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STUDY ON HEAT TRANSFER CHARACTERISTICS OF A VOLUMETRIC SOLAR RECEIVERS

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ABSTRACT

In this paper, study on a volumetric receiver which use for solar energy season storage and heating system. This type of volumetric receiver has a high heat capacity, so that volumetric receiver can be ensured under severe weather conditions. In order to provide a reference for design and modification of volumetric receiver, the heat transfer characteristics of the volumetric heat absorber are studied. The influence of extinction coefficient and wind speed on the heat transfer characteristics of the volumetric receiver is analyzed by single factor analysis.

Keywords: volumetric receiver, high heat capacity, heat transfer characteristics

Symbols	*Interpretation*
A	Area (m^2)
c	specific heat (J/(kg•°C))
d_{ab}	equivalent particle diameter (m)
d_p	average pore diameter (m)
r	thickness(m)
v	velocity(m/s)
L_1	receiver height (m)
L_2	receiver width (m)
L_3	receiver length (m)
I	thermal flux (W/m^2)
Greek characters	
α	absorption rate
α_{sf}	surface area density(m^{-1})
β	extinction coefficient
γ	reflectivity
ρ	density(kg/m^3)
λ	thermal conductivity(W/(m•°C))
t	temperature (°C)
ε	porosity
h	heat transfer coefficient(W/(m^3·℃))
h_v	volumetric heat transfer coefficient (W/(m^3·℃))

Dimensionless numbers	
Nu	Nusselt number
Ra	Rayleigh number
Pr	Prandtl number
Re	Reynolds number
Gr	Grashof number
Subscripts	
g	glass window
a	air
ab	porous ceramic absorber panel
w	water
Abbreviations	
DNI	direct normal irradiance(W/m^2)

1.INTRODUCTION

In the solar heat storage and heating system by using the season storage body, the temperature stratification of the season storage body is beneficial to improve the system performance of the solar heat storage and heating system[1-2]. In order to improve the temperature stratification of the seasonal storage body in the tower solar energy season storage and heating system, Zhifeng Wang et al. proposed a volumetric receiver which use in tower solar collector system with a higher heat capacity. This volumetric receiver has a high heat capacity, so it can ensure the outlet temperature of volumetric receiver under complicated weather conditions, and is favorable for temperature stratification of the season storage body.

At present, there are few related researches on such volumetric receiver. Therefore, in order to provide reference for the design and modification on volumetric receiver, a one-dimensional unsteady model of volumetric receiver is established. The model is solved by MATLAB software, and the influence of glass extinction coefficient and wind speed on the heat transfer characteristics of the volumetric receiver was analyzed.

2. MODELLING

2.1 Physical model

The physical structure of the volumetric receiver studied in this paper is shown in Fig. 1. The volumetric receiver is composed of a glass window, porous ceramic absorber panel, a supporting structure and an insulating layer.

When the volumetric receiver is working, the focused solar radiation is incident on the volumetric receiver, part of the solar radiation is absorbed by the glass window and the absorber panel and converted into heat energy which is then transferred to the water by convection heat transfer. The remaining solar radiation passing through the glass window is directly absorbed by the water as internal energy of the water. The cold water enters the volumetric receiver from the bottom and is heated and discharged from the top of the volumetric heat absorber.

Therefore, when the volumetric receiver is working, the heat transfer process of the volumetric receiver mainly includes the absorption of incident solar radiation by the water, the glass window and the absorber plane. The convective heat transfer of glass window between the air and the water. The convective heat transfer between the absorber plane and the water. The heat conduction of the glass window and the absorber plane. Since the volumetric receiver is mainly used in a solar heating system and the working temperature is not high, the radiation heat exchange between the glass window, the absorber plane and the water can be neglected. The insulation is very good, so the convective heat loss between the insulation layer and the air can be neglected.

