Design and Experiment of Low Temperature Grain Storage System Based on Natural Cold Energy

Xiaoli Pan 1,2, Yu cui Ning 1, Dongxing Zhou 1

1 College of Resources and Environmental Science, Northeast Agricultural University, Harbin 150030, China
2 College of Physics Science and Engineering, Yulin Normal University, Yulin, 537000, China

*Corresponding author (E-mail: zhboshi@163.com) The main research direction for the agricultural ecosystem and soil ecology.

Abstract
In order to keep rice in good quality in its storage through market circulation, the abundant natural cold energy resource in north China-ice reserves from winter to summer (May-Sept.) is utilized to keep rice fresh. The mixture of water and ice can be utilized to exchange heat with hot air indirectly, which has the advantages of saving energy, protecting environment, improving air quality and providing favorable storage conditions for the moisture retention and quality maintaining of rice. Based on this, a low temperature grain storage system based on natural cold energy has been designed. The optimal match of parameters of the system are ice water flow rate 0.9m³/h, air face velocity 3m/s and air inlet angle +30°, with which the system has best heat exchange performance. The system provides a relevantly stable freshness preservation environment with temperature range of 6-20℃ and relative air humidity of 65%. What’s more, the grain pile heat and moisture transfer mathematical model was built using finite element software COMSOL, and the calculation result was compared with experimental result. The result showed that the difference between numerical simulation and experiment was within 3%, indicating high accuracy of the model; the temperature of grain pile decreased from 25℃ to 15℃ and then kept steady in the 40 hour’s ventilation; the moisture of grain kept at about 12%; the relative humidity of the air in grain pile remained at 62%; when temperature was below 15℃, the critical relative air humidity for mycete growth was 80.04%; the system has cut down the payment for electricity for about 5,800 yuan during the summer compared to relevant mechanical cooling system, demonstrating good economic efficiency, zero pollution, and zero emission.

Key words: Natural cold energy, Low temperature grain storage, Rice pile, Multi-field coupling, COMSOL Multiphysics

1. INTRODUCTION
The cold winter in north China can be as long as half a year, so natural cold energy exists in abundance there. Since the summer there is short and torrid and the transition from summer to winter is short too, ice can be stored in winter and used in summer for the preservation of grain, fruits, vegetables and other agricultural products. For summer storage of finished rice product, temperature and humidity in granary are two important parameters to maintain its high quality(Zhou et al., 2011). Currently, large-scale refrigerating systems are electrically driven, consuming too much energy and using refrigerants that pollute the atmosphere. As the energy crisis becomes severer and severer, the abundant and renewable natural cold energy is a clean and green energy resource that can be utilized in the storage of agricultural products for the purposes of resource saving and environment protection.

Safe storage of grain is an issue at the state level, and a various types of grain storage have been profoundly studied by scholars at home and abroad. The global grain loss cause by moulding or inset attack every year is 3% and 5% respectively, which is closely connected to the temperature and humidity of storage environment(Wang et al., 2012). In 2008, Thorpe G R used the numerical simulation software CFD to build heat and moisture transfer mathematical model for grain pile and studied the regularities of its temperature and moisture transfer (Thorpe, 2008). In 2013, Jian et al. studied the changes of rape seed status in silo with temperature, humidity and storage duration(Jian et al., 2013). In 2012, Xiangli Li et al. employed numerical simulation technology to study the changes of temperature and moisture of the grain pile in horizontal bin(Li et al., 2012). In 2015, Guixiang Chen et al. constructed the heat and moisture transfer control equation for ventilation process, built grain pile mycete growth index model, analyzed the heat and moisture transfer regularities during ventilation using the simulation software CFD, and predicted the moulding in actual grain storage with ventilation(Chen et al., 2015). Guangyue Ren et al. implemented numerical simulations of the distribution of temperature field and flow field for quasi-static storage in horizontal bin and mechanical ventilation storage in squat silo(Ren et al., 2012). In 2013, Zidan Wu et al. proposed to combine grain pile multi-field coupling theory with CAE model which is applicable for all kinds of granary structures and able for short-term prediction of grain pile storage status according to measured temperature(Wu et al., 2014).

