

A study of the heating and heat storage problems in passive solar heated room with greenhouse

CHEN Wei, LIU Wei

Department of Power Engineering Huazhong University of Science and Technology, Wuhan, 430074, P.R. China

Abstract: In this paper, heating and heat storage in passive solar heating room with greenhouse has been studied. The unsteady numerical simulation is employed to analyze the performance of the flow and temperature field for the typical sunny day of Wuhan, China, in winter in the heating system. The floor of passive solar heating room with a convective hole or not has great effects on temperature distribution and gas flow in heat storage layer of this system. Properties of the bed worked as solar absorber and storage layer have also been studied.

Keywords: heating; heat storage; solar application

1. Introduction

Passive solar heating is often applicable in cold climates. Many kinds of passive heating techniques, such as Trombe wall, transparent insulation, etc have been used in building design. Earlier studies show that the passive solar heating room with greenhouse and heat storage performed well in winter [1]. Energy storage is an essential part of solar heating system. Rock bed is generally preferred for the air-based thermal energy storage system.

In the present work, the building of heating system works as solar absorber and heat storage, so the cost of the solar heating reduces. The unsteady numerical simulation is employed to analyze the performance of the flow and temperature field in the heating system, and the heat storage performances of the rock bed have also been studied in the experiments, which were influenced by various material of the rock.

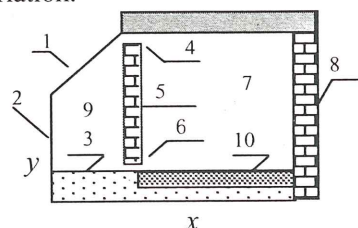
2. System description and mathematical analysis

2.1 System description

The passive solar heating room with greenhouse and heat storage under investigation is schematically shown in Fig1. The system consists of greenhouse and heating room. A lean-to type greenhouse with a south-inclining roof is built on the south side of the heating room. The partition wall of the heating system, which has a top and a bottom vent, consists of two conjoint parts, one part as absorber on the side of the greenhouse, the other as insulator on the side of the heating room. The rock bed works as heat storage layer and locates at bottom of the heating system, on which the concrete floor is paved. The roof and wall except partition wall in greenhouse consists of plate glass.

2.2 Theoretical modeling

The flow is assumed to be two-dimensional and the Boussinesq approximation is used to account for the density variation.



- | | | |
|---------------------|--------------------------|------------------|
| 1. greenhouse roof; | 2. greenhouse enclosure; | 3. heat storage; |
| 4. top vent; | 5. partition wall; | 6. bottom vent; |
| 7. heating room; | 8. north wall; | 9. greenhouse; |
| 10. concrete floor | | |

Fig.1. Schematic of the passive solar heating room with greenhouse and heat storage

The rock bed is considered as a fluid saturating the porous medium and form drag and boundary effects are significant. Under these circumstances, the governing equations for flow and heat transfer in a porous layer are [2]:

Continuity equation

$$\frac{\partial(\rho u_d)}{\partial x} + \frac{\partial(\rho v_d)}{\partial y} = 0 \quad (1)$$

Momentum equations

$$\frac{\rho}{\theta} \frac{\partial u_d}{\partial \tau} + \frac{\rho}{\theta} (u_d \frac{\partial u_d}{\partial x} + v_d \frac{\partial u_d}{\partial y}) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} (\mu_{eff} \frac{\partial u_d}{\partial x}) + \frac{\partial}{\partial y} (\mu_{eff} \frac{\partial u_d}{\partial y}) - \frac{\mu u_d}{K} + \frac{\rho C \theta}{\sqrt{K}} |\vec{v}_d| u_d \quad (2)$$

$$\begin{aligned} \frac{\rho}{\theta} \frac{\partial v_d}{\partial \tau} + \frac{\rho}{\theta} (u_d \frac{\partial v_d}{\partial x} + v_d \frac{\partial v_d}{\partial y}) = & -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} (\mu_{eff} \frac{\partial v_d}{\partial x}) + \frac{\partial}{\partial y} (\mu_{eff} \frac{\partial v_d}{\partial y}) - \frac{\mu v_d}{K} + \frac{\rho C \theta}{\sqrt{K}} |\vec{v}_d| v_d + \rho g \beta (T - T_c) \\ & - \frac{\mu v_d}{K} + \frac{\rho C \theta}{\sqrt{K}} |\vec{v}_d| v_d + \rho g \beta (T - T_c) \end{aligned} \quad (3)$$

