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INTERNAL HEAT AND MASS TRANSFER MECHANISM OF SOLAR CPC CONCENTRATOR ADSORBER BASED ON CFD SIMULATION

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Abstract: With the global energy crisis and increasingly serious environmental problems, solar adsorption refrigeration system has been widely concerned because of its environmental protection characteristics and advantages of using renewable energy. In this paper, a new type of solar CPC adsorption refrigeration system is designed. By establishing the CFD model of the adsorption bed and using the finite control volume method, the heat transfer characteristics of the refrigerant in the desorption process of the adsorption bed are simulated and calculated, and the flow characteristics of the refrigerant in the adsorption bed and its influence on the surrounding wall are analyzed according to the changes of the temperature, phase and flow rate of the refrigerant. The results show that the refrigerant near the outlet of the adsorption bed is more likely to absorb heat and desorb. The average velocity of mixed-phase refrigerant is around 1m/s at the transverse section of the pipeline, and the temperature near the wall in the adsorption pipe can reach 360K. In the longitudinal direction, the velocity near the outlet pipeline is faster, and a small area of turbulence appears at the upper side.
Keywords: Solar CPC; Adsorbent bed; Desorption process; Numerical simulation

1 INTRODUCTION

The effective use of solar energy resources to cope with global climate change, coordinate and realize human sustainable development has gradually become an increasingly important issue for human beings. Different from traditional compression refrigeration, solar adsorption refrigeration can effectively utilize solar radiation, without using HCFC and HFC refrigerants, without CFCs and greenhouse effect, and is more friendly to the environment. Adsorption bed is the core component of adsorption refrigeration and an indispensable part of physical processes such as adsorption and desorption of refrigerant. Its heat and mass transfer performance will determine the performance of the whole system. The adsorption bed is filled with adsorption working pairs (mainly zeolite-water, silica gel-water, activated carbon methyl alcohol, calcium chloride-water, etc.) in a certain shape of the shell, and the granular packed adsorption bed, that is, the characteristics of porous media, cause problems such as slow heat transfer process and long periodicity [1].

The traditional solar energy collection system will lose the solar radiation energy passing through the interlayer due to the vacuum interlayer, and it cannot be absorbed by the selective absorption coating in the pipe. The performance improvement of solar adsorption refrigeration is mainly through adopting different enhanced mass transfer to improve refrigeration efficiency. Some scholars have added fins to enhance heat transfer inside the adsorption bed or adopted a double-bed solar adsorption model. Although double-bed solar adsorption refrigeration effectively solves the problems of discontinuous refrigeration process, low power and long cycle, there are some problems such as unstable heat source and energy waste [2].

In this paper, a "light-heat-cooling" comprehensive energy-saving refrigeration system based on solar CPC concentrating adsorber with silica gel-water as working pair is established, and the heat and mass transfer characteristics of adsorption bed are studied by computational fluid dynamics. Through numerical analysis of the interaction of fluids and the variation of temperature field in the process of heat transfer, some theoretical basis is provided for the optimization of solar refrigeration.

2 DESIGN OF SOLAR CPC ADSORPTION REFRIGERATION SYSTEM

Combining concentrated photovoltaic with adsorption refrigeration technology can improve the efficiency and form a combined cooling and heating system, which is of great significance to alleviate energy shortage and reduce energy consumption [3-5]. Traditional solar adsorption refrigeration mostly depends on the pressure difference in the system, which belongs to natural mass transfer characteristics [6]. The circulation of high temperature and high pressure refrigerant desorbed from the adsorption bed in the mass transfer pipeline is mainly self-diffusion, and some scholars have made many contributions to the heat transfer enhancement of the adsorption bed [7]. In this paper, the heat transfer performance of the adsorption bed is numerically simulated with silica gel-water as the adsorption working medium. The filling height of the adsorption material is in the range of 70-100mm, and the overall design size of the adsorption bed should not be too large. In order to improve the heat and mass transfer performance of the adsorption bed and

reduce the heat and heat resistance of the adsorption bed, the size of the adsorption bed should be reduced as small as possible [8].
The size of the adsorption bed used in this simulation is shown in Figure 1, with a length of 1150mm and a width of 1150 mm. The single mass transfer pipeline is filled with the space in a circular tube with a diameter of 47-94mm, and the filling length is 1050 mm. The filling material is C-type silica gel, which is easy to form a composite working medium with $CaCl_2$, and its performance is better [9-10]. See Table 1 for its main physical parameters. The heat source is mainly provided by CPC concentrator using solar radiation energy, and can be supplemented by hot water system when the solar illumination is insufficient.

