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Review

Mechanisms of natural ventilation in livestock buildings: Perspectives on past achievements and future challenges

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Studies on the mechanisms of natural ventilation in livestock buildings are reviewed and influences on discharge and pressure coefficients are discussed. Compared to studies conducted on buildings for human occupation and industrial buildings which focus on thermal comfort, ventilation systems, indoor air quality, building physics and energy etc., our understanding of the mechanisms involved in natural ventilation of livestock buildings are still limited to the application of the orifice equation. It has been observed that the assumptions made for application of the orifice equation are not valid for wind-induced cross ventilation through large openings. This review identifies that the power balance model, the concept of stream tube and the local dynamic similarity model has helped in the fundamental understanding of wind-induced natural ventilation in buildings for human occupation and industrial buildings. These concepts have distinguished the flow through large openings from that of 'cracks' (i.e. small openings), which is where the orifice equation is normally used for prediction of airflow rate. More field measurements on the effect of wind turbulence on ventilation rate need to be encouraged, particularly under conditions where the mean pressure differences through building openings are much lower than the fluctuations of pressure differences. Research on bidirectional flow that occurs at openings is also limited.

1. Introduction

Natural ventilation (NV) has been used in buildings for thousands of years. With the development of mechanical ventilation systems late in the 19th century, NV has been decreasingly used because mechanical ventilation is more predictable and the observation that there are more failures than successes with NV designs (Bruce, 1978; Maccormack, Clark, & Knowles, 1984). From the beginning of 20th century, more research has been conducted in mechanical ventilation. The original ventilation approach, NV, lost its importance in building research

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Nomenclature

A	area of the opening, m^2
A_1	total area of side openings, m^2
A_2	area of ridge opening, m^2
A_i	area of the i^{th} opening, m^2
A_m	m^{th} fraction of control volume surface
CFD	computational fluid dynamics
C_d	discharge coefficient
C_p	pressure coefficient
$C_{pe,i}$	external pressure coefficient at the i^{th} opening
$C_{pe,in}$	external pressure coefficient at inlet
$C_{pe,out}$	external pressure coefficient at outlet
$C_{U,ref}$	ventilation coefficient
g	gravitational acceleration, m s^{-2}
$\overline{h}$	height of the neutral plan, m
H	height between side and ridge opening, m
l	building length, m
LB	livestock buildings
LDSM	local dynamic similarity model
LES	large eddy simulation
LP	lost power
n	number of openings
NV	natural ventilation
P	mean pressure, Pa
$P_{in,0}$	indoor pressure at the ground level, Pa
P_n	normal pressure, Pa
P_n^*	dimensionless normal pressure
$P_{out,0}$	outdoor pressure at the ground level (height of 0), Pa
p_{ref}	static pressure of free flow, Pa
P_R	interior pressure in the room, Pa
P_R^*	dimensionless room pressure
P_t	tangential dynamic pressure at the opening
P_t^*	dimensionless tangential pressure
p_w	wind pressure, Pa
$p_{w,m}$	measured wind pressure, Pa
ΔP	pressure difference through opening, Pa
q	airflow rate (into the building with positive value and vise verse), m^3 s^{-1}
Q_m	airflow rate through the mth control volume
U	wind velocity at free air stream, m s^{-1}
U_{ref}	reference wind speed, m s^{-1}
U_Z	wind speed at the reference height of Z (usually 10 m), m s^{-1}
V	ventilation rate, m^3 s^{-1}
T	outdoor temperature, K
ΔT	temperature difference between indoor and outdoor, K
z	height of the room, m
Greek symbols	
β	wind incidence angle
ρ	air density, kg m^{-3}
ρ_{out}	outdoor air density, kg m^{-3}
ρ_{in}	indoor air density, kg m^{-3}

until the oil crisis in 1970s. Today NV is an intensive research field due to its potential for energy saving and for adaptive thermal comfort (Stathopoulos, 2009) as well as the complexity of NV systems.

In livestock buildings (LB), particularly cattle buildings, NV is the dominant ventilation system. It removes heat, moisture and contaminant gases from indoor space. From the literature on NV applied to LB, it is clear that many studies/research has concentrated on the quantification of ammonia, methane and odour emissions from naturally ventilated LB to assess the efficiency of abatement techniques for emissions, especially in recent two decades. A special issue on emissions from naturally ventilated LB was published in a journal, Biosystems Engineering (volume 116, issue 3) in 2013 with topics including uncertainty in measurements of ammonia emissions (Calvet et al., 2013), mechanisms of models to estimate ammonia emissions (Bjerg, Norton, et al., 2013), approaches and models to evaluate the airflow rate of NV (Bjerg, Liberati, et al., 2013), CFD (computational fluid dynamics) modelling for prediction of ammonia emissions (Bjerg, Cascone, et al., 2013), tracer gas methods to measure airflow rate by experimental measurements (Kiwan et al., 2013), methods for gas emission measurements (Ogink, Mosquera, Calvet, & Zhang, 2013) and multi-location velocity measurements by ultrasonic anemometers (Fiedler, Berg, et al., 2013). This promotes knowledge of the challenges facing the measurement and modelling of gaseous emissions, and evaluation of airflow rate and CFD modelling in predictions of ammonia emissions from NV applied to LB. In particular, Bjerg, Liberati, et al. (2013) summarised the methods used to evaluate the ventilation rate including balance methods (heat and/or CO_2 balance), pressure-based modelling (both stack and wind effect) and the dynamic lumped model. The dynamic model was preferred by the authors because the model considered the effects of dynamic outdoor climate, variation of heat production from animals, building design and thermal characteristics of building materials so that the hourly ventilation rate could be estimated.

Certainly, there is no doubt that these topics related to the emissions are important, but more knowledge about how to control the ventilation system is also required in order to reduce the emissions from the perspectives of ventilation system. To develop such control systems, a good understanding of the mechanisms involved in NV are required. Because NV is highly dependent on the climate and outdoor weather, it not only requires a supply of sufficient airflow in warm and 'still' weather, but it also requires the openings that can regulate the indoor environment in cold and windy weather. The designs of NV for LB have to not only provide a proper indoor thermal environment but also consider the abatement of gaseous emissions. All these requirements demand better knowledge of the mechanisms involved in NV and the development and application of appropriate theoretical models so that NV can be applied successfully in practice and used most effectively. Also, since the standard/reference method for quantifying the ventilation rate of NV applied to LB is still under development, understanding the mechanism of NV through large openings in LB could promote the development of such a reference method.

The objective of this paper is to review the research on mechanisms involved in NV applied to LB from the