizontal inline position of the bricks (model 1) out put air temperature is higher compared to the others.



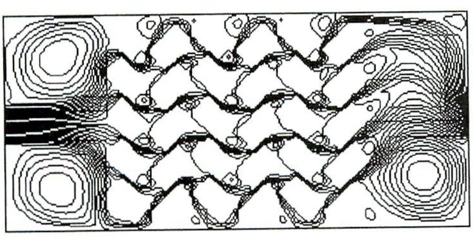
Model 1



Model 2

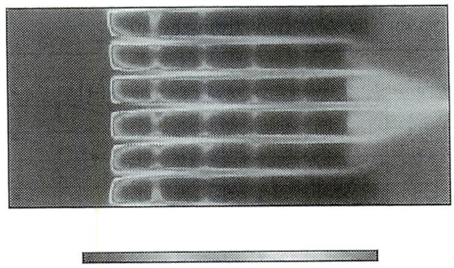


Model 3

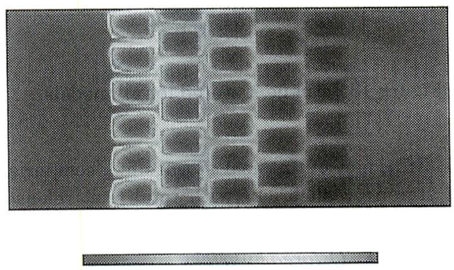


Model4

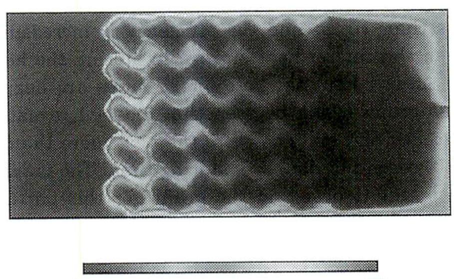
Figure 11 Streamlines at Δt =1 h 6 minute for all models



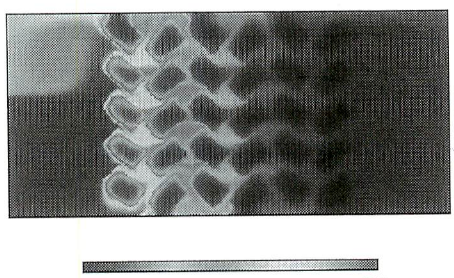
Model 1



Model 2



Model 3



Model 4

Figure 12 Temperature distribution at Δt =1 h 6 minute for all models

Total heat stored for all models are depicted in Figure 13. The figure shows that the model 4 reveals the best performance to store heat from the air.

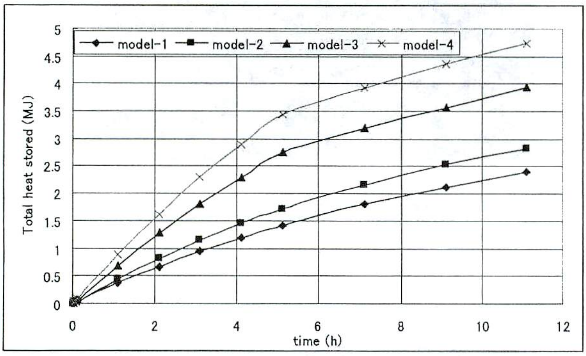


Figure 13 Total heat stored for all models

Efficiency of the heat storage is a comparison of the heat stored by all bricks with total heat released by warm air.

$$\eta_{th} = \frac{Qstored\ by\ bricks}{Qrelease\ by\ air} \tag{11}$$

Efficiency for all models is depicted in Figure 14. In the graph *x* axis is time in second and logarithmic scale is used in this axis. The graph shows that for all models at the time less than 10^3 second the efficiency is increasing. It does mean the rate of heat storage in storing the heat is positive. After 1 hour the rate for all cases are negative. From this graph it can be seen that model-4 reveals the best efficiency and still can store the heat more than 50% until 2.10^4 second (5 hours) of storing time. The judgment also can be made based on the graph for this particular type and dimension it is not recommended to operate this heat storage tank more than 5 hours because the efficiency will be less than 50%.

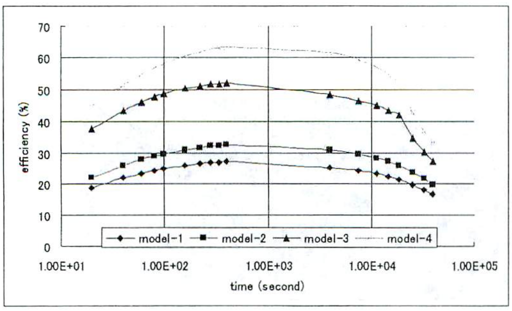


Figure 14 Storage Efficiency for all models

Pressure drop is an essential problem in the heat storage application. In this numerical study the pressure drop inside the heat storage for all model also calculated and the results are presented in Figure 15. The graph shows that pressure drop for model-4 is the higher compared to the other models. It is true that pressure drop for model-4 is more than 500% compared to model-1 and model-2. But the value of the pressure drop for model-4 is only 0.5N/m^2 because the inlet velocity is small.

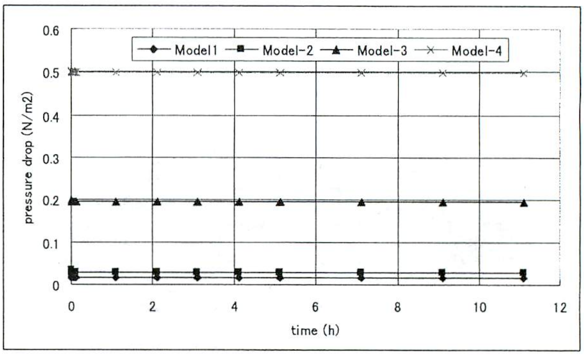


Figure 15 Pressure drop for all models

6. Conclusions

The conclusions can be made are as follows:

1. The presence of the dimples on the surfaces of the bricks is reducing the total heat stored inside the brick.
2. The dimples also reducing the rate of heat transfer from the air into the brick.
3. Incline position of the brick reveals the best position in order to enhance the heat transfer on the bricks.
4. Application to the heat storage tank combination of inclined and staggered position of the bricks reveals the best performance.
5. For the particular problem that cited above the storing duration should not be more than 5 hours.

7. References

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