Experiment and simulation research of storage for small grain steel silo

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Abstract: Knowing the temperature distribution in silo is a convenient and efficient way to control the process of grain storage. A three-dimensional (3-D) numerical model was used to study the temperature variation in small grain steel silo under quasi-steady state. In this study, experiments were conducted and porous media model was adopted. Results of numerical simulation and experiment were compared and the results indicated that grain temperature was influenced by temperature of the wall, grain stacking height, and the distance between grain and wall. The higher the wall temperature, the more the temperature increases. If the wall temperature is low, the effect of wall temperature on temperature distribution is significant. The temperature at the top part of grain varied obviously with the changes of temperature in air layer. Overall, numerical simulation results coincided with experimental results and the model established in this study is valuable for predicting grain temperature in steel silo.

Keywords: small grain steel silo, quasi-steady state storage, numerical simulation, porous media model, grain storage
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1 Introduction

The growing demand for quality food requires improved techniques to dispose the problems of storage[1-3]. Local temperature in granary is too high leads to grain deterioration. A common and traditional method to prevent the spoilage of stored grain is to measure grain temperature. If the temperature of the stored grain exceeds a certain threshold value, microorganism's activity is likely to increase.

The ways to know, monitor, and predict the temperature distribution in storage silo have attracted a lot of attention[4-6]. A temperature measurement system of the fiber Bragg grating was designed by Wang et al.[7] In their system, precise temperature in the granary is decided by the function of spectrum linear frequency shift. Their experimental results showed that system could meet the requirements of the granary large range temperature monitoring. A temperature monitoring method for stored grain based on acoustic tomography was proposed by Yan et al.[8] In their model, the relationship between grain temperature and sound travel time in stored grain was considered. They indicated that acoustic temperature measurement is useful in the early prediction

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of temperature anomalies in stored grain. The feasibility of ZigBee technology for the measurement system in large-scale barns was explored by Zhang et al. In their paper, the grain-temperature monitoring system using ZigBee technology was established. The results showed that using ZigBee technology could be an alternative way to monitor grain temperature.

Temperatures inside a metal silo filled with 20 t of wheat were monitored from August 2003 to October 2004 in Western Canada by Jian et al.[10] Their experiment results showed that headspace temperature (2.9±0.2) K higher than that of the ambient air with a maximum of 291.3 K and a minimum of 273 K. The temperature fluctuation of the headspace was larger than that of inside the grain stack. The average temperature gradient was (278.09±274.24) K/m inside the grain stack. The highest temperature gradient was 305.4 K/m and it was located at the center of the silo at 1.6 m high.

A 2D finite element dynamic, heat and mass transfer model that applied to predict natural convection, temperature distribution and moisture migration in soybean storage was established by Barreto et al.[11] In their research, soybean was stored in a cylindrical granary that without aeration in the weather conditions of Rosario Argentina from autumn to spring. Their results showed that permeability had the strongest effect on natural convection and a 50% increase of this parameter resulted in the development of spoilage areas in the upper part of the granary. The model of the relationship between wheat storage temperature, air temperature, wheat quality evaluation and prediction were established by Ji et al.[12] Their model could run well to evaluate, monitor and predict wheat storage quality.

The transient heat and mass convection of grain storage in a cylindrical silo were studied by Carrera-Rodríguez et al.[13] In their research, temperature gradients were induced by the respiration heat and the surrounding of cavity. The model was developed using the equations of heat, mass, and momentum transport for multiphase media. Their results indicated that the ambient temperature had a significant effect on the formation of hot regions inside the cavity. The dynamics of grain storage in cylindrical silos was performed by Carrera-Rodriguez et al.[14] In their research, the equations of momentum and energy for multiphase media were used, and the thermodynamic properties of sorghum grain stored in a silo of 44 m^3 grain capacity were adapted, the effect of environmental temperature on 2D convection of heat in grain stored at cylindrical silos was researched. Their results indicated that the time reached equilibrium was different for different boundary condition.

