Aalborg Universitet

Parameter Estimation of Dynamic Multi-zone Models for Livestock Indoor Climate Control

Wu, Zhuang; Stoustrup, Jakob; Heiselberg, Per Kvols

Published in:
The 29th AIVC Conference in 2008

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

Parameter Estimation of Dynamic Multi-zone Models for Livestock Indoor Climate Control

Zhuang Wu and Jakob Stoustrup
Automation and Control, Department of Electronic Systems, Aalborg University, Fredrik Bajersvej 7C, 9220, Aalborg East, Denmark

Per Heiselberg
Department of Building Technology and Structure Engineering, Aalborg University, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark

ABSTRACT

In this paper, a multi-zone modeling concept is proposed based on a simplified energy balance formulation to provide a better prediction of the indoor horizontal temperature variation inside the livestock building. The developed mathematical models reflect the influences from the weather, the livestock, the ventilation system and the building on the dynamic performance of indoor climate. Some significant parameters employed in the climate model as well as the airflow interaction between each conceptual zone are identified with the use of experimental time series data collected during spring and winter at a real scale livestock building in Denmark. The obtained comparative results between the measured data and the simulated output confirm that a very simple multi-zone model can capture the salient dynamical features of the climate dynamics which are needed for control purposes.

1. INTRODUCTION

Livestock environmental control plays crucial role in alleviation of thermal strain and the maintenance of a good indoor air quality, preserving animal health and welfare and improving the efficiency of animal production. The investigations in this respect (Cunha *et al.*, 1997, Gates *et al.*, 2001, Pasgianos *et al.*, 2003, Taylor *et al.*, 2004, Soldatos *et al.*, 2005, Arvanitis *et al.*, 2007) have shown the indispensability for control and perspective for future research.

Indoor climate model of livestock building are essential for improving environmental performances and control efficiencies. The aim of this work is to identify the developed models that should unite simplicity on the parameter level and a correct description of the intern-zonal climate that are important for multi-variable control studies. Concerning the indoor climate and energy consumption for the large scale livestock building, neglecting the horizontal variations could obviously result in significant deviations from the optimal environment for the sensitive pigs or chickens. On the other hand, the ventilation has become an important part of the energy consumption of the ventilated building. Therefore it is necessary to study more specifically the mass transfers of air inside and outside of the building, in order to control more specifically the heating and ventilating systems.

For livestock building with localized ventilation and heat source, with persistent spatial temperature/concentration gradient, the single well-mixed compartment approach may be inappropriate. Instead of using Computer Fluid Dynamic (CFD) codes, though proves to give detailed inter-zonal flow and temperature distribution, and higher order model approach like Active Mixing Volume (AMV) described in Young *et al.*, 2000, we suggest a so-called conceptual multi-zone method to satisfy the necessary precision for evaluating local climate within various conceptual zones of a building. This approach is different with the conventional multi-zone modeling method (O'Neill, 1991, Sohn and Small, 1999), for its partition-less structure, but similar with the zonal model principle as proposed in Gagneau and Allard, 2001 and Haghighat *et al.*, 2001, that consists in breaking up the entire indoor air volume into macroscopic homogeneous conceptual zones in which mass and energy conservation must be obeyed. This method maintains the simplicity of the first order model, yet captures the major heterogeneity in the room to reach the desired controlling objectives.

2. LABORATORY LIVESTOCK BUILDING

The livestock building located in Syvsten, Denmark, is a large scale concrete building which used to be a broiler house, with floor area of 753 m^2, length of 64.15 m, width of 11.95 m, and approximate volume of 2890 m^3, see Figure 1. In order to control its climate, hybrid ventilation system is equipped. Figure 2 demonstrate the major installed hardware inside the livestock building.

Figure 1 A Full Scale Poultry Stable in Denmark

The installed actuators are five exhaust fans evenly distributed on the ridge of the roof, totally sixty-two inlet units controlled by winch motors mounted on the windward and leeward side walls. Through the inlet system, the incoming fresh cold air mixes with indoor warm air, then drop down to the animal environmental zones slowly in order to satisfy the zonal comfort requirement. The heating system consists of two major heat sources, one for heating up the indoor temperature through the steel pipes, the other for simulating the animal heat production with six water heating radiators. They are both coupled to an oil furnace placed in the monitor (see Fig. 3). The inside temperature sensors are positioned around one meter above the floor. The air flow and position sensors are mounted in the exhaust fans and inlet openings. The pressure sensors are mounted on the side walls to measure the pressure difference across the inlet (see Fig. 4). Table 1 and 2 illustrate the function of the hardware and sensors.