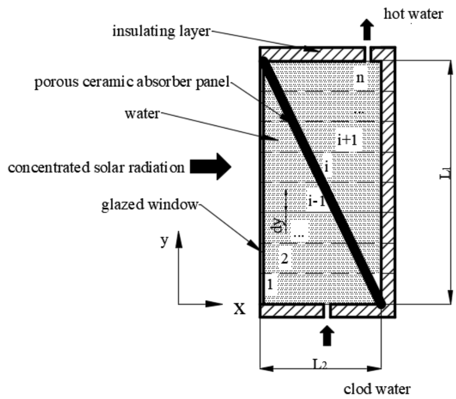


Fig.1 Physical structure of a volumetric receiver

2.2 Governing equations

A reduced-order unsteady model of a volumetric receiver was developed by simplifying the three-dimensional volumetric receiver design based on the following assumptions:

(1) The absorption of the solar insolation incident on the volumetric receiver can be described by a one-dimensional normal distribution in the y direction.

(2) The temperatures of the porous ceramic absorber panel, the glass window and the water are uniform in the x direction

(3) The surfaces are all adiabatic.

(4) The water flow inside the receiver can be modeled as plug flow.

With these assumptions, the energy equations for volumetric receiver can be given as:

For the glass window:

$$c_g \rho_g \frac{\partial t_g}{\partial \tau} = \lambda_g \frac{\partial^2 t_g}{\partial y^2} + \frac{h_{g,a}}{r_g}\left(t_a - t_g\right) + \frac{h_{g,w}}{r_g}\left(t_w - t_g\right) + \frac{I_g}{r_g}\left(1-\gamma_g\right)\left(1-e^{-\beta_g r_g}\right) \quad (1)$$

Where β_g is the extinction coefficient of the glass and r_g is the thickness of the glass. The γ_g is reflectance of the glass surface.

For the porous ceramic absorber panel:

$$(1-\varepsilon)c_{ab}\rho_{ab}\frac{\partial t_{ab}}{\partial \tau}=(1-\varepsilon)\lambda_{ab}\frac{\partial^2 t_{ab}}{\partial y^2} +h_v(t_w-t_{ab})+\frac{I_{ab}}{r_{ab}}\left(1-e^{-\beta_{ab}r_{ab}}\right) \quad (2)$$

For the water:

$$c_w\rho_w\left(\frac{\partial t_w}{\partial \tau}+v_w\frac{\partial t_w}{\partial y}\right)=\lambda_w\frac{\partial^2 t_w}{\partial y^2} +h_v(t_{ab}-t_w)+\frac{h_{g,w}}{r_g}(t_g-t_w)+\frac{I_w}{L_2}\alpha_w \quad (3)$$

In Eq.(1) the I_g is the solar radiant energy density incident on the glass window can be calculated as[3-4]:

$$I_g=\frac{A_{hel}}{A_g}DNI\frac{1}{\sqrt{2\pi(L_1^*/6)}}e^{-\frac{\left[y-(L_1/2+\mu)\right]^2}{2(L_1/6)^2}} \quad (4)$$

Where A_{hel} is concentrator field aperture area and A_g is glass window area. The L_1^* is dimensionless length and the μ is correction factor.

In Eq. (3) the I_w is the solar radiant energy density incident on the water can be calculated as:

$$I_w=I_g e^{-\beta_g r_g} \quad (5)$$

In Eq. (2) the I_{ab} is the solar radiant energy density incident on the absorber plane can be calculated as:

$$I_{ab}=I_w(1-\alpha_w) \quad (6)$$

In Eq. (2) the β_{ab} is the extinction coefficient of the porous ceramic absorber panel can be calculated as[5-8]:

$$\beta_{ab}=\frac{0.56}{d_{ab}} \quad (7)$$

Where d_{ab} is the average pore diameter of the porous ceramic absorber panel.

In Eq. (2) the h_v is the volumetric heat transfer coefficients of the porous ceramic absorber panel can be calculated by[9-10]:

$$h_v=\alpha_{sf}h_{sf} \quad (8)$$

Where α_{sf} is the surface area density of the porous ceramic absorber panel.

