Effect of molten salt phase change layer on thermal performance of solar vacuum collector

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Abstract: A novel straight through vacuum solar energy collector with molten salt phase change thermal storage layer was proposed. Solar salt (60% NaNO₃-40% KNO₃) was used as phase change materials (PCMs), and the effect of phase change material layer on the thermal performance of straight-through type vacuum solar energy collector has been studied numerically. The results show that: A 13 mm thick phase change material layer was added to the collector tube with an outer diameter of 17 mm, and the heat storage was increased by 53.57%; when the solar radiation is stopped, a constant temperature of 4min-16min is maintained, and then the temperature drops more slowly than that without addition. Molten salt phase change layer can significantly reduce the influence of solar cycle and instability on the straight-through solar vacuum collector tube.

1. Introduction
Solar thermal technology has been widely studied by domestic and foreign researchers in recent years due to its advantages of clean, pollution-free, renewable and nearly infinite resource reserves[1]. The heat collection effect of the straight-through solar vacuum collector tube is affected by the intensity of light, the alternations of day and night, the seasonal changes of climate, and the differences of geographical location, which has the defects of discontinuity and instability of heat collection. Different explorations have been conducted at home and abroad, and sensible heat storage materials such as water, sand, ceramics and concrete have been used successively to improve the thermal performance of solar collectors [2]. However, these materials have limited heat storage capacity in limited space, so it is particularly important to develop and utilize phase change heat storage materials. The phase change heat storage material can realize the heat storage and release by its own reversible phase change reaction, thus improving the low efficiency of the current solar collector tube and effectively alleviating the current energy shortage. In recent years, phase change materials have been widely used in the field of solar energy. The latent heat absorption and release energy during phase change are very considerable, which greatly improves the heat storage effect.

At present, domestic and foreign researchers have carried out many researches from the aspects of the preparation of the ratio of multiple mixed molten salts of phase-change heat storage materials and the addition of nanoparticles to enhance the thermal and physical properties of HTF. D.L. Ling et al. [3] studied the solar heating performance of phase change heat storage. Tests and analyses were carried out to obtain useful energy and thermal efficiency of the system. ALEXANDER et al. [4] showed that the binary molten salt of 40%KNO₃-60%NaNO₃ as the heat transfer medium had good thermal stability below 727.55 K, while the heat storage medium was 53%KNO₃-40%NaNO₂-7%NaNO₃ ternary nitrate molten salt, and the upper limit temperature of molten salt was 723.15K. D. KEEARNEY et al. [5] also studied and
determined that the upper limit temperature of molten salt was 808.15K. Kaygusuz K[6], Jiang et al. [7] studied the application of phase change material CaCl₂·6H₂O in the solar heat pump system, and the study showed that the phase change heat storage technology had better heating performance, especially the solar heat pump system at night has better heating performance. Nallusamya[8] selected paraffin as a phase change material, and Eman-Bellah et al. [9] added aluminum powder in paraffin as a phase change material. The performance of the system was improved through latent heat storage of solar energy for the utilization of the heat pump. However, the system utilized sensible heat of water to transfer solar energy, and then stored and transferred to the heat pump system through phase change material, multistage heat transfer has great heat loss.

In this paper, the phase change material and collector are combined directly, which has more advantages than setting up heat storage device and collector respectively. Using solar salt (60% NaNO₃-40% KNO₃) as phase change heat storage material, it has the advantages of large heat capacity, wide use temperature, strong thermal stability, low price and so on, and is suitable for phase change materials in medium and high temperature environment. The phase transition temperature of the molten salt used in the simulation is 486.75K, and the molten salt has a small mass loss rate in the working environment, which can play a role in long-term stability. In this paper, the effect of adding phase change heat storage material layer on the temperature field of a straight through solar vacuum collector tube is studied by numerical simulation.

2. Numerical simulation and calculation method

2.1 Mathematical Model

The simulation mainly involves three physical fields, namely fluid heat transfer, solid heat transfer and phase change heat transfer. Solid heat transfer is suitable for the inner and outer wall heat transfer of stainless steel tube. Phase change heat transfer is suitable for heat transfer in molten salt phase change layer. In the physical field of solid heat transfer, the following equations are used to simulate the solid heat transfer:

\[
\frac{\partial v}{\partial t} = \text{div}(Uv) = k\left(\frac{\partial v}{\partial x^2} + \frac{\partial v}{\partial y^2} + \frac{\partial v}{\partial z^2}\right) = k(u_{xx} + u_{yy} + u_{zz})
\]

where \(\frac{\partial v}{\partial t}\) is the rate of change of temperature over time at a point in space, K/s; \(u_{xx}\), \(u_{yy}\) and \(u_{zz}\) are the second derivatives of temperature with respect to three spatial coordinate axes; \(k\) is the thermal diffusivity, which depends on the material's thermal conductivity, density and heat capacity, m²/s.

There is a working medium flow in the stainless steel tube. The following equation is used to simulate the fluid heat transfer:

\[
\frac{\partial (\rho v)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho v)}{\partial z} = 0
\]

where \(v\), \(V\), \(\omega\) are the velocity of the micro element hexahedron in three directions, m/s.

