MODELING AND CONTROL OF LIVESTOCK VENTILATION SYSTEMS AND INDOOR ENVIRONMENTS

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ABSTRACT

The hybrid ventilation systems have been widely used for livestock barns to provide optimum indoor climate by controlling the ventilation rate and air flow distribution within the ventilated building structure. The purpose of this paper is to develop models for livestock ventilation systems and indoor environments with a major emphasis on the prediction of indoor horizontal variation of temperature and concentration adapted to the design of appropriate controlling strategy and control systems. The Linear Quadratic (LQ) optimal control method taking into account of the effect of necessary constraints and random disturbances is designed through system linearization. The well designed control systems are able to determine the demand ventilation rate and airflow pattern, improve and optimize the indoor Thermal Comfort (TC), Indoor Air Quality (IAQ) and energy use.

KEYWORDS

Livestock Ventilation, Thermal Comfort, Indoor Air Quality, LQ Optimal Control.

NOMENCLATURE

c_p	Heat capacity	q	Volume flow rate
ρ	Air density	*subscripts*	
P	Pressure	i	Zone i
H	Average height of inlet vent and leakage	o	Outside
A	Area of openings and leakage	in	Flow in
U	Heat transfer coefficient of building envelope	out	Flow out
V_{ref}	Wind speed	NPL	Neutral Pressure Level
$\dot{m}$	Mass flow rate	$wall$	Building envelope

INTRODUCTION

Hybrid ventilation systems have been widely used for livestock buildings. Livestock ventilation is concerned with comfort interpreted through animal welfare, behavior and health, and most importantly, it is concerned with factors such as conversion ratio, growth rate and mortality (J.A.Clark, 1984). Most existing analyses for the livestock ventilation system assume that the indoor air temperature and concentration is uniform. However, the actual indoor environment at any controlling sensor (especially when the sensors are located horizontally) will depend on the air flow distribution that is usually depicted as a map of the dominant air paths. Therefore, the control system for large scale livestock barns neglecting the horizontal variations could obviously result in significant deviations from the optimal environment for the sensitive pigs or chickens in the livestock barn.

In this paper, the livestock indoor environment and its control system will be regarded as a feedback loop in which the controller provide the optimal actions to the actuators taking into account of the necessary disturbances and random noises based upon the developed indoor climate model and ventilation equipment models. The purpose of this paper is to design an appropriate controlling strategy to improve the indoor animal Thermal Comfort (TC) and Indoor Air Quality (IAQ) through an optimal energy approach.

MATHEMATICAL MODELLING

The fan assisted natural ventilation principle will be investigated in this work. As seen in Figure 1(a), 1(b) and 1(c), the system consists of evenly distributed fans and fresh air openings on the walls. From the view of direction A and B, Figure 1(A) and 1(B) provide a description of the dominant air flow map of the building includes the airflow interaction between each conceptual zone by applying the multi-conceptual zone method. In each zone, it is possible to monitor the zonal climate and concentration and effect of the control signals through the actuators movements: inlet vents and exhaust fans.

The necessary simplifying assumptions for developing models are as follows:

- The interactive airflow between internal zones, which is influenced by the inlet air jet trajectory, thermal buoyancy forces and convective heat are assumed to be constant.
- Heat gain from animals and solar radiation are assumed to be constant.
- The rate of the heat loss by evaporation is neglected.
- The thermal properties of the airflow are assumed to have bulk average values.
- Airflow involves no mass accumulation inside the building.
- The heat transfer coefficient of building envelope is assumed to be constant.
- The pressure is assumed to be constant on each building surface (same value of pressure coefficient C_p is used for all openings on the same side of the building).
- A hydrostatic pressure distribution is assumed in the space.
- Opening characteristics are assumed independent on flow rate, pressure difference and outside temperature (constant discharge coefficient C_d are used for all openings).

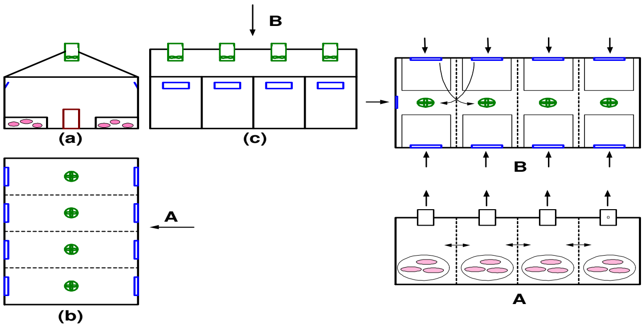


Figure 1: Synoptic of Large Scale Livestock Barn and the Dominant Airflow Map of the Barn

Models of Indoor Climate

A conceptual multi-zone method will be employed to analyze and develop the indoor climate model. The livestock building will be divided into several macroscopic homogeneous conceptual zones horizontally so that the nonlinear differential-algebraic Eqn. 1 and Eqn. 2

relating the zonal temperature T_i and zonal concentration $C_{r,i}$ can be derived by applying the theory of conservation of energy and mass. By substituting *i* with the zone number into Eqn. 1 and Eqn. 2, we could derive four coupled differential equations for indoor thermal comfort in terms of zonal temperature and indoor air quality in terms of zonal air concentration respectively.