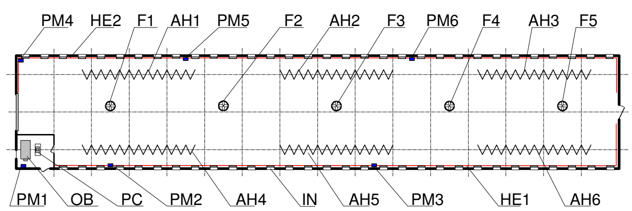


Figure 2 Overview of the Hardware Equipped in the Stable

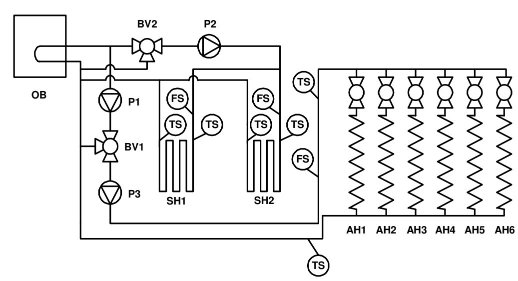


Figure 3 The Complete Heating System in the Stable

The control PC in the stable is a Commercial Off-The shelf System (COTS) as given in Jessen *et al.*, 2006. The computer runs Linux as the operating system and uses Comedi as an open source library to communicate with the I/O cards which connect to the sensors and actuators in the stable. The control demand and the sensor values could be accessed and acquired through a network interface card (NIC) over the Internet or a local area network (LAN) to a web browser.

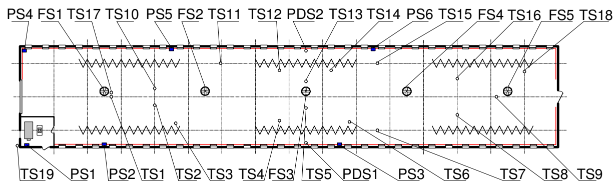


Figure 4 Overview of the Sensors Mounted inside the Stable

Table 1 List of Hardware

Symbol	Function
AH1 - AH6	Animal Heat Production
SH1 - SH2	Stable Heating System
IN	Inlet
OB	Oil Furnace
PC	System Computer
PM1 - PM6	Winch Motor
F1 - F5	Axial Exhaust Fan
BV	Ball Valve
P	Pump

Table 2 List of Sensors

Symbol	Function
FS1 - FS5	Flow Sensors (outlet)
PDS1 - PDS2	Pressure Difference Sensors
TS1 - TS19	Temperature Sensors (air)
PS1 - PS6	Position Sensors (inlet)

3. PROCESS MODELS

3.1 Inlet Unit Model

The inlet system provides variable airflow directions and the amount of incoming fresh air by adjusting the bottom hanged flaps. The volume flow rate is calculated by Equation (1). The pressure difference ΔP_{inlet} across the opening can be computed by solving thermal buoyancy and wind effect as Equation (2). The value of wind induced pressure coefficient C_p changes according to the wind direction, the building surface orientation, the topography and roughness of the terrain in the wind direction.

$$q_{in} = C_d A_{inlet} \sqrt{\Delta P_{inlet} / \rho_o} \tag{1}$$

$$\begin{aligned} \Delta P_{inlet} &= 0.5 \cdot C_P \rho_o V_{ref}^2 - P_i \\ &+ \rho_o g (1 - T_o / T_i)(H_{NPL} - H_{inlet}) \end{aligned} \tag{2}$$

3.2 Exhaust Unit Model

In the exhaust unit, the airflow capacity is controlled by adjusting the r.p.m. of the fan impeller and angle of the shutter. The relationship between the total pressure difference ΔP_{fan}, volume flow rate q_{out} and supplied voltage V_{volt} with a specific shutter opening angle can be approximated in a nonlinear static equation as (3), where the parameters a_0, a_1, a_2, b_0, b_1, b_2 are empirically determined from experiments. As shown in Equation (4), the total pressure difference ΔP_{fan} across the fan is the difference between the wind pressure on the roof and the internal pressure at the entrance of the fan which considers the pressure distribution calculated upon the internal pressure at reference height P_i .

$$\begin{aligned} \Delta P_{fan} &= (b_0 + b_1\theta + b_2\theta^2) q_{out}^2 \\ &+ a_0 (V_{volt})^2 + a_1 q_{fan} (V_{volt}) + a_2 q_{fan}^2 \end{aligned} \tag{3}$$

$$\begin{aligned} \Delta P_{fan} &= 0.5 \cdot \rho_o C_{P,r} V_{ref}{}^2 \\ &- P_i - \rho_i g (T_i / T_o - 1)(H_{NPL} - H_{fan}) \end{aligned} \tag{4}$$