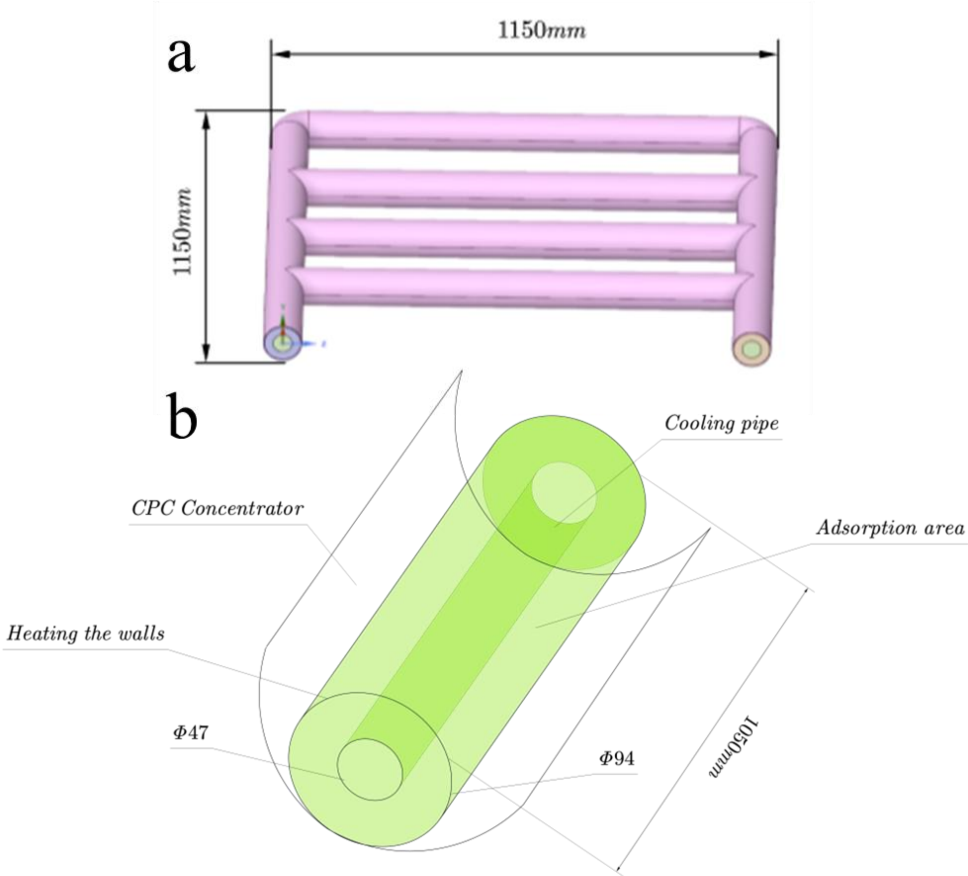
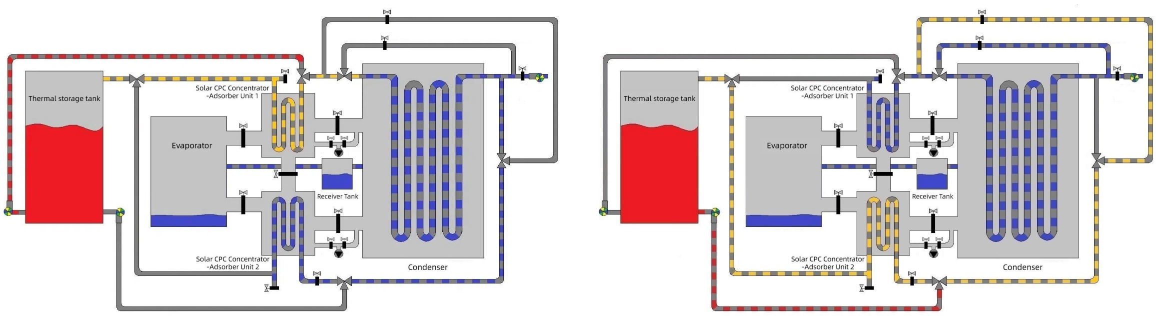


