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Conceptual design of porous volumetric solar receiver using molten salt as heat transfer fluid

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HIGHLIGHTS

- Porous volumetric solar receiver based on molten salt heat transfer fluid is proposed.
- Spectrally selective absorption of different molten salts is characterized.
- Direct pore-scale numerical simulation method is applied for Hitec and air receivers.
- High efficiency and low pressure drop are found for Hitec porous receiver.

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ABSTRACT

Thermal radiation loss hinders the high-efficient operation of solar receiver at high temperature. Porous volumetric solar receiver using molten salt instead of air as heat transfer fluid is proposed. A comprehensive literature review is done to investigate the optical and radiative properties of molten in solar and infrared spectra. Direct pore-scale numerical simulation method based on X-ray computed tomography technique is applied to compare the fluid flow and heat transfer performance of molten salt and air porous volumetric solar receiver. The results present that some types of molten salts behave to be transparent in solar spectrum and opaque in infrared spectrum, which allow the penetration of solar radiation while strongly absorb the infrared emission in the receiver. The thermal efficiency of Hitec porous volumetric solar receiver is higher than traditional air porous receiver especially at higher working temperature, and it is improved by 9.6% at receiver's outlet temperature of 1000 K. Due to its large heat storage capability and efficient convective heat transfer, small mass flow rate is required in the molten salt receiver to absorb solar radiation, which leads to orders-magnitude smaller pressure drop for the Hitec porous receiver. Further research related to this type of porous volumetric solar receiver is outlined with respect to experiment verification and application of high temperature molten salt.

1. Introduction

Solar energy could play an important role in the future global energy system. As one of the promising technologies, CSP (concentrating solar power) system promotes the efficient utilization of solar thermal energy at large scale [1,2]. In CSP system, the main component to absorb and convert solar energy into thermal energy is the solar receiver [1,3]. The surface solar receiver akin to tubular receiver has commercialized and utilized in solar thermal plant such as Gemasolar and Shouhang Dunhuang plants. However, the surface absorption technique has limit to higher concentrated incident solar radiation because the maximum allowable heat flux on the tube surface. Meanwhile, the maximum receiver temperature lies always in its surface, and the thermal radiation loss is evitable which hinder the efficient power generation at higher temperature. In order to overcome the aforementioned disadvantages of surface absorption, the concept of volumetric absorption is put forward. Basically, two main methods have been proposed which are direct absorption receiver and porous volumetric solar receiver.

Some heat transfer fluid could be considered as semi-transparent media, in which the solar radiation is gradually attenuated and absorbed by the fluid. The commonly investigated one is nanofluid which is prepared by dispersing nanoparticle materials into the base fluid [4,5]. By adding the nanoparticles such as carbon nanotubes, graphite, and

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Nomenclature

c_p	specific heat (J/(kg•K))
D	pore diameter (m)
I	radiation intensity (W/(m^2·sr))
P	pressure (Pa)
S_r	energy source term (W)
T	temperature (K)
u	velocity (m/s)
x	penetration depth (m)
Greek symbols	
β	extinction coefficient (m^{-1})
ε	porosity
λ	thermal conductivity of the fluid (W/(m·K))
μ	dynamic viscosity (Pa·s)
ρ	density (kg/(m^3))
Subscripts	
Air	properties of air
f	fluid
Hitec	properties of Hitec
r	radiation
s	solid

metal oxide, the nanofluid becomes highly absorptive and could absorb solar radiation volumetrically within a layer of several centimeters. The optical properties of nanofluid could be adjusted by altering the nanoparticle material type and the volume fraction of nanoparticle, etc., which adjusts the optical and thermal performance of the solar receiver. It has to mentioned that the nanofluid is usually designed for low or moderate temperature utilization because of the temperature limit of base fluid. For instance, the most commonly used base fluid is water, and it is obvious that the water should stay in liquid form. Moreover, the synthetic heat transfer fluid Therminol® VP-1 is also widely used and upper temperature limit is about 400 ℃. Some researcher attempted to investigate the performance of molten salt nanofluid [6,7], which has the potential to enlarge the working temperature range of the nanofluid. The bottleneck for the long-term operation and promotion of this type of receiver lies in the stability and durability of the nanofluid. Another method for direct absorption by heat transfer fluid is to avoid adding additives to the fluid but enlarge the fluid depth. Cengel and Özişik [8] analyzed the solar pond using water to directly absorb the solar radiation. The numerical results presented that the pond depth of 1 or 2 m could be suitable for direct absorption of solar radiation. Moreover, the influence of reflectivity of pond bottom surface and incident angle of solar radiation was discussed. As for a promising heat transfer fluid and storage media, the molten salt has always been a good candidate in different thermal applications. The CSPonD (Concentrated Solar Power on Demand) project was launched and proposed to use molten salt for direct solar radiation absorption [9]. A tank containing molten salt of several meter depth serves as both receiver and thermal storage device, which volumetrically absorbs the solar radiation. A movable divider plate is placed to separate the hot and cold salt and regulate the charging process. Following this idea, a 25 kW demonstrative prototype is built at Masdar Institute Solar Platform [10]. Due to the transparent feature of solar salt in solar spectrum, a thin layer of black dust is added on the top of the salt to increase absorption coefficient.