A mathematical model and software were developed by Khatchatourian and Binelo[15] for the 3-D simulation of airflow through high capacity grain storage bins. In their research, the non-uniformity of the seed was considered. The simulation showed good performance and the method could be applied to optimize the performance of existing grain stores and lower the engineering costs of new grain stores. Soya bean movement in mixed-flow dryers was explored by Khatchatourian et al.[16] In their research, a 3-D model of soya beans flow was developed by the Yade software package with the discrete element method, the soya bean seeds were considered as single spheres. The equations that describe the conservation of heat, mass, and momentum was used to predict heat and mass transfer processes inside a grain stack of maize, stored in a flat bin were solved by Oliveira Rocha et al.[17] A 3-D computational fluid dynamics was used and the geometry of a two-capacity bin prototype was considered. Their results indicated that the predicted results were very well consistent with experimental data.

A headspace computational model was formulated by Lawrence et al.[18] to predict air temperature in a grain silo using energy and mass balance principles. In their research, the headspace domain consist the headspace volume between the grain surface and the roof. Their results showed that the developed model can be used to predict temperature in the headspace of a silo filled level to its eave with reasonable accuracy.

Computational modeling of the fluids flow in porous media is traditionally at the macroscopic level. Modeling fluid flow at the grain level is paramount and how this can be done with the SPH technique were showed by Pereira et al.[19] They present 3-D SPH simulations of fluid flow in an idealized porous medium and showed that the technique produces flows which were physically realistic. Ambaw et al.[20] used a porous medium computational fluid dynamics model to numerically analyze the distribution of 1-MCP in cool store rooms for apple fruit. 1-Methylcyclopropene (1-MCP) is a synthetic plant growth regulator used commercially to delay ripening of fruits.

The storage condition is different for the distinct grain. A 2-D finite element model that predicts temperature distribution, moisture migration and natural convection currents in stored grain is described by Barreto et al.[21] Their results indicated that moisture migration was higher in soybean than in corn and wheat for a given temperature gradient. Quasi-Steady state storage accounts for the vast majority of the storage period.

Quasi-Steady state storage occupies the most part of storage time and is important to grain storage. Until now, there are still no researches on the precise temperature distribution in small grain steel silo during Quasi-Steady state storage. In this study, choosing wheat as research object, porous media model was introduced and headspace domain without grain was considered to study the temperature distribution during Quasi-Steady state storage in small grain steel silo.

2 Experimental materials and methods

2.1 Materials

Wheat (Wenmai 6) and indoor small grain steel silo were used in this study. A schematic diagram of the grain steel silo is shown in Figure 1a. The size of the grain steel silo is 1.4 m×1.4 m×2.1 m, the thickness of the steel silo is 1 cm with thermal conductivity of 45.4 W/m·K, the height of grain in silo is 1.9 m. The schematic of sample connection in grain steel silo is shown Figure 1b. The distance from sample connection to the bottom of grain steel silo is 37 cm, 82 cm, 127 cm, and 172 cm, respectively. The schematic of needle-point sampler is shown Figure 1c. The inner diameter of needle-point sampler is 20 mm; there are five rectangular sample connections in needle-point sampler with the size of 60 mm×12 mm.

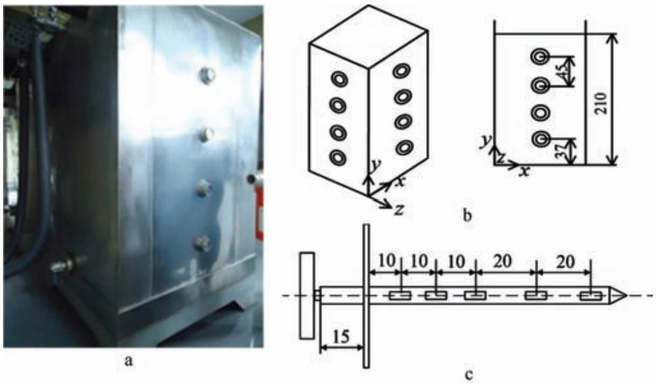


Figure 1 Picture and the schematic of small grain steel silo and the needle-point sampler

2.2 Methods

After taking samples from a certain sample connection by the needle-point sampler, the sample temperature was considered as a temperature of corresponding position in grain steel silo. The temperature of the sample was obtained by a portable infrared thermo-detector (Raynger 6ST, Raytek Inc.) with the precision of 2 K. The temperature outside grain steel silo was obtained by mercurial thermometer with the precision of 1 K. The wall temperature of grain steel silo was controlled by a thermostat water bath with the precision of 1 K.

The experiment was implemented from March to April for the low humidity, the variation range of indoor temperature is small (287 K-290 K), the temperature variation from day to night was not obvious, so the environmental temperature is considered to be constant.