The volumetric heat transfer coefficient can then be calculated as:

$$\alpha_{sf}=\frac{20.346(1-\varepsilon)\varepsilon^2}{d_p} \quad (9)$$

$$d_v=\frac{4\varepsilon}{\alpha_{sf}} \quad (10)$$

$$h_{sf}=0.0035\left(\frac{d_v}{d_p}\right)^{0.35}\left(\frac{\lambda_f}{d_p}\right)Pr^{0.33}Re_d^{0.7089},\ Re_d\le 75 \quad (11)$$

$$h_{sf}=1.064\left(\frac{\lambda_f}{d_p}\right)Pr^{0.33}Re_d^{0.59},\ Re_d\ge 350 \quad (12)$$

Where d_p is equivalent particle diameter of the porous ceramic absorber panel.

when 75<Red<350, h_{sf} is obtained by linear interpolation of Eqs. (11) and (12). The R_{ed} is defined as：

$$Re_d=\frac{v_w d_p}{\nu_w} \quad (13)$$

In Eq.(1) and (3) the h is the convective heat transfer coefficient can be calculated by:

$$h=Nu\frac{\lambda}{l} \quad (14)$$

Where l is feature length of the glass window.

Since the glass window converts part of the solar radiation into heat energy, the influence of natural convection on convective heat transfer must be considered when calculating the convective heat transfer coefficient of the glass surface.

The reference [11-12] gives the basis for the judgment of mixed convection under the condition that both natural convection and forced convection exist simultaneously.

When $Gr_w/Re_w^2<0.1$, the effect of natural convection can be ignored. When $0.1\leqslant Gr_w/Re_w^2\leqslant 10$, the flow is in the mixed convection regime. When $Gr_w/Re_w^2>10$, the effect of forced convection can be neglected.

In the mixed convection condition, if forced convection is in the same direction as natural convection, the Nusselt number can be calculated as:

$$Nu=\sqrt[3]{Nu_n^3+Nu_p^3} \tag{15}$$

Where the Nu_n is the natural convection heat transfer coefficient can be calculated by[13]:

$$Nu_n=0.825+\frac{0.387Ra_l^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}} \tag{16}$$

And the Nu_p is the forced convection heat transfer coefficient can be calculated by:

$$Nu_p=0.664Re_l^{1/2}Pr^{1/3},\left(Re\le 5\times10^5, Pr\ge 0.6\right) \tag{17}$$

Boundary conditions and initial conditions are

$$\begin{cases}\frac{\partial t_g}{\partial x}=\frac{\partial t_w}{\partial x}=\frac{\partial t_{ab}}{\partial x}=0, & x=0\\ t_w=t_{w,in}, & x=0\\ \frac{\partial t_g}{\partial x}=\frac{\partial t_w}{\partial x}=\frac{\partial t_{ab}}{\partial x}=0, & x=L_1\end{cases}$$

$$t_g=t_w=t_{ab},\quad \tau=0 \tag{18}$$

2.3 Solution method and calculation parameters

In order to solve the receiver model, the volumetric receiver is first uniformly cut into several regions along the y direction, as shown in Figure 1. Using the control volume balance method [14], the corresponding equations in the model are integrated on each region of the volumetric receiver to discretize the energy balance equation. The calculation program is written by MATLAB software to solve the discrete energy balance equation.

In order to avoid the influence of other parameters other than the analysis object on the analysis results, in the following analysis process, the parameters involved in the model are unified, as shown in Table 1.

Table 1 parameters used in model

Item	Number
Wind speed （m/s）	6
inlet temperature （℃）	10
DNI （W^2/m）	600
air temperature （℃）	20
extinction coefficient of glass (m^{-1})	10
concentrator field aperture area(m^2)	738
flow rate (m^3/h)	6
receiver height L_1 (m)	1.9
receiver width L_2 (m)	0.738
receiver length L_3 (m)	2.88
thickness of glass r_g(m)	0.01
thickness of absorber panel r_{ab}(m)	0.02

3. RESULTS AND DISCUSSION

3.1 The thermal efficiency of the volumetric receiver

In order to study the thermal performance of the volumetric receiver, the thermal efficiency of the volumetric receiver is defined here to evaluate the thermal performance of the volumetric receiver. When the volumetric receiver is in steady state, the thermal efficiency of the volumetric receiver can be calculated as:

$$\eta_{rec}=\frac{\int_{\tau 1}^{\tau 2} c_w \dot{m}_w \left(t_{w,out}-t_{w,in}\right)d\tau}{\int_{\tau 1}^{\tau 2}\left(\int_0^{L_1} I_g dy\right)d\tau} \tag{19}$$

3.2 The Effect of glass extinction coefficient

The Fig.2 shows the temperature distribution of the glass window under six different glass extinction coefficients when the other parameters are the same.