On the other hand, the porous media which process a complex three dimensional geometry allow the solar radiation to penetrate into the structure and be gradually absorbed. The heat transfer fluid passes through the porous media and absorbed heat from the structure [11]. The volumetric absorption is beneficial for reducing the receiver's front surface temperature, and the torturous fluid channel in porous media enhances the convective heat transfer between porous skeleton and heat transfer fluid. The air is by default selected as heat transfer fluid for the porous volumetric solar receiver because of its availability in atmosphere and transparency in solar spectrum. Many prior experimental and numerical studies have been conducted to examine the performances of air porous volumetric solar receiver [11,12]. However, the air porous volumetric solar receiver has several drawbacks need to be overcome. Firstly, the thermal radiation loss in the front surface severely influence the thermal efficiency of receiver at high temperature. The thermal performance of a cellular metal honeycomb porous receiver was experimentally studied [13]. Obvious decrease in thermal efficiency could be observed that it drops from about 93% to 82% as the outlet air temperature increases from about 250 ℃ to 700 ℃. Similarly, in the research of Roldán et al. [14], both ceramic and metallic receivers were experimentally investigated. Thermal efficiency decrease exists for both receivers that the 7.9% and 4.4% drops were seen for ceramic and metallic receivers, respectively as the average temperature becomes higher. Secondly, the density of air is relatively low which leads to the weak heat storage capacity comparing to liquid heat transfer fluid. As a result, a large mass flow rate of air is required to absorb high intensity of solar radiation and the flow resistance for the receiver becomes large as the inlet fluid velocity is large. Several designs of porous structure are proposed to ameliorate the thermal performance, such as porosity gradually-changed porous receiver [15] and concave front surface geometry [16]. However, the thermal radiation loss is evitable and could only be alleviated to some extent. Furthermore, all types of solar absorption techniques face the same problem as the highest temperature usually lies in the front surface of the receiver. One attempt to overcome this problem is the application of spectrally selective materials. Many efforts have been done in selecting and designing materials with high solar absorptivity and lower infrared emissivity, such as intrinsic materials [17], multilayer absorbers [18], and nanophotonic structures [19]. However, the ideal solar absorber is hard to design and these materials still face several difficulties when applied in CSP system, such as the durability and effectiveness at high working temperature. As for the porous volumetric solar receiver, several studies [20–22] designed multilayer structures that have different absorption properties. Menigault et al. [20] designed a two-slab selective volumetric receiver with silica honeycomb front layer and SiC particles rear layer. These two layers were adopted to reutilize the infrared emission and enhance the solar radiation absorption. Compared with pure SiC porous receiver, the thermal efficiency for the two-slab selective volumetric receiver was improved by 5%. Zhu and Xuan [23] conducted numerical simulation for the multi-layer porous volumetric solar receiver with $MoSi_2$-Si_3N_4 coating or ideal coating with cut-off wavelength of 2 μm. Compared with traditional porous receiver, these two coatings could improve the thermal efficiency by 1.2% and 2.9%, respectively.

Considering that air porous volumetric solar receiver does not perform excellent at higher working temperature, the novel porous volumetric solar receiver is proposed by altering heat transfer fluid from traditional air to molten salt. The concept of the spectrally selective absorption is not confined in the porous receiver, and the optical properties of the heat transfer fluid is taken into account. The spectrally selective absorption properties of the molten salt could retain the volumetric absorption of porous media, while the disadvantages mentioned above of using air as heat transfer fluid is overcome and the thermal emission loss of the receiver could be reutilized. As a result, the solar-to-thermal efficiency could be dramatically increased especially at high working temperature. The optical properties of molten salt are reviewed from different literatures in order to evaluate the applicability of molten salt as heat transfer fluid in Section 2. Direct pore-scale numerical simulation models are established which considering the transparency of air and spectrally selective absorption properties of molten salt in Section 3. The potential advantages of using molten salt in porous volumetric solar receiver are characterized.

2. Optical and radiative properties of molten salt

The solar radiation and thermal radiation transfer are two importance energy transfer processes inside the porous volumetric solar receiver, which is influenced by the optical and radiative properties of heat transfer fluid. In previous researches, the techniques based on transmission, reflection, and emission measurement are widely used to analyze the different spectra behaviors of different molten salts under different temperature ranges.

When used as the heat transfer fluid in porous volumetric solar receiver, the basic requirement is that the fluid should be transparent in the solar spectrum. In this case, the solar irradiation could be attenuated gradually inside the receiver. Therefore, the absorption spectra of molten salt are firstly investigated. Theoretically, the Lorentz model [24] predicts that inorganic salt presents several absorption bands in some infrared (IR) and ultraviolet (UV) ranges, while it keeps transparent between absorption bands. Drotning [25] applied both transmission and reflection experiment to investigate the absorption properties of Hitec (KNO_3-$NaNO_2$-$NaNO_3$, 53–40-7 wt%) in the wavelength range of 300 to 2500 nm. In the reflection technique, the relationship of absorption coefficient on the reflection and thickness of molten salt was established. The experiment results showed that the undoped Hitec is essentially transparent throughout the solar spectrum, and only 8 percent of the solar energy would be absorbed in a 1 cm layer of pure Hitec. Two relatively strong absorption peaks were observed near UV and at around 2500 nm, which accords well with the Lorentz model. Moreover, the shift of absorption edge to longer wavelength with increasing temperature in 200–500 ℃ was characterized. A molten salt light absorption facility was developed based on CSPonD project, which dedicates to investigate the direct solar absorption of molten salt. Passerini [26] experimentally analyzed the light absorption property of binary nitrate salt (KNO_3-$NaNO_3$, 40–60 wt%) and binary chloride salt (NaCl-KCl, 50–50 wt%) in visible spectrum (500–800 nm). The operating temperature ranges for nitrate and chloride salts are 250–500 ℃ and 700–800 ℃, respectively. The transparent feature of these two types of molten salts were observed, and attenuation coefficient for chloride salt is even smaller than that of the nitrates salt. An attempt to measure the attenuation coefficient of the ternary carbonate mixture was failed because of the reactivity of carbonate salt with quartz. Similarly, Berdibek [27] investigated the binary nitrate salt (KNO_3-$NaNO_3$, 40–60 wt %) in the wavelength range of 822–2500 nm. The temperature-dependent property of attenuation coefficient was revealed, while the molten salt becomes more transparent as the temperature increases and the attenuation coefficient is nearly 0 in 800–1800 nm. Furthermore, the purity and decomposition of molten salt at higher temperature was considered in the study of Tetreault-Friend [28]. The refined commercial grade and high purity grade binary nitrate salt (KNO_3-$NaNO_3$, 40–60 wt%) was selected. During the test, the high purity grade molten salt was less stable and thermally decomposed at 350 °C, leading to an increase in absorption of solar radiation. The aforementioned experimental results are summarized in Fig. 1. It could be concluded that a consistent experimental results are obtained in different studies, and the molten salt is almost transparent in the entire range of the solar spectrum, which could possibly be used in the porous volumetric solar receiver.