Energy equation

$$(\rho c)_m \frac{\partial T}{\partial \tau} + \rho c (u_d \frac{\partial T}{\partial x} + v_d \frac{\partial T}{\partial y}) = \frac{\partial}{\partial x} (k_{eff} \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_{eff} \frac{\partial T}{\partial y}) \quad (4)$$

where c is specific heat, g is gravitational acceleration vector, P is pressure, T is temperature, $|\vec{v}_d|$ is mean velocity ($= \sqrt{u_d^2 + v_d^2}$), β is thermal expansion coefficient, τ is time, μ is dynamic viscosity, ρ is density, θ is porosity of the porous medium, Subscripts d, eff, m refer to Darcy, effective, apparent mean.

The values for permeability K and inertia coefficient C was given for packed beds of rock diameter d_r and porosity:

$$K = \frac{d_r^2 \theta^3}{175(1-\theta)^2}; C = \frac{1.75}{\sqrt{175}} \theta^{-3/2}$$

In present study, the conductivity of the medium k_m and $(\rho c)_m$ is calculated by

$$k_m = \theta k_f + (1-\theta) k_s,$$

$$(\rho c)_m = \theta (\rho c)_f + (1-\theta) (\rho c)_s,$$

where k_f is fluid thermal conductivity, k_m is apparent thermal conductivity, k_s solid thermal conductivity.

Above the heat storage bed in the heating room with greenhouse, the airflow is considered as turbulence natural convection and the Low-Re $k-\varepsilon$ model of turbulence is used [3]:

Continuity equations:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (5)$$

Momentum equations:

$$\frac{\partial(\rho u)}{\partial \tau} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho v u)}{\partial y} = \frac{\partial}{\partial x} (\mu_{eff} \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y} (\mu_{eff} \frac{\partial u}{\partial y}) + S_u \quad (6)$$

The source terms in momentum equation are

$$S_u = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} (\mu_{eff} \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y} (\mu_{eff} \frac{\partial v}{\partial x});$$

$$S_v = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} (\mu_{eff} \frac{\partial u}{\partial y}) + \frac{\partial}{\partial y} (\mu_{eff} \frac{\partial v}{\partial y}) + \rho g \beta (T - T_c)$$

General transported fluid scalar, ϕ (e.g. T, k, ε)

$$\frac{\partial(\rho \phi)}{\partial \tau} + \frac{\partial(\rho u \phi)}{\partial x} + \frac{\partial(\rho v \phi)}{\partial y} = \frac{\partial}{\partial x} (\Gamma_\phi \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y} (\Gamma_\phi \frac{\partial \phi}{\partial y}) + S_\phi \quad (8)$$

where Γ_ϕ is the exchange coefficient for the transport of property, k is turbulence kinetic energy, ε is dissipation rate of turbulent kinetic μ_{eff} is effective dynamic viscosity for the turbulence model. The source terms in the ϕ equations are:

$$S_k = \mu_t G - \rho \varepsilon - 2\mu (\frac{\partial k^{1/2}}{\partial y})^2$$

$$; S_\varepsilon = \frac{\varepsilon}{k} c_1 f_1 \mu_t G - c_2 \rho \frac{\varepsilon^2}{k} f_2 + 2 \frac{\mu \mu_t}{\rho} (\frac{\partial^2 u}{\partial y^2})^2;$$

$$S_T = 0; G = \frac{\mu_t}{\rho} \{ 2[(\frac{\partial u}{\partial x})^2 + (\frac{\partial v}{\partial y})^2] + (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})^2 \}$$