Figure 1 Three-Dimensional Effect Diagram of Adsorption Bed
(a) Schematic Diagram of Adsorption Bed; (b) Schematic diagram of a single adsorption tube

This project designs a refrigeration system based on solar CPC concentrator, which mainly includes two solar CPC concentrator, evaporator, condenser, air cooler, liquid storage tank, heat preservation water tank and micro vacuum pump. Two solar CPC condensing adsorbers work alternately, which can realize continuous cooling of the system during the day, and the supporting heat preservation water tank can store solar heat, which can provide heat for the system to work at night, thus realizing all-weather cooling of the system. Silica gel-$CaCl_2$ composite adsorbent is used in solar CPC concentrator, which can improve the adsorption capacity and capacity of the system and increase the refrigeration capacity of the system. At the same time, the system combines the dual operation strategy of natural-enhanced mass transfer, simplifies the system structure by adding some pipelines and equipment, effectively avoids the desorption of gas by low-temperature active adsorbent, and avoids the inevitable intermittent refrigeration problem in natural mass transfer mode. This system makes full use of solar energy through the compound parabolic concentrator, and combines with the compound adsorption mode to realize the effective utilization of low-grade energy, reduce the power consumption, relieve the power shortage, and has the dual functions of saving the environment.



(a) Desorption by adsorption bed 1 and adsorption by adsorption bed 2 (b) Desorption by adsorption bed 2 and adsorption by adsorption bed 1

Figure 2 Schematic Diagram of Adsorption and Desorption in Adsorption Bed

When one adsorption bed is heated for desorption, cooling water is introduced into the other adsorption bed to reduce the temperature for adsorption, and the heat source is directly supplied by solar energy. When rainy weather or night occurs, hot water in the heat preservation water tank provides heat for desorption, and a micro vacuum pump is installed in a pipeline between the condenser and the adsorption bed in parallel, so as to avoid reverse adsorption due to insufficient temperature, and at the same time, the mass transfer process can be enhanced and the refrigeration capacity can be increased. The inevitable intermittent refrigeration problem in the natural mass transfer mode is solved. During the alternation of two adsorption beds, the heat of the condenser is taken away by cooling water to preheat the adsorption beds, so that the working state can be switched faster and the energy utilization rate can be improved. The adsorption and desorption process of adsorption bed is shown in Figure 2 and Table 1.

Table 1 Various Performance Parameters of C-Type Silica Gel Selected in this Paper

grain size	specific surface area	Kong Rong	specific heat	Thermal conductivity	stacking density	True density
mm	*m^2/g*	*ml/g*	*KJ/(kg·K)*	*W/(m·K)*	*kg/m^3*	*kg/m^3*
0.6-1.5	700-800	0.40-0.50	0.92	0.175	750	2100

3 NUMERICAL MOFRL AND BOUNDARY CONDITIONS

Under the condition of sunlight, it is assumed that the intensity of solar radiation received by the outer wall of the CPC concentrating adsorption tube is uniform, and the outer wall of the adsorption tube is heated by a heat flow of 800W/m^2 [6]. The particles of adsorption working medium filled in the adsorption bed are evenly distributed, and there is no air thermal resistance between the particles, and the other walls are insulated.

3.1 Basic Conditions of Model

Here, the fractional equation, momentum calculation, energy conservation and mass conservation of fluid will be introduced respectively. Regarding the fluid volume fraction, implicit formula is used here in this study, and the volume fraction equation is discretized as follows:

$$\frac{a_q^{n+1}\rho_q^{n+1}-a_q^n\rho_q^n}{\Delta t}V+\sum_f\left(\rho_q^{n+1}U_f^{n+1}a_{qf}^{n+1}\right)=\left[S_{a_q}+\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)\right]V \tag{1}$$

Where $n+1=$ Current index time step; $n=$ The index of the previous time step; $a_q^{n+1}=$ Step n+1 of unit volume value of current volume fraction; $a_q^n=$ Unit volume value of volume fraction at current step n; $a_{qf}^{n+1}=$ Volume fraction of face value in time step$n+1q^{th}$; $U_f^{n+1}=$ The volume flux through the face is at time step n+1; $V=$ Unit volume.

In the aspect of momentum calculation, a single momentum equation is solved in the whole domain, and the generated velocity field is shared among all phases, and the momentum equation depends on the ergodic property sum of all stages.