In order to develop a low temperature grain storage system, the experiment aimed at designing and developing the system’s key equipment of heat transfer-finned tube heat exchanger. Aluminum fins are added in
order to increase heat exchange area and improve the efficiency. The mixture of ice and water whose temperature is nearly 2°C is used to provide cold energy for granary. The cold water circulates through copper pipes with constant speed, and the hot air is blown to finned tubes by fan to exchange heat with the refrigerant, so that air quality can be improved. The equipment room and the storage room are separated from each other, and the system is capable of automatic temperature control and simultaneous multi-point cooling. When humidity is below the preset value, the spray atomizing system will start and adjust the temperature and humidity in granary automatically within the specified range. Grain storage experiments of the low temperature storage system using natural cold energy were carried out; the finite element analysis software COMSOL Multiphysics was used; according to the heat and mass transfer theory of porous media and the moisture absorption and desorption of grains, the local thermal equilibrium principle and macro volume averaging method were adopted to build mathematical model for the coupled heat and moisture transfer inside grain pile with low temperature ventilation; the model was compared to experimental data to verify its correctness. This provides theoretical evidence to the prevention of grain mildew.

2. NATURAL COLD ENERGY LOW TEMPERATURE GRAIN STORAGE EQUIPMENT DESIGN

2.1. Overall Structure Design

The size of granary is 2m*2m*2m; the material of its six inner sides is polyurethane foaming plastic; outside are wood plank walls with thickness of 0.05mm; and its bottom is 20cm above ground level. The structure of the experimental equipment is shown in Figure 1. Major devices include fan, water pump, finned tube heat exchanger, temperature and humidity sensor, atomizing nozzle, flow meter, pipeline, etc (Zhou et al., 2015; Pan et al., 2016). When the relative humidity of environment is below the preset value, the spray atomizing system will start automatically. The fan-shaped oblate two-fluid atomizing nozzle, which can accurately control the mixing ratio of water and air, is adopted as air atomizer. It is connected to the air interface through air compressor, so it can produce fogdrops of tens of micrometers, which is impressive. The colded and humidified air flows into the granary, but to improve air quality the ventilator needs to be switched on to inlet some fresh air.

![Figure 1. Structure of experimental equipment](image)

The temperature of the mixture of water and the ice balls that has been stored since last winter whose diameter is 25cm is about 2°C. 40% of the ice water channel is ensured to be filled with circulating cold water which flows into finned tube heat exchanger with fixed speed from above to below. The inlet water flow is measured by the flow meter. The hot air blows across the finned tubes with the powerful effect of axial flow fan; the cold water absorbs the heat and humidity on the outside surface of copper pipes and fins as it flows through
copper pipes. The temperature difference of the water flowing in and out of heat exchanger is about 3℃. Cold air is blown into ventilation cage transversely to lower the temperature of grains in granary. In that the finned tube surface temperature is lower than the dew-point temperature of air, the vapor in the air condenses, so the relative humidity decrease slightly.

The physical quantities to be measured include the dry and wet bulb temperatures and the air flow at air entrance and exit, the temperatures and water flow at ice water entrance and exit, relative humidity and face velocity of air, the inter-grain air humidity, etc. The integrated temperature and humidity sensor sends its collected signals to computer through data acquisition card PCI-6225 to be controlled by visual instrument. Therefore, a complete monitoring system has been built to supervise and store experimental data timely. All the apparatuses and instruments has been revised before the experiment so that they have qualified accuracy. The speeds of 5 points on fan exit interface are averaged to determine air face velocity. The air blowing rate of fan and water flow rate of water pump is adjusted by frequency converter in the experiment. The arrangement of temperature and humidity sensors in grain pile is shown in Figure 2.