2.2 Physical Model

In the numerical simulation, the straight-through solar vacuum collector tube model using solar salt as working medium was simplified, and the three dimensional model was simplified into a two-dimensional axisymmetric model, as shown in Figure 1.
In the heating process of the straight through solar vacuum collector tube, the selective absorption coating on the stainless steel surface receives the radiation $q$ from the sun, and the heat conduction from the stainless steel outer wall to the inner wall, and finally the heat is transferred to the air by means of heat convection, and with the air flow out of the tube; During the cooling process, the solar radiation intensity is 0 W/m$^2$, the heat stored in the stainless steel tube passes the heat to the air by means of heat convection, so as to achieve the purpose of cooling; When the straight-through solar vacuum collector tube with phase change material is heated, the selective absorption coating is placed on the surface of the phase change material layer, and after absorbing solar radiation, the heat is stored in the phase change material layer. The specific heat capacity of solar salt is relatively large, and the phase transition will occur when the temperature of the salt layer reaches 486.75K. At this time, the phase change material layer has great latent heat storage capacity. When the solar radiation intensity fluctuates and disappears, the heat in the phase change material layer will continue to supply the heating fluid in the tube, which overcomes the defect of solar discontinuity.

The molten salt used in this paper has a phase transition temperature of 486.75 K, a phase transition latent heat of 119.66 kJ/kg, a decomposition temperature of 825.01 K, a maximum operating temperature of 823.15 K, and an optimal operating temperature of 773.15 K. At this temperature, molten salt has a mass loss rate of less than 1.01% and can play a role in long-term stability.

2.3 Boundary and initial conditions
In this paper, a two-dimensional axisymmetric model is used for numerical simulation. Solid heat transfer physical field and laminar physical field are coupled. Moreover, incompressible fluid is assumed to be the working medium for heat transfer in the tube. The entrance is set as the speed entrance; Not taking into account the effects of gravity; Stainless steel tubes are not considered to radiate heat transfer working medium. The structure parameters and model boundary conditions of the simplified straight through solar vacuum collector tube are as follows:

(1) Straight through solar vacuum collector tube length L=630mm, stainless steel heat exchanger tube inner diameter $a=10$mm, outer diameter $b=17$mm, phase change material layer thickness $c=13$mm, shape belongs to fine long type ($b + c < 0.5$ L).
(2) Initial conditions of the straight through solar vacuum collector tube in the heating stage: axial flow rate $V_{in}=0.6\text{m/s}$, initial ambient temperature $T_0 = 287\text{K}$, solar radiation intensity $q = 300\text{W/m}^2$, initial temperature of the working medium in the tube is the same as the ambient temperature $T_0$.

(3) Solar salt ($60\%\text{ NaNO}_3-40\%\text{ KNO}_3$) is selected as the phase change layer heat storage material in this paper. Its basic physical parameters change with the change of temperature. When the temperature increases, molten salt changes from solid to liquid, and its liquid rate satisfies the subsection function in Table 1:

| Start (K) | End (K) | Function |
|-----------|---------|----------|
| 0         | 476.78  | 0        |
| 476.78    | 529.21  | $(T-529.21)/52.43$ |
| 529.21    | 1000    | 1        |

3. Results and analysis

3.1 Influence of molten salt on the temperature distribution of tube diameter center bus

Figure 2 shows the temperature change of the straight-through solar vacuum collector tube bus heated for 4h under the condition of no molten salt phase change layer. Figure 2 (a) shows that from the heating stage of 0min-210min, the temperature of working medium in the tube keeps rising, but the average temperature of working medium in the tube of 240 min is lower than the average temperature of working medium in the tube of 180 min. According to Stefan-Boltzmann's law, the total power radiated per unit area of a black body surface in per unit time is directly proportional to the fourth square of the thermodynamic temperature $T$ of the black body itself. This shows that with the continuous temperature rise of the working medium in the tube, the heat dissipated in the tube is also increasing exponentially, so the temperature is going to go down later. By comparing Figure 2(a) and (b), it can be found that the temperature rise slope of the straight-through solar vacuum collector tube with molten salt phase change layer added is smaller than that of the straight-through solar vacuum collector tube without molten salt phase change layer added in the heating stage. Moreover, the temperature in the heating stage of 0min-240min has been steadily rising without a downward trend. That shows after adding molten salt phase change layer, outside the selective absorption of solar energy by phase change layer coating absorbed first passed to the molten salt phase change layer, this paper adopted by the binary nitrate molten salt heat capacity is bigger, small coefficient of thermal conductivity is relatively stainless steel [10], leading to early warming less add molten salt phase change slightly lower layer of the straight tube collectors. In the later stage, the temperature rises steadily and does not decrease. This is because the addition of molten salt phase transition layer is equivalent to an additional layer of insulation with low thermal conductivity, which effectively reduces the heat loss.
3.2 The influence of adding phase change heat storage layer on the temperature on the axial section

