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Research Paper

# Evaluation of a precision air-supply system in naturally ventilated freestall dairy barns

Xiaoshuai Wang [a,b], Guoqiang Zhang [a,*], Christopher Y. Choi [c]

[a] Department of Engineering, Aarhus University, Blichers Allé 20, P.O. Box 50, 8830, Tjele, Denmark
[b] College of Biosystems Engineering and Food Science, Zhejiang University, 866 Yuhangtang Road, Hangzhou, 310058, Zhejiang, China
[c] Department of Biological Systems Engineering, University of Wisconsin-Madison, 460 Henry Mall, Madison, 53706, WI, United States

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A good ventilation system is critical to the success of any commercial cattle raising operation. Most dairies rely on natural ventilation systems, with supplemental cooling systems (e.g. cooling fans, ceiling ventilation, polytube cooling, etc.) to help mitigate the heat stress imposed on the cows when natural ventilation proves insufficient, usually during hot, humid and windless situations. However, the effects of these supplemental cooling are insufficient in many cases. Therefore, the current study assessed an alternative supplemental cooling system, referred to as a precision air supply system (PASS), with respect to how effectively it could remove excess heat from cows inside barns. The effects of three key parameters (i.e. supply-air speed, distribution tube diameter, and air-supply angle) on the performance of PASS were evaluated with respect to both a standing cow and a reclining cow, by means of a response surface methodology and a series of properly validated computational fluid dynamics (CFD) simulations. The results showed that PASS performed better when the bulk air was still and that all three investigated parameters helped to improve heat dissipation. A perturbation plotting indicated that adjusting the air-supply angle may well be the best first option when seeking to improve the cooling performance of PASS, followed by increasing tube diameter as the next best option. When serving as a supplemental cooling system deployed in a freestall, naturally ventilated barn, PASS should work well to mitigate heat stress when the temperature and humidity index (THI) increases beyond the threshold value (i.e., THI > 68).



## 1. Introduction

In many regions, heat stress is a common threat to profitable dairy cattle farming during warm periods because a heat stressed cow will eat less and produce less milk (Schneider, Beede, & Wilcox, 1988; West, 2003). The US dairy industry alone suffers a tremendous economic loss due to heat stress (annual losses averaged $897 million for dairy) (St-Pierre,

* Corresponding author.
E-mail address: guoqiang.zhang@eng.au.dk (G. Zhang).
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**Nomenclature**

*Roman letters symbols*

| | |
|---|---|
| D | distribution-tube diameter (m) |
| K | number of investigated parameters |
| C | specified number of replicated central points |
| U | velocity ($ms^{-1}$) |
| S | source term |
| SA | skin surface area ($m^2$) |
| W | body weight (kg) |
| $V_{fan}$ | airflow rate provided by fan |
| ΔP | differential pressure (Pa) |
| T | time (s) |
| $T_t$ | tissue temperature (°C) |
| V | supply-air velocity ($ms^{-1}$) |
| N | number of tests |

Acronyms

| | |
|---|---|
| PASS | Precision air supply system |
| AOZ | Animal occupant zone |
| RSM | Response surface methodology |
| CFD | computational fluid dynamics |
| RANS | Reynolds-averaged Navier-Stokes |
| SST | shear stress transport |
| THI | Temperature humidity index |

Greek letters

| | |
|---|---|
| P | density ($kgm^{-3}$) |
| Φ | variables |
| $\delta_s$ | thickness of skin layer (mm) |
| $\delta_h$ | depth of hair coat layer (mm) |
| β | coefficient |
| ν | kinematic viscosity ($m^2s^{-1}$) |
| θ | air-supply angle (°) |

Cobanov, & Schnitkey, 2003). Increasing airflow in the animal occupied zone (AOZ) by means of a properly designed and controlled cooling system can usually alleviate the threat of heat stress, improve thermal comfort in AOZ, and ensure a healthy and productive herd. Natural ventilation systems are used widely because they can produce an adequate ventilation rate cheaply, but they cannot be precisely controlled and are highly dependent on exterior wind conditions. In contrast, mechanical ventilation systems are relatively easy to control and far less dependent on exterior conditions. A properly designed and operated mechanical ventilation system can usually provide a desired airflow pattern and adequate ventilation rate even during hot and humid conditions. However, since these systems generally require more energy and tend to be noisy, the optimal solution would seem to be a system that combines the advantages of natural and mechanical ventilation (Hoff et al., 2009).

Many hybrid ventilation systems have been developed and tested over the last several decades. Two early and widely used designs, developed by Strøm and Zhang (1989) and Zhang, Morsing, and Strøm (1992), rely on natural ventilation most of the time, with the mechanical component switching on only when the difference between the indoor and outdoor temperatures exceeds the system's set point (thus avoiding an overly chilly downdraft). Most systems using this concept for summer cooling employ both low-volume, high-speed and high-volume, low-speed supplemental cooling fans that cool the cows when they are confined for extended periods (usually in holding pens, feeding alleys, and freestall areas (Holmes et al., 2013)) and whenever the cows voluntarily spend considerable amount of time bunched closely together. This practice has proven to be effective regardless of which type of fan is operated (Kammel, Raabe, & Kappelman, 2003; Worley & Bernard, 2005, 2008); however, such hybrid systems generally increase the speed of the air passing over the cows; thus, their cooling capacity declines as indoor temperature and humidity levels rise, because such rises hinder the heat loss that results from both cutaneous convection and evaporation. In another words, the supplemental cooling fans can fail to cool a cow when the indoor air is hot and humid. Also, these supplemental, fan-driven systems cannot guarantee that every cow will receive enough airflow. Cows not in the system's target areas will often receive an insufficient cooling benefit.

Since the advent of Zhang, Morsing and Strøm's early designs, a type of dairy house known as a "Saudi barn" has become a popular ventilation solution when combined with roof-mounted evaporative coolers that blow cooled air downward into the bedding area. Most recently, Mondaca and Choi (2016a) proposed a system based on the concept of channelling fresh air to the animal-occupied zone (AOZ) through large-diameter polycarbonate plastic tubes and then jetting it downward, through smaller-diameter holes, directly onto AOZ. The computational and experimental results obtained from tests of this "polytube ventilation system," showed that the system could achieve a satisfactory cooling effect. Both of these approaches are similar to the ceiling jet ventilation system used in pig houses (Zong, Li, & Zhang, 2015), which relies on diffuse ceiling inlets most of time to target animals during warm summer periods, and all of the described systems can to some degree overcome the decline in cooling performance that occurs when the indoor air temperature increases; however, none can ensure that every animal will receive a sufficient amount of fresh air that it will be properly cooled. For this reason, a cooling system that could provide either fresh or pre-cooled air even more precisely to each cow could significantly benefit the industry.

Developing such a cooling system for specific use in dairy barns should first entail a thoughtful consideration of bovine behaviour and in particular the behaviour of dairy cows, because the modern dairy cow spends so much time indoors in her stall (often over 13 h a day) (Cook, Mentink, Bennett, & Burgi, 2007). What is more, so long as a cow remains in her thermal comfort zone, she will spend as many as 12–13 h a day resting in a reclining posture (Cook, Bennett, & Nordlund, 2004; Jensen, Pedersen, & Munksgaard, 2005), whereas, if she suffers heat stress, she will stand for longer periods to expose more skin area and thereby enhance heat dissipation (Hillman, Lee, & Willard, 2005). However, long standing times have been associated with higher incidences of such health issues as lameness (Whay & Shearer, 2017), while, conversely, increasing lying time may well benefit a cow's health and welfare. Given such findings, it seems reasonable to conclude that dairy producers could improve the health of their herds if