Analysis of the Non-uniform Temperature Distribution and Performance Optimization of a Nanofluid-based Direct Absorption Solar Collector

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SUMMARY

Efficient solar-thermal technology applied in building heating, air conditioning and heating water can effectively reduce energy consumption of buildings. Nanofluid-based direct absorption solar collector (NDASC) is a novel solar collector using transparent evacuated glass tube in which nanofluid acts as the solar absorbing and heat transfer fluid. In order to investigate the solar collection characteristics of a NDASC operated with a parabolic trough concentrator, non-uniform temperature distribution of CuO/oil nanofluid in the NDASC operated on various conditions was numerically studied, by using Computational Fluid Dynamics (CFD) simulation. Furthermore, the effect to efficiency factor \( F' \) and heat removal factor \( F_R \) of the solar collector was analyzed respectively by changing the inlet temperature of nanofluid, the solar radiation intensity and the mass fraction of nanofluid. It has been found that the temperature in the center area of the nanofluid is higher than that at the tube wall of the collector. Consequently, for a NDASC using nanofluid with mass fraction of 0.055%, the \( F' \) and \( F_R \) could be both greater than 1.0 when the inlet temperature of nanofluid was above 90°C, which was caused by the temperature distribution mentioned above. Also, the results showed that when the mass fraction of nanofluid increased from 0.055% to 0.100%, the total absorptivity reached the maximum value, nearly 100%, while the \( F_R \) decreased from 1.038 to 1.012, which was consistent with the change tendency of the collection efficiency. Therefore, the NDASC could achieve a maximum collection efficiency when the mass fraction of 0.055% was preferred.

INTRODUCTION

Nanofluid-based direct absorption solar collector (NDASC) is a new type of solar collector employing transparent evacuated glass tube in which nanofluid with strong solar absorption properties acts as working fluid. Researches have shown that nanofluid significantly improves the collector efficiency compared to the base fluid (Luo 2014, Javad 2017). Karami et al. (2014) prepared carbon nanotubes nanofluid and investigated its optical and thermal properties, as well as the feasibility when applied in low-temperature solar collector. Kasaeian et al. (2017) compared the outlet temperature of nanofluids and the thermal efficiency when using different MWCNT/ethylene glycol (EG) and nanosilica/EG nanofluid in a trough collector. However, there are few researches on the non-uniform temperature distribution and the effect to efficiency factor \( F' \) and heat removal factor \( F_R \) of the solar collector. Gorji and Ranjbar (2016) numerically evaluated the nanofluid temperature distribution and experimentally studied the effect of solar radiation intensity, nanoparticle concentration and volumetric flow rate on the thermal efficiency when using graphite magnetite and silver nanofluids. The research group also optimized the solar collector geometry and operating conditions by using response surface methodology (Gorji and Ranjbar 2015, 2017).

In the previous researches of our research group, the NDASC using nanofluid for medium-temperature applications was proposed and its feasibility was demonstrated (Xu 2015). A novel collector using magnetic nanoparticles to form the special array structure to absorb solar radiation was put forward and the performance was experimentally investigated (Xu 2016). Researches have shown the temperature distribution is non-uniform, and the effect to collector efficiency need to be further studied. The purpose of the present study is therefore to investigate the non-uniform temperature distribution, analyze this characteristic using efficiency factor \( F' \) and heat removal factor \( F_R \) and finally optimize the collector efficiency of NDASC.

METHODS

System description

A computational fluid dynamics (CFD) simulation model was developed to investigate the non-uniform temperature distribution of nanofluid and the solar absorption performance of the collector. The schematic diagram of the nanofluid-based direct absorption solar collector operated with a parabolic trough concentrator is shown in Fig. 1. The central line of the solar collector tube coincides with the focal line of the parabolic trough concentrator, which makes sure the collector tube could receive solar radiation reflected from the concentrator. The collector consists of outer tube and inner tube. The CuO/oil nanofluid in the inner tube absorbs solar energy and transforms it to heat, which leads to its temperature rise. Meanwhile, the vacuum between the two tubes prevents heat loss to environment in some degree.