For Eqn. 1, the rate of energy $\dot{Q}$ transferred by mass flow can be calculated by Eqn. 3. $\dot{Q}_{i+1,i}, \dot{Q}_{i,i+1}$ indicate the heat exchange due to the air flow across the conceptual boundary of zone i and zone $i+1$, while for the middle zones which have heat exchange with neighbor zones on each side, two more parts $\dot{Q}_{i-1,i}, \dot{Q}_{i,i-1}$ will be added to Eqn. 1. The value of interactive mass flow between internal zones is the sum of influence from air jets, heat plume, thermal buoyancy and air exchange rate. $\dot{Q}_{inlet,i}, \dot{Q}_{outlet,i}, \dot{Q}_{leakage,i}$ represent the heat transfer by mass flow through inlet, outlet and leakage of the zone respectively. The convective heat loss through the building envelope is denoted by $\dot{Q}_{conve}$ and described as $U \cdot A_{wall} \cdot (T_i - T_o)$. The heat source of the zone $\dot{Q}_{source,i}$ includes the heat gain from animal heat production, solar radiation and heating system. For Eqn. 2, the rate of concentration is indicated as $C_r \cdot n$, where C_r represents the concentration level and the air exchange rate *n* is calculated by Eqn. 4. For the middle zones which have mass flow interaction with neighbor zones on both sides, two more parts $C_{r,i} \cdot n_{i,i-1}, C_{r,i-1} \cdot n_{i-1,i}$ should be added to Eqn. 2. The rate of contaminant generation is denoted by G_i and the zonal volume is denoted by V_i.

$$M_i c_{p,i} \frac{dT_i}{dt} = \dot{Q}_{i+1,i} + \dot{Q}_{i,i+1} + \dot{Q}_{in,i} + \dot{Q}_{out,i} + \dot{Q}_{leakage,i} + \dot{Q}_{conve,i} + \dot{Q}_{source,i} \tag{1}$$

$$\frac{dC_{r,i}}{dt} = C_{r,i} \cdot n_{out} + C_{r,o} \cdot n_{in} + C_{r,i+1} \cdot n_{i+1,i} + C_{r,i} \cdot n_{i,i+1} + \frac{G_i}{V_i} \tag{2}$$

$$\dot{Q} = \dot{m} \cdot c_p \cdot T_i \tag{3}$$

$$n = \frac{\dot{m} \cdot 3600}{\rho \cdot V} \tag{4}$$

Models of Inlet Vent and Motor Fan System

$$\sum q_{in} \cdot \rho_o \cdot \frac{\Delta P}{|\Delta P|} + \sum q_{out} \cdot \rho_i = 0 \tag{5}$$