The expression for the turbulent viscosity includes the damping function f_μ , given below, in which the damping parameter R_t is the local Reynolds number of turbulence defined as

$$R_t = \rho k^2 / (\mu \varepsilon),$$

$$\mu_t = \rho c_\mu f_\mu k^2 / \varepsilon,$$

$$f_\mu = \exp[-3.4/(1+0.02R_t)^2]$$

The damping function: $f_2 = 1 - 0.3 \exp(-Re_t^2); f_1 = 1$

The turbulence model contains five constant which were assigned the following values

$$c_\mu = 0.09, c_1 = 1.44, c_2 = 1.92, \sigma_k = 1, \sigma_\varepsilon = 1.3, \sigma_\eta = 1$$

2.3 Boundary conditions and initial conditions

The assumptions of the energy-balance equations for different components of the heating system:

- 1) No air temperature difference in the system
- 2) The surface of the glass cover, the porous absorber and the thermal storage wall are considered as gray body.
- 3) The roof and wall except the south thermal storage wall, which are well-insulated, are considered as thermal insulator.
- 4) The air radiation absorbcency is neglected.

The Initial and boundary conditions drawn from Energy-balance equations together with the assumptions (1-4) are given below.

For the glass enclosure and roof of the greenhouse

$$G_{sun} + Q_{sky} + Q_{ai} + Q_{ao} + Q_{hg} = 0, \quad (9)$$

$$u=0, v=0$$

For the surface of thermal storage layer on the side of the greenhouse

$$k_m A_r \frac{dT_s}{dy} = G_{rsun} A_r + Q_{hr} + Q_{ar} \quad (10)$$

$$u \Big|_{y=L_{po}} = u \Big|_{y=L_{po}^*}, v \Big|_{y=L_{po}} = v \Big|_{y=L_{po}^*}, p \Big|_{x=L_{po}} = p \Big|_{x=L_{po}^*},$$

$$\mu_m \left(\frac{\partial u_d}{\partial y} + \frac{\partial v_d}{\partial x} \right) \Big|_{x=L_{po}} = \mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \Big|_{x=L_{po}^*}$$

For the partition wall on the side of greenhouse

$$k_w A_w \frac{dT_w}{dx} = G_{wsun} A_w + Q_{cnv} + Q_{hw} \quad (11)$$

$$u=0, v=0$$

The bottom of the rock bed, the roof and wall on the side of heating room: $\frac{\partial T}{\partial x} = 0, \frac{\partial T}{\partial y} = 0, u = 0, v = 0$

Initial conditions $\tau = 0, T = const, u = 0, v = 0$
 where A_r is surface area of rock bed on the side of greenhouse; A_w is surface area of partition wall; G_{gsun} is rate of solar flux absorbed by the glass enclosure; G_{rsun} is rate of solar flux absorbed by the rock bed surface on the side of greenhouse; G_{wsun} is rate of solar flux absorbed by the partition wall surface; h_r is thickness of rock bed; k_w is thermal conductivity for the partition wall.

Numerical simulations were performed for sunny and control based on air temperature and operative temperature was considered:

$$T_{ao}(\tau) = \overline{T_{ao}} + T_{ar} \cos\left(\frac{\pi}{12}(\tau - 14)\right) \quad (12)$$

$$G_{sun}(\tau) = \hat{G}_{sun} \sin\left(\frac{\tau - a}{b - a}\pi\right), \quad a < \tau < b \quad (13)$$

where $\overline{T_{ao}}$ = average outside temperature of 15 °C ;
 T_{ar} = amplitude of 6 °C ; $\hat{G}_{sun}$ = maximum solar irradiance of 350 W/m²; a = sunrise hour of 6 o'clock in the morning b = sunset hour of 18 o'clock in the afternoon; τ : time, hours

3. Numerical procedures

For the present study, the governing equations (1-4) and equations (5-8) together with the boundary conditions were solved with the SIMPLER method. The time step of $\Delta\tau = 45s$ together with the grid size of 128×148 were used for the unsteady-state numerical calculations performed in this study.