![Figure 2. Layout of temperature and humidity sensors](image)

2.2. Design of Finned Tube Heat Exchanger

The finned tube heat exchanger uses Φ10 copper pipe which is 0.35mm thick as its heat pipe. The heat pipes are arranged in staggered regular triangles with longitudinal distance of 12.5mm and horizontal distance 21.65mm; the integral plain aluminum fin with thickness of 0.2mm is used; the horizontal length of the fins is 80.45mm and the distance between fins is 4mm; the face area is 0.16m², total heat transfer area 8.6m², total length of heat pipes 25.5m, height of heat exchanger 400mm and its width 398mm. Here the integral staggered plate fine structure is adopted. The fins with proper thickness are installed on tube bundles. The double turnups at fin root can ensure certain distance between fins and close contact between fins and parent tube. Here the thermal contact resistance is ignored.

3. EXPERIMENT OF COOLING SYSTEM

The major purpose of cooling system experiment is to test the heat exchange performance of cooling equipment and the influence of functional parameters on it. The initial temperature in the experiment is 20℃.

3.1. Influence of Ice Water Flow Rate on Heat Exchange Capacity

In the experiment, the face velocity is fixed at 3m/s. The influence of ice water flow rate on heat exchange capacity can be seen in Figure 3, as the flow rate of ice water increases, heat exchange capacity shows a growing tendency with a growth of 124%. When the flow rate of ice water reaches 0.9m³/h, its continuous increase no longer has great impact on heat exchange capacity. The reason is that with the increase of flow rate, ice water flows faster and more turbulently in heat pipes, which intensifies the heat convection between ice water and the inner wall of heat pipes and thus improves the heat exchange capacity. The increase of flow velocity makes ice water stays shorter in the pipes, and the low temperature of the outside surface of fin pipe makes it exchange more heat with the hot air, so that the temperature at air outlet has been lowered. After the flow rate has increased to its optimal value, its increase almost no longer has influence on heat exchange capacity.
3.2. Influence of Face Velocity on Heat Exchange Capacity

Face velocity is an important parameter for the system. As Figure 4 shows, when face velocity is 1.5-3m/s, remarkable increase of heat exchange capacity occurs as face velocity rises; after face velocity reaches 3m/s, the growth of heat exchange capacity slows down.

The reason is that the increase of face velocity enables more air to flow through finned tube heat exchanger and makes the air disturbance on fin surface more intense, which enhances the heat convection and thus increases heat exchange capacity. When face velocity surpasses the optimal value 3m/s, hot air stays for a shorter time between fins, so there is less time for the heat exchange between the hot and cold fluids, in other words, the heat exchange is inadequate. At this time, continuous increase of face velocity will cause greater pressure loss. When the velocity increases to a certain value, the intensified fluid flow will not strengthen heat exchange, but instead, it may impair heat exchange.

3.3. Influence of Air Inlet Angle on Heat Exchange Capacity

With fixed amount of airflow, a deflector is installed between the fan and the finned tube heat exchanger in order to improve the performance of the later. It changes air distribution by adjusting the angle of flow-guiding vane, thus the influence of face velocity on heat exchange capacity can be studied. The change regularities is shown in Figure 5. The angle between airflow velocity and horizontal plane is \( \theta \), which is negative with downward deflection and positive with upward deflection. When deflection angle is 0°, the fan blows air to finned tubes in horizontal direction, at this time, the distribution of face velocity is even; when \( \theta \) is between -15°~15°, air inlet angle has no big change, and the airflow is basically evenly distributed too; when \( \theta \) has remarkable change, airflow short circuit occurs. In this circumstance, some areas lack airflow or vortexes exist there, causing bigger angle between velocity vector and temperature vector, poorer field synergy and unsatisfying heat exchange result. In the experiment, ice water flows downward along finned tube heat exchanger, so the temperature of the outside surface of finned tube decreases linearly in the height direction of
heat exchanger. With the growth of deflection angle, refrigerating capacity increases first and then decreases, reaching its peak when air inlet angle is +30°, where the refrigerating capacity has increased 25% compared to air inlet angle of 0°. This indicates that face velocity distribution has great influence on heat exchange. The reason is that when the angle is +30°, the airflow concentrates in the low temperature area of the upper part of finned tube, so heat exchange intensifies. The decrease of airflow from top to bottom of finned tube heat exchanger is better for heat exchange.

