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Model-based control of natural ventilation in dairy buildings

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ABSTRACT

Without automatic control, the ventilation rate in naturally ventilated dairy buildings is often significantly higher than the required to provide good conditions for the animal in windy conditions, and this over ventilation will result in increased ammonia emission. Therefore, automatic control of the ventilation via adjustment of the ventilation openings in relation to the weather conditions can be used to reduce the ammonia emission. In this context, the model-based control method can be used and a predictive model can estimate the wind driven ventilation rate of a naturally ventilated dairy building as a function of the outdoor wind conditions and sizes of sidewall openings. In the present study, the Response Surface Methodology (RSM) was applied to develop the predictive model. Three dimensional numerical simulations for a real dairy building were conducted to estimate the ventilation rate under different wind and opening conditions. The model was formulated by the results of thirty cases of CFD simulation, which were planned by the experimental design method: optimal design. Results showed that sizes of two sidewall openings significantly influenced the ventilation rate of the building. Based on the developed RSM model, the most desirable level of opening sizes can be determined for control of the ventilation air exchange rate in prevailing wind conditions.

1. Introduction

Natural ventilation is commonly preferred for dairy farms. Dairy buildings are often designed with sufficiently large wall openings so as to ensure the required air change at calm wind conditions. In windy weather, the ventilation rate can be several times higher than required for providing good air conditions for the animal. This over-ventilation may result in more ammonia emissions from the buildings, leading to negative impacts on both the local and global environment (FAO, 2006). Those emissions from the livestock building can affect the ecosystem by causing water eutrophication and soil acidification (Ngwabie et al., 2009).

Previous researches have shown that the ventilation rate was highly correlated with the emission rate of ammonia in mechanically ventilated livestock buildings. Through laboratory scale model experiments, higher ventilation rate will lead to higher ammonia emission rate (Saha et al., 2011; Ye et al., 2008; Zhang et al., 2008a, 2008b). Similar finding has been reported by the field experiment in several mechanically ventilated livestock buildings (Aarnink et al., 1995; Fabbri et al., 2007; Saha et al., 2010) and naturally ventilated buildings (Demmers et al., 2001; Zhang et al., 2005; Wu et al., 2012a, 2012b). To reduce the ammonia emission from livestock buildings, the ventilation rate should be maintained at a level not higher than what is necessary to ensure the desired conditions for the animal welfare and production.

The ventilation rate is often controlled according to the indoor air temperature (Boaventura Cunha et al., 1997) and CO_2 concentration (Chao and Hu, 2004) in mechanical and natural ventilation systems. Thermal control with feedback sensors has been applied in some NVLB equipped with adjustable openings to avoid high indoor air velocities at cool and windy weather conditions (Hoff, 2004; Strøm and Morsing, 1984). In many dairy farms the openings size can be controlled by sidewall curtains response to the indoor climate relative to the desired set-point room temperature (Duncan et al., 1975; Samer et al., 2012). When the indoor temperature is higher than the set-point, the curtains will move down and leave a larger opening size so as to attract more ventilation rate from outside. In contrast, when the indoor temperature is lower, the curtain will move up to reduce the opening size to decrease the ventilation rate. In this context, when the indoor temperature is commonly higher than the set-point in summer conditions, all the openings will open maximally. CO_2 based ventilation strategy is often applied to maintain the indoor air quality in mechanical ventilation systems by control of the minimum ventilation so that indoor CO_2, not exceed the desired concentration level (Lu et al., 2011).

However, the thermal and CO_2 control method may face difficulty in choosing the representative position for sensors since the indoor air is hardly perfect mixed and involves high spatial

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variance of concentration in naturally ventilated buildings (Hoff, 2004). Multiple locations for monitoring the indoor thermal or concentration conditions may improve the measurements but it will make the system complex and expensive. Operation of control devices of the NVLB is a challenge for these systems because of the potential variance, such as time delay between the feedback of the sensors and the action of devices. In this context, a model-based approach in NVLB ventilation controls may provide a better solution. The control model can be statistically developed based on the measurement data under different control operations in varied outdoor climate conditions and indoor occupied settings (Mahdavi and Pröglhöf, 2008). Based on the model, the optimal control of the ventilation rate can be achieved to acquire the most favorite indoor climate for occupants.

For a model-based method, it is essential to develop a predictive model to estimate the building air change rate by related variables such as outdoor wind conditions and building opening sizes. Using this model, we can operate the opening sizes to maintain the desired ventilation rate according to the weather conditions. In earlier researches, some empirical models were built up for naturally ventilated buildings by wind tunnel experiments (Barrington et al., 1994; Ji et al., 2011; Lou et al., 2012; Román et al., 2012; Sherman, 1990). However, those researches mostly focused on building structure with two sidewall openings, which was different from the dairy buildings that contains with additional roof openings. Besides, wind tunnel experiments may suffer from the poor dynamic similarity as compared with the realities (Chu et al., 2009).