Wall temperature was set to be 273 K, 298 K, 303 K, and 308 K, respectively. When the wall temperature was set to 273 K, 298 K, and 303 K, the temperature of samples was measured after the storage time was 0 h, 2 h, 4 h, 7 h, 10 h, 14 h, 18 h, and 22 h, respectively. When the wall temperature was set to 308 K, the temperature of samples was measured after the storage time was 0 h, 1.5 h, 3.5 h, 5.5 h, 9.5 h, 13.5 h, 17.5 h and 21.5 h, respectively.

3 Model formulation

3.1 Governing equations

The respiration heat generation was not considered in the simulation. The medium was continuous, and the governing equations were consisted by continuity, momentum and energy conservation equations.

Continuity equation:

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

Momentum equation:

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

Energy equation:

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

where, $\vec{u}$, T_{air}, ρ_{air} , $C_{p,air}$ and k_{air} are air velocity, air temperature, air density, specific heat of air and heat conduction coefficient of air, respectively. The boundary condition was assumed no slip condition for velocity and temperature.

Grain stack is composed by grain and air, the air inside grain stack is hard to reconstruct. Taking the whole grain stack region as a porous medium and it could be established with the continuous transport channel in grain stack in the simulation. The porous media approach involved the application of the principle of heat transfer and fluid mechanics in a fluid-saturated perfused media to obtain a model of equation that will govern heat transfer and fluid flow in a biological system (living tissue). It was assumed that the medium was isotropic.

3.2 Parameters used in model

The wall of steel silo is isothermal surface, the top and bottom of steel silo are thermal conductive surface, and there are air layers between the top surface of grain and the top surface of steel 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 steel silo. Gambit was used and the meshes were created in geometry as shown in Figure 2. The grid cell body was a hexahedron.

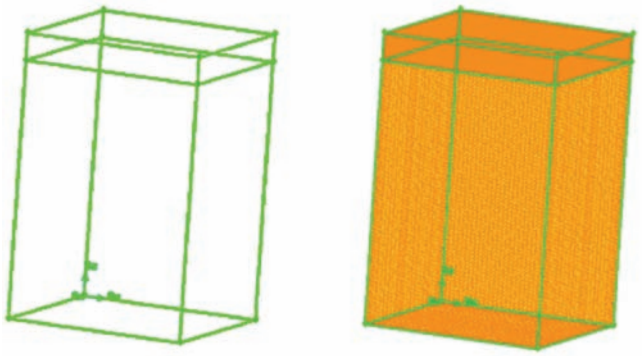


Figure 2 Geometric system studied and the 3-D computational domain

During storage period, wall temperature was constant and set to 273 K, 298 K, 303 K, and 308 K, respectively. There were heat convection between ambient air and the top and bottom surface of steel silo, so, convection boundary condition in Fluent was introduced to the top and bottom surface. The surrounding temperature was set to 288 K.

Porous medium model in Fluent was introduced to describe wheat stacking zone. The relative moisture content, heat conduction coefficient λ_g, average particle diameter D_p, specific heat capacity C_g, and volume density of wheat ρ_g were 17.2%, 0.13 W/m·K, 0.0045 m, 1780 J/kg·K, 750 kg/m^3, respectively. The permeability C_2 and inertial resistance factors of wheat α was 7102 and 63 556 569, respectively.

4 Results and discussion

Figure 3 shows the average temperature of the whole silo regarding to storage time under different wall temperature. When the wall temperature was low, for example 293 K and 298 K, the average temperature of the whole silo was low, and there was no obvious temperature variation during storage, the maximum temperature variation during storage was 1.1 K. When the wall temperature was 303 K, the average temperature of the whole silo had small amplitude augment and the increase rate of temperature was in relative uniformity. When the wall temperature reached 308 K, the average temperature of the whole silo had obvious change and increasing with the increase of storage time, the temperature increase rate and the amplitude of temperature rise are bigger than that of the wall temperature of 293 K, 298 K and 303 K.