![Figure 5](image)

**Figure 5.** Influence of air inlet angle on heat exchange capacity

### 4. NUMERICAL SIMULATION OF GRANARY VENTILATION SYSTEM

#### 4.1. Physical Model

Grain storage experiment is done for the low temperature grain storage system which uses natural cold energy. The granary is filled with grain, and the size of grain pile is consistent with that of granary, namely \(2m \times 2m \times 2m\). The two inner walls in the width direction of granary are equipped with ventilation cages which enable press-in ventilation using axial flow fan, and the air flows horizontally inside the grain pile. COMSOL Multiphysics is a multiphysics finite element analysis software, designing the coupling of velocity field, temperature field and humidity field during grain storage. The 3-dimension physical model is shown in Figure 6. The simulating process includes geometric modelling, parameter setting, physical field selecting, boundary condition setting, mesh generating, model solving, and post processing. Non-structured grid partition is adopted for the granary model. The total number of grid points is 16565.

![Figure 6](image)

**Figure 6.** 3D Physical model

#### 4.2. Numerical Simulation Parameter Setting (Table 1)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Types</th>
<th>Relevant conditional parameter setting for COMSOL simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance</td>
<td>Velocity at entrance</td>
<td>Apparent airflow velocity at entrance (v = 0.05m/s)</td>
</tr>
<tr>
<td>Exit</td>
<td>Pressure at exit</td>
<td>After low temperature air penetrates through grain pile, it enters into atmosphere at air outlet exit, thus the press at the exit is 0Pa.</td>
</tr>
<tr>
<td>Walls</td>
<td>Boundary</td>
<td>The four walls around are made of thermal insulation material and are non-slipping, which is assumed to be adiabatic boundary</td>
</tr>
</tbody>
</table>
Grain pile Porous media
Initial temperature of grain pile is 25℃, initial humidity of air 70%, moisture content of rice 13% w.b, density $\rho_r = 1250 \text{ kg/m}^3$, porosity $\varepsilon = 0.4$, specific heat capacity $c_p = 1940 \text{ J/kg} \cdot \text{k}$, effective thermal conductivity of grain pile $K_{eff} = 0.157 \text{ w/m} \cdot \text{k}$, permeability $1/\alpha = 5.96 \times 10^{-9} \text{ m}^2$.

Air Air at entrance
Constant temperature 15℃, relative humidity 65.6%, moisture content $d = 5 \text{ g/kg}$, density $\rho_a = 1.247 \text{ kg/m}^3$, viscosity $\mu = 1.79 \times 10^{-5} \text{ pa} \cdot \text{s}$, apparent velocity $u = 0.05 \text{ m/s}$.

5. GOVERNING EQUATION

Grain pile is typical for the heat and mass transfer of moisture-containing porous media. The mathematical model of the coupled heat and moisture transfer inside grain pile during the low temperature cooling process is built based on principle of heat and mass equilibrium. The governing equation is follow (Chen et al., 2013).

5.1. Governing Equation of Heat Transfer inside Grain Pile

Gain pile is deemed as porous media. The distributions of temperature and humidity inside grain pile are calculated, as well as the heat transfer between moist air and grains, for which the heat transfer equation is:

$$
\rho_e \cdot c_a \cdot \frac{\partial T}{\partial t} + \rho_e \cdot c_a \cdot \nabla \cdot W + \frac{\partial H_w}{\partial t} + c_e \cdot \nabla (\rho_e \cdot u \cdot T) = K_{eff} \cdot \nabla^2 T + S_k
$$

(1)

Where, $c_e$, $c_a$ and $c_w$ are the specific heat capacities at constant pressure of air, grain and water(J/kg·k); $H_w$ is total absorbed heat of grain(J/kg); $\frac{\partial H_w}{\partial T}$ can be ignored because it’s far less than grain’s specific heat at constant pressure.