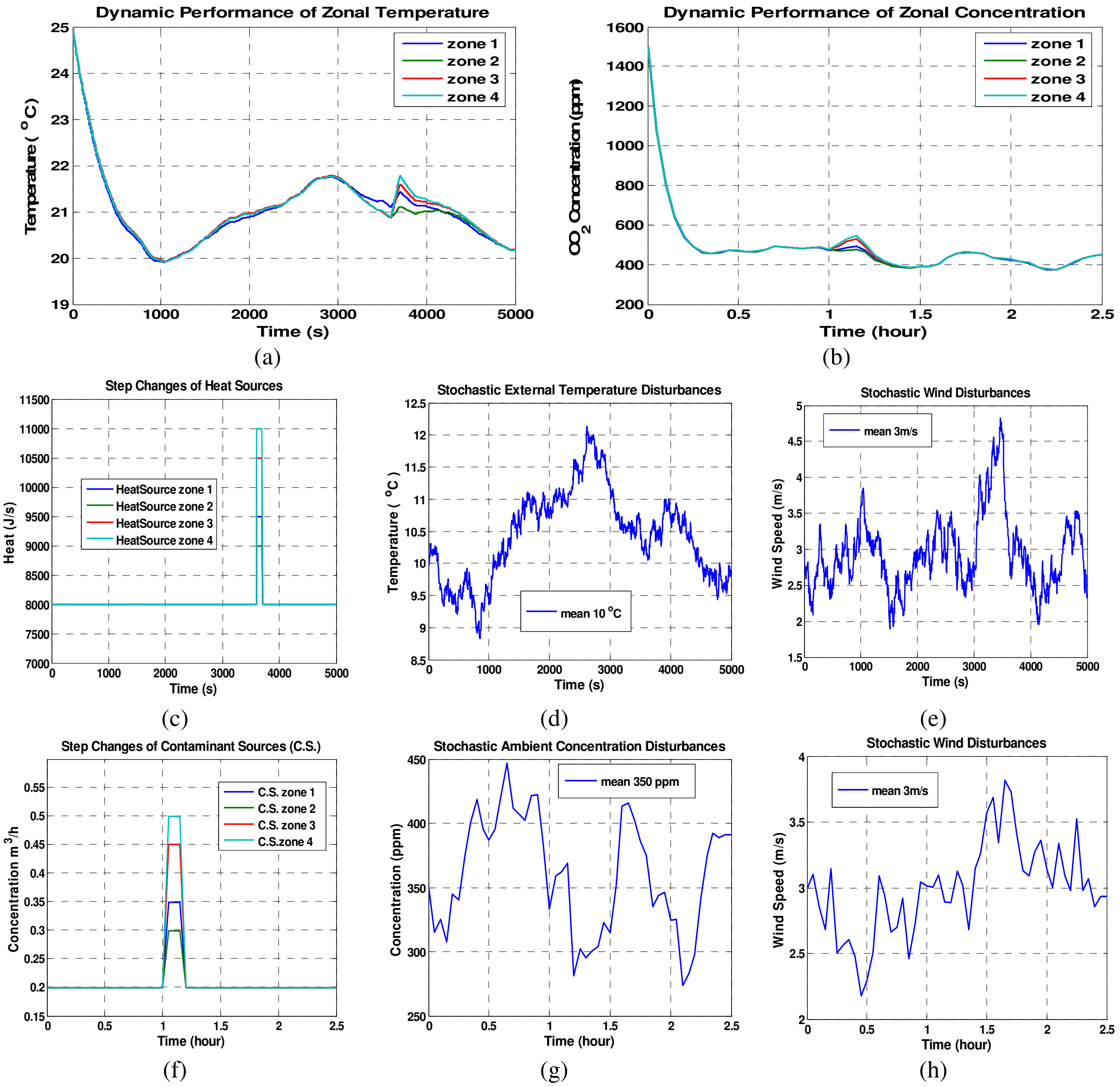
$$q = C_d A \cdot \sqrt{\frac{2|\Delta P|}{\rho}} \operatorname{sgn}(\Delta P) \tag{6}$$

$$\Delta P = \frac{1}{2} C_P \rho_o V_{ref}^2 - P_i + \rho_o g \frac{T_i - T_o}{T_i} (H_{NPL} - H) \tag{7}$$

Eqn. 5 gives the relationship between the volume flow rate and pressure difference across the openings based on mass balance equation with single zone method. The ventilation flow rate can be determined from Eqn. 6 and the pressure difference is the combing driving forces of thermal buoyancy and wind as Eqn. 7. Therefore, Eqn. 5 will then result in a linear equation from which we can solve for the internal pressure P_i. With fan law, the straightforward relationship between total pressure difference, volume airflow rate and motor speed is clarified in a nonlinear static equation (P.Heiselberg, 2004).

Performance Simulation

The open loop dynamic performances of zonal variation for indoor temperature and CO_2 concentration within a day based on the developed TC model and IAQ models are demonstrated in Figure 2(a) and (b). The system started from operating points which maintain the system behavior (indoor climate and indoor air quality) at the required condition with exceptionally low horizontal variation. The system is stimulated by a serious of step changes of the indoor zonal heat source and zonal contaminant load during the entire time horizon. The simulation is implemented with stochastic external temperature, ambient concentration and wind speed disturbances generated from random sources through low-pass filters.



(a) (b)

(c) (d) (e)

(f) (g) (h)

Figure 2: Open loop Dynamic Performance for (a) Zonal Temperature and (b) Zonal CO_2 Concentration; Step Changes of (c) Heat Source (f) Contaminant Source; Stochastic Wind Speed (e) and external temperature (d) for TC model; Stochastic Wind Speed (h) and Ambient CO_2 Concentration (g) for IAQ model.

It proves to be evident from the simulation results, that the conceptual multi-zone models for TC and IAQ contain significant information on horizontal variation which is not able to be captured by the single zone model with mean temperature and concentration, under the circumstances that the zonal disturbances changes.