4. Experiments

The rock bed, the pebble bed and soil bed located at bottom of the greenhouse. The heat-insulated material was laid at bottom of each bed and between the various heat storage beds. Measurements of the temperature were made with thermocouples connected with numerical voltage setting, which were placed on the surface and at the depth of 15cm. within each heat storage bed. The ambient temperatures were measured with a mercurial thermometer. More than three times were carried out for each experimental data used.

Rock (I): $c = 0.836 \text{ kJ}/(\text{kg} \cdot \text{K})$, $k_s = 1.74 \text{ W}/(\text{m} \cdot \text{K})$

$\rho = 1400 \text{ kg}/\text{m}^3$,

Basalt (Pebble): $c = 0.92 \text{ kJ}/(\text{kg} \cdot \text{K})$, $\rho = 2695 \text{ kg}/\text{m}^3$,
 $k_s = 1.71 \text{ W}/(\text{m} \cdot \text{K})$; [4]

5. Results and discussion

Figs.2 shows that the temperature of the rock bed and partition wall surface on the side of greenhouse is higher comparatively, which works as the main solar absorber in the heating system. The air temperature in the greenhouse are more than 20 °C above the ambient. As the heat exchange occurs between the glass enclosures and ambient, the air temperature near the glass enclosure in the greenhouse is lower, in contrast, the air temperature near the up vent of the heating is higher. The farther the position in the heating room is from the up vent, the lower air temperature is. Heated in the greenhouse, the air rises upward and out through the top vent and into the heating room. Cooler room air simultaneously is drawn through the bottom vent and into the greenhouse. It produces an air cycle in the heating system. The air temperature in the heating room is nearly 10 °C above the ambient, which may meet the heating requirements.

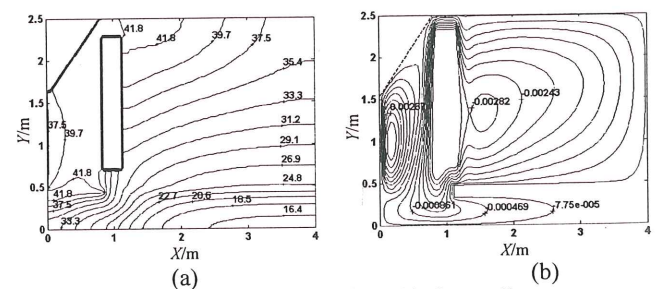


Fig.2 (a) Isotherms (°C) (b) Streamlines at 15:00 in the afternoon in heating system

From the temperature distribution in the rock bed, we can see that in contrast to the rock bed in the heating room, the bed temperature of the greenhouse is higher. When the sun is no shining, heat stored in the rock bed releases to raise the temperature in the heating room. Thus, the solar radiation absorbed by the surface of the storage layer, is divided into parts, one part is stored in the rock bed, the other is used to raise temperature of greenhouse.

As shown in Figs.3, heat loss by air convection works in close conjunction with the conduction loss through the glass enclosure skin at night, the air temperature in the greenhouse is lower relatively. Besides, one part of the heat stored in the rock bed releases to the heating room, the other transfers to the

greenhouse and loses. So, the glass enclosure of the greenhouse should be thermal insulated when no solar irradiation is available.

Comparison between Figs.2 and Figs.4 shows that as a convective hole of the floor exists near the north wall in the heating room, the heat convection inside the rock bed increases, as a result, the temperature near the north wall and average temperature of the rock bed rise. So, the amount of thermal storage increases.