3.3 Multi-zone Climate Model

By applying a conceptual multi-zone method, the building will be divided into several macroscopic homogeneous conceptual zones horizontally. The nonlinear differential equation relating the zonal temperature can be derived for each zone as Equation (5). The following energy transfer terms appear in the zonal model: the convective inter-zonal heat exchange $\dot{Q}_{i+1,i}$; the heat transfer by mass flow through inlet and outlet $\dot{Q}_{inlet,i}$, $\dot{Q}_{outlet,i}$; the transmission of heat loss through building envelope by convection and radiation $\dot{Q}_{transmission,i}$; the zonal heat source $\dot{Q}_{source,i}$.

$$M_i c_{p,i} \frac{dT_i}{dt} = \dot{Q}_{i+1,i} + \dot{Q}_{i,i+1} + \dot{Q}_{in,i} + \dot{Q}_{out,i} + \dot{Q}_{transmission,i} + \dot{Q}_{source,i} \quad (5)$$

in which,

$$\dot{Q}_{transmission,i} = U \cdot A_{wall,i} \cdot (T_i - T_o) \quad (6)$$

$$\dot{Q}_{i,i+1} = c_{p,i} \cdot \rho_i \cdot q_{i,i+1} \cdot T_i \quad (7)$$

where the inter-zonal mixing volume flow rate $q_{i,i+1}$ is the sum of the airflow $q_{i,i+1,V}$ caused by differentiate zonal ventilate rate and inlet jet trajectory, and the airflow $q_{i,i+1,T}$ due to the convective phenomenon. We propose $k_{i,i+1}\Delta T_{i,i+1}$ to compute $q_{i,i+1,T}$, where $k_{i,i+1}$ is the inter-zonal airflow mixing parameter and could be determined through experimental calibration.

4. PARAMETER ESTIMATION

The dynamic models of inlet and exhaust system are expressed nonlinearly with respect to some dynamic parameters, which then can be estimated by using constrained nonlinear least square techniques based on the data-set collected from experiments. The constraints to the optimization routines are the non-negativity for all of the parameters employed in the models. This constrained nonlinear least square method not only yields consistent positive estimates of the parameter values, but also exhibits close to optimum performance in the analyzed models.

For inlet system, the discharge coefficient C_d varies considerably with the inlet type, opening area, as well as incoming air temperature and flow rate. However, for simplicity, a constant value is determined through experiment and applied for all openings, even though it might lead to over/under-prediction of airflow capacity and thereby larger openings than necessary. Figure 5 demonstrates the comparison of the characteristic curve of inlet system obtained from the measurement and the model simulation.

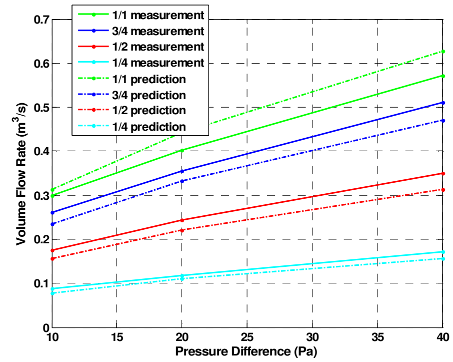


Figure 5 Inlet Characteristic Curve

Figure 6 illustrates the performances of the exhaust fan at a specific swivel shutter opening with the measurement and the prediction. The surface represents the character of the fan with pressure-voltage-flow data, and is approximated by the quadratic equation (3).

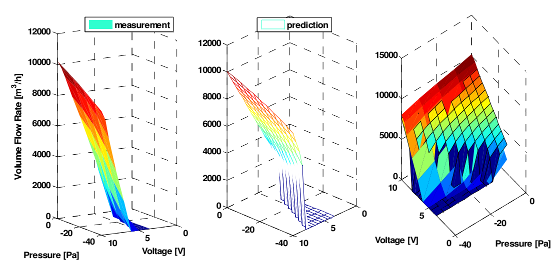


Figure 6 Comparison of Exhaust Fan Characteristic Curve

The livestock indoor climate model is identified through the experiments carried out in the full scale livestock building. In the experiments, the data were obtained from dynamic experiments with sampling rate 30 seconds.

