Experimental and numerical research on squat silo and large size horizontal warehouse during quasi-steady-state storage

Ren Guangyue, Liu Yanan, Peng Wei, Duan Xu, Zhang Ledao*

(*College of Food and Bioengineering, Henan University of Science & Technology, Luoyang* 471023, *China*)

Abstract: Traditional method to prevent stored grain from deterioration is to control grain temperature. A three dimensional (3-D) numerical model was established to study the temperature variation in outdoor squat silo and large size horizontal warehouse at quasi-steady-state. In this research, porous media model and solar radiation model were adopted. Numerical and experimental results showed that grain temperature was influenced by temperature of wall, height of grain and the distance between grain and the wall. Temperature changes dramatically at the top layer of grain heap due to solar radiation and heat convection at air layer. Temperature of grain close to wall increased with the increasing of ambient temperature. The model established in this research is suitable for predicting grain temperature in outdoor squat silo and large size horizontal warehouse.

Keywords: squat silo, large size horizontal warehouse, porous media model, solar radiation model, three dimensional numerical model, grain temperature, quasi-steady-state storage

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1 Introduction

In order to gain high-quality food, the increasing storage problems, such as mildew, germination, and pests, et al. need to be solved[1-3]. The traditional method to prevent the deterioration of stored grain is to measure the grain temperature to make the grain temperature not exceeding a certain threshold value, and to keep microorganism activity not increasing.

The approaches to know, monitor and predict the temperature distribution in storage bin have drawn a lot of concerns[4-6]. In 2013, a temperature monitoring system composed of fiber Bragg grating was designed[7]. Yan et al.[8] proposed a temperature monitoring method to store grain using acoustic tomography. The feasibility of using ZigBee technology for the measurement system in large-scale barns was developed by Zhang et al.[9]

A model for predicting natural convection flows, temperature distribution and moisture migration in soybean storage was established by Barreto et al.[10] In their researches, soybeans were stored in a cylindrical bin and there was no aeration from autumn to spring. The results indicated that natural convection was strongly affected by permeability. The model used to evaluate and predict wheat quality was established by Ji et al.[11] In their research, the relationship between wheat temperature and air temperature was discussed, and the storage surroundings and quality were researched.

The transient heat and mass convection model was established by Carrera-Rodríguez et al.[12] to study grain

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Biographies: Ren Guangyue, PhD, Professor, research interests: drying science and technology of agricultural product as well as medicinal and edible food, Email: rgy@haust.edu.cn; **Liu Yanan**, graduate student, research interests: agricultural product drying technology, Email: 1105320621@qq.com; **Peng Wei**, Master, research interests: agricultural product drying technology, Email: elonlucy@sina.com; **Duan Xu**, Master, Associate Professor, research interests: energy-saving technology of freeze drying and freeze drying technology using microwave, Email: duanxu_dx@163.com.

***Corresponding author: Zhang Ledao**, PhD, Lecturer, research interests: drying science and technology of agricultural product. College of Food and Bioengineering, Henan University of Science & Technology, Luoyang 471023, China. Email: ldzhang@haust.edu.cn.

stored in a cylindrical silo. In their research, multi-phasic media was considered and the model with the equations of heat, mass and momentum transport was developed. Their results showed that the effect of ambient temperature was obviously during the formation of hot regions inside the cavity. The dynamics model was established by Carrera-Rodriguez et al.[13] to research two-dimensional grain temperature during storage in cylindrical silos, and their results indicated that the time reached to equilibrium was different once boundary conditions were changes.

The equations that describing the conservation of heat, mass, and momentum were solved by Oliveira Rocha et al.[14] In their research, three-dimensional computational fluid dynamic was used, and the heat and mass transfer inside a grain mass of maize that stored in a flat bin was predicted. Their results indicated that the predicted results were in good agreement with experimental data. A 3-D model of airflow through high capacity grain storage bins was established by Khatchatourian and Binelo[15]. In their research, the seed mass was considered to be non-uniformity. The results indicated that the model had good performance and the method could be applied to existing grain stores and minimizes engineering costs for new grain stores. A 3-D model was established by Khatchatourian et al.[16] to explore the movements of soya beans in mixed-flow dryers. In their research, the discrete element method was applied to the Yade software package, and the soya bean seeds were considered as single spheres. Simulation results indicated that there was significant non-uniformity in particle velocity and residence time.

