A Multi-objective Control Strategy Considering the Ambient and Controlled Air Conditions for Stored Grain Forced Air Ventilation Process

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Abstract. Based on the principle of heat and mass transfer in stored grain aeration, a new multi-objective optimization strategy considering both the ambient and controlled air conditions was proposed. The control variables are inlet air temperature and humidity which also considered the ambient air conditions. A multi-objective optimization function was worked out with the inlet control variables and optimization objectives are the energy consumption, and grain temperature, moisture content. The proposed strategy was simulated with Matlab. The results showed that, with the proposed strategy, the grain moisture content and temperature can finally be controlled to safe aim values with optimized energy consumption.

Introduction

In-bin grain moisture content and temperature are the most important factors that influence safe grain storage [1-2]. Aeration was one of the most important and effective methods to control grain moisture content and temperature. By adjusting the inlet air temperature, humidity, and velocity, the stored grain aeration process can be optimized and the grain moisture content and temperature can be controlled to the safe level. During the process of aeration, large amount of energy was consumed and grain quality might be influenced greatly, requiring process optimization. In previous studies, attention has been paid to the design of aeration devices and duct structure. Nowadays, the development of computer techniques and advanced control theory make it possible to develop good solutions for optimizing stored grain aeration process.

In previous studies, the expert experience was mostly used to control the on and off status of mechanical devices for stored grain aeration [3-8]. In these studies, the temperature and humidity of inlet air used for aeration are often kept constant with mechanical devices, or kept within a certain small range near to the ambient climate. With such kind of control method, it was very difficult to realize the process control with good accuracy. Moreover, aeration process optimization was also hard to be realized because the stored grain aeration process optimization objectives include not only controlling the grain temperature and moisture at safe level, but also saving energy. It was important to work out an effective and efficient aeration control method with multi-objective optimization. From the viewpoint of control, stored grain aeration system was a multi-input and multi-output (MIMO) nonlinear system and there exists multi-objectives to be optimized. Model predictive control (MPC) can realize multi-objective optimization based on various models, and provides an effective solution for MIMO nonlinear system control. Zhou et al [9] proposed a DPMPC method for aeration process control of stored grain. However, the influence of ambient air condition on energy consumption was ignored.

This paper studied the application of multi-objective control strategy for stored grain aeration considering both the ambient and controlled air condition influences. Small scale stored grain aeration case was studied first to test the effectiveness of this strategy.
Multi-objective Control Strategy for Aeration of Stored Grain

The significance of stored grain aeration control was to ensure the quality and quantity of grain storage, so the problem of grain storage aeration control was also the optimization problem of grain storage aeration control. The control target was temperature and moisture reach the target value, while the system consumes the lowest energy. There are two control variables, the air relative humidity $H_{a-in}$ and the temperature $T_{a-in}$ at the air inlet. The controlled variables are grain moisture content and temperature.

Control Strategy

The block diagram of the proposed control strategy for stored grain aeration process through stored grain was developed as shown in Figure 1. The controlled variables of aeration system were grain temperature $T_g$ and moisture content $M_g$, and controlling variables were inlet air temperature $T_{a-in}$ and relative humidity $H_{a-in}$. Two controllers (Controller 1 and Controller 2) were included. The ambient air temperature $T_{ac}$ and absolute humidity $M_{ac}$ were used to decide which controller was used. Controller 1 was the ON/OFF controller which was used to start or stop the aeration fan using the ambient air. Controller 2 was the model predictive model controller, where the inlet air temperature and relative humidity were calculated with the optimization algorithm. In each control cycle $k$, the controller minimized the objective function and got the optimized set points of $T_{a-in}(k)$ and $H_{a-in}(k)$, with which the grain moisture content and temperature could be adjusted approaching to the set points of $T_{gset}$ and $M_{gset}$.

Predictive Model

The grain bulk was taken as a control volume. One-dimensional stored grain heat and mass transfer model during aeration was expressed in the form of a set of partial differential equations.

