Three-dimensional Numerical Simulation of the Flow Field in the Potato Storage in Summer

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Abstract. In recent years, with the rapid growth of potato demand, potato storage has become extremely important. It is vital that controls the ambient temperature and wind speed during potato storage. Therefore, this work simulated the temperature field and air flow organization in a potato storage using the underfloor air supply. The established computational fluid dynamics (CFD) model was used to study the temperature field and airflow organization in the warehouse under different air supply parameters, and compared the results to get their change rule. On this basis, the influence of the underfloor air supply on the flow field was studied to verify its feasibility. The results show that under reasonable conditions, the underfloor air supply can effectively guarantee the required temperature and airflow organization.

1. Introduction
The potato is the world’s fourth largest food crop and plays an irreplaceable role in ensuring food security and achieving the millennium development goals. However, due to the high moisture content of potato tubers, improper moisture and temperature control during storage may cause a large amount of rotten potatoes.

In order to reduce post-harvest deterioration, the potatoes should be properly stored. This storing is generally accomplished in a ventilated warehouse, where the condition of low temperature and the desired airflow organization is maintained [1]. Relevant studies have shown that the best temperature in the warehouse is 10-15°C and the air circulation is increased to quickly dry the potato surface, the potatoes in this environment have difficulty breathing, tubers do not germinate, and nutrient loss is reduced [2].

The experimental studies are expensive and time consuming, Computational Fluid Dynamics (CFD), a numerical technique based on the solution of mean flow conservation equations coupled with suitable turbulence models, has been used in studies of room air movement to predict the velocity and turbulence fields [3]. The objective of the present work was to simulate the internal temperature field and air distribution in an empty warehouse using CFD technique, a mathematical model is established to study the influence of different air supply parameters on the internal flow field and discuss the feasibility of setting the air supply port at the bottom of the warehouse. We hope that these numerical results can provide some inspiration and guidance for further research on potato storage and engineering practices in the future.

2. Model development

2.1. Description of the actual physical system
The cross-sectional view of this potato warehouse is shown in figure 1. It is 27.4 m long, 18 m wide and 4 m high with a 15 degree pitched roof. We set the air supply pipes at the bottom, as shown in figure 2, the main air supply pipe with a width of 0.76 m is arranged in the center, and the branch air supply pipes are evenly arranged on both sides. Rectangular air inlets are uniformly distributed on each branch air supply pipe, and the size of a single inlet is 0.36m × 0.36m. Air enters the main air pipe, and then flows into the warehouse through the air inlets on the branch pipes.

2.2. The computational fluid dynamics model

Due to the high pressure of cold air in the storage, it will flow out of the storage through the doors and windows continuously. Therefore, the field of simulation will be further expanded. It consists of the storage building and the outdoor atmosphere. By simulating the flow state of the al fresco atmospheric boundary layer, the flow field of the air in the storage can be simulated under the combined action of wind pressure and heat pressure.

This simulation chose the structured grid for partitioning, mainly considering that the physical model is regular, and the topological structure of the structured grid is strict and orderly, has high calculation accuracy and easy to generate. At the same time, considering that there are great differences in geometric scale in the research of different computing field objects, the structured grid of partition is adopted. For outdoor air, the grid accuracy is controlled at 0.20 m, for building and indoor air, the grid accuracy is controlled at 0.12 m.

2.3. Governing equations

2.3.1. The basic governing equation. Because the air pipes supply cold air from bottom to top, the density of cold air is large, so the gravity field effect of air needs to be considered. For its density, this model assumes that it follows the Boussinesq hypothesis, or the chimney effect, which can more truly express the natural flow of air in the storage. Boussinesq hypothesis are generally used in steady-state calculation when the density of the fluid does not change greatly. In this method, the fluid density is regarded as a constant by the following formula:

\[ (\rho - \rho_0) g \approx -\rho_0 \beta (T - T_0) g \]  

(1)
Where: \( \rho_0 \) is the normal density of the fluid and \( T_0 \) is the operating temperature. In this model, the outdoor temperature set at 35°C. At this time, the air density is \( \rho_0 = 1.29 \text{kg/m}^3 \) and the thermal expansion coefficient is \( \beta = 0.00335 \text{K}^{-1} \). Under natural conditions, the temperature difference of air heated is within 50°C, so this method is applicable \(^4\).

2.3.2. The turbulence model. In order to solve the basic governing equations, it is necessary to use a turbulence model to close it. The main role of the turbulence model is to link the new unknown with the average velocity gradient. This simulation uses the Renormalization Group (RNG) \( k-\varepsilon \) models. This model had been applied to numerous indoor air flow problems with good predictive accuracy. And recent results specifically show that this model was quite successful in simulating ventilation flows in greenhouse \(^5\).

2.3.3. The solar radiation model. For the analysis of the flow field in an indoor room, it is necessary to consider the radiative heat transfer between the gas and the particles, and comprehensively consider the calculation volume and calculation accuracy requirements. This time, the model was selected as the P-1 model.