Numerical modeling of the fluids flows in porous media has traditionally been at the macroscopic level. A porous medium computational fluid dynamics model was used by Ambaw et al.[17] to numerically analyze the distribution of 1-Methylcyclopropene (1-MCP, commercially used to delay ripening of fruits) in cool store rooms stacked with apples. Modeling of fluid flow at the grain level was the most important and how this can be done with the SPH (Smoothed Particle Hydrodynamics) technique was showed by Pereira et al.[18] The 3-D SPH simulations of fluid flow presented in an idealized porous medium showed that the technique produces flows were physically realistic.

Temperature inside a metal silo filled with 20 t wheat were monitored by Jian et al.[19] They monitored the temperature from August 2003 to October 2004 in Western Canada. Their results showed that there was larger temperature fluctuation in the headspace than inside the grain. A headspace numerical model could be used to predict the air temperature in the headspace of a silo filled level to its eave was established by Lawrence et al.[20], and the result was of reasonable accuracy.

The reduced scale model of flat-bottomed silo was used by Yuan et al.[21] In their work, the static lateral pressure in silo walls was determined. Their results indicated that the existence of the silo dynamic overpressure during the engineering design cannot be ignored. In order to build the method of calculating static lateral pressure, the appearance of stored solids in silos after eccentric discharge was researched by Zhu et al.[22] Their results indicated the necessity of lateral pressure calculation in squat silos. The scale model of squat silo in large diameter was established by Yuan et al.[23] This scale model used centrifuge model test principle for reference and provided the gravity field in the archetypal squat silo. The lateral pressure formula for squat silos and equations of failure plane about sliding cuneiform volume were obtained by Shao and Zhang[24]. In their paper, the calculation results were available for squat silo design when the friction was neglected. Their results indicated that it was a reasonable calculation method for design squat silo.

Different grain needs different storage conditions. A 2-D finite element model could be used to predict temperature distribution, moisture migration and natural convection currents in stored grain was established by Barreto et al.[25] Their numerical results showed that moisture migration in soybean was faster than that in corn and wheat for a certain temperature gradient.

Quasi-Steady state storage occupies the most part of storage time and is important to grain storage. To study the temperature variation in small grain steel silo during quasi-steady state, a 3-D numerical model was established by Zhang et al.[26] In their research, experiments were conducted indoor and porous media model was adopted. The results indicated that numerical results agreed well with experimental results and the model established was valuable for predicting grain temperature in steel silo. However, the grain steel silo used in their research is small, indoor, and not subjected to sunshine; the models of their research cannot be extended to outdoor large granary. Until now, no specific studies have precisely described the temperature distribution in squat silo and large size horizontal warehouse during Quasi-Steady state storage. In this research, the solar radiation model and porous media model were used, and the temperature distribution in squat silo and large size horizontal warehouse were studied. The results could give a good guide for the grain temperature prediction system.

2 Materials and methods

The squat silo come from grain reserve depot of China located in Zhumadian, Henan Province, China. The material is steel and the whole structure is shown in Figure 1a. The total height is 18.8 m with 15.7 m cylindrical part and 3.1 m circular cone part, the radius is 6.11 m, and the height of grain in squat silo is 12.5 m.

a. b.

Figure1 The photos of (a) squat silo and (b) large size horizontal warehouse

The temperature inside squat silo can be obtained by a light temperature sensor cable (SCWP-7, Raytek Inc.) with a precision of 1 K. The temperature of outdoor squat silo can be obtained by a grain situation measuring and controlling system. At the beginning of experiment, data was recorded every seven days, and the average of recorded data in 30 days was considered as the average temperature in a month.

The experiment was implemented from December 2010 to May 2011. In a horizontal grain layer direction, temperature monitoring point was placed at east, south, west and north direction and distances from central of circle were 5 m, temperature test point was placed in southeast 45º, southwest 45º, northeast 45º, and northwest 45º direction, respectively. The distance between temperature test point and circle central was 4 m. In vertical grain layer direction, there were seven layers of temperature sensors, the distance from the first layer to the bottom of squat silo was 2 m, and the distance between two adjacent layers of temperature sensor was 2 m.