The drying rate equation [10] was:

$$\frac{\partial M_g}{\partial t} = -R_v$$

The mass conservation equation for control volume of intergranular air was:

$$\frac{\partial W_{g_a}}{\partial t} = W_{a}(M_{a-in} - M_{a}) + W_{g}R_{v}$$

The heat conservation equation for control volume of grain was:

$$\rho_g c_p \frac{\partial T_g}{\partial t} = h_{g-a}(T_g - T_{a}) - R_w \rho_g \left( L_{vap} + c_p(T_{a} - T_g) \right)$$

The heat conservation equation for control volume of intergranular air was:
\[
\rho_a c_{pa} \frac{dT_a}{dt} = f_a c_{pa} (T_{a-in} - T_a) - h_{g-a} \xi (T_a - T_g) + c_{pa} T_a R \mu \rho_g
\] (4)

**Determination of Objective Function**

To control the grain moisture content and temperature and realize multi-objective optimization during aeration, the following gradients were taken into account when developing the objective function [9].

Grain moisture content was one of the main objectives and had to be kept in an appropriate range during aeration. Objective function of grain moisture content was:

\[
J_M = (M_g - M_{gd})^2
\] (5)

Where, \( M_{gd} \) was the set point of grain moisture content in kg·kg\(^{-1}\).

The grain temperature objective function was:

\[
J_T = (T_g - T_{gd})^2
\] (6)

Where, \( T_{gd} \) was the set point of grain temperature in °C.

To reduce the harmful influence on grain quality during aeration, the temperature and moisture content of inlet air were kept in an appropriate range, which was considered in the selection of restraints for objective function.

The system energy was consumed by fan and mechanical devices during aeration. The fan energy consumption was related to aeration time and power rate, the objective function of which was obtained as follows:

\[
J_{E_{fan}} = 3600P_{fan} \cdot t_v'
\] (7)

Where, \( P_{fan} \) stands for the power rate in kW, \( t_v' \) stands for the aeration time in h.

The mechanical device was used to adjust the temperature and humidity of inlet air. Energy consumption of mechanical devices could be obtained according to energy load generated by heating or cooling the inlet air [11]. The objective function was expressed as follows:

\[
J_{E_{mac}} = m_a [T_{a-in} - T_{a-in}] (c_{pa} - c_{pa, M_{a-in}}) v'
\] (8)

Where, \( m_a \) stands for the inlet air mass flow rate in kg·h\(^{-1}\), \( M_{a-in} \) stands for the humidity of inlet air in kg·kg\(^{-1}\).

The energy consumption of the aeration system as used in controller 2 was obtained as follows:

\[
J_E = J_{E_{fan}} + J_{E_{mac}}
\] (9)

According to the above formula, the aeration system objective function and restraints were obtained. By minimizing the objective function, grain temperature control and multi-objective optimization could be achieved.

\[
\min_{T_{a-in}, T_{a-out}} J = \alpha J_M + \beta J_T + \gamma J_E
\] (10)

s.t. \( T_{min} \leq T_{a-in} \leq T_{max} \)

\( H_{min} \leq H_{a-in} \leq H_{max} \)

\( T_{DPr} < T_{a-in} \)

\( T_{DPa} < T_g \)

If \( M_g \geq M_{gd} \), \( \beta = 0 \); else \( M_{gd} - \Delta M \leq M_g \leq M_{gd} \) and \( \beta \neq 0 \).

Where, \( \alpha, \beta \) and \( \gamma \) stands for the objective function weight coefficients for grain moisture content, grain temperature, and system energy consumption respectively. \( T_{min}, T_{max}, H_{min}, H_{max} \) stands for the minimum value and maximum value of inlet air temperature and humidity. \( T_{DPr} \) and \( T_{DPa} \) stands for the dew point of grain and dew point of air respectively. \( M_{gd} \) stands for the boundary of grain
moisture content for system control. Above the boundary, aeration process was dominated by drying
and system control was aimed at reducing grain moisture content as quickly as possible. When the
grain moisture value was more than $M_{gd, \text{div}}$, then $\beta = 0$. $\Delta M$ was the acceptable deviation range of grain
equilibrium moisture content from set point. When the grain moisture content was less than $M_{gd, \text{div}}$, the
aeration was conducted to keep the grain equilibrium moisture content between $M_{gd}$ and $M_{gd} - \Delta M$ so
as to avoid over dry or over wet of the grain.