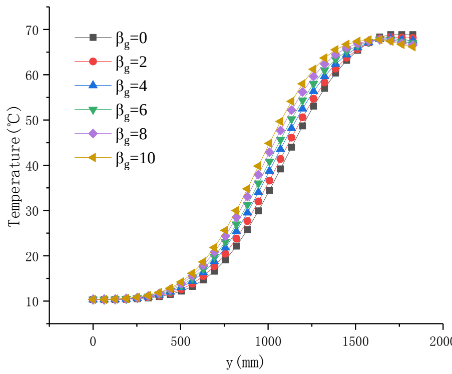


Fig.2 temperature distribution of the glass window

As shown in Fig 2， when the extinction coefficient of the glass is 0 m^{-1}, the average temperature of the glass window is 37.5 °C, and the maximum temperature of the glass window is 68.9

°C. As the glass extinction coefficient increases, the average temperature of the glass window also increases, but the maximum temperature has dropped. When the extinction coefficient of the glass is increased to 10 m^{-1}, the average temperature of the glass window is 41.6 °C, which is increased by 4.1 °C; the maximum temperature of the glass window is 67.8 °C. It dropped by 1.1 °C.

The Fig.3 shows the temperature distribution of the water under different glass extinction coefficients when the other parameters are the same. It can be seen from Fig.3 that as the glass extinction coefficient increases, the average temperature and the maximum temperature of the water will decrease. When the extinction coefficient of the glass is 0 m^{-1}, The average temperature of the water is 34.9 °C, the maximum temperature of the water is 69.2 °C; when the extinction coefficient of the glass is increased to 10 m^{-1}, the average temperature of water is 33.4 °C, which was reduced by 1.5 °C; the maximum temperature of the water is 65.5 °C, which dropped by 3.7 °C.

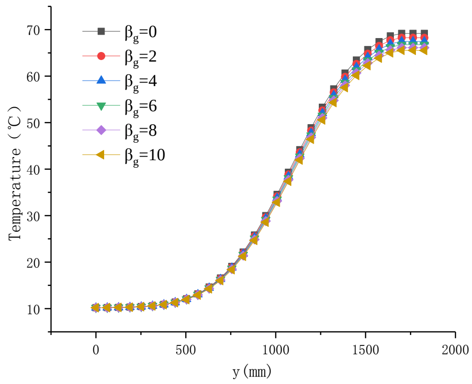


Fig.3 temperature distribution of the glass window

The Fig.4 shows the effect of the extinction coefficient of glass on the convective heat transfer coefficient of the glazing surface.

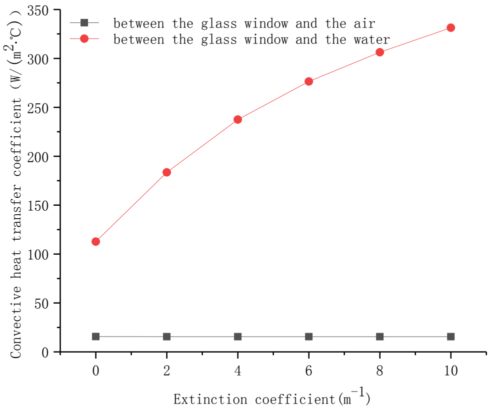


Fig.4 The effect of the extinction coefficient of glass on the convective heat transfer coefficient

It can be seen from Fig.4 that as the extinction coefficient of glass increases, the convective heat transfer coefficient between the water and the glass window increases, but the convective heat transfer between the glass window and the air is almost unchanged. When the extinction coefficient of glass is 0 m^{-1}, the convective heat transfer coefficient between the water and the glass window is 112 W/(m^2•℃), when the extinction coefficient of glass is increased to 10 m^{-1}, the convective heat transfer coefficient between the water and the glass window rises to 331 W/(m^2•℃).

As shown in Fig.5, the efficiency of the volumetric receiver decreases with the increase of the extinction coefficient of glass. When the extinction coefficient of the glass is 0 m^{-1}, the thermal efficiency of the volume receiver is 92.2%; When the extinction coefficient of the glass increase to 10 m^{-1}, the thermal efficiency of the volumetric receiver is 86.1%, decrease of 6.1 percentage points.