The experiments were conducted in two seasons: spring and winter. The following figures depict the comparison with the prediction and measurement results. Case No. 1

is with constant actuators setting for ventilation rate 4.8 m^3/s, inlet opening area 1.46 m^2 and input water temperature for the heating system 55 ^oC; Cases No. 2 is with a Pseudo-Random Digital Signal (PRDS) as the ventilation actuators setting to the indoor climate system. The ventilation rate varies between 3.4 m^3/s to 4.4 m^3/s, inlet opening area varies between 1.1 m^2 to 2.1 m^2. These two scenarios are thought to represent typical but not the only two cases encountered in the static and dynamic behavior of the model for parameter estimation.

Validations are carried out with the input signals which were not used in the estimation processes and then the output of model was compared with the measured results. It is observed from Figure 7 (a) and 8 (a) that the average temperatures are in reasonably good accord. The steady state oscillations come from the surface temperature fluctuation of heating system due to the neglect of the slow dynamic of the building materials. All of the experiments are made when external wind is mild and stay below 3m/s. The fan and inlet position are indicated with voltage which is generated by the analog output card (0 - 10 VDC). Table 3 summarizes the estimated parameter values for each scenario. Roughly compared to the reality values, the estimated effective zonal volume is around 10 order magnitude bigger than the geometrical values. This phenomena could be explained by the fact that we neglect some influencing factors and the existence of uncertainties, for example the shot-circuiting and stagnant zones in ventilated spaces (Daskalov, 1997, Soldatos *et al.*, 2005), the heat capacity of the construction material, the latent heat loss through evaporation, the degree of air mixing, building leakage and wind effect.

The important phenomena, represented in the model, are analyzed experimentally and by detailed simulation. From this analysis, a further understanding for the development of our conceptual multi-zone models is obtained. The proposed model is appropriate for quantifying the temperature gradients with time variation in large, heterogeneous, partition-less buildings.

5. CONCLUSIONS

The comparative results between the measured data and the simulated output confirm the value of conceptual multi-zone approach in capturing the salient dynamical features of the indoor climate of the large scale partition-less livestock building, show the potential of applying the model-based multi-variable control.

REFERENCES

Arvanitis, K. G., Pasgianos, G. D., Daskalov, P. I., Vougioukas, S. and Sigrimis, N. A. (2007). A nonlinear PI controller for climate control of animal buildings. *Proceedings of the European Control Conference*.

Cunha, J. B., Couto, C. and Ruano A. E. (1997). Real-time parameter estimation of dynamic temperature models for greenhouse environmental control. Control Engineering Practice, 5(10): 1473 – 1481.

Daskalov, P. I. (1997). Prediction of temperature and humidity in a naturally ventilated pig building. Journal of Agricultural Engineering Research, 68: 329 – 339.

Gagneau, S. and Allard. F. (2001). About the construction of autonomous zonal models. Energy and Buildings, 33: 245 – 250.

Gates, R. S., Chao, K. and Sigrimis, N. (2001). Identifying design parameters for fuzzy control of staged ventilation control systems. Computers and Electronics in Agriculture, 31: 61 – 74.

Haghighat, F., Li, Y. and Megri, A. C. (2001). Development and validation of a zonal model - poma. Building and Environment, 36: 1039 – 1047.

Jessen, J. J., Nielsen, J. F. D. and Schiler, H. (2006). Cots technologies for internet based monitoring of livestock buildings. *Proceedings of the 10th IASTED International Conference on Internet and Multimedia Systems and Applications*, pages 10 – 15.

O'Neill, P. J. (1991). Identification of flow and volume parameters in multizone systems using a single-gas tracer technique. ASHRAE Transactions, 97(1): 49 – 54.

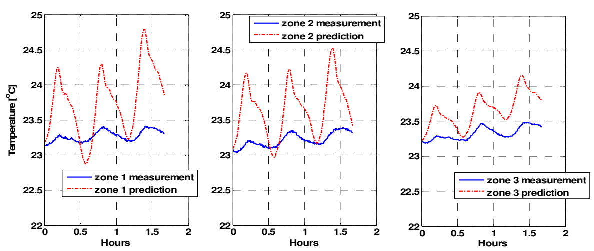
Pasgianos, G. D., Arvanitis, K. G., Polycarpou, P. and Sigrimis, N. (2003). A nonlinear feedback technique for greenhouse environmental control. Computers and Electronics in Agriculture, 40: 153 – 177.

Sohn, M. D. and Small, M. J. (1999). Parameter estimation of unknown air exchange rates and effective mixing volumes from tracer gas measurements for complex multi-zone indoor air models. Journal of Building and Environment, 34: 293 – 303.

