Two-dimensional model of trapezoidal solar pond based on large eddy simulation

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Abstract. A two-dimensional unsteady large eddy simulation model of a trapezoidal solar pond is carried out on the platform of Fluent17.2. On the basis of verifying the validity of the model, the characteristics of temperature change, velocity and vorticity distribution, and salt concentration change at the interface are analyzed. The result shows that the overall temperature of the solar pond increases over the running time, and the maximum temperature (314 K) appears in the lower convective zone after 10 days of operation. The velocity field and vorticity field are mainly distributed in the lower convective zone (LCZ), and the velocity remains at the order of 10⁻⁴ m/s. The salt concentration at the upper and lower interface decreases obviously under the influence of salt diffusion.

1. Introduction

The salt gradient pond is a solar energy collector that combines the effects of both heat accumulation and heat storage.

In the past decades, the theories of double diffusion of thermal and salt have been explored and studied in depth. Kurt et al. built an one-dimensional numerical model of solar pond that the salt water was divided into equidistant thin layers, and the salinity diffusion between each layer had been ignored. Karakilcil et al. proposed that the difference between the experiments and simulation results was about 8 K, which indicated that the error of the Kurt model might be very large if the salt gradient of the solar pond was not maintained. Hammami et al. coupled the natural convection phenomenon and the salt gradient diffusion with the governing equations to build a numerical simulation and simplify the flow in the solar pond. Li Nan et al. presented a two-dimensional simplified model of heat and salt diffusion in a salt-gradient solar pond. Liu et al. established a turbidimetric model of trapezoidal solar pond and the double diffusion discrete model of heat and salt diffusion, the influences of solar pond structure, water turbidity and reflectivity on the thermal performance of solar pond were discussed.

2. Physical model of the solar pond

2.1 Governing equations

The continuity equation is:
The momentum equation is:

\[ \frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} - 2\frac{\partial \sigma_{ij}}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \]  

(1)

The energy equation is:

\[ \frac{\partial (\rho h)}{\partial t} + \frac{\partial u_i (\rho h u_i)}{\partial x_i} - \frac{\partial \mu_{ij} \Delta h_{ij}}{\partial x_i} = \frac{\partial}{\partial x_i} \left( C_p \frac{\partial T}{\partial x_i} \right) + Q \]  

(2)

Salt transport equation:

\[ \frac{\partial (\rho S)}{\partial t} + \nabla \cdot (\rho \nabla S) = \nabla \cdot (\rho \kappa \nabla S) \]  

(3)

In the formula: \( \rho \) is the density of salt water, kg/m\(^3\); \( u \) is flow velocity; \( t \) is the length of time; "-, ~" represent physical spatial filtering and Favre filtering; \( p \) denotes pressure, Pa; \( \sigma_{ij} \) is the viscous stress tensor; \( \mu \) is the dynamic viscosity of fluid, N·s/m\(^2\); \( h \) denotes enthalpy, kJ; \( C_p \) is isobaric specific heat capacity, J/Kg·K; \( Pr \) means Planck number; \( S \) represents salt water concentration, %; \( \nabla \cdot (\rho \kappa \nabla S) \) is the convection term, representing the salinity flux from the flow of water in the pond; \( \nabla \cdot (\rho \kappa \nabla S) \) is the diffusion term, which represents the salinity flux caused by the change of salt gradient.

2.2 Boundary conditions

According to the solar pond structure in reference [2], the third kind of boundary condition can be expressed as follows:

\[ -\lambda(T) \left( \frac{\partial T}{\partial x} \right)_b = h(T_a - T_b) \]  

(4)

Where \( h \) represents convection heat transfer coefficient on the outer wall of brick layer, W/(m\(^2\)·K), as a constant; \( \lambda(T) \) denotes thermal conductivity of brick layer, W/(m\(^2\)·K) which is a function with temperature as a variable and obtained by fitting the experimental data; \( T_a \) indicates the temperature of the brick, K.

3. Numerical simulation method

In the present work, a large eddy model is used to simulate the flow in a trapezoidal solar pond as shown in reference [11], a semi-implicit pressure coupling method is used to couple the pressure velocity, and a second order upwind difference is used to discrete the N-S equation using the flow equation of Fluent17.2. In the large eddy simulation model, the solar radiation transmission source terms varying with time and depth are added, the salt mass fraction and temperature in the unit of calculation are extracted by user define function.