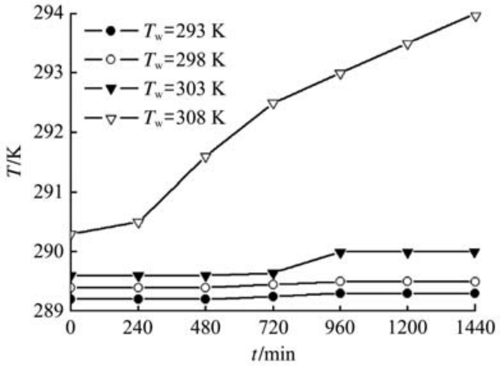


Figure 3 Average temperature of the whole silo with respect to storage time under different wall temperatures

The grain height in silo is 190 cm. There are four layers in silo as test sample. The first grain layer H_1= 37 cm indicates that the height between the grain layer and the bottom surface of silo is 37 cm, the second layer H_2=82 cm indicates that the height between the grain layer and the bottom surface of silo is 82 cm, the third layer H_3=127 cm indicates that the height between the grain layer and the bottom surface of silo is 127 cm, the fourth layer H_4=172 cm indicates that the height between this grain layer and the bottom surface of silo is 172 cm.

Figure 4 shows the temperature variation at the four grain layers under the wall temperature of 308 K. The average temperature at each grain layer increased with the increase of storage time. The average temperature variation was most obvious at the fourth layer H_4 and the tendency of the average temperature variation in the other three layers was basically the same. There were heat transfer between the roof of silo and external environment, hence, the temperature variation in the vicinity of the top of grain was obvious and the temperature variation far from the top of grain was relative inconspicuous.

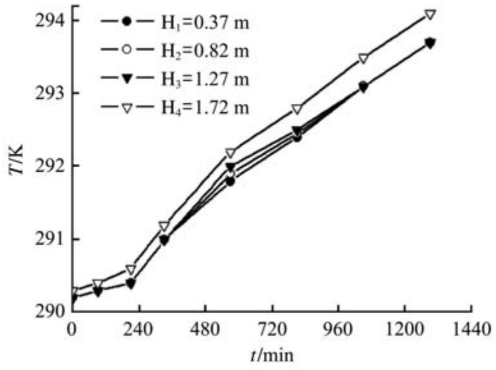


Figure 4 Average temperature of a certain layer regarding to storage time under wall temperature of 308 K

The needle-point sampler can take five samples once a time. The samples located at 10 cm, 20 cm, 30 cm, 50 cm, and 70 cm, respectively away from wall. The sample temperature variation during storage is shown in Figure 5. In Figure 5, wall temperature is 308 K. There is distinct temperature difference when the distance between grain and wall is different. The amplitude of temperature variation in the place that located at 10 cm away from wall is the biggest. After 21 h storage with the wall temperature of 308 K, the temperature of the place inside silo that located at 10 cm away from wall could reach 295.75 K. During storage period, the maximum temperature could reach 292.65 K and 291.25 K when the distance between samples and wall was 20 cm and 30 cm, respectively. When the sample was far away from wall, for example 50 cm and 70 cm, the grain temperature tended to constant and basically has no variation with storage time.

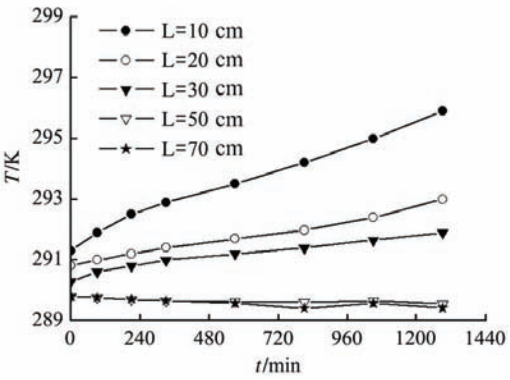
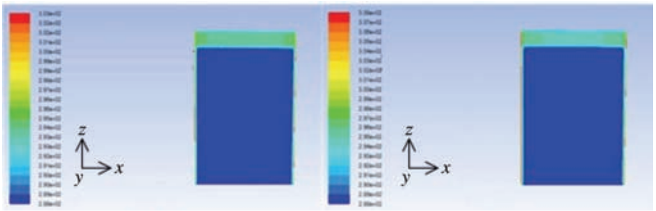
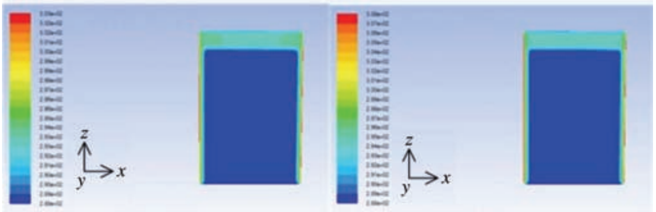