On the other hand, the thermal radiation transfer becomes dominant when the receiver's temperature goes higher, and the front surface radiative loss could dramatically decrease the thermal efficiency of the receiver [29]. In the previous design of porous volumetric solar receiver, the air is considered as heat transfer fluid which is transparent in the infrared range. When changing air to molten salt, the optical and radiative properties of molten salt in IR should be analyzed. A literature review is done and summarized in Table 1.

Greenberg and Hallgren [30] developed both transmission and reflectance measurement setups to analyze the infrared absorption spectra (Wavelength: 2–15 μm) of $NaNO_2$ and $LiNO_3$. The average

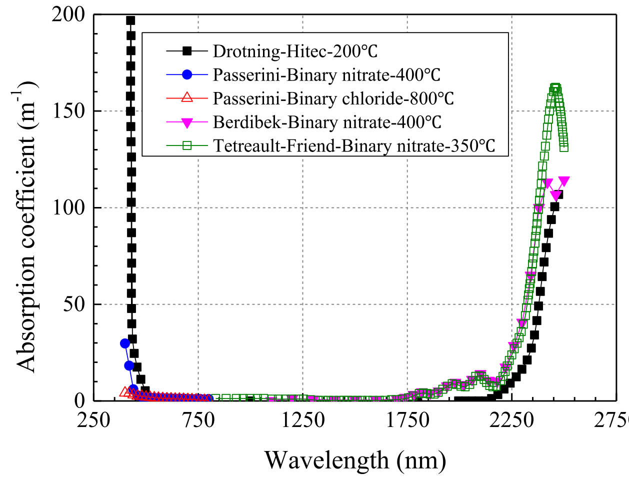

Fig. 1. Absorption coefficient of molten salts in solar spectrum.

Table 1
Investigation of infrared spectrum behavior of molten salt.

Author	Method	Material	Wavelength or wavenumber	Results and remarks
Greenberg [30]	Transmission and reflection test;	$NaNO_2$, $LiNO_3$.	2–15 μm	Small average transmission (0.46) with small fused $NaNO_2$ salt thickness (0.05 mm).
Kozlowski [31]	Emission test	KNO_3	660–1500 cm^{-1}	Reflection in melt-air, blackplate-melt interface and absorption coefficient are measured.
Wegdam [32]	Transmission test	$NaNO_3$, $CsNO_3$.	600–30 cm^{-1}	Strong far infrared absorption is observed for solid and fused alkali metal nitrates.
Barker [33]	Reflection test	KBr, NaCl, LiF.	250–4000 cm^{-1}	Solid and molten phases behave similarly in infrared spectrum as for absorption; Cut-off wavenumbers for KBr, NaCl, LiF are 500, 800, and 2400 cm^{-1}, respectively.
Kusabiraki [34]	Emission measurement	Li_2CO_3, Na_2CO_3, K_2CO_3, Rb_2CO_3.	5000–650 cm^{-1}	Na_2CO_3 of 10 mm is considered as opaque; Strong absorption is observed in wavenumber of 2300, 1360, 870, 694 cm^{-1} for Na_2CO_3.

transmission of a 0.05 mm molten $NaNO_2$ is about 0.46, which suggests an absorption coefficient of more than 10000 m^{-1} in IR range. As for the $LiNO_3$, it could be considered as opaque in both solid and molten phase when the wavelength is larger than 4 μm. The IR absorption of nitrate molten salts was also investigated by Kozlowski [31] and Wegdam et al. [32]. Very large value of absorption coefficient for different nitrate molten salts was characterized in different infrared ranges. In the study of Barker [33], the infrared absorption spectra of KBr, NaCl, and LiF were measured by obscured-mirror technique. The salt in solid state at different temperature and the salt in fused state slightly above the melting point were investigated. The results presented that the solid and molten phases behaved similarly in infrared spectra as for absorption. The cut-off wavenumbers for KBr, NaCl, LiF molten salt are 500, 800, and 2400 cm^{-1} respectively, below which the molten salt could be considered as opaque material. The vibrational spectra of a series of molten alkaline metal carbonates (Li_2CO_3, Na_2CO_3, K_2CO_3, Rb_2CO_3) was studied by Kusabiraki and Shiraishi [34]. An emission spectrometry technique was adopted, which establishes the relationship of transmission with emission of molten salt with different thicknesses. Taking the experimental results of Na_2CO_3 as an example, strong absorption was observed in wavenumber of 2300, 1360, 870, and 694 cm^{-1}. In the infrared range (Wavenumber: 5000 – 650 cm^{-1}), the average transmission of Na_2CO_3 molten salt at 900 ℃ with thickness of 10–20 μm is about 0.65. Therefore, an extremely large absorption property of infrared emission was determined for carbonate molten salts.

From the above review, it could be inferred that some kinds of molten salts, such as nitrate and carbonate salts are opaque for the infrared emission. It is possible that the thermal radiation emitted by the front receiver's surface could be absorbed by molten salt, and the thermal efficiency of receiver could be potentially increased.