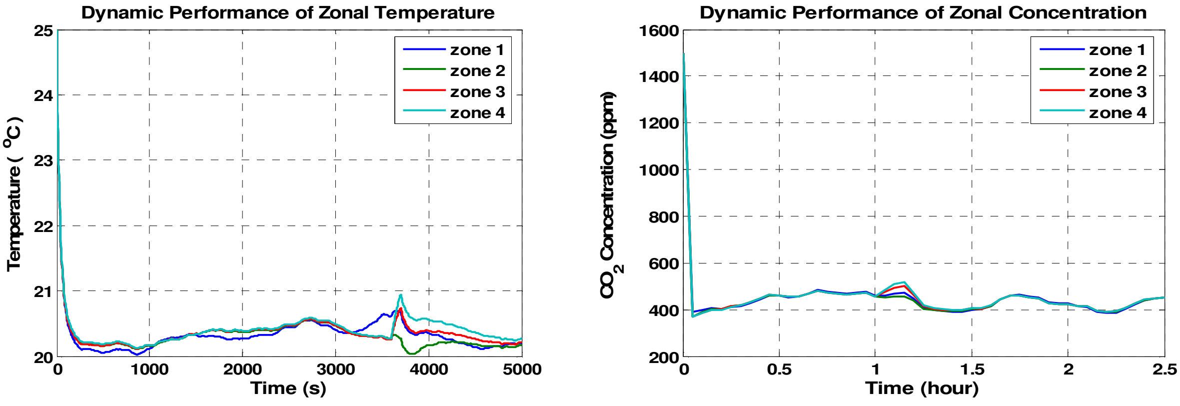
DESIGN OF CONTROL SYSTEM

The entire livestock ventilation system and indoor environment is a Multiple Input and Multiple Output (MIMO) dynamic nonlinear process and strongly coupled intrinsic system. It is exposed to external disturbances and noise and has actuators with saturation. Consequently, it is necessary to explore the application of advanced control algorithms, such as the optimal control, predictive control etc. to satisfy the equilibrium between the indoor air quality, thermal comfort and energy consumption. Linear Quadratic (LQ) optimal control is a good method for ventilation control system analysis before applying other more complex control schemes. The LQ control deals with a linear state space model which is derived from the system linearization around the equilibrium points, where the Thermal Neutral Zone and animal demand concentration are selected to be the reference values.

The performance function for LQ control is:

$$\min \sum_{k=0}^{N-1} \left[x^T(k) Q_1 x(k) + u^T(k) Q_2 u(k) \right] + x^T(N) Q_N x(N) \tag{8}$$

where k denotes the sample time, x is measurable states or controlled variables (zonal temperature and zonal concentration) matrix, and u is control signal or manipulated variables (inlet vents and fan speed) matrix, N denotes the time horizon, the weighting matrices Q_1 and Q_N are positive definite and Q_2 is positive semi-definite, and they are defined as diagonal matrices. The diagonal elements are the inverse value of the square of the maximum allowed deviations in the states and the control signals (G.F.Franklin *et al.*, 1998). By using Dynamic Programming, we could obtain a linear time varying controller, where the dynamic gain is determined by the *Riccati* Equations. The optimal control signals are generated from this linear feedback MIMO controller taking into account of the disturbances variables (external temperature, heat source, ambient concentration and contaminant load). Then, this generated control signals are input to the process to predict the zonal temperature and concentration. The sensor and motor dynamics is relatively fast compared with the entire system response and could be neglected.



(a) (b)

Fig. 3 Close Loop Dynamic Performance with Feedback Gain for (a) Zonal Temperature, (b) Zonal CO_2 Concentration.

Figure 3 illustrates the close loop dynamic performances of the indoor temperature and air concentration with a linear feedback gain for animal thermal comfort and indoor air quality by applying the same variation of the disturbances for open loop simulation as shown in Figure 2. A certain amount of trial and error is required with an interactive computer simulation before a satisfactory design is obtained, for example, one of possibilities is to adjust the weighting matrix. Through comparing the close loop and open loop of the simulation results, we could recognize that the system with controller has much shorter response time to reach the steady state and has the capability to reject the indoor and outdoor disturbances oscillation and noise relatively by adjusting the air flow rate through eight inlet vents and four exhausted fans.

DISCUSSION

Aiming at improvement of performances and optimization of energy, the main achievement of this work is the successful application of the LQ optimal controller for livestock ventilation systems analyzed by a conceptual multi-zone method. The results prove to be fruitful that the designed control scheme is feasible and flexible to satisfy the purpose.

Some parameters of the mathematical models will be identified through experiment in a real scale livestock barn equipped with hybrid ventilation systems. The interfacial mixing parameters which describe the airflow interaction of internal zones will be calibrated with experimental measurement by using gas tracer. Advanced control methods, dynamic disturbances models, estimator for weather condition, augmented control signals for more actuators such as the operation of the heating system for cold weather, air-conditioning systems for warm weather, shade screen for solar radiation will be applied in future and the result will be compared with those obtained with currently used classical PID controller.

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