5.2. Governing Equation of Moisture Transfer inside Grain Pile

The partial differential equation for moisture transfer inside grain pile is follow:

$$
\frac{\partial (\rho_e \cdot d)}{\partial t} + \nabla \cdot (\rho_e \cdot u \cdot d) = \nabla \cdot (\rho_e \cdot D_{eff} \cdot \nabla d) + S_w
$$

(2)

Where $S_w$ is moisture source item (J/kg·m·s).

$$
S_w = (1-\varepsilon)k \cdot \rho_e \cdot (W - W_e)
$$

(3)

Where, $k$ is common dry coefficient; $W$ is wet-basis moisture content of grain pile(J/kg); $W_e$ is equilibrium moisture content(J/kg).

$$
k = 2000 \exp \left( 1 - \frac{5094}{T + 273.15} \right)
$$

(4)

$$
W_e = -\frac{1}{B} \log \left( \frac{T + C}{A} \log r \right)
$$

(5)

$$
r = \exp \left( -\frac{A}{T + C} \exp (-B \cdot W) \right)
$$

(6)

Where, $A$, $B$ and $C$ are constants that are assigned 921.69℃, 18.077 and 112.35℃; $T$ is the temperature of the air inside grain pile(℃); and $r$ is the relative humidity of the air inside grain pile(%)..

5.3. Momentum Equation

A momentum source item $S_i$ is added to the standard momentum partial differential equation to describe the airflow resistance inside grain pile.

$$
\frac{\partial \left( \rho_e \cdot u \right)}{\partial t} + u \cdot \nabla (\rho_e \cdot u) = -\frac{\nabla p}{\rho_e} + \nabla \left( \frac{\mu}{\rho_e} \nabla u \right) + S_i
$$

(7)

$$
S_i = -\sum_{i=1}^{3} \sum_{j=1}^{3} D_{ij} \cdot \mu \cdot v_i + \sum_{i=1}^{3} G_i \cdot |v| \cdot v_i
$$

(8)

Where, $S_i$ is the source item in the $i$-th (in $x$, $y$, or $z$ direction) momentum equation; $v_i$ is the velocity in
j direction in 3-dimension space \((m/s)\); \(D_i\) and \(C_i\) are empirical coefficients.

6. ANALYSIS AND DISCUSSION ON RESULTS OF NUMERICAL SIMULATION AND EXPERIMENT

All the key functional parameters of the low temperature storage system using natural cold energy must match each other well. If flow rate of ice water rises, the heat convection between ice water and the inner wall will be more intense, and the heat exchange amount between outside surface of finned tubes and environmental air will increase, as a result the temperature at granary entrance will be lowered. In this experiment, ice water flow rate is set to 0.9\(m^3/h\), face velocity 3\(m/s\), and ventilation rate 117.6\(m^3/(h\cdot t)\). Temperature and humidity sensors are installed in ventilation cages which inlets cold air, thus fan, water pumps and atomizing system can be controlled accordingly to make the temperature and humidity of the air flowing into granary maintain at about 15\(^\circ\)C and 65% respectively. This way, freshness and quality preservation of grain can be realized.