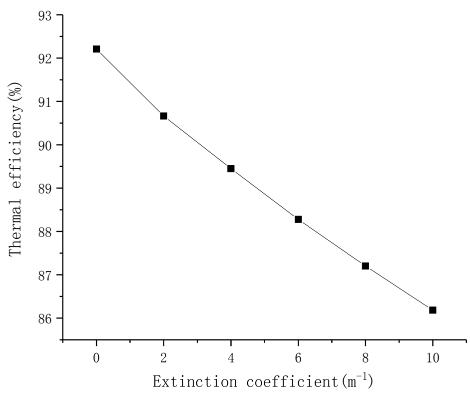


Fig.5 Effect of extinction coefficient on thermal efficiency

3.3 The Effect of glass extinction coefficient

The Fig.6 shows the temperature distribution of the glass window under different wing speeds when the other parameters are the same.

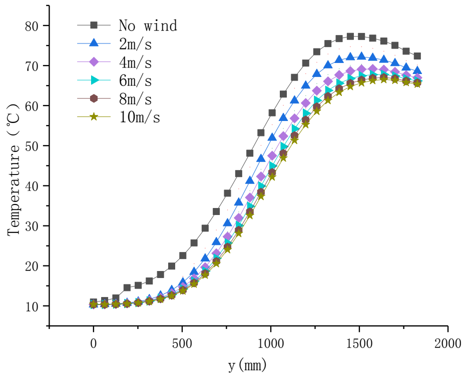


Fig.6 Effect of wind speed on temperature distribution of the glass window

It can be seen from Fig.6 that as the wind speed increases, the average temperature and the maximum temperature of the glass window will decrease. In the absence of wind, the average temperature of the glass window is 47.5 °C, and the maximum temperature of the glass window is 77.3 °C. When the wind speed is increased to 10 m/s, the average temperature of the glass window is 37.2 °C, which is decreased by 10.3 °C. The maximum temperature of the glass window is 66.5 °C, which is decreased by 10.8 °C.

The Fig.7 shows the temperature distribution of the water under different wind speeds when the other parameters are the same. As shown in Fig. 6 that the average temperature and the maximum temperature of the water decrease as the wind speed increases. The average temperature of the water inside the volumetric receiver is 35.1 °C and the maximum temperature of the water inside the volumetric receiver is 69.6 °C under the absence of wind; when the wind speed is increased to 10 m/s, the average temperature of water is 33.1 °C, which is decreased by 2.0 °C; the maximum temperature of water is 64.9 °C, which is decreased by 4.7 °C.

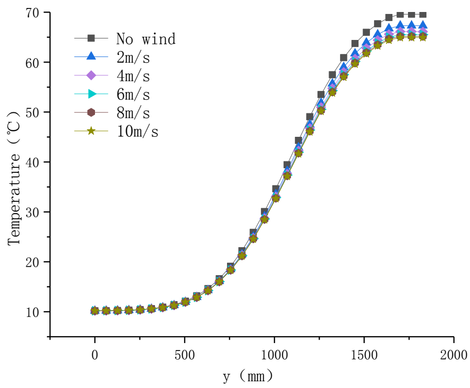
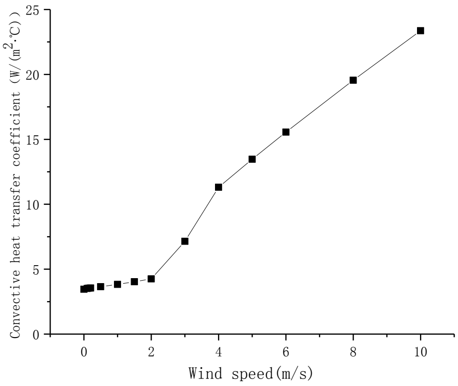
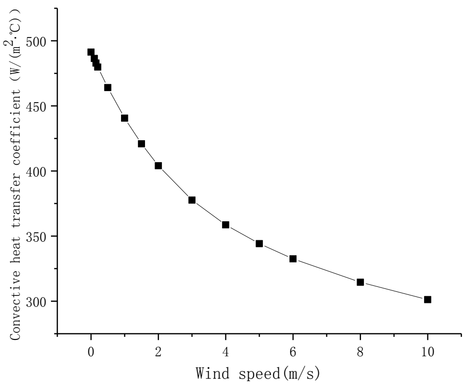


Fig.7 Effect of wind speed on temperature distribution of the water

The Fig.8 shows the effect of the wind speed on the convective heat transfer coefficient of the glass window surface.