2.4. The boundary condition
In the calculation domain, the duct air inlet is set as the velocity inlet boundary condition (Velocity inlet). Due to the low air temperature in the storage, the speed and pressure on the door and window exits in the storage building are unknown, considering the scope of the calculation domain and the chimney effect, the cold air can be considered from the bottom to the top and eventually flow out through the top surface of the calculation domain. Therefore, in this model, it is assumed that the top surface of the calculation domain is the exit boundary condition. Since the velocity and pressure at the outlet are unknown, they are set as free flow boundary conditions (outflow). The air around the calculation area is 35°C, so the surrounding surface of the calculation area is set as the wall of 35°C, and the wall thickness is set as 0mm. The bottom is fixed to the ground. In order to simplify the model, the heat transfer process between the atmosphere and the ground is not considered, so it is set as a surface with a heat flux of 0. For the internal and external walls of the building, the complex heat transfer process between indoor and outdoor should be thought, so it is set as a 240mm thick wall, and its heat transfer is automatically calculated by FLUENT.

3. Results and discussion
This simulation has studied the influence of air velocity, air temperature and the number of air inlets on the temperature field and air distribution when using underfloor air supply, discussed the setting of optimal air supply parameters, and finally demonstrated the rationality of this air supply mode.

3.1. The simulation results
In this paper, four operating conditions are simulated and compared. The details are as follows: A: the air supply speed is 1 m/s, the air supply temperature is 7°C and the number of air inlets on each branch air pipe is 6; B: the air supply speed is 1 m/s, the air supply temperature is 10°C and the number of air inlets on each branch air pipe is 6; C: the air supply speed is 0.2 m/s, the temperature is 10°C and the number of air inlets on each branch air pipe is 6; D: the air supply speed is 1 m/s, the air supply temperature is 10°C and the number of air inlets on each branch air pipe is 4.
Figure 5. Simulation results under operating condition A: (a) Temperature cloud at the height of 1.5 m (b) Temperature cloud at the height of 3.5 m (c) Velocity streamline diagram.

Figure 6. Simulation results under operating condition B: (a) Temperature cloud at the height of 1.5 m (b) Temperature cloud at the height of 3.5 m (c) Velocity streamline diagram.

Figure 7. Simulation results under operating condition C: (a) Temperature cloud at the height of 1.5 m (b) Temperature cloud at the height of 3.5 m (c) Velocity streamline diagram.

Figure 8. Simulation results under operating condition D: (a) Temperature cloud at the height of 1.5 m (b) Temperature cloud at the height of 3.5 m (c) Velocity streamline diagram.

3.2. Comparison of results

(1) Compared the simulation results of A and B, other things being equal, but the air supply temperature is 7 ℃ and 10 ℃ respectively, the overall temperature of the lower plane (1.5m) and the higher plane (3.5m) in the bin can be maintained at the air supply temperature. The storage temperature of potato raw materials used for processing is 10-15 ℃. Because of the floor air supply, the air can be directly contacted with the potato, and the air supply temperature can be properly increased. Therefore, considering the energy saving, the air supply temperature of 10 ℃ is appropriate.
(2) Compared A and B, other things being equal, but the supply air velocity is 0.2 m/s and 1 m/s respectively, the temperature of the warehouse can meet the storage requirements, but the internal air velocity is quite different. When the air supply speed is 1 m/s, the air flow speed in the warehouse is about 10 m/s. When the air supply speed is 0.2 m/s, the internal air flow speed is only about 3 m/s. When the warehouse is used to store potatoes, a certain wind speed shall be ensured to take away the heat and CO\textsubscript{2} generated by respiration, so as to avoid excessive surface temperature of potatoes and carbon dioxide poisoning. Therefore, air supply speed of 1 m/s is more appropriate.

(3) Compared B and D, when the air supply volume is the same, the number of air inlets on each branch pipe is different, because the total number of air inlets is reduced and the export pressure of a single air inlet is increased, the air flow rate in the warehouse is increased accordingly. Compared with six air inlets, when four air inlets are set on each branch pipe, the air flow rate in the warehouse can reach 30 m/s, which may cause a series of safety hazards. When six air inlets are set on each branch pipe, the air velocity is about 10 m/s, which can effectively take away the heat and CO\textsubscript{2} produced by potato respiration and ensure the quality of potato.

4. Conclusion
According to the above comparative analysis, when the air inlets are set at the bottom of the potato storage, the reasonable setting of air supply parameters can not only keep the temperature of each plane in the warehouse uniform, but also make the air distribution relatively reasonable. The cold air flowing from bottom to top directly contacts with the potato, taking away the heat and CO\textsubscript{2} generated by respiration in time, ensuring the temperature in the warehouse while reducing the concentration of CO\textsubscript{2}, avoiding the occurrence of CO\textsubscript{2} poisoning, and achieving long-term storage of potatoes. Therefore, underfloor air supply is a simple and effective way for potato storage.

5. References
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