Figure 5 Temperature variation under wall temperature of 308 K and height of 1.72 m

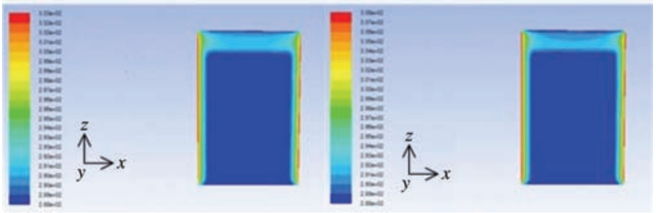
The temperature variation in silo is small and the general trends are basically agreed if the wall temperatures are 293 K and 298 K. When wall temperatures are 303 K and 308 K, the range of temperature variation gradually increases and the temperature gradient is gradually obvious. The wall temperatures of 303 K and 308.15 K were adopted in following numerical research, the results are shown in Figure 6. Under the influence of convective heat transfer, the temperature of the air layer close to wall increased quickly. When the storage time is 6 h, the temperature of air layer is relatively uniform, the temperature of grain close to wall gradually increases and the rate of temperature rise is small, the region with low grain temperature shrinks gradually. After 10 h storage time, grain temperature increases and bigger temperature gradient appears in the vicinity of wall, the region with high grain temperature gradually increases. At this time, the effect of external environment with low temperature on the temperature of air layer is gradually obvious, low temperature region appears in the central region of air layer. With the increase of storage time, low temperature region in air layer gradually draw back in the direction of silo axial, air temperature gradually change from high to low, a connecting channel is formed and link the top of silo with low temperature to grain stack with low temperature.



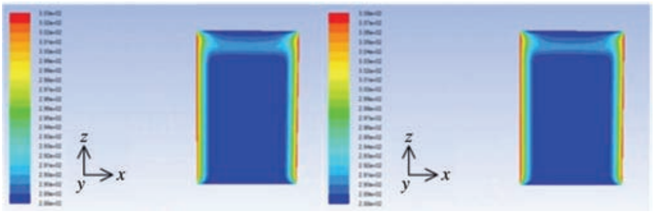
a1. 20 min, 303 K a2. 20 min, 308 K



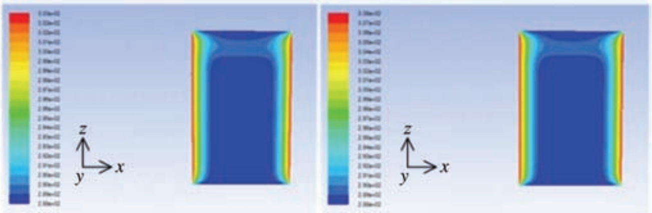
b1. 2 h, 303 K b2. 2 h, 308 K



c1. 6 h, 303 K c2. 6 h, 308 K



d1. 10 h, 303 K d2. 10 h, 308 K



e1. 22 h, 303 K e2. 22 h, 308 K

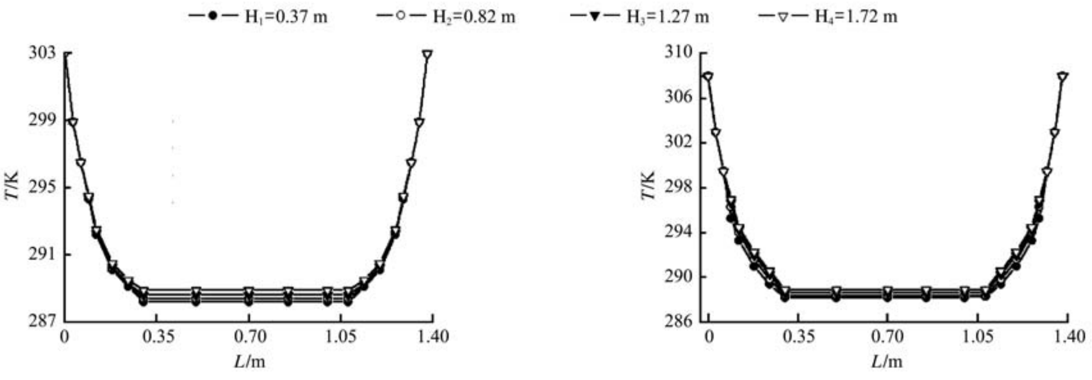
Figure 6 Temperature distribution of silo under different storage time and wall temperature