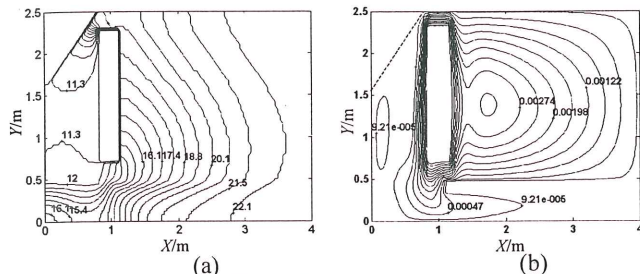


Fig.3 (a)Isotherms(°C) (b)Streamlines in heating system at 24:00 in night

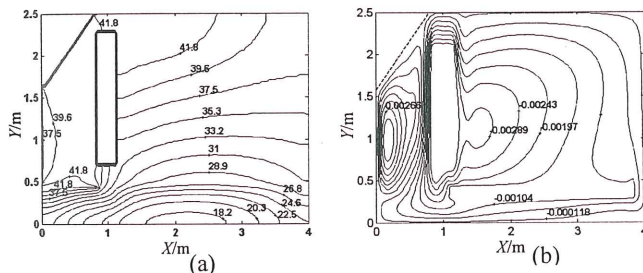


Fig.4. (a)Isotherms(°C) (b) Streamlines in heating system with a convective hole across floor, at 3:00 in the afternoon

Fig 5 shows that the temperature of different material thermal storage varies versus time: Rock (I) and Basalt have the characteristics necessary for thermal storage. When the sun is shining, the temperature of rock bed with lower specific heat capacity (ρc) is higher relatively. Duo to the decrease in the solar radiation intensity, the temperature of the rock with lower specific heat capacity (ρc) reduced more greatly. Therefore, the special heat (ρc) of the rock plays an important role in the thermal storage process.

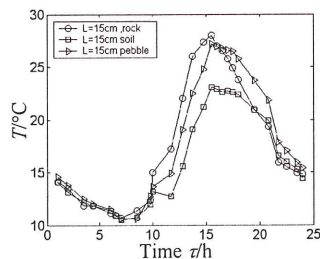


Fig.5. temperature measured at depth of 15cm. for the rock bed, the pebble bed and soil in greenhouse

6. Conclusion

From above discussion, we can conclude that solar irradiation can be utilized to increase more than 10°C above ambient in the passive solar heating room, so the

energy consumption of the building reduces. Heat collection, heat storage and heat insulation are the main factors in passive solar heating system. As a convective hole exists in the floor of the heating room, the temperature of the thermal storage bed increase relatively. The specific heat capacity (ρc) has a remarkable effect on the temperature of rock bed in the heating system. So, working as solar irradiation absorber and the heat storage layer, the materials of rock bed should be chosen properly.

Acknowledgement

The current work is financially supported by the National Key Basic Research Development Program of China.(No.G2000026303), the National Natural Science Foundation of China and the Doctoral Foundation of Education Ministry of China (No.2000048731).

Nomenclature

- Q_{ai} heat exchange between air inside the heating system and glass enclosure of greenhouse, J
- Q_{ao} heat exchange between air outside the heating system and glass enclosure of greenhouse, J
- Q_{ar} heat exchange between the air inside heating system and the surface of rock bed, J
- Q_{aw} heat exchange between air inside heating system and surface of partition wall on the side of greenhouse, J
- Q_{hg} thermal radiation exchange of glass enclosure with rock bed and other wall in greenhouse, J
- Q_{hr} thermal radiation exchange of rock bed surface with the enclosure in greenhouse, J
- Q_{hw} thermal radiation exchange of partition wall with rock bed and glass enclosure in greenhouse, J
- Q_{sky} thermal radiation exchange between glass enclosure of greenhouse and sky, J
- Re Reynolds number
- V volume of greenhouse and heating room, m^3

References

- 1 William C.Dickinson et al. Solar Energy Technology Handbook. 1980. 130-131. New York.
- 2 D. A. S. Rees. The onset of Dary-Brinkman convection in a porous layer: an asymptotic analysis. Int. J. Heat Mass Transfer. 2002, 45: 2213-2220.
- 3 H. Iacovides and M. Raisee. Computation of flow and heat transfer in two-dimensional rib-roughened passages, using low-Reynolds-number turbulence models. International Journal of Numerical Methods for Heat & Fluid Flow. 2001,11:138-155.
- 4 Ma Qing-Fang (1986), Practical thermal physical property handbook, pp701-710. The Chinese Agriculture Mechanics Press. In Chinese.