BIOSYSTEMS ENGINEERING 167 (2018) 87–98

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Effect of airflow speed and direction on convective heat transfer of standing and reclining cows

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ARTICLE INFO

Article history:
Received 25 September 2017
Received in revised form
14 November 2017
Accepted 19 December 2017

Keywords:
Convective heat removal
Ventilation airflow
Posture of dairy cow
Numerical modelling
Air motion
Animal occupied zone

An effective ventilation system can mitigate the heat stress suffered by dairy cows by increasing the rate at which heat is transferred convectively from a cow into the air flowing around the animal. To achieve a better understanding of the main factors involved in the heat-transfer process (i.e., the cow's posture and the airflow magnitude and direction), numerical investigations were conducted during the course of this study. By applying a computational fluid dynamics (CFD) modelling method, a virtual wind tunnel, and simplified geometric models representing a standing cow and a reclining cow, the heat transfer associated with a typical cow was simulated and analysed. The shear stress transport (SST) $k-\omega$ turbulence model was adopted, and it was shown that using a CFD method to analyse the heat-transfer data generated by this setup could produce results that are accurate and support the following conclusions: 1) airflow speed has a positive effect on the convective heat-transfer coefficient associated with both postures; 2) airflow direction affects the convective heat transfer coefficient, with the largest coefficient occurring in the cross flow case and the lowest in the downward airflow case; 3) the effect of posture on the convective heat transfer coefficient in a horizontal airflow is limited, whereas the effect in a downward airflow is relatively significant. However, the rate at which heat dissipates from a standing cow is greater than that of reclining cow, since a standing cow has more surface area in contact with the air. Based on these conclusions, it is recommend that, to cool cows under hot conditions, the airflow in the animal-occupied zone should be increased and that using a horizontal airflow to target the animal occupied zone should be encouraged whenever it is feasible to create.

1. Introduction

Heat stress is a common problem at commercial dairies in many regions during warm periods because in order to compensate for excess sweating and to reduce heat generation a cow suffering heat stress will drink more water, eat less feed and yield less milk (Collier, Hall, Rungruang, & Zimbleman, 2012; Kadzere, Murphy, Silanikove, & Maltz, 2002; Nardone, Ronchi, Lacetera, & Bernabucci, 2006; West, 2003). The annual average economic losses the dairy industry incurs as a result of heat stress have been reported as high as $897 million only in United States (St-Pierre, Cobanov,

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https://doi.org/10.1016/j.biosystemseng.2017.12.011
1537-5110/

Nomenclature

Roman letters symbols

a, b	constant
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity of air (W m^{-1} K^{-1})
l	characteristic length (m)
u	velocity (m s^{-1})
E	relative error
HG	heart girth (m)
S	source term
SA	skin surface area (m^2)
W	body weight (kg)

Acronyms

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
CFD	computational fluid dynamics
NLSC	legless standing cow
NLRC	legless reclining cow
RANS	Reynolds-averaged Navier-Stokes
SST	shear stress transport

Greek letters

ρ	density (kg m^{-3})
ν	kinematic viscosity (m^2 s^{-1})

& Schnitkey, 2003). To avoid such losses, sustain a profitable level of production and keep the animals in a thermal comfort zone requires an adequate and well-managed cooling system.