The temperature at the region of top grain stack and the layer close to wall changed quickly, the temperature at the other region changed slowly. Because the temperature at the bottom of silo is equal to that at external environment, the temperature at the bottom of silo changed slowest and there always exists low temperature region at the bottom of silo. The temperature variation tendency within 24 h under the wall temperature of 308 K is similar to that under the wall temperature of 303 K. Compared to the wall temperature of 303 K, temperature increase rate changes more quickly and low temperature region at air layer formed earlier when the wall temperature is 308 K. Under the same storage time, the effect of wall temperature on grain temperature is mainly in the temperature gradient. The temperature gradient at the region of grain temperature rise region increases with the increase of wall temperature. The temperature in low temperature region keeps in constant with the augment of storage time. No matter the wall temperature is 303 K or 308 K, low temperature region could be formed at the air layer and the bottom of silo. The low temperature regions at grain stack and air layer decrease with the increase of wall temperature.

To further analyze temperature distribution and temperature variation inside silo, XY plot command in Fluent was adopted to obtain temperature in certain place. Figure 7 shows temperature distribution in the middle vertical plane under the height of H_1=0.37 m, H_2=0.82 m, H_3=1.27 m, and H_4=1.72 m. In Figure 7a, wall temperature is 303 K. In Figure 7b, wall temperature is 308 K. The grain temperature increases with the decrease of distance between grain and wall. In the middle vertical plane, the grain temperature is identical under a certain height once the distance between grain and wall is same. The grain temperature changes quickly once the distance between grain and wall is smaller than 0.2 m, the grain temperature variation is small (not exceeding 2 K) once the distance between grain and wall is between 0.2 m and 0.3 m. That is, the distance between grain and wall that wall temperature could leads to grain temperature variation is smaller than 0.3 m. When the grain height is H_1=0.37 m, H_2=0.82 m, and H_3=1.27 m, the grain temperature variation in grain stack is small and the variation tendency tend to coincide. At this time, the top part of grain stack influenced by air layer, the temperature of the surface of grain stack is highest; grain temperature decreases with the increase of the depth of grain stack and tends to relatively stable.

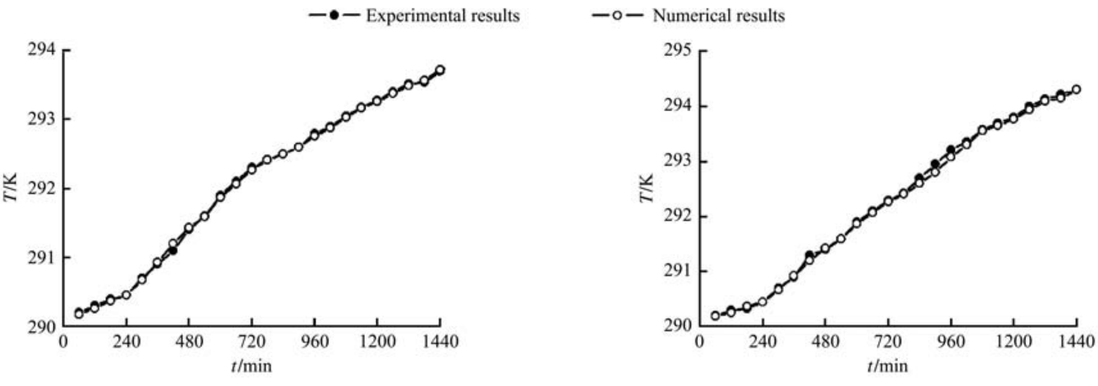
To validate the correctness of the project, the comparisons between experimental and numerical results under different gain height is shown in Figure 8, grain temperature regarding to storage time under wall temperature of 308 K is also showed. Figure 8a shows the difference between numerical results and experimental results at the height of H_1=0.37 m. Figure 8b shows the difference between numerical results and experimental results at the height of H_4=1.72 m. The temperature rise tendency of numerical results is consistent with experimental results, and only a little difference between numerical and experimental results. That is, the porous media model and boundary conditions used in this paper matched the practical case under the wall temperature of 308 K.