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla p+\nabla\cdot\left[\mu\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)\right]+\rho\vec{g}+\vec{F} \tag{2}$$

The energy equation is satisfied in the process of interaction between phases:

$$\frac{\partial(\rho E)}{\partial t}+\nabla\cdot[\vec{v}(\rho E+p)]=\nabla\cdot\left[k_{eff}\nabla T-\sum_q\sum_j h_{jq}\vec{J}_{jA}+\left(\overline{\overline{\tau}}_{eff}\cdot\vec{v}\right)\right]+S_h \tag{3}$$

It is difficult to calculate the mass of a single phase when calculating the overall mass, so the average method is used to calculate the average mass variable instead of calculating the mass of a single phase.

$$E=\frac{\sum_{q=1}^{n}\alpha_q\rho_qE_q}{\sum_{q=1}^{n}a_q\rho_q} \tag{4}$$

$$E_q=h_q-\frac{p}{\rho_q}+\frac{v^2}{2} \tag{5}$$

The porous medium model is to add momentum source to the standard momentum equation, and the obstacles to the velocity are not expressed in the model. The velocity calculated in this area is the apparent velocity, and the porous medium area is regarded as completely open. The correlation coefficient is defined based on this assumption. For the calculation of porosity, using C-type silica gel (easy to compound with CaCl2 _ 2, etc. to form a better composite silica gel), the bulk density =400g/L and the real density = 1.12 g/cm, the porosity is:

$$\varepsilon\ =1-\frac{\rho_b}{\rho_p}\ =0.67 \tag{6}$$

Among them, the resistance source term f in the momentum equation is:

$$F=-\left(\sum_{j=1}^{3}D_{ij}\mu v_j+\sum_{j=1}^{3}C_{ij}\frac{1}{2}\rho|v|v_j\right) \tag{7}$$

Sticky term: $\sum_{j=1}^{3}D_{ij}\mu v_j$;

Inertia term: $\sum_{j=1}^{3}C_{ij}\frac{1}{2}\rho|v|v_j$;

$$\frac{\Delta P}{L}=\frac{150\mu(1-\varepsilon)^2}{D_p^2\ \varepsilon^3}v+\frac{1.75\rho(1-\varepsilon)}{D_p\varepsilon^3}v^2 \tag{8}$$

ErgunEquation is used to deduce the input of porous media:

Viscous resistance coefficient: $D_{ij}=\frac{1}{\alpha}=\frac{150(1-\varepsilon)^2}{D_P^2\varepsilon^3}$

Inertia resistance coefficient: $C_{ij}=C_2=\frac{3.5}{D_P}\frac{(1-\varepsilon)}{\varepsilon^3}$ (Equivalent Sphere Diameter)

3.2 Boundary Conditions and Initial Conditions

In the adsorption process, the heating wall is used to exchange heat with the adsorbent, and the other walls are set as adiabatic walls. The solid material is copper, and the heat transfer fluid medium is steady incompressible water, and its physical parameters are constant at the equivalent temperature. The inlet of heat transfer fluid adopts velocity boundary condition and the outlet adopts pressure boundary condition. Coupled heat transfer calculation is used for internal measurement pipeline and wall.

Initial conditions for heating wall temperature of adsorption bed:

$$T(x,y,z)|_{t=0}=348K \tag{9}$$

Initial conditions for calculating regional pressure:

$$P_b(x,y,z)|_{t=0}=0Pa \tag{10}$$

4 ANALYSIS OF CALCULATION RESULTS

In the model, the initial time step is set to 1e-5s, and the Adaptive type and Multiphase-Specific method are selected. When the step is 83000, the flow is stable, and the parameter characteristics at this moment are selected.