4. Results and discussions

4.1 Temperature variation of solar pond
Figure 1. Solar pond temperature cloud map

Figure 1 shows the temperature cloud map of the solar pond. It can be seen from the diagram that LCZ is mainly concentrated in the heat absorption region of the solar pond on the first day, the maximum temperature hovering between 301 K and 302 K. While on the fourth day, the lowest temperature in the pond was concentrated in the non-convective gradient zone (NCZ), the position of the highest temperature in the pond gradually shifts from the UCZ to the LCZ, and the temperature rises to a large extent by 13.5K.

After the fourth day, the temperature of the UCZ gradually decreased, and the high temperature region of the solar pond was mainly distributed in the LCZ. The simulation results show that on the 5th to 10th day, UCZ has a narrow strip of high temperature, which is obviously lower than the LCZ. The maximum temperature in the pond can reach 314K on the 10th day.

4.2 Velocity distribution of solar pond

Figure 2 shows the velocity distribution in the solar pond. Salt water as you can see the sun in the pond area of the velocity distribution is mainly in LCZ, at the same time in the troposphere near the wall also has a certain speed. Starting from the second day, the velocity field has basically covered the whole region of the troposphere, and the velocity remains at the magnitude of $10^{-4}$ m/s.
Figure 2. solar pond velocity distribution cloud image

Over time, the velocity field appears obvious vortex structures, the troposphere and vortex phenomenon, merge and split solar pond movement to the 10th day, the troposphere within three to four obvious vortex area, in which a maximum velocity distribution in the central area is larger vortex near the edge, the maximum speed of $4 \times 10^{-4}$ m/s, at this point in the troposphere the average speed of $1.7 \times 10^{-4}$ m/s.

4.3 Vorticity distribution of the solar pond

Figure 3 shows the vorticity distribution in the solar pond. It can be seen that on the third day, there were two obvious vortex areas in the upper convective zone (UCZ) close to the wall surface, and there were a large number of small vortex areas with disordered distribution and low vorticity in the LCZ, without obvious large vortex area distribution. Starting from the third day, the disorderly small vortex area gradually merges.

Figure 3. cloud pattern of vorticity distribution in solar pond

It shows that several strip vortexes with average vortex amount of $4.38 \times 10^{-3}$ s$^{-1}$ appears in the LCZ. Comparing Fig.3 and Fig.2, it can be seen that the high vorticity area corresponds to the area with a large velocity gradient, indicating that the velocity changes drastically, the rotation of the local fluid microcluster intensifies, the curl of the flow field increases, and the vorticity value increases, which inevitably leads to the increase of the local viscous force.

4.4 Variation of salt gradient in solar pond boundary layer
Figure 4. Variation of NaCl salt concentration at the interface

Figure 4 shows the variation of NaCl at the interface between the UCZ and NCZ, the NCZ and LCZ. The overall trend of salt concentration decreases by 0.6% in the interface between NCZ and LCZ, and the salt concentration in the interface between NCZ and UCZ decreases by 0.4%. The salt concentration of NCZ and LCZ boundary decreased rapidly on the first day of operation, and the salt concentration remained unchanged from the second day to the third day. The salt concentration at the interface between NCZ and UCZ drops rapidly by 0.15 percent in the first few hours of operation of the solar pond, followed by a gradual, rapid, and gentle decline.

5. Conclusion

(1) The maximum temperature of the trapezoidal solar pond can reach 314 K and appears stably in LCZ after 10 days of operation.

(2) The velocity field in the solar pond is mainly caused by the variation of the temperature field, which mainly distributes in LCZ and forms three to four large eddies with a velocity of $10^{-4}$ m/s. The velocity range of NCZ is only $10^{-9}$ m/s which is negligible.

(3) The vorticity region in the solar pond mainly concentrates in LCZ, and gradually develops from the disorderly vortex region to the large vorticity region with large vorticity gradient. The average vorticity is $4.38\times10^{-3}$ s$^{-1}$.

(4) The NaCl concentration at the interface between the UCZ and NCZ, the NCZ and LCZ, in the solar pond decrease with time.

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