Mathematical modelling

When lights spreads in the nanofluid, the radiation intensity weakens gradually. According to the Beer Lambert law, the optical transmittance of nanofluid is calculated as:
\[ \tau_{nf} = e^{-\nu K_e} \] 

where, \( r \) is the distance of light propagation in the nanofluid, \( K_e \) is the extinction coefficient of the nanofluid. The attenuation of solar energy results from the transmitted radiation and scattered radiation. The portion of solar energy absorbed by nanofluid is calculated by using absorption coefficient \( K_e \) of nanofluid as follows:

\[ \varepsilon (r) = 1 - e^{-\nu K_e} \] 

The solar radiation absorbed by nanofluid was assigned as inner heat source (Xu 2015). In order to analyze the heat source term, the controlling volume in the section of nanofluid was chosen, whose area was \( dA \). Then the inner heat source is:

\[ \Phi = \delta I(\theta) \varepsilon (r) rd\theta \] 

The radiation heat flux distribution around the transparent evacuated glass tube is given as:

\[ I(\theta) = 4 \eta_{opt} I_0 \frac{W}{D_1} \frac{1 - \cos \theta}{\sin^2 \theta} \] 

where \( \eta_{opt} \) is the optical efficiency factor of the concentrator. \( I_0 \) is the solar radiation intensity, \( D_1 \) is the diameter of the inner tube and \( W \) is the width of the concentrator. \( \theta \) is the angle between the axis line of the concentrator and the reflected optical line.

The heat transfer equation is:

\[ \frac{\partial(u_x T_x)}{\partial x} + \frac{\partial(u_y T_y)}{\partial y} + \frac{\partial(u_z T_z)}{\partial z} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\Phi}{\rho} \] 

where \( u_x, u_y \) and \( u_z \) are the velocities in \( x, y \) and \( z \) directions; \( T \) is the temperature of the nanofluid.

**Simulation**

In this study, the flow in the collector tube was assumed to be incompressible, steady and continuous. The finite volume method adopted to solve the three-dimensional heat transfer equation based on the computational fluid dynamics (CFD) simulation. In the simulation, structured grids were used to divide the flow field area into 1728000 cells, and the grids near the tube wall were more intensive than that in the central area. To judge the convergence of the computation, the residuals of continuity, velocities and energy acted as monitors and their convergence criterion was set as \( 1 \times 10^{-6} \). Furthermore, the residuals of velocity and temperature of the outlet flow were also used to monitor the convergence.

**Thermal and optical properties**

The nanoparticle uniformly suspended in the base fluid. According to the classical mixing theory, the nanofluid density is expressed as:

\[ \rho_{nf} = (1 - \phi) \rho_{bf} + \phi \rho_{np} \] 

The specific heat capacity of the nanofluid is:

\[ c_{np} = (1 - \phi) c_{bf} + \phi c_{np} \] 

The thermal conductivity of nanofluid was calculated by Maxwell’s model

\[ k_{nf} = k_{bf} + \frac{2 k_{bf} (k_{nf} - k_{ap})}{k_{ap} + 2 k_{bf} + \phi (k_{bf} - k_{ap})} \]

When the effect of Brownian motion is taken into consideration, the viscosity of the nanofluid is (Batchelor 1977):

\[ \mu_{nf} = (1 + 2.5\phi + 6.2\phi^2) \mu_{bf} \] 

The absorption coefficient of CuO/oil nanofluid with different mass fraction had been measured. The average absorption coefficient of nanofluid in full spectral range is calculated as Table 1.

<table>
<thead>
<tr>
<th>The mass fraction of CuO/oil nanofluid, w</th>
<th>Average absorption coefficient ( K_{nf} ), m(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05%</td>
<td>75.94</td>
</tr>
<tr>
<td>0.055%</td>
<td>103.06</td>
</tr>
<tr>
<td>0.060%</td>
<td>150.01</td>
</tr>
<tr>
<td>0.075%</td>
<td>214.38</td>
</tr>
<tr>
<td>0.100%</td>
<td>345.49</td>
</tr>
</tbody>
</table>

**Collector thermal efficiency and efficiency factor**

The thermal efficiency of the collector is the ratio of the usable solar energy to the total incident solar energy. It can be expressed as follows:

\[ \eta_c = \frac{mc_p (T_{out} - T_{in})}{I_0 WL} \] 

where \( L \) and \( W \) are respectively the length and width of the parabolic trough concentrator. The solar energy absorbed by working fluid is:

\[ Q_{in} = \eta_{opt} \alpha_{nf} \cdot I_0 WL \] 

where \( \alpha_{nf} \) is the absorptivity of nanofluid. \( \tau \) is the optical transmittance of transparent evacuated glass tube. The heat loss from the inner tube wall to the environment is given as:

\[ Q_{loss} = U \cdot A (T_i - T_e) \] 

where \( A \) is the surface area of the inner tube, and \( T_i \) is the temperature at the inner tube wall.