4.1 Transverse Characteristics of Refrigerant

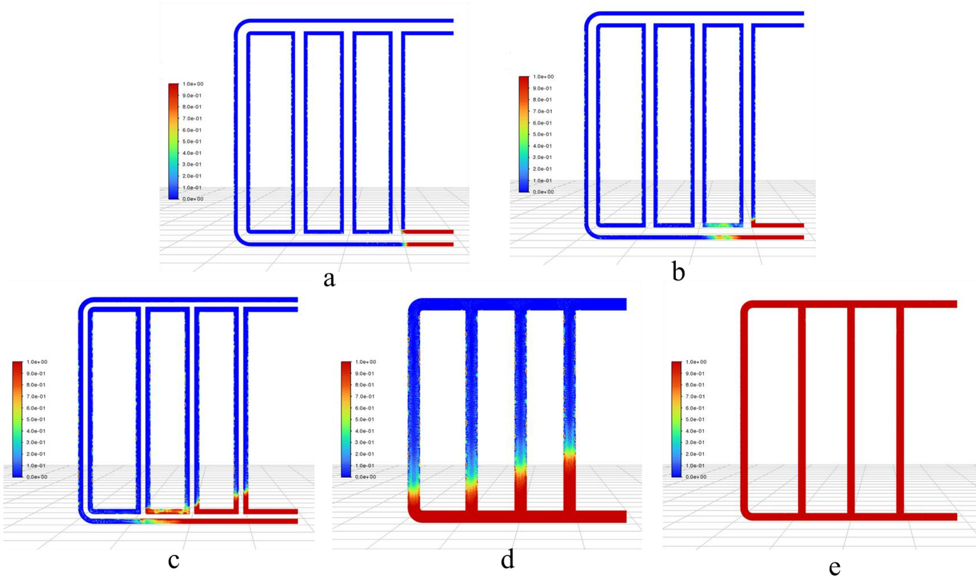


Figure 3 Steam distribution

In the model, the Y-axis is 0mm as the datum, and five positions are taken at intervals of 10mm upward. Figure 3 reflects the distribution of refrigerant vapor during desorption at this time. In the adsorption area, due to the poor thermal conductivity of the adsorbed working medium, the working medium in the upper position is more likely to absorb heat and desorb during heating. Compared with the inlet position, the working medium in the pipeline near the outlet is more likely to absorb heat and evaporate, and at the same time, the refrigerant vapor is generated near the wall and gradually converges to the outlet pipeline by small bubbles.

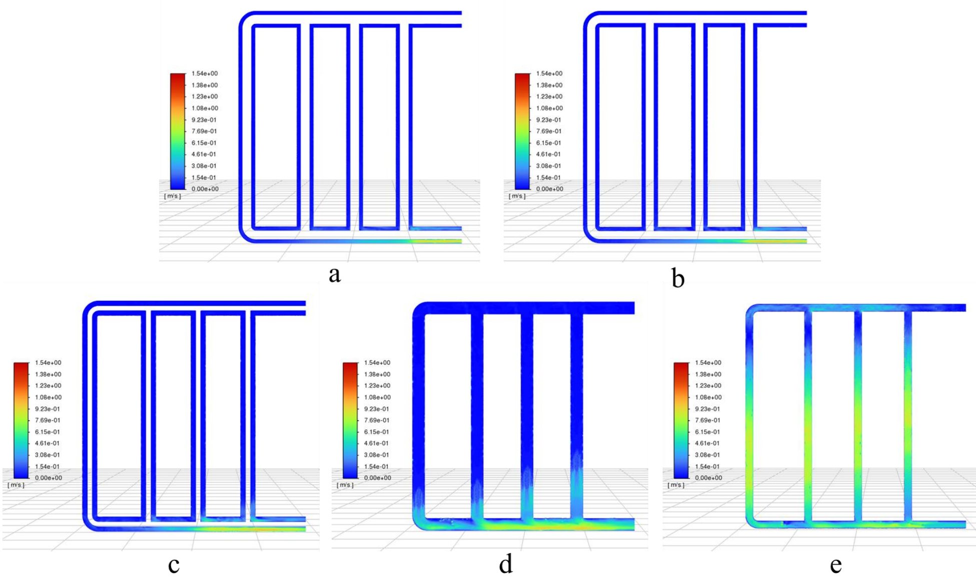


Figure 4 Velocity Distribution of Mixed Phase

Figure 4 shows the velocity distribution of two-phase mixture of refrigerant. The flow characteristics of working medium are consistent with the distribution of steam state. The more intense the desorption of working medium is, the faster the flow rate of steam is compared with other positions. At the upper position of the pipeline in the adsorption area, the working fluid velocity is closer to the inlet of the pipeline than the outer pipeline, which may be caused by the pressure difference. The maximum velocity of the mixed phase can reach 1.54m/s, and the average velocity is around 1 m/s.