3. Direct pore-scale numerical simulation

3.1. Numerical model

The performances of porous volumetric solar receiver could be investigated by both direct pore-sale numerical simulation and volume-averaging simulation methods [29,35]. Direct pore-scale numerical simulation, which reflects the real heat transfer process inside the of the porous media is applied to evaluate the proposed porous volumetric solar receiver using molten salt as heat transfer fluid.

Firstly, the sophisticated porous structure is established by X-ray computed tomography technique and image processing. One porous foam sample is scanned by YXLON Cheetah x-ray inspection system with a resolution of 25 μm, which derives a series of cross-section images. These images are post-processed and used to render the 3D structure of the porous media. More detailed treatments of the cross-section images and 3D structure could refer to our previous publications [29,36]. The 3D model in stereolithography (STL) format is presented in Fig. 2, and its geometrical parameters are measured with commercial software Mimics and VGStudio as shown in Table 2. This 3D model is then imported to a fluid channel, and the porous interface serves as the boundary between porous media and heat transfer fluid.

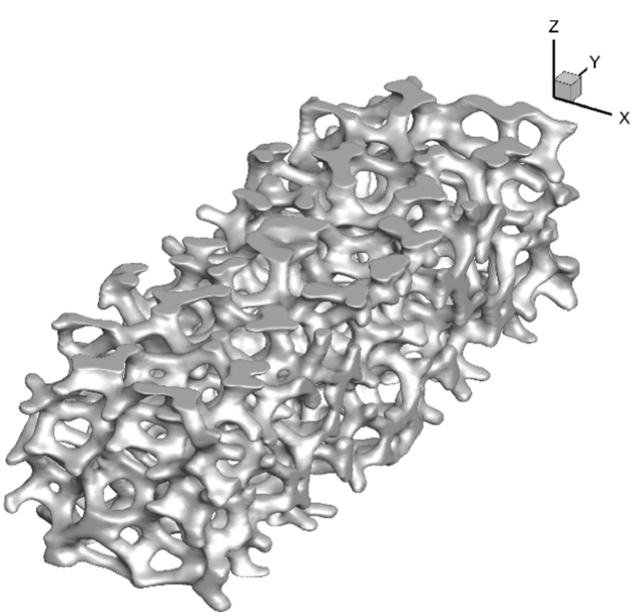

Fig. 2. Reconstructed porous model.

Based on the reconstructed pore-scale model above, the fluid flow and heat transfer of air or molten salt in the porous volumetric solar receiver could be numerically studied. The fluid flow and heat transfer of the heat transfer fluid is governed by Eqs. (1)–(3). The heat conduction in the porous domain is described by Eq. (4). The heat exchange between the two domains is achieved by the coupled wall boundary condition of the porous interface.

$$\frac{\partial}{\partial x_j}(\rho u_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu\frac{\partial u_i}{\partial x_j} - \rho\overline{u_i^{'}u_j^{'}})(i = 1,2,3) \tag{2}$$

$$\frac{\partial}{\partial x_j}(\rho u_j T_f) = \frac{\partial}{\partial x_j}[\frac{\lambda_f}{c_p}\frac{\partial T_f}{\partial x_j} - \rho\overline{u_j^{'}T_f^{'}}] \tag{3}$$

$$\frac{\partial}{\partial x_j}(\lambda_s\frac{\partial T_s}{\partial x_j}) + S_r = 0 \tag{4}$$

In the equations, u, p, T_f, and T_s are the parameters to be determined, which are velocity, pressure, fluid temperature, and solid temperature, respectively. ρ, μ, c_p, and λ_f are the thermophysical properties of heat transfer fluid, which are density, dynamic viscosity, specific heat, and thermal conductivity, respectively. $-\rho\overline{u_i^{'}u_j^{'}}$ and $-\rho\overline{u_j^{'}T_f^{'}}$ are introduced as additional terms in momentum and energy conservation equations due to the effect of turbulence, which are calculated based on standard SST k-ω model. Details of the turbulence model could refer to references [36,37]. S_r is the energy source due to solar radiation and thermal radiation transfer. The thermal radiation transfer is solved by implementing discrete ordinates (DO) method. In the air porous volumetric solar receiver, the air is totally transparent in all wavelengths and only the thermal radiation exchanged between the porous surface are considered. On the other hand, the absorption of infrared emission by the molten salt is considered in the molten salt porous volumetric solar receiver. Detailed model for the optical properties of the molten salt is elaborated in the following section. As for the solar radiation distribution, the Beer's law shown by Eq. (5) is applied to determine the penetration of solar energy for simplicity. The porous media as a whole could be regarded as the semi-transparent structure to the solar radiation, and the extinction coefficient is the key parameter to describe the penetration depth in the porous receiver.

$$I(x) = I(0)e^{-\beta x} \tag{5}$$

In Eq. (5), I is the intensity of solar radiation, while β is the extinction coefficient referring to the light absorption ability of the porous media. The extinction coefficient could be estimated by Eq. (6) proposed by Hendricks and Howell, as a function of porosity and pore diameter of porous media.

$$\beta = \frac{4.8(1-\varepsilon)}{d} \tag{6}$$

3.2. Thermophysical properties

In the concentrating solar power system, the nitrate salt has already

Table 2
Geometrical parameters of porous model.