Multi-objective Optimization Control Strategy Program Flow

To choose the controller in control cycle $k$, the system energy consumption $J_{E1}$ and $J_{E2}$ were used. If
controller 1 was used, the total energy consumption was $J_{E1} = J_{Efan}$; else, the total energy consumption
was $J_{E2} = J_{Efan} + J_{Emac}$.

The Multi-objective optimization control strategy program flow chart was shown in Figure 2.

The process flow was as follows:
(1) Calculate the equilibrium moisture content $M_{ae}$ with ambient air temperature and relative
humidity according to Equation (11). If $M_{ae}$ was within the range of [12%, 14%], calculate the
natural aeration energy consumption $J_{E1}$ and $J_{E2}$; otherwise, use controller 2 to run the aeration.

$$M_{ae} = -\frac{1}{C_3} \ln \left[ \frac{(T_{ae} + C_2) \ln H_{ae}}{-C_1} \right]$$

(11)

Where $T_{ae}$ was the initial ambient air temperature in °C; $H_{ae}$ was the initial ambient air relative
humidity in %. $C_1$, $C_2$ and $C_3$ were obtained with experiment.

(2) Compare the energy consumption by ventilation with ambient air (using controller 1) $J_{E1}$ and
controlled inlet air $J_{E2}$. If $J_{E1} > J_{E2}$ controller 2 was used; if not, controller 1 was used.

(3) Calculate the equilibrium moisture of the top-layer grain $M_{gN}$ in the bin. If $M_{gN} < 14\%$, end the
ventilation; if not, repeat the control process until $M_{gN} < 14\%$.

Simulation Results and Discussion

The proposed control strategy was simulation with matlab using wheat as the simulation objective.
Simulation Conditions

Ambient air condition represented by air temperature and relative humidity at the wheat harvest time was chosen, ranging from 22 to 24 June. The initial wheat moisture content was 20% d.b., and temperature was 20 °C. The aeration process was one-dimensional. The height of the wheat bulk was 65 cm. 12 sampling points were deployed for measurement of wheat temperature and moisture content, intergranular air temperature and humidity. The objectives of the simulation were to control the wheat moisture content at 13% d.b. and temperature at 15 °C, together with saving energy.

Simulation Results

The simulations were run with the control strategy proposed in this paper and the DPMPC proposed by Zhou et al [9]. The simulation results of the two methods were shown in Figure 3 and 4.

(a) 
(b) 
(c) 
(d) 

Figure 3. Simulation results with the multi-objective control strategy proposed in this paper.
Discussion

Simulation results showed that both the two control methods could control the stored grain moisture content and temperature to the objective. The total energy consumption of the aeration process with the control strategy proposed in this paper is $1.1596 \times 10^5$ J, which takes 2880 min. The control process using DPMPC only consumes $1.2340 \times 10^5$ J, which takes 2848 min. However, if pure natural aeration is used, aeration conditions are often difficult to achieve. Although the control strategy proposed in this paper took a little more time than the DPMC, energy consumed was less than the DPMPC. It also showed that if the inlet air condition was not controlled at all, the ambient air condition would be not suitable for aeration all the time. The inlet air shifting between the ambient air and controlled air could achieve the control objective and save energy.

Summary

The multi-objective control strategy for stored aeration proposed in this paper considered both the ambient air condition and controlled inlet air condition, and two controllers were developed respectively. By shifting between the two controllers, the aeration process was controlled. The control strategy could not only control the grain moisture content and temperature to the safe level, but also save energy. It was applicable for stored grain ventilation process control.

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