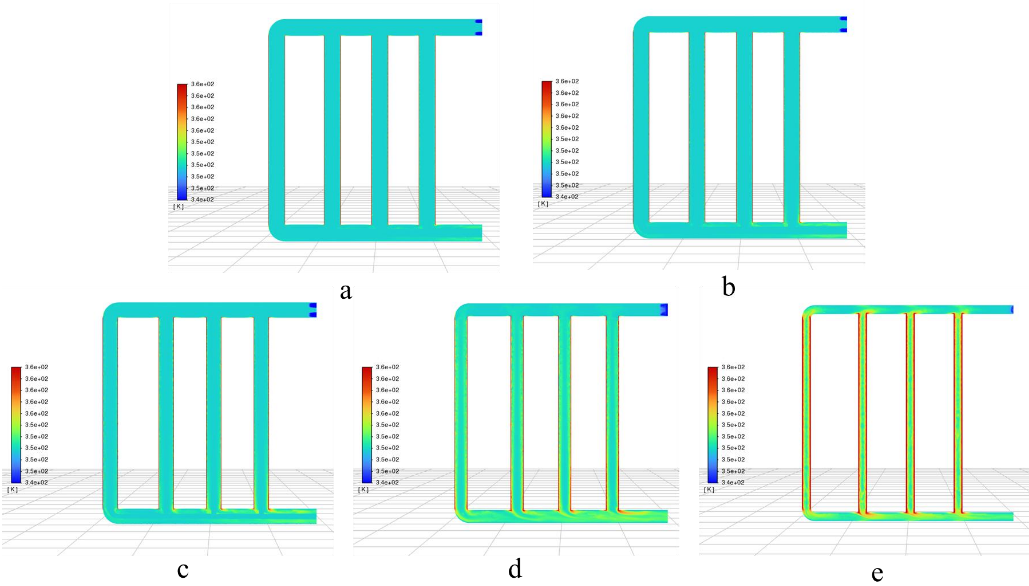


Figure 5 Mixed Phase Temperature Distribution

Figure 5 shows the temperature distribution of the mixed phase in the mass transfer pipeline. Because of the low thermal conductivity of the material, the desorption process of refrigeration wages mostly occurs near the upper wall of the pipeline. How to increase the heat transfer effect and enhance the thermal conductivity of the material is also the main research direction at present. It is worth noting that when the position is in the middle and upper part of the adsorption bed, the temperature near the second tube wall intersects with other tube walls higher, which may be caused by the flow of working fluid in the tube, that is, the change of pressure in the surrounding tube enhances the disturbance of fluid in the middle tube, and then enhances the heat transfer effect.

4.2 Longitudinal Characteristics of Refrigerant

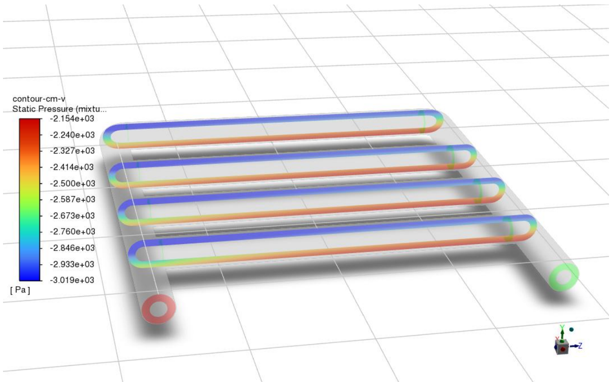
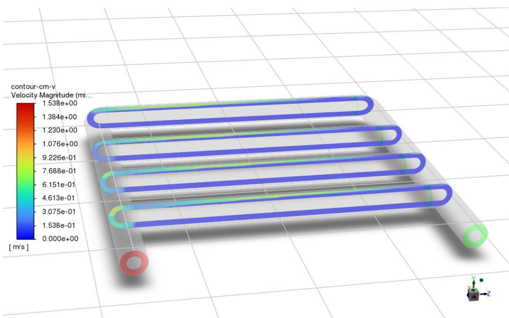


Figure 6 Pressure Distribution

Based on the center of each pipeline, four positions are separated. Figure 6 shows that the pressure distribution of the longitudinal mass transfer pipeline is high in the lower side and low in the upper side, and the side with higher pressure closer to the Z axis is more inclined to the entrance. Therefore, when optimizing the characteristics of the adsorption bed, it is considered to design the pipeline materials in different regions to save costs.