Dimension (mm^3)	Porosity	Pore diameter (mm)	Strut thickness (mm)	Specific surface area (mm^{-1})
7 × 20 × 6	0.79	1.06	0.49	1.40

been widely used as heat transfer and energy storage material. However, its optical properties do not get much attention in previous studies. Base on the investigation in section 2, the nitrate salts are deemed to be transparent in the solar spectrum and opaque in infrared spectrum, which are appropriate candidate for the solar radiation penetration and the absorption of thermal radiation in the porous volumetric solar receiver. Therefore, the ternary nitrate mixture, Hitec (KNO_3-$NaNO_2$-$NaNO_3$, 53–40-7 wt%), is selected as molten salt heat transfer fluid, and the comparison with traditional air is conducted. The temperature-dependent specific heat and thermal conductivity of Air from reference [38] are shown in Eqs. (7) to (8). The air density and dynamic viscosity are calculated based on ideal gas law and Sutherland law.

$$c_{p,\mathrm{Air}} = 1.93\times10^{-10}T^4 - 8\times10^{-7}T^3 + 1.14\times10^{-3}T^2 - 4.49\times10^{-1}T + 1.06\times10^3 \tag{7}$$

$$\lambda_{\mathrm{Air}} = 1.52\times10^{-11}T^3 - 4.86\times10^{-8}T^2 + 1.02\times10^{-4}T - 3.93\times10^{-3} \tag{8}$$

The thermophysical properties (density, specific heat, thermal conductivity, and dynamic viscosity) of Hitec in temperature range of 420 K to 800 K are taken from reference [39] and presented by Eqs. (9) to (12).

$$\rho_{\mathrm{Hitec}} = -0.733T + 2280.22 \tag{9}$$

$$c_{p,\mathrm{Hitec}} = 1560 \tag{10}$$

$$\lambda_{Hitec} = \begin{cases} -1.863\times10^{-8}T^3 + 2.551\times10^{-5}T^2 - 1.176\times10^{-2}T + 2.263, & 420K \le T < 536K \\ -6.47\times10^{-4}T + 0.7663, & 536K < T \le 800K \end{cases} \tag{11}$$

$$\mu_{Hitec} = \begin{cases} -1.742173\times10^{-6}T^3 + 2.27615\times10^{-3}T^2 - 0.99143T + 143.9826, & 420K \le T < 440K \\ -7.2058\times10^{-9}T^3 + 1.08225\times10^{-5}T^2 - 5.4754\times10^{-3}T + 0.93845, & 440K \le T < 500K \\ 8.507\times10^{-13}T^4 - 2.4331\times10^{-9}T^3 + 2.6275\times10^{-6}T^2 - 1.2768\times10^{-3}T + 0.23816, & 500K \le T \le 800K \end{cases} \tag{12}$$

Special attention is paid on the temperature-dependent dynamic viscosity of air and Hitec, which is presented in Fig. 3. Under the non-uniform solar radiation, the local intensified heat flux imposes local overheating. For the air receiver, the locally increased temperature leads to locally increased air viscosity, which causes the locally increased flow resistant preventing air from passing through. As a result, less heat transfer fluid is allocated to the local overheating zone which may causes local failures for the receiver. Unlike air, the dynamic viscosity of Hitec decreases as the temperature increases. This feature could be beneficial for the distribution of heat transfer fluid which could alleviate local overheating problem.

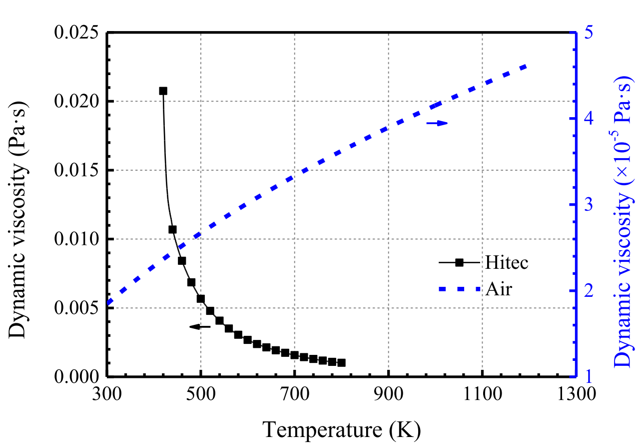

Fig. 3. Comparison of dynamic viscosity of Hitec and air.

3.3. Boundary conditions

The typical schematic of porous volumetric solar receiver is illustrated in reference [38]. In the computational domain presented in Fig. 2, the solar energy is irradiated to the front XZ plane, and the flow direction is along the Y coordinate axis. The total length in the Y direction is 20 mm, which is sufficient to achieve the thermal equilibrium between the porous media and the heat transfer fluid. In the front surface of the receiver, the mass flow inlet and constant temperature boundary condition is applied. The inlet temperature of air and Hitec are 300 K and 420 K, respectively because the melting point of Hitec is reported to be 142℃. The intensity of concentrated solar radiation is set to 1000 kW/m^2, and the reflection losses of the receiver is fixed to 7.8% which is calculated based on the previously established correlation [40]. The non-slip boundary is applied to the porous surface and the coupled energy condition is also satisfied.

When considering the radiation transfer, the porous surface is considered to be opaque to radiation, and emits thermal radiation with emissivity fixed to 0.95. Air is considered to be fully transparent to radiation in the entire wavelength. For simplicity, Hitec is supposed to have two cut-off wavelengths at 250 nm and 2500 nm respectively, between which it is transparent to radiation. Otherwise, it is opaque and attenuates radiation in a very short thickness. The side wall of the porous receiver is set as adiabatic and does not absorb the incident solar and thermal radiation.

4. Results and discussions

4.1. Heat transfer in porous receiver

The heat transfer process in molten-salt porous volumetric solar receiver is analyzed and compared with traditional air porous receiver as shown in Fig. 4. It could be firstly seeing that the Hitec reaches thermal equilibrium with porous skeleton within a relatively short flow path comparing to that of air. Possible reason could account for the superior heat transfer performance of molten salts. Moreover, the temperature distribution in porous skeleton of molten salt porous receiver is more uniform, which also proof the excellent heat transfer using molten salt as heat transfer fluid. Secondly, the heat zones extended from the porous surface is large in the molten salt porous receiver. In the previous section, it has been shown that the thermal conductivity of Hitec is far larger than that of the air, and the heat transfer is more efficient through conduction in Hitec. On the other hand, Hitec is a participating media towards the infrared thermal radiation. The high-temperature porous skeleton emits the thermal radiation which could be absorbed by Hitec, while the radiation interacts only with surfaces because air is considered to be transparent. The temperature increase in the molten salt and air porous receiver under the same mass flow rate is presented in Fig. 5.