6.1. Average Temperature Distribution in Granary

The measured temperature values during the ventilation cooling process using natural cold energy and the numerical simulation values are compared in Figure 7. It can be seen that after 40 hour’s constant low temperature ventilation, the average temperature of grain pile has been lowered from 25\(^\circ\)C to 15\(^\circ\)C, a decrease of 40\%, and the distribution of temperature inside grain pile is even. The temperature drop is relatively sharper during the former 0-15 hours, showing a decrease of 34.4%; then the temperature goes down mildly from 15\(^{th}\) hour to 40\(^{th}\) hour with a decrease of 7.9%. The simulated temperature is slightly lower than the measured value but with the same changing trend. The difference between the simulated value and measured value of the average temperature of grain pile is within 3\%, which indicates that the heat and moisture transfer governing equation has high accuracy.

![Figure 7. Change of grain pile average temperature with time](image)

6.2. Inter-grain Relative Air Humidity Distribution

The predicted value of inter-grain relative air humidity and the critical relative air humidity for mycete growth are shown in Fig.5. It can be seen that the relative humidity decreases with time and maintains at between 60%-70% after the system becomes stable, enabling a good result of rice moisture and quality preservation. The critical relative air humidity for mycete growth on grain pile surface is 80.04% (Chen et al., 2015), which is above the actual relative air humidity during the whole storage process, thus grain moulding has been avoided. Since the grain pile contains moisture itself, the moisture of the whole pile is distributed evenly and maintains at around 12% after 27 hours’ ventilation.

6.3. Analysis on Economic Benefits of Low Temperature Grain Storage System

The power consumption of this system is mainly of the water pump, fan, air compressor, lighting equipment and automatic control equipment, the total power is 1.5 kW, the main operating cost of the system is electricity expenses, and the electricity bill is 1.05 yuan. The general mechanical refrigerator has two pumps less than the system, and the total power of the equipment is 6.11 kW. The running duration of the low temperature grain storage system using natural cold energy is 5 months from May to September, 8 hours per day. The electricity expense of the system is calculated as follow:

\[ R_i = 1.5 \times 30 \times 8 \times 5 \times 1.05 = 1890 \text{ (yuan)} \]

For ordinary mechanical refrigeration, the electricity expense is calculated as follow:
$R_2 = 6.11 \times 30 \times 8 \times 5 \times 1.05 = 7698$ (yuan)

It shows that the low temperature granary using natural cold source can cut down electricity expense by 5808 yuan each year, and meanwhile reduce the discharge of CO$_2$ produced during standard coal power generation, which saves a large amount of electric energy and has no pollution to environment.

**Figure 8.** Predicted value and critical value of inter-grain average relative air humidity

7. **RESULT AND DISCUSSION**

The low temperature grain storage system based on natural cold energy has been designed in this study, enabling low energy consumption and zero pollution for the summer storage of final rice product. The structural parameters of its core equipment-finned tube heat exchanger were designed and calculated, showing qualified parameters are: face area 0.16m$^2$, total heat transfer area 8.6m$^2$, height of heat exchanger 400mm and its width 398mm. The influence of the major functional parameters of the low temperature system on heat exchange capacity has been studied, and conclusion shows that when ice water flow rate is 0.9m$^3$/h, face velocity is 3m/s and air inlet angle is $+30^\circ$, the system has its best heat exchange performance, and a relatively stable fresh-keeping environment with temperature range of 6°C-20°C and relative humidity of 65% can be built.

Finite element numerical simulation and experiment for grain storage were carried out, showing that the difference between the two is less than 3%, which has proved the correctness of the model. The temperature of grain pile went down during the former 15 hours' horizontal ventilation; later the temperature drop slowed down; when the ventilation had lasted for 40 hours, the temperature of the air inside grain pile were evenly distributed with the average value kept at around 15°C; meanwhile the inter-grain relative air humidity was about 62% and the moisture of grain pile was 12%, which are good conditions for moisture and quality preservation during the storage. With temperature of 15°C, the corresponding critical relative air humidity for mycete growth is 80.04%, therefore, moulding will not occur in the low temperature grain storage system. The cold temperature granary using natural cold energy can save electricity cost by 5808 yuan every year compared to mechanical refrigerating granary, and it has realized zero pollution and zero emission.

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