Moreover, those experiments were based on the experiment design method named as One-factor-at-a-time (OFAT) method (Barrington et al., 1994; Ji et al., 2011; Lou et al., 2012; Román et al., 2012; Sherman, 1990; Wen et al., 2012). The OFAT method considers the independent relation among design variables and aims to establish an additive linear model. However, this method is not efficient because it requires massive experimental runs to formulate a model (Hoff, 2001). In addition, it is not truthful of the method to assume the independence of variables and neglect the potential interaction effect among variables (Anderson and Whitcomb, 2004). To overcome this, several design of experiment (DOE) method can be statistically based to depict the relation of design variables and responses. For deterministic experiments such as computer experiments that contain no errors, the Modern DOE methods are popularly utilized (Box et al., 1978; Giunta et al., 2003). Optimal design is one of the well-known modern DOE methods, which aims to develop an approximate functional model with less prediction variance and model bias (Shen et al., 2012). It also requires less experimental runs and more efficient than the OFAT method. Based on results of suitable experimental designs, Response Surface Methodology (RSM) can be applied to develop Taylor-series polynomial models between the response and variables.

Above all, the objective of this study is to develop a model-based control method of NVLB to reduce the gas emission. In order to achieve that, a predictive model of the ventilation rate is formulated based on the opening sizes and local wind conditions. RSM method is utilized for the model development. CFD simulation is conducted to estimate the ventilation rate in real-size dairy houses. Consequently, the optimal change interval of the building openings to achieve the target ventilation rate is addressed.

2. Method and materials

2.1. Targeted ventilation rate in dairy buildings

The dimensions of ventilation openings in NVLB is generally designed to be able to provide a sufficient ventilation rate at the warmest weather with the maximum heat production in the building space (Anonymous, 2001; Bruce, 1978). Table 1 shows the information of the maximum required ventilation rate without wind effects (CIGR, 1984). It was computed for building with 270 herd dairy cows (625 kg) and allowed temperature differences of three degree in the hottest weather conditions (27 °C). The building envelop was assumed to be well insulated and indoor heat are mainly transferred through air convection through openings. The yielding maximum required ventilation rate is equal to 34.74 m^3/s, (ACR = 4.155/h), which yields an average of 463.2 m^3/h for each cow. The minimum ventilation rate was also considered to remove ammonia, carbon dioxide, dust, and moisture and maintain healthy working environment both for animals and workers (Anonymous, 2001; Seedorf et al., 1998). As seen in Table 1, the minimum ventilation rate required to maintain a suitable CO_2 and moisture conditions inside the investigated building is equal to 8.49 m^3/s (ACR = 1.02/h), 113.2 m^3/h per cow.

2.2. Response Surface Methodology

RSM is a statistical method that applies quantitative data collected from appropriately designed experiments to formulate regression models between observed response and design variables (Anderson and Whitcomb, 2004). This method can be used for evaluation of the relative significance of the variables that influence the response and have been widely used for process development and optimization.

The optimization process of RSM method is to determine the optimum set of design variables that can make the response target the goal. The method comprises of four basic steps: (a) Experimental design; (b) Conducting the experiment; (c) Response surface modeling; (d) Optimization.

Before conducting the experiment, the statistical experimental designing can reduce the model variance, experimentation time and overall cost (Carpenter, 1993). On behalf of that, several design of experiment (DOE) methods have been widely used for the planning of experiment (Shen et al., 2012). Optimal design (OD) method, a standard RSM experimental design method has widely been used for fitting a second-order model and it requires a minimum number of experiments to be performed (Anderson and Whitcomb, 2004; Shen et al., 2012). The total number of experiments (N) to be performed in this type of design is usually given by doubling the minimum required number (n). This n is calculated by $n = (d + k)!/d!k!$, where k is the number of design variables, and d is the order of model. The OD method can search the experiments in the way of minimizing the variance of the modeling, and providing the adequate quality of space filling within the k-dimensional space constructed by the k design variables (also named as design space) (Simpson et al., 2001). The purpose of space filling is to make the experiments (design points) spread evenly inside the design space and consequently make the RSM model be able to cover extensive information all over the space.

The information of design variables and experiments in our study are listed in Tables 1 and 2, respectively. In Table 2, the exterior wind speed and direction was sampled at the location outside the building, which is close to the sidewall and 10 m high above the ground (Wu et al., 2012a). The range of wind speed was determined according to the prevailing wind conditions around the local dairy building in Foulum, Viborg, Denmark (König and Kaufmann, 1999). The minimum wind speed was set as 1 m/s, corresponding to a level that the wind driven ventilation begins to dominate over the stack effect by typical summer temperature differentials of 2–3 °C (Barrington et al., 1994). The maximum wind speed was determined according to field measurement (Wu et al., 2012b). The low limit size of the sidewall opening was 0.3 m and was equal to the ridge opening. The high limit of the openings was determined in