The temperature increase in Fig. 5 is defined as temperature difference between outlet and inlet of heat transfer fluid. It could be observed that the temperature increase of Hitec under the same solar radiation distribution is small comparing with air in all inlet mass flow rate. From the perspective of energy balance, the Hitec could absorbed more energy than the air under the same mass flow rate because its density and specific heat are relatively larger. Therefore, it could be also stated that small amount of heat transfer fluid is needed to absorbed the same amount of solar energy when changing air to Hitec. An additional benefit related to minor requirement of molten salt is that the flow resistance is decreased, and this property will be elaborated in the following section.

4.2. Thermal efficiency of porous receiver

The primary advantages in changing air to molten salt lies in the increased thermal efficiency, which is defined as the ratio of absorbed energy by heat transfer fluid to the total incident solar energy. Fig. 6

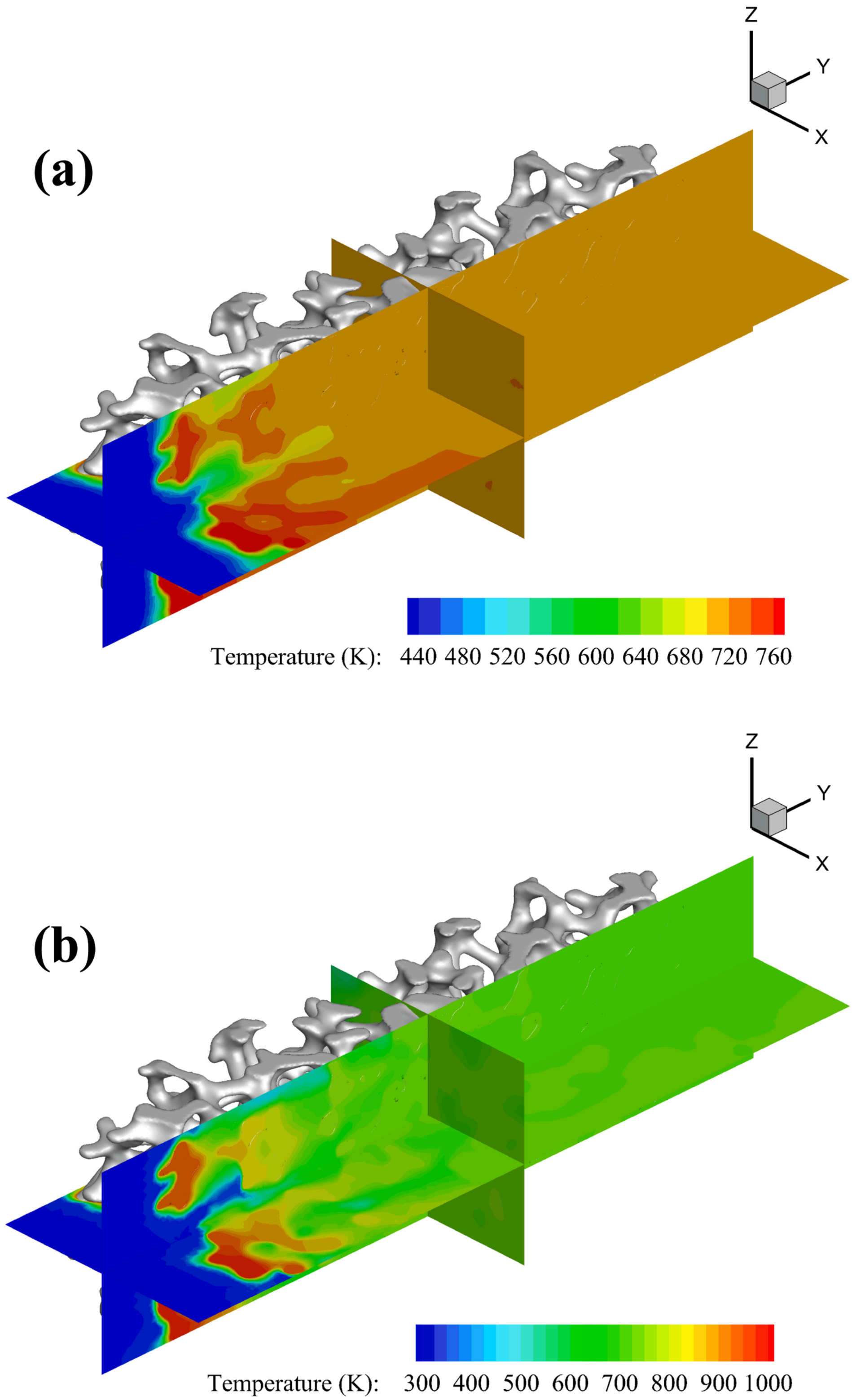

Fig. 4. Temperature field in (a) Hitec (b) air porous receivers with inlet mass flow rate of 2 kg/(m^2•s).

presents the thermal efficiency of porous receiver using Hitec or air as heat transfer fluid as a function of outlet fluid temperature.