Since airflow speed can significantly affect the convective heat transfer rate, a number of ventilation systems work by increasing local air movement to accelerate heat dissipation (Arkin, Kimmel, Berman, & Broday, 1991; McArthur, 1987; Mitchell, 1976; Turnpenny, McArthur, Clark, & Wathes, 2000; Turnpenny, Wathes, Clark, & McArthur, 2000). Several studies, using either experimental (Wiersma & Nelson, 1967) or numerical techniques (Li, Rong, & Zhang, 2016; Mondaca & Choi, 2016), have sought to quantitatively evaluate the influence of airflow on convective heat transfer. These works all concluded that 1) the convective heat transfer coefficient increases as the airflow speed increases, and 2) the convective coefficient of a cross airflow (air flowing perpendicular to the axis of the animal's trunk) is larger than that of a front airflow (air flowing parallel to the trunk axis). However, all of these studies were restricted to animals in a standing posture. In reality, many farm animals, cows included, spend a large part of their time (e.g., up to 12–14 h daily for dairy cows) resting in a reclining posture when in a comfort zone (Cook, Mentink, Bennett, & Burgi, 2007; Jensen, Pedersen, & Munksgaard, 2005). To maintain thermal comfort and stable body temperature, a cow suffering heat stress will stand for longer periods because a standing posture exposes a larger surface area of skin to the surrounding air than does a reclining posture, and, consequently, a greater heat dissipation rate can be achieved (Cook et al., 2007; Hillman, Lee, & Willard, 2005). Yet, as recent studies showed, too much time spent standing can cause lameness; conversely, increasing lying time may well benefit a cow's health in other ways (Cook, Bennett, & Nordlund, 2004; Cook et al., 2007; Whay & Shearer, 2017). Given these findings, it seems reasonable to conclude that dairy producers could improve the health of their herds if they could induce their cows to spend more time reclining during hot weather. Such would depend, of course, on finding ways to help a cow maintain her comfort zone for longer periods while reclining, and accomplishing this would, in turn, require a comprehensive investigation of the heat convection process at work when a cow is both standing and reclining.

Horizontal airflow is a very common occurrence inside a dairy barn; however, a number of widely used mechanical cooling methods (i.e. low-speed-high-volume fans and ceiling fans) generate vertical airflow in the animal-occupied zone to stimulate air circulation, especially in calm and warm weather. Another, similar method, often used in structures known as Saudi barns, involves roof-mounted evaporative coolers that blow cooled air downwards into the bedding area. The industry's frequent use of vertical airflow to cool cows suggests that a downward airflow must be roughly as effective as a horizontal airflow, yet only one study to date (Wiersma & Nelson, 1967) has investigated vertical airflow and its effect on the convective heat released from a cow. In order to represent a cow standing on the sort of slotted floor used in many dairy barns, the authors of that study relied on an experimental setup that involved an artificial cow (consisting of six cylinders of various sizes arranged to represent torso, neck and legs) placed in a wind chamber that was equipped with a slotted floor. Based on the study's results, the authors concluded that the coefficient difference between horizontal and vertical airflows was relatively small. However, a slotted floor in a wind tunnel will affect airflow in ways that differ from the effects produced by a solid floor in a cubicle. Consequently, this study considered the effects produced by a vertical airflow impinging on a cow (reclining and standing) on a solid surface (bedding/floor).

The limitations and difficulties associated with conducting an experimental investigation, especially one having to do with maintaining a defined airflow velocity and surface temperature – not to mention the confining of living animals for extended periods – hampers the generation of the data needed for analysis. Furthermore, experiments are expensive, time consuming and labour intensive. Such costs and difficulties can be avoided by using computational fluid dynamics (CFD) to create numerical models of both the animal and its environment. Also, CFD simulation has already been used widely in studies of animal housing environments (Li et al., 2016; Mondaca, Rojano, Choi, & Gebremedhin, 2013; Mondaca & Choi, 2016; Wu, Zhai, Zhang, & Nielsen, 2012; Zong, Feng, Zhang, & Hansen, 2014). Hence, the CFD simulation method was chosen for this study.

Previous researchers have conducted investigations using simple geometries, such as spheres and cylinders, to simulate actual cows (Berman & Horovitz, 2012; Gebremedhin & Wu, 2001a, 2003; Gebremedhin, Wu, & Perano, 2016; Kimmel, Arkin, Broday, & Berman, 1991; Mondaca et al., 2013; Turnpenny, McArthur, et al., 2000; Wiersma & Nelson, 1967). Also, Mondaca and Choi (2016) performed assessments of the geometric effect on convective heat transfer using five different geometric cow models: a sphere, a cylinder, a rectangular