The large size horizontal warehouse was located in grain reserve depot of China, Daxing, Beijing. The photo is shown in Figure 1b. The width of large size horizontal warehouse was 24 m and the length was 54 m, with brick-concrete structure wall and reinforced concrete casting roof. The height of grain was 6 m, the air layer in the top part was 2 m, and taper part was 4 m.

The inside and outside temperatures of large size horizontal warehouse were also obtained by using a light temperature sensor and grain situation measuring and controlling system. The experimental recorded methods were the same with those used in squat silo.

The experiment was implemented from January 2011 to June 2011. At the length direction, there were 12 temperature sensors, the distance between first temperature sensor and wall was 30 cm, between last temperature sensor and wall was 490 cm, between two temperature sensors was 485 cm. At the width direction, there were six temperature sensors, the distance between first temperature sensor and wall was also 30 cm, and the distance between two temperature sensors was equal. At vertical direction, there were four layer temperature sensors, the distances between temperature sensor and the bottom of large size horizontal warehouse were 2.1 m, 3.9 m and 5.7 m, respectively.

3 Numerical modeling

3.1 Governing equations

The respiration heat was not considered in this research. The medium was considered as continuous, and the governing equations were as follows.

Continuity equation:

$$\nabla \cdot (\rho_{air} u) = 0 \tag{1}$$

Momentum equation:

$$\rho_{air} u \cdot \nabla u = -\nabla P + \nabla \cdot (\mu_{air} \nabla u) \tag{2}$$

Energy equation:

$$\rho_{air} C_{p,air} (u \cdot \nabla T_{air}) = \nabla \cdot (k_{air} \nabla T_{air}) \tag{3}$$

where, μ is air velocity, Pa·s; T_{air} is air temperature, K; ρ_{air} is air density, kg/m^3; $C_{p,air}$ is specific heat of air, J/(kg·K); and k_{air} is heat conduction coefficient of air, W/(m^2·K), and, There was no velocity slip and temperature jump at boundary condition in the simulation.

A grain heap was grain particles packed with air. The whole grain heap region was considered as a porous medium. In the porous media model, the principle of heat transfer and fluid mechanics are applied to a fluid-saturated media, and finally form a model that will govern heat transfer and fluid flow in a biological system (living tissue). It was assumed that the grain heap was isotropic. Solar radiation model was adopted since both the large size horizontal warehouse and squat silo located outdoors and were subjected to sunshine.

3.2 Parameters used in the model

The wall and cone roof of squat silo was made of stainless steel plate with a thickness of 0.5 cm; the bottom surface was also made of steel plate with air holes. All of the top surface, bottom surface, and wall of squat silo are thermal conductive surface. There were air layer between the top surface of grain and cone roof of squat silo. The computational domain was divided into two parts, one was wheat stacking zone, and the other was air layer at the top part of squat silo. Gambit (3.2) was used and the meshes created in geometry are shown in Figure 2a.

The wall and roof of large size horizontal warehouse were 0.5 m thickness concrete structure. The wall was thermal conductive surface, and the bottom surface was ground and assumed to be adiabatic surface. The computational domain was divided into two parts, one was wheat stacking zone, and the other was air layer at the top part. GAMBIT was used and the meshes created in geometry are shown in Figure 2b.

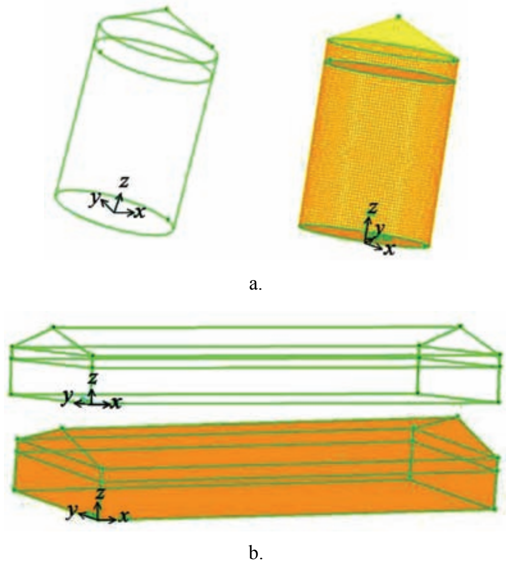


Figure 2 Geometric system studied and the 3-D computational domain of (a) squat silo and (b) large size horizontal warehouse

The UDF function in Fluent was adopted in the model of squat silo and large size horizontal warehouse. The variation of ambient temperature with time in squat silo and large size horizontal warehouse can be expressed as Equation (4) and Equation (5) respectively according to the measured data during experiment.