Firstly, the thermal efficiency of the porous receiver decreases as the outlet fluid temperature increases because the thermal radiation loss of the receiver becomes dominant at higher temperature. Secondly, when using Hitec as heat transfer fluid, the thermal efficiency of porous receiver is higher than that of the air porous receiver. This disparity becomes larger at higher temperature due to the forth-power law obeyed by emitted thermal radiation on temperature. Thirdly, the slightly decrease in thermal efficiency of molten salt porous receiver is also due to the shift of emission spectra towards shirt wavelength. For instance, 0.5% of emitted energy for a black body of 500 K lies in the solar spectrum, whilst this value increases to 28.9% for a black body of 1200 K. By all means, the decreases in thermal efficiency for molten salt and

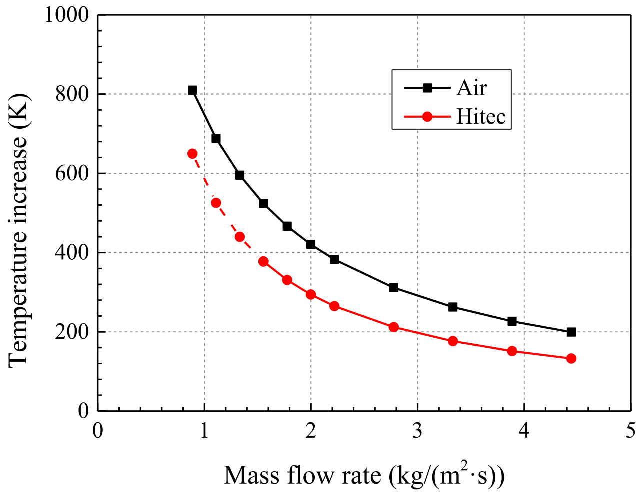

Fig. 5. Temperature increase under different mass flow rates.

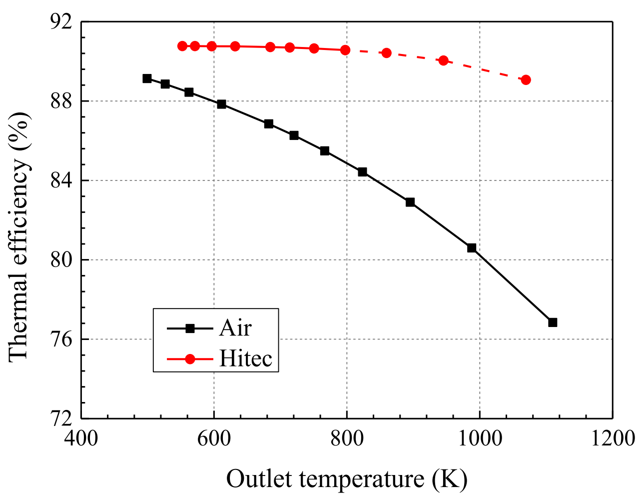

Fig. 6. Thermal efficiency of different porous receivers.

air porous receivers from about 500 K to 1100 K are 1.7% and 12.3%, respectively. Therefore, it could be assumed that molten salt is an excellent heat transfer fluid to limit thermal radiation loss.

One good advantage to use porous volumetric solar receiver is its volumetric effect, which could be described as lower inlet solid temperature and higher outlet fluid temperature [41]. The difference between maximum solid temperature and outlet fluid temperature is shown in Fig. 7. It is seen that temperature difference is much higher in the air porous receiver, and it is due to the weak heat transfer performance of air comparing with molten salt. As a result, the temperature of porous skeleton is higher in air porous receiver than that in molten salt porous receiver to reach the same outlet fluid temperature, which induces more energy loss by thermal radiation. Furthermore, the temperature difference gradually decreases as the outlet fluid temperature goes larger. It should be mentioned that it does not indicate an enhanced volumetric effect at higher temperature. The fact is that the thermal radiation loss becomes dominant and the air could not limit this kind of energy loss. On the contrary, the temperature difference is relatively lower and stable for the molten salt porous receiver due to its better heat transfer performance and the ability in absorbing thermal radiation.

4.3. Pressure drop of porous receiver

Another aspect to evaluate solar receiver is its flow resistance

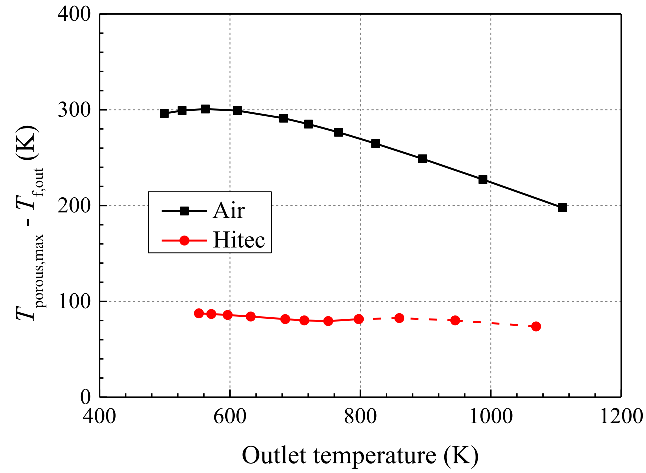

Fig. 7. Difference between maximum solid temperature and outlet fluid temperature.

property, and the ultimate goal is to develop a solar receiver with low flow resistance and high thermal efficiency. The pressure drop per unit length under difference mass flow rate for molten salt and air porous receivers are calculated and presented in Fig. 8. Although the dynamic viscosity of Hitec is far larger than that of air as mentioned in section 3, the pressure drop per unit length in air porous receiver is orders-magnitude larger than that of the molten salt porous receiver. Due to its large density, the inlet velocity of Hitec is far smaller than that of air under the same inlet mass flow rate. According to the Forchheimer