To further validate our model, the comparisons between experimental and numerical results under different distance from wall at the height of gain H_4= 1.72 m are shown in Figure 9. In Figure 9a, wall temperature is 308 K, the distance between grain and wall L is 0.1 m. The tendency of grain temperature variation is consistent between experimental and numerical results. The maximum deviation between experimental and numerical results appears at the storage time of 720 min. At this time, numerical value is 293.3 K, experimental value is 292.6 K, and relative deviation is 3.6%. The relative deviation in other storage time is less than 3.6%. In Figure 9b, the distance L between grain and wall is 0.3 m and the tendency of grain temperature variation is consistent between experimental and numerical results. Compared to the case of L=0.1 m, the temperature variation is small and within 1 K. This result is in accordance with the previous experimental result. The maximum deviation between experimental and numerical results appears at the storage time of 1200 min. At this time, relative deviation is 6.5%, and more than relative deviation of other storage time. In Figure 9c, the distance between grain and wall is 0.5 m and the tendency of grain temperature variation is consistent between experimental and numerical results. Compared to the case of L=0.3 m, the temperature variation increases within 4 K, the temperature variation increases with the extending of storage time. This result is in accordance with the previous experimental result. The maximum deviation between experimental and numerical results appears at the storage time of 1440 min. At this time, numerical value is 291.8 K, experimental value is 292.2 K, and relative deviation is 2.1%. In general, numerical results coincide well with experimental results at the whole storage period.



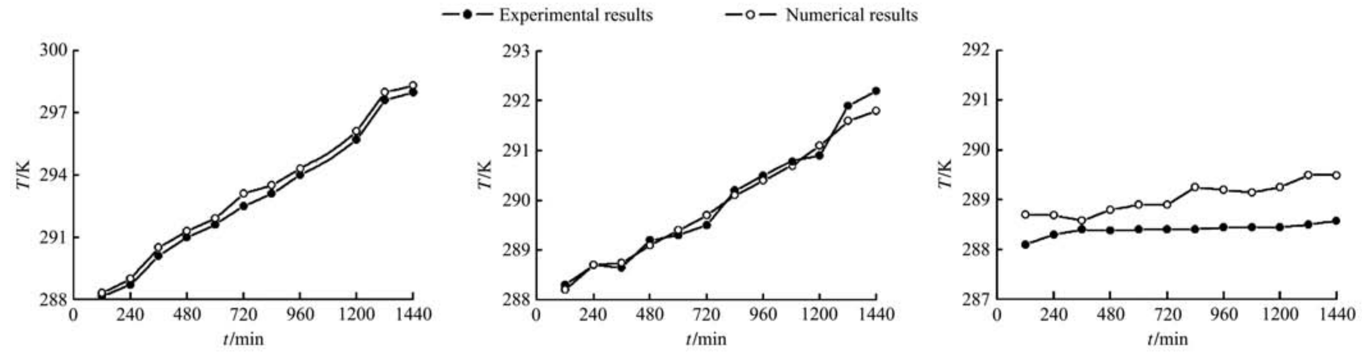
a. T_w = 303 K b. T_w = 308 K

Figure 7 Temperature distribution under different grain heights at the temperatures of 303 K and 308 K.



a. T = 303 K, H_1 = 0.37 m b. T = 303 K, H_1 = 1.72 m

Figure 8 Comparison between experimental and numerical values at the heights of 0.37 m and 1.72 m under 308 K wall temperature



a. L = 0.1 m b. L = 0.3 m c. L = 0.5 m

Figure 9 Comparison between experimental and numerical values at the height of 1.72 m and the wall temperature of 308 K

5 Conclusions

A 3-D numerical model was established to study the temperature variation within small grain steel silo under quasi-steady state. In this study, experiment was performed and porous media model was adopted. Numerical results and experimental results were compared and the results indicated that grain temperature was influenced by wall temperature, grain stack height, and the distance between grain and wall.

When wall temperature is different, the temperature increase and the amplitude of temperature increase are distinct. The higher the wall's temperature, the bigger the temperature increase rate and temperature increase amplitude. If wall temperature is low, the effect of wall temperature on temperature distribution is not significant. For indoor small grain steel silo, grain temperature variation obviously if the distance between grain and wall is smaller than 30 cm and less obviously if the distance between grain and wall is larger than 30 cm. The grain located at the top part of grain is subjected to the heat convection of air layer connected to the roof of silo. The temperature of grain located at the top part of grain varies obviously with the temperature changes in air layer. On the whole, numerical results are consistent with experimental results and the model established is suitable for grain storage in steel silo.

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