(a) The effect of the wind speed on the convective heat transfer coefficient between the glass window and the air



(b) The effect of the wind speed on the convective heat transfer coefficient between the glass window and the water

Fig 8 The effect of the wind speed on the convective heat transfer coefficient

It can be seen from Fig. 8(a) that when the wind speed increases, the convective heat transfer coefficient between the glass window and the air increases. When the wind speed is 1 m/s, the convective heat transfer coefficient between the glass window and the air is 3.8 W/(m^2•℃). When the wind speed is increased to 10 m/s, the convective heat transfer coefficient between the glass window and the air increases to 23.4 W/(m^2•℃). As shown in Fig.8(b) that when the wind speed increases, the convective heat transfer coefficient between the glass window and the water decreases. When the wind speed is 1 m/s, the convective heat transfer coefficient between the glass window and the water is 440 W/(m^2•℃). When the wind speed is increased to 10 m/s, the convective heat transfer coefficient between the glass window and the water drops to 301 W/(m^2•℃).

Fig.9 shows the effect of wind speed on the thermal efficiency of a volumetric receiver when the other parameters are the same. It can be seen from the figure that as the wind speed increases, the thermal efficiency of the volumetric receiver decreases. When the wind speed increases from 0 m/s to 6 m/s, the thermal efficiency of the volumetric receiver decreases by 6.7 percentage points. When the wind speed is greater than 6m/s, the influence of wind speed on the thermal efficiency of the volumetric receiver reduced. When the wind speed is increased from 6 m/s to 12 m/s, the thermal efficiency of the volumetric receiver is only decreased by 1.2 percentage points.

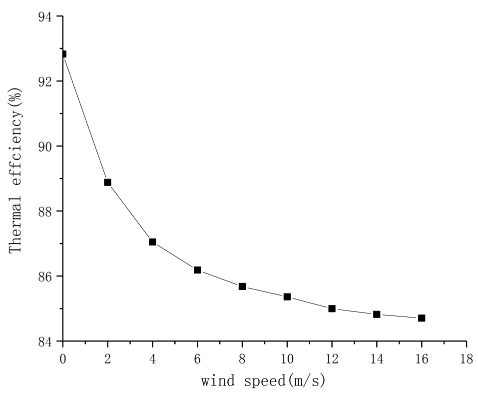


Fig.9 The effect of wind speed on the thermal efficiency

4. CONCLUSIONS

This paper analyzes a volumetric receiver with a high heat capacity and a one-dimensional unsteady model of volumetric receiver is established. The program was solved based on the MATLAB software. The effect of glass extinction coefficient and wind speed on the thermal performance of the volumetric receiver was analyzed by a one-dimensional unsteady model of volumetric receiver.

The thermal efficiency of the volumetric receiver decreases with the increase of the glass extinction coefficient, and the convective heat transfer coefficient between the glass window and the water increases with the increase of the glass extinction coefficient. When the extinction coefficient of glass increases from 0m^{-1} to 10m^{-1}, the thermal efficiency of the volumetric receiver decreases from 92.2% to 86.1%, and the convective heat transfer coefficient between the glass window and the water rises from 112 W/(m^2•°C) to 331. W/(m^2•°C).

The thermal efficiency of the volumetric receiver and the convective heat transfer coefficient between the glass window and the water decrease with the increase of the wind speed. When the wind speed increases from 0 m/s to 10 m/s, the thermal efficiency of the volumetric receiver decreases from 92.8% to 85.4% and the convective heat transfer coefficient between the glass window and water drops from 440 W/(m2•°C) to 301 W/(m2•°C).

In conclusion, a glass window made of a glass material having a low extinction coefficient can significantly increase the thermal efficiency of the volumetric receiver. Volumetric receiver have higher operating efficiencies when ambient wind speeds are low. The analysis results in this paper can provide reference for the design and operation strategy of volumetric receiver.

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