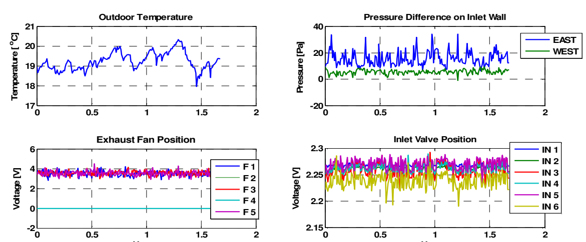
Soldatos, A. G., Arvanities, K. G., Daskalov, P. I., Pasgianos, G. D. and Sigrimis, N. A. (2005). Nonlinear robust temperature-humidity control in livestock buildings. Journal of Computers and Electronics in Agriculture, 49: 357 – 376.

Taylor, C. J., Leigh, P., Price, L., Young, P .C., Vranken, E. and Berckmans, D. (2004). Proportional-integral-plus (pip) control of ventilation rate in agricultureal buildings. Control Engineering Practice, 12: 225 – 233.

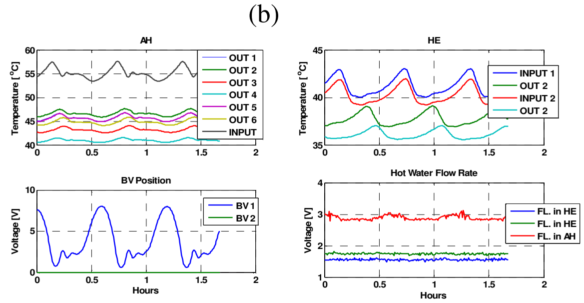
Young, P. C., Price, L., Berckmans, D. and Janssens, K. (2000). Recent developments in the modelling of imperfectly mixed airspaces. Computers and Electronics in Agriculture, 26: 239 – 254.



(a)

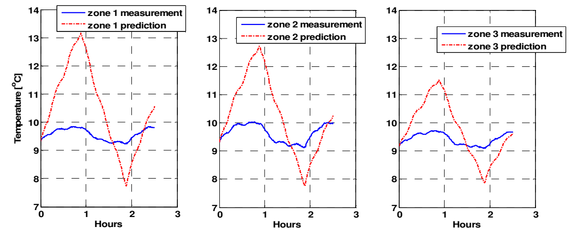


(b)

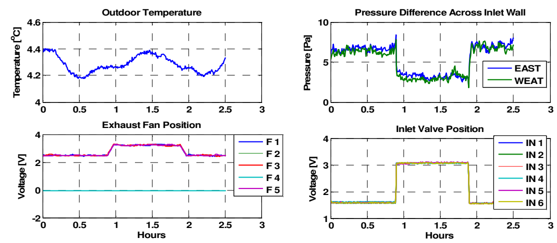


(c)

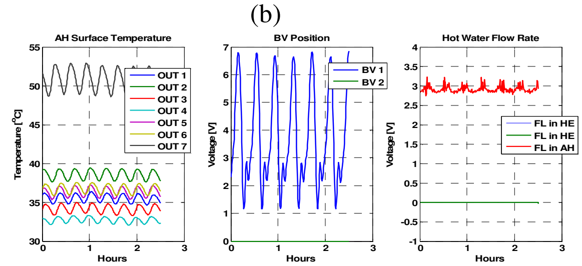
Figure 7 Case No. 1 (a) Comparison of Indoor Zonal Air Temperatures (b) Outdoor Weather Condition and Actuators Action (c) Heat Exchanger and Radiator.



(a)



(b)



(c)

Figure 8 Case No. 2 (a) Comparison of Indoor Zonal Air Temperatures (b) Outdoor Weather Condition and Actuators Action (c) Heat Exchanger and Radiator

Table 3 Numerical Values of the Model Coefficients Determined from Parameter Estimation

Coefficients	Case 1	Case 2	Units
k_{12}	1.04	0.12	$m^3/(sK)$
k_{21}	1.02	0.08	$m^3/(sK)$
k_{23}	0.76	0.12	$m^3/(sK)$
k_{32}	0.80	0.18	$m^3/(sK)$
q_{12}	1.13	0.19	m^3/s
q_{21}	0.91	0	m^3/s
q_{23}	1.02	0.99	m^3/s
q_{32}	1.01	0.82	m^3/s
$q_{in,1}$	1.53	1.48	m^3/s
$q_{in,2}$	1.17	1.42	m^3/s
$q_{in,3}$	1.33	1.13	m^3/s
V_1	6135.04	31186.95	m^3
V_2	6913.57	34044.13	m^3
V_3	18154.01	46750.56	m^3
$UA_{wall,1}$	3780.20	31788.58	J/(sK)
$UA_{wall,2}$	3757.23	36963.98	J/(sK)
$UA_{wall,3}$	3700.32	30602.88	J/(sK)