Solar radiation was considered. The longitude and latitude of squat silo and the large size horizontal warehouse were east longitude 116.02°, northern latitude 32.98° and east longitude 116.38°, northern latitude 39.70°, respectively. In the model, the east direction was set as x axis, due north direction y axis, and the right above direction z axis. The simulations were started from 00:00, 1st December, 2010 and 00:00, 1st January, 2011.

$$T = 1666\sin(0.0008\pi t/2592000 + 0.0432\pi) + 40.18 \tag{4}$$

$$T = 0.071(t/2592000 + 48.824)^2 + 90.380 \tag{5}$$

where, T is ambient temperature, K; t is time, s.

Porous medium model in Fluent was introduced into wheat stacking zone. The heat conduction coefficient, average particle diameter, specific heat capacity, and volume density of wheat were λ_g=0.13 W/m·K, D_p= 0.0045 m, C_g = 1780 J/kg·K and ρ_g = 750 kg/m^3, respectively. The permeability and inertial resistance factors of wheat were C_2 = 7102 and α = 63556569, respectively.

4 Results and discussion

The grain height in squat silo was 12.5 m. Three layers in squat silo were considered as test samples. H=12 m, 8 m and 4 m indicate that the distances between the first, second, and third grain layer and the bottom surface of silo were 12 m, 8 m and 4 m.

Figure 3 shows the average temperatures of different grain layers with respect to storage time. In Figure 3a, squat silo was a granary. The distance between the first grain layer and the top surface of grain heap was 0.5 m. The amplitude of temperature variation in the first grain layer was maximal because ambient temperature affected the temperature of the first grain layer evidently. Temperature variations of the second and third grain layer were small. Compared to the second layer, grain temperature of the third layer was lower, because the temperature of mattess was lower than that of external air and there was heat conduction between mattess and grain in the bottom of squat silo.

The grain height in large size horizontal warehouse was 6 m; there were also three layers in large size horizontal warehouse considered as test sample. The H=5.7 m, 3.9 m and 2.1 m represent that the distances between the first, second, and third grain layer and the bottom surface of large size horizontal warehouse was 5.7 m, 3.9 m and 2.1 m, respectively.

In Figure 3b, large size horizontal warehouse was a granary, the distance between the first grain layer and the top surface of grain heap was 0.3 m. Ambient temperature only affected the temperature of the first grain layer greatly. At the end of February, grain temperature of the first layer started to rise. From the end of February to the end of June, grain temperature of the first layer increased with the increase of ambient temperature and approached the maximum value of 295.55 K at the end of June. Compared to the first layer, temperature variation tendencies of the second and third grain layer always kept smooth and steady. From the end of January to the end of March, grain temperatures of the second and third layer had very little variation with respect to storage time and from the end of March to the end of June, the temperatures increased with the increase of ambient temperature and reached to the maximum value of 278.1 K and 275.9 K at the end of June.

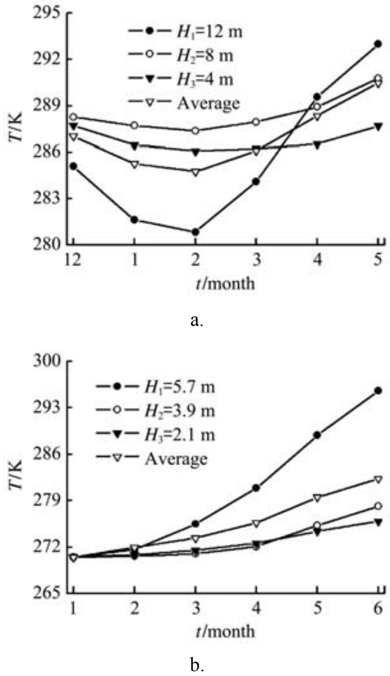


Figure 3 The average temperature of different grain layer with respect to storage time in (a) squat silo and (b) large size horizontal warehouse