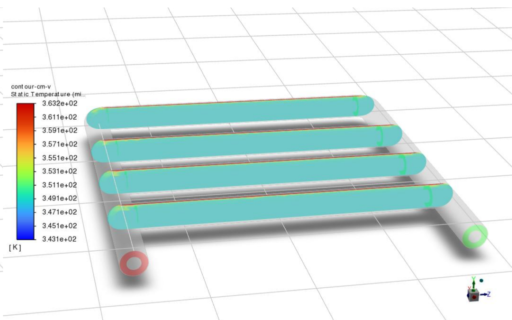


Figure 7 Velocity Distribution **Figure 8** Temperature Distribution

Figure 7 and Figure 8 respectively show the velocity and temperature of the mixed phase in the mass transfer pipeline in the longitudinal direction. The velocity in the middle of the pipeline is higher at the upper side, and the velocity near the left wall of the outlet pipeline is relatively higher, which is due to the change of fluid velocity caused by the shape of the pipeline, and the longitudinal temperature distribution in each pipeline is similar, which is mainly heat transfer at the upper side. When making pipeline materials, the influence of material deformation on the upper and lower surfaces due to different heating should be considered.

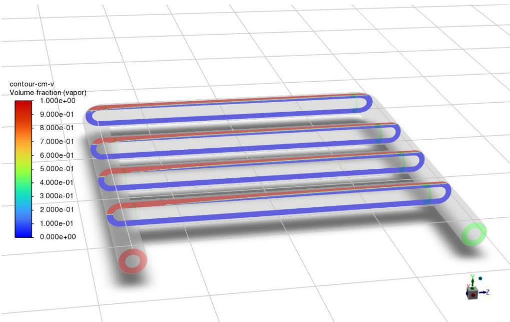


Figure 9 Steam Distribution

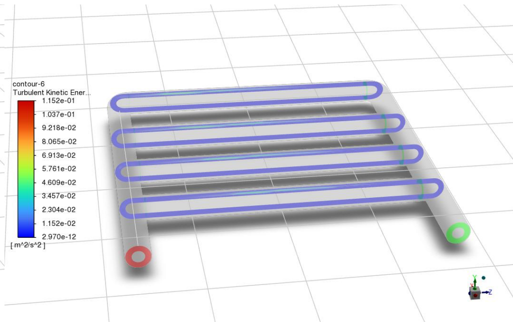


Figure 10 Turbulence Situation

Figure 9 shows the distribution of refrigerant vapor in the longitudinal direction, and fig. 10 shows the turbulent distribution in the longitudinal direction. In the longitudinal position of the middle pipeline, the desorption of refrigerant on the upper side of each pipeline is almost the same, but there is a small area of turbulence in the middle part. The turbulence in the pipeline closer to the inner side is closer to the middle of the pipeline, and this position is affected by the pressure in the whole area. When considering the size of the adsorption bed and the number of mass transfer pipelines, it should be selected by measuring the change of pressure in the pipeline to enhance efficiency.

5 CONCLUSION

During the operation of the system, in the transverse direction, the refrigerant near the outlet of the adsorption bed is more likely to absorb heat and desorb, and at the same time, under the action of pressure difference, the maximum flow rate of the refrigerant is closer to the outlet pipeline when it goes to the outside, while the temperature distribution is higher when it is close to the upper side of the pipeline. In the longitudinal direction, the pressure in the pipeline is in a state of low and high, which is beneficial to the flow of refrigeration steam, while the velocity is higher at the outer side wall of the outlet pipeline. The desorption rate of longitudinal refrigerant in each pipeline is almost the same, and turbulence appears in the middle of the pipeline. Due to the influence of pressure, the turbulence position of the outer pipeline is close to the outlet pipeline.

Based on computational fluid dynamics, supplemented by CFD, this paper provides an idea and framework for studying the change process of characteristic parameters of solar adsorption refrigeration during operation, and how to choose a suitable plane to show the change process. By showing the system designed in this paper, it proves the feasibility of applying this idea to explore the process of solar adsorption refrigeration. On this basis, the follow-up research on the operating characteristics of adsorption refrigeration system can be carried out in this way, and other refrigeration methods can also follow this method to understand the internal characteristics of the system, providing a basis for the real construction of the system.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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