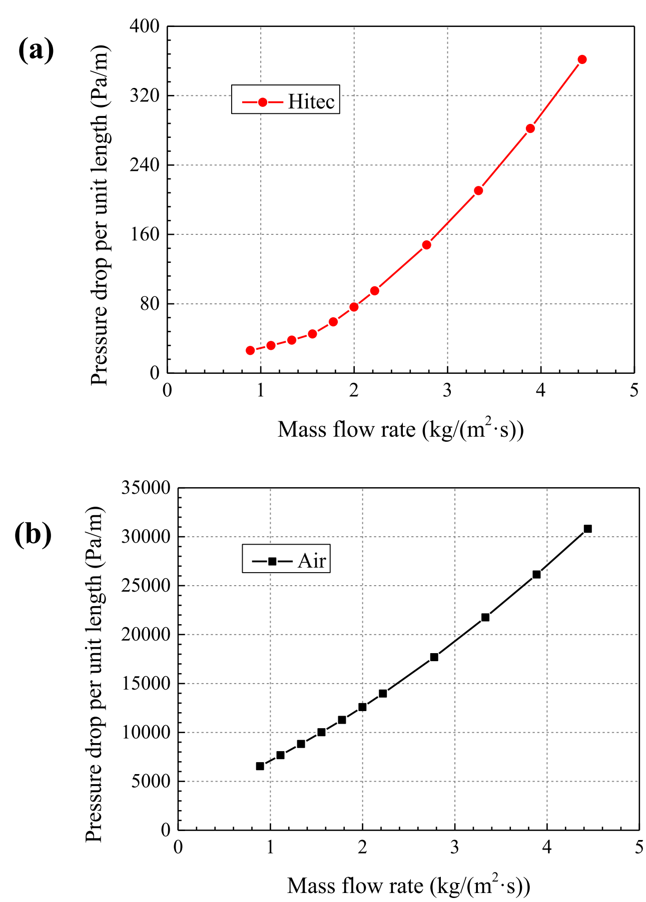

Fig. 8. Pressure drop in porous receivers with (a) Hitec (b) air as heat transfer fluid.

extended Darcy's equation, the viscous flow resistance and inertia flow resistance in porous media are proportional to the velocity and square of velocity, respectively. To absorb the same amount of solar energy, the inlet velocity of air should be extremely large comparing to that of molten salt, which in turn consumes more pump power.

5. Future research perspective

5.1. Detailed numerical model and experiment verification

In this paper, the numerical model of molten salt porous volumetric solar receiver is simplified in order to demonstrate the idea to change traditional air to molten salt. Intuitively, a close-loop receiver system should be designed for molten salt circulation, and a high temperature and high corrosive resistant window is needed. Therefore, the complex reflection process in the air-window, and window-salt interfaces should be taken into account. The complex index of molten salt and optical properties of window material should be determined. Moreover, the spectra properties of molten salt could be more precise. The Hitec is considered to be transparent to solar radiation and totally opaque to thermal radiation which leads to the optimum thermal performance of molten salt porous receiver. As the temperature increases, the shift of absorption spectrum of molten salt towards the infrared region should be evaluated.

Furthermore, the lab-scale test bed of molten salt porous volumetric solar receiver should be built, which aims at demonstrating the feasibility and effectiveness of this novel type porous volumetric solar receiver. Firstly, the material of porous media should be selected according to the corrosion mechanism of molten salt with different types of material. The blockage issue of molten salt inside the porous structure should be analyzed. Compared to the porous foam which has tortuous pore structures, the porous honeycomb with straight channels could be considered. Secondly, excellent properties, such as highly transparent in solar spectrum and corrosion resistance of window material are needed. Considering the non-uniform distribution of incident solar radiation, a steep temperature gradient may cause large thermal stress on the window surface. Special attention should be paid on the durability of window and safety operation of the entire system. Thirdly, the purity of molten salt and decomposition at high temperature working condition needs considering. These factors could greatly influence the optical properties of molten salts.

5.2. Optical and radiative properties of high temperature molten salt

The nitrate molten salts, such as Hitec and solar salt usually work at temperature less than 600 ℃. The Gen3 roadmap proposes to increase the outlet fluid temperature to more than 600 ℃ to achieve high efficiencies [2]. As a result, alternative molten salts are required and the chloride or carbonate salts are potential candidates. However, only limited information on the spectra properties of these high temperature molten salt is available. The experimental results of Kusabiraki and Shiraishi [34] confirmed the efficient absorption of thermal radiation of carbonate salts. Nonetheless, the absorption behaviors of solar radiation for carbonate and chloride salts are not found in the literatures. And several chloride salts (K–Na)Cl were reported to be transparent to infrared radiation according to the research of Myers et al. [42], and various transition metal chloride additives were added to increase the infrared absorption ability. Therefore, the optical and radiative properties of potential candidates of high temperature molten salts should be systematically studied. In order to be used as heat transfer fluid in porous volumetric solar receiver, the ideal absorption behavior in both solar spectrum and infrared spectrum are indispensable.

6. Conclusions

The porous volumetric solar receiver using molten salt as heat transfer fluid is proposed, and its performance are analyzed and compared with air porous volumetric solar receiver. The conclusions and potential advantages of molten salt porous volumetric solar receiver are summarized as follows:

(1) Nitrate salt and chloride salt shows spectrally selective absorption in solar spectrum and infrared spectrum, which are the potential candidates for the porous volumetric solar receiver with high thermal efficiency.
(2) The thermal efficiency of Hitec porous volumetric solar receiver is higher than traditional air porous receiver, especially at high working temperature. The decreases in thermal efficiency for molten salt and air porous receivers from about 500 K to 1100 K are 1.7% and 12.3%, respectively. The thermal efficiency of molten salt porous receiver is larger by 9.6% compared with air porous receiver at outlet temperature of 1000 K.
(3) Small mass flow rate is required in the molten salt receiver to absorb the same amount of solar energy comparing with air porous receiver because of large heat storage capability of molten salt. The relatively small inlet velocity leads to orders-magnitude smaller pressure drop for the molten salt porous receiver.

CRediT authorship contribution statement

Shen Du: Investigation, Methodology, Formal analysis, Validation, Writing - original draft, Software. **Ming-Jia Li:** Conceptualization, Validation, Investigation. **Ya-Ling He:** Supervision, Project administration, Conceptualization, Writing - review & editing, Funding acquisition. **Sheng Shen:** Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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