According to energy balance, the usable solar energy the nanofluid got is the difference between the absorbed solar energy and the heat loss stated above. Consequently, the collector thermal efficiency could also be written as:

\[ \eta_c = \frac{Q_{in} - Q_{loss}}{I_0 WL} = \eta_{opt} \alpha_{nf} \frac{U \cdot (T_i - T_e)}{r \cdot I_0} \] 

where \( r \) is the geometric concentrating ratio of the parabolic trough concentrator.

However, the temperature in the inner tube wall \( T_i \) is usually hard to measure, so the temperature of the nanofluid is adopted to represent the collector thermal efficiency as follows:

\[ \eta_c = F' \left[ \eta_{opt} \alpha_{nf} - \frac{U \cdot (T_{in} - T_w)}{r \cdot I_0} \right] \] 

or

\[ \eta_c = F_R \left[ \eta_{opt} \alpha_{nf} - \frac{U \cdot (T_{in} - T_w)}{r \cdot I_0} \right] \]
RESULTS AND DISCUSSION

The non-uniform temperature distribution of nanofluid

Fig. 2 displays the temperature distribution of fluid at several sections L=900 along the collector tube (whose total length was L=1800mm), under the different inlet fluid temperature condition. The solar radiation intensity was 700W/m² and the ambient temperature was 30°C. For NDASC using CuO/oil nanofluid, the mass fraction of nanoparticle was 0.055%; while for indirect absorption solar collector (IASC), the heat transfer oil acted as working fluid. It could be found that the temperature distribution between NDASC and IASC is obviously different. For NDASC, the nanofluid temperature in the central area is much higher than that at the tube wall of the collector. In the contrary, the highest temperature appears at the tube wall for IASC system. This is because the nanoparticle in the base fluid of NDASC absorbs solar radiation, instead of absorbing coating as IASC. In addition, when contrasting the temperature distribution of fluid near the tube wall, it is more uniform for NDASC whose maximum temperature difference is 24.66°C when \( t_{in}=150°C \). However, it could reach to 58.89°C for IASC at the same inlet fluid temperature. The temperature distributions of NDASC (\( t_{in}=90°C, 120°C \) and 150°C) are also varied as shown in Fig. 2.

The efficiency factor and heat removal factor

Fig. 3 shows the change of efficiency factor \( F' \) and heat removal factor \( F_R \) corresponding to the inlet fluid temperature (\( I_{0e}=700W/m², t_0=30°C \)).

With the increase of the inlet fluid temperature, the \( F' \) and \( F_R \) gradually increase, this is because the heat loss from the inner tube wall to the ambient air increases under the same solar radiation and ambient temperature. Consequently, the position with high temperature moves to the central area of the collector tube. Therefore, enhancing the thermal insulation of the vacuum tube may significantly improve the efficiency of the solar absorber.

Fig. 4 explores the variation of efficiency factor \( F' \) and heat removal factor \( F_R \) versus radiation intensity on the same mass fraction of nanofluid and inlet fluid temperature. There is a tendency of reducing and reaching a steady value for both \( F' \) and \( F_R \) when the radiation intensity increases. In the condition of low solar radiation intensity, the solar energy is easily absorbed by a thin layer of nanofluid near the tube wall. While increasing the solar radiation intensity, the fluid in the central area could also receive the incident light, which contributes to the uniform temperature distribution of nanofluid in the whole collector tube. Consequently, the temperature difference between central area and tube wall decreases, as \( F' \) and \( F_R \) decreasing in Fig. 4. It can be also observed that the \( F_R \) is greater than \( F' \) under the radiation temperature difference is 24.66°C (when \( t_{in}=150°C \)). However, it could reach to 58.89° C for IASC at the same inlet fluid...
intensity of 400 W/m², which means the average fluid temperature is lower than the inlet fluid temperature. This is because the inlet fluid temperature is too high, resulting in the excessive heat loss compared to the solar energy absorption in the low radiation.

The performance optimization of NDASC

Fig. 5 shows the change of collector thermal efficiency $\eta_c$ corresponding to the mass fraction at a constant inlet fluid temperature and solar radiation intensity. The collector thermal efficiency reached to the maximum of 0.428 at the mass fraction of 0.055%. When increasing mass fraction from 0.055% to 0.100%, the collector thermal efficiency declined. Since the non-uniform temperature distribution could hardly be experimentally observed, the experiment was conducted and the collector thermal efficiencies of NDASC and IASC were compared to analyze the feasibility of NDASC in the previous researches of our research group (Xu 2015). It shows that the experimental collector thermal efficiency of NDASC was higher than that of IASC when the normalized temperature difference $(T_t - T_0)/T_0$ was below 0.125, where $T_t$ was the temperature of fluid.