Figure 4 shows the temperature distribution of mid perpendicular plane at the height of 12 m in squat silo under different storage time. In Figure 4, the height of grain layer was 12 m, x=−6.11 indicates the west side wall of squat silo and x=6.11 indicates the east side wall. The highest grain temperature appeared at May and the change features of grain temperature were basically the same. From December to January, ambient temperature decreased and the temperature of grain closed to wall was the lowest, grain heap temperature gradually increased from the outside in. When the distance between grain and wall was larger than 0.7 m, grain temperature tended to stable and constant. From January to March, ambient temperature gradually increased and was lower than the average temperature of grain heap, hence, the temperature of grain closed to wall increased and the temperature of grain heap still trended to decreases. From April to May, ambient temperature was high, the temperature of grain closed to wall increased quickly. When the distance between grain and wall was larger than 0.9 m, temperature of grain tended to stable and constant.

Figure 5 shows the temperature with respect to the grain height in mid perpendicular plane of squat silo at different months. From the end of December to the end of March, the temperature of top layer changed dramatically. At the end of March, grain temperature changed dramatically once the distance between grain and the top surface of grain heap was less than 1.6 m, grain temperature trended to constant once the distance between grain and the top surface of grain heap was larger than 1.6 m. Temperature variation of the bottom layer in grain heap was coinciding with that of the mattess due to the heat conduction at the bottom surface. Grain temperature changed dramatically once the distance between grain and the bottom surface of grain heap was less than 0.96 m and it trended to constant once the distance between grain and the bottom surface of grain heap was larger than 0.96 m.

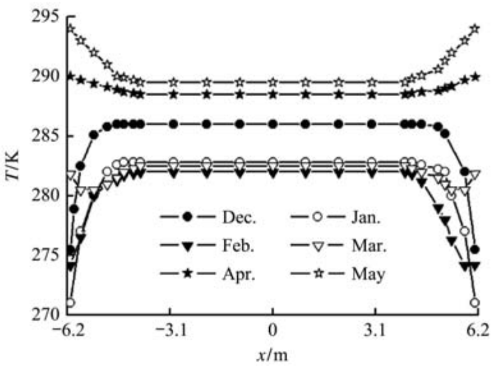


Figure 4 Temperature distribution of mid perpendicular plane at the height of 12 m in squat silo under different storage time

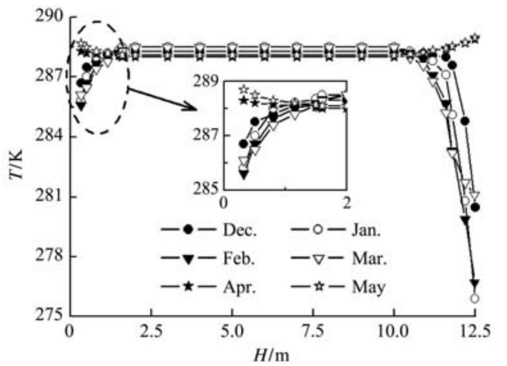
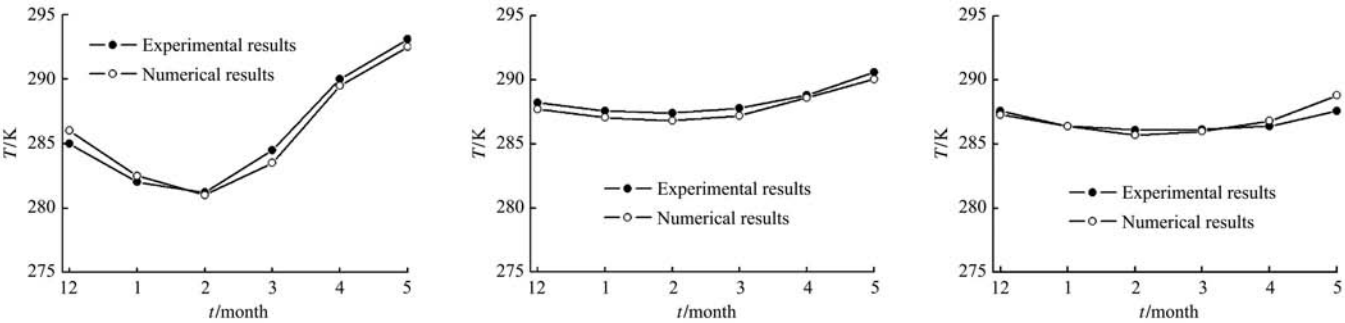