Figure 3 shows the temperature change with time at the three-dimensional intersection point of a straight-through solar vacuum collector tube heated for 4h and cooled for 2h under the condition of no molten salt phase change layer. Seven three-dimensional intercept points were defined, with coordinates point 1 (0,0,0), point 2 (0,0,0.1), point 3 (0,0,0.2), point 4 (0,0,0.3), point 5 (0,0,0.4), point 6 (0,0,0.5), and point 7 (0,0,0.6). By comparing Figure. 3(a) and (b), it can be found that (a) the temperature change rate during heating and cooling process is relatively large, and the temperature inflection point of all 3D cut-off points is 216min. The image in (b) is relatively flat compared with that in (a). When the heating was stopped, the constant temperature of each intercept point was maintained at 315.87K-356.45K for 4min-16min, respectively. In (b), the temperature inflection point of intercept point 2 was 251min, and that of intercept point 3, 4, 5, 6, 7 was 245 min, 246 min, 248 min, 249 min, and 254 min, respectively. Relative to the inflection point of the three-dimensional temperature image at the cut-off point in (a), In (b), the inflexion point of each three-dimensional intercept image has different degrees of right shift. This is because the phase change heat storage material layer by phase change store a lot of heat in the molten salt layer, although phase change after heating has stopped outside layer of selective absorption coating to absorb energy from the sun no longer, but phase transition layer in the store has a lot of heat, can continue to heat the working medium, after the stop heating, the temperature will not drop immediately. Therefore, the inflexion of the three-dimensional intercept image in (b) moves to the right relative to the image in (a). As shown in Figure. 4, after heating for 4 hours and cooling for 2 hours, the phase transition molten salt layer in the back part of the tube still maintains a temperature of 364K-375.2K. The molten salt phase transition layer has low thermal conductivity and good buffering effect on the periodicity and discontinuity of solar energy. Therefore, the image in (b) is more gentle than that in (a), which greatly extends the heat release stage of medium and high temperature [11]. By comparing the temperature curves at each point in Figure. 3(a) and (b), the area enclosed by the temperature curve in (b) is larger than the area enclosed by the temperature curve in (a), and the heat storage can be increased by 53.57% at most in the same period. This indicates that the straight-through solar vacuum collector tube can store more heat under the same condition after adding phase change material layer.

![Figure 3 Instantaneous temperature change at 3D intercept point after 4h heating and 2h cooling](image-url)
Figure. 4 Temperature field of the collector tube after 4h heating and 2h cooling

4. Conclusion
The influence of the molten salt phase change material layer on the performance of the straight through solar vacuum collector tube was analyzed and compared by numerical simulation, and the following conclusions were drawn:

1) Adding molten salt phase change layer significantly reduces the influence of solar energy periodicity and instability on the straight through solar vacuum collector, which is more conductive to creating a relatively stable medium and high temperature environment.

2) Molten salt phase change layer has low thermal conductivity, which can reduce heat loss of collector.

3) The heat storage capacity of the collector tube was greatly improved by adding molten salt phase change layer.

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References
[1] Z.C. Gao. (2011)Research on System Integration of Parabolic Trough Solar Energy Collector Technology D. Graduate University of Chinese Academy of Sciences.
[2] C.T. Chen, C.M. Yao, C.P. Yin. (2019) Preparation of kaolin-based phase change thermal storage materials for solar thermal power stations J. Renewable energy. 37(03):349-353.
[3] D.L.Ling,G.M Mo,Q.T. Jiao,... & X.J.Wang.(2016).Research on solar heating system with phase change thermal energy storage. J.Energy Procedia,91: 415-420.
[4] ALexander JR, Hindin SG. (1993)Phase relations in heat transfer salt systems J. Industrial and Engineering Chemistry, 39(8):1044-1049.
[5] Kearney D. Hermann U, Nava P.(2003)Assessment of molten salt heat transfer fluid in a parabolic trough solar filed J.Sol. Energy Eng. 125(2):170-176.
[6] Kamil Kaygusuz,(1995) Experimental and theoretical investigation of latent heat storage for water based solar heating systems.J. Energy Conversion and Management. 36(5): 315-324.
[7] Y.Q.Jiang, Q.Qi, Y.Yao, Z.L.Ma.(2007) Simulation study on application of solar energy seasonal phase change heat storage heat pump system in Harbin J. HVAC.(03):15-20.
[8] N. Nallusamy,S. Sampath,R. Velraj. (2006) Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources. J. Renewable Energy.32(7):1206-1227.
[9] Eman-Bellah S. Mettawee,Ghazy M.R.(2006) Thermal conductivity enhancement in a latent heat
storage system. J. Solar Energy, 81(7):839-845.
[10] M.K. Saranprabhu, K.S. Rajan. (2019). Magnesium oxide nanoparticles dispersed solar salt with improved solid phase thermal conductivity and specific heat for latent heat thermal energy storage. J. Renewable Energy. 141:451-459.
[11] H. Wang. (2013) Research progress of heat storage materials in solar photovoltaic power generation System. J. Science and Technology Information, 03:399-400.