![Fig. 5. The variation of collector thermal efficiency corresponding to the mass fraction ($t_0 = 140^\circ C, I_0 = 700 W/m²$).](image)

The performance optimization of NDASC

Eq. (15) displays the factors influencing the collector thermal efficiency. At the certain solar collection system parameters, constant inlet fluid temperature, ambient temperature and radiation intensity, the collector thermal efficiency is mainly dominated by heat removal factor $F_R$ and total absorptivity $\alpha_{nt}$ of nanofluid. Actually, the concentration of nanoparticle directly influences the absorption ability and the temperature distribution of nanofluid. Consequently, the effect of mass fraction of nanofluid on collector thermal efficiency is caused by multiple factors, and it is necessary to analyze them to ascertain the optimum mass fraction.

Fig. 6 depicts the variation of efficiency factor $F$, heat removal factor $F_R$ and total absorptivity of nanofluid when increasing mass fraction of nanofluid. It can be seen that the $F$ and $F_R$ decreased while mass fraction changing from 0.050% to 0.100%. Meanwhile, the total absorptivity increased from 96.72% to nearly 100%. Fig. 7 shows the temperature distribution of nanofluid in the NDASC with different mass fraction. While contrasting the temperature distribution in various mass fraction, it is more uniform in low concentration. On the one hand, the position where the biggest temperature appeared in the sections moved from the central area to the tube wall when the mass fraction changing from 0.050% to 0.100%. On the other hand, the inner tube wall temperature was significantly higher when the mass fraction was 0.100%, comparing to that in lower concentration. When increasing the mass fraction, the portion of solar energy absorbed by nanoparticle near the tube wall widely enlarged and the solar radiation attenuated quickly before reaching the central area of the collector tube. It intensified the non-uniform temperature distribution of nanofluid and led to the relative high temperature of nanofluid near the tube wall, so the $F$ and $F_R$ reduced.

![Fig. 6. The efficiency factor, heat removal factor and total absorptivity of nanofluid as a function of the mass fraction ($t_0 = 140^\circ C, I_0 = 700 W/m², D_i = 45mm$).](image)

![Fig. 7. The temperature distribution of nanofluid in the NDASC with different mass fraction ($I_0 = 700 W/m², t_0 = 140^\circ C, t_i = 30^\circ C$).](image)

When the mass fraction increasing from 0.050% to 0.055%, the collector thermal efficiency improved though the fact that the $F_R$ declined, as shown in Fig. 6. This is due to the enhancement of solar absorption ability of nanofluid when adding more nanoparticles. However, when the mass fraction changing from 0.055% to 1.000%, the total absorptivity reached to nearly 100%, so the collector thermal efficiency was primarily determined by heat removal factor $F_R$. The $F_R$ decreased from 1.038 to 1.012. Therefore, the collector thermal efficiency reduced with $F_R$ while mass fraction was higher than 0.055%. The results showed that the NDASC could achieve a maximum collection efficiency when the mass fraction of 0.055% was preferred.
The results provided effective ways to optimize the performance of NDASC by using efficiency factor $F'$ and heat removal factor $F_R$. When the solar absorption ability of nanofluid reached to the plateau, the higher $F'$ and $F_R$ indicated a higher collector thermal efficiency. The optimum mass fraction of nanofluid could be ascertained to gain the preferable performance of NDASC by using $F'$ and $F_R$.

CONCLUSIONS

In this study, a numerical model was developed to investigate the non-uniform temperature distribution of CuO/oil nanofluid and system performance of a nanofluid-based direct absorption solar collector (NDASC). The effects on efficiency factor $F'$ and heat removal factor $F_R$ of the collector are also analyzed. It can be concluded from the obtained results:

1) The nanofluid in the NDASC showed non-uniform temperature distribution, and the temperature in the central area of the collector tube was higher than that at the tube wall.
2) The efficiency factor $F'$ and heat removal factor $F_R$ could be greater than 1, which is significantly different from the performance of indirect absorption solar collector (IASC).
3) The efficiency factor $F'$ and heat removal factor $F_R$ increases with inlet fluid temperature, and decreases with mass fraction of nanofluid and solar radiation intensity.
4) The higher $F'$ and $F_R$ indicates the higher collector thermal efficiency when the solar absorption ability of nanofluid reaches to its plateau. Therefore, the $F'$ and $F_R$ could be used to choose the optimum mass fraction and finally optimize the collector performance.

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