Figure 5 Temperatures with respect to the grain height in mid perpendicular plane of squat silo at different storage time

To test the reliability of the proposed models, the comparison between the experimental and numerical results under gain height of 12 m, 8 m and 4 m are shown in Figure 6. In Figure 6a, grain height was 12 m. The maximal deviation between experimental and numerical results appeared at the end of May. At this time, deviation value was 1.28 K and relative deviation was 3.6%. In Figure 6b, grain height is 8 m. The maximal deviation between experimental and numerical results appeared at the end of December. At this time, deviation value was 0.63 K and relative deviation was 2.1%. In Figure 6c, grain height is 4 m. The maximal deviation between experimental and numerical results appeared at the end of May. At this time, deviation value was 1.07 K and relative deviation was 7.4%.



a. H_1=12 m b. H_2=8 m c. H_3=4 m

Figure 6 Comparisons between experimental and numerical values in squat silo under different grain height

To further validate the proposed model, the comparison between experimental and numerical results of average temperature in squat silo was done, the result is shown in Figure 7. It was found that numerical values were coincide with experimental values in December, January, April, and May. The maximum deviation between experimental and numerical results appeared at the end of March. At this time, deviation value was 0.65 K and relative deviation was 5%. In general, numerical results agreed well with experimental results at the whole process of storage.

Figure 8 shows the temperature distribution of mid perpendicular plane at the height of 5.7 m in large size horizontal warehouse. In Figure 8a, temperature distribution is in x direction, while in Figure 8b, temperature distribution is in y direction. Grain temperature changes gently at the height of 5.7 m and the highest grain temperature at the height of 5.7 m appeared at June. From the end of January to the end of February, ambient temperature was lower than the average temperature of grain heap, the temperature of grain close to wall was the lowest, grain temperature gradually increased outside-in. From the end of March to the end of June, ambient temperature increased at accelerating rate and was higher than the average temperature of grain heap, the temperature of grain that close to wall was highest. Under the effect of solar radiation, grain temperatures of the south and west wall were higher than that of inside grain heap from the end of February.

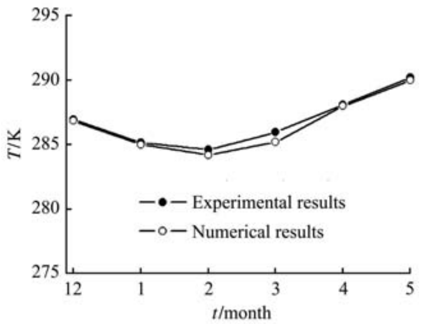
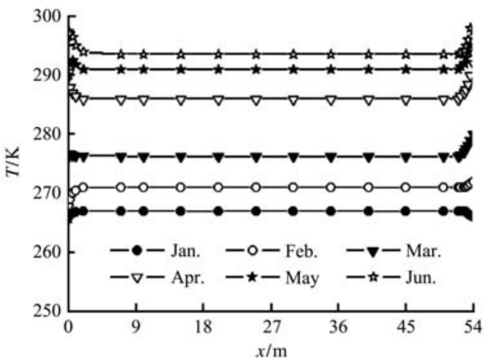
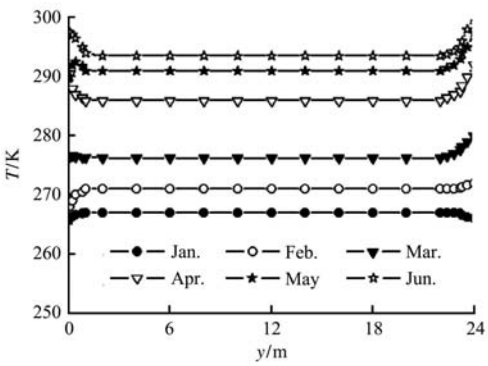


Figure 7 Comparison between experimental and numerical values of the average temperature of the whole squat silo



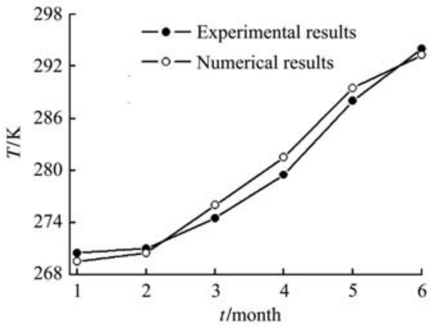
a.



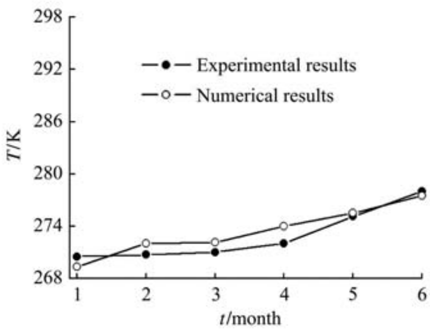
b.

Figure 8 Temperature distribution of mid perpendicular plane at the height of 5.7 m under (a) x-dimension and (b) y-dimension in large size horizontal warehouse

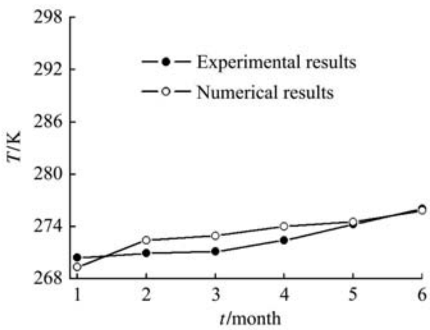
To test the reliability of the proposed program, the comparison between experimental and numerical results under gain height of 5.7 m, 3.9 m and 2.1 m are shown in Figure 9. In Figure 9a, grain height was 5.7 m. The maximum deviation between experimental and numerical results appeared at the end of May. At this time, deviation value was 2.25 K and relative deviation was 14.3%. In Figure 9b, grain height was 3.9 m. The maximum deviation between experimental and numerical results appeared at the end of February. At this time, deviation value was 1.91 K. In Figure 9c, grain height was 2.1 m. The maximum deviation between experimental and numerical results appeared at the end of February. At this time, deviation value was 1.59 K.



a. H_1=5.7 m



b. H_2=3.9 m



c. H_3=2.1 m

Figure 9 Comparison between experimental and numerical values in large size horizontal warehouse under different grain height

To further validate the proposed models, the comparison between experimental and numerical results of average temperature in squat silo is shown in Figure 10. It was found that numerical values were close to experimental values from the end of February to the end of April. The maximum deviation from experimental results appeared at the end of January. At this time, deviation value was 1.11 K. In general, numerical results agreed well with experimental results during the whole storage period.

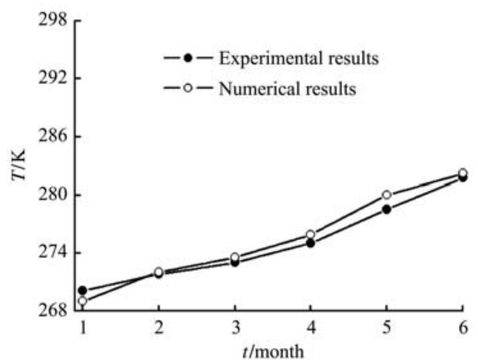


Figure 10 Comparison between experimental and numerical values under the average temperature of the whole large size horizontal warehouse

5 Conclusions

A three dimensional numerical model was established to study the temperature variation in outside squat silo and large size horizontal warehouse under Quasi-Steady state. Experiment was performed; porous media model and solar radiation were adopted. Numerical and experimental results were compared and the comparison results indicated that grain temperature influenced by wall temperature, grain height, and the distance from wall to grain.

In outdoor squat silo, temperature changes remarkably at the top layer of grain heap due to solar radiation and heat convection in air layer. Grain temperature tended to be constant when the distance between grain and wall was larger than 1.6 m, grain temperature also tended to be constant if the distance between grain and bottom surface of squat silo was larger than 0.96 m. In outdoor large size horizontal warehouse, temperature of grain closed to wall increased with the increase of ambient temperature. Grain temperature decreased gradually with the increase of the distance between grain and wall. When the grain height was 5.7 m, grain temperature in the length direction tended to be constant if the distance between grain and wall was larger than 2.4 m; grain temperature in the width direction tended to be constant if the distance between grain and wall was larger than 1.3 m.

In conclusion, numerical results were coinciding with experimental results and the model established in this paper is suitable for grain storage in outdoor squat silo and large size horizontal warehouse. The models developed in this paper are feasible to predict grain temperature and save energy.

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