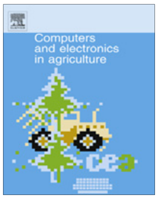
Computers and Electronics in Agriculture 93 (2013) 217–228

Contents lists available at SciVerse ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag



A computational analysis of a fully-stocked dual-mode ventilated livestock vehicle during ferry transportation

Tomás Norton[a,*], Peter Kettlewell[b], Malcolm Mitchell[c]

[a] Engineering Department, Harper Adams University, Newport, Shropshire TF10 8NB, UK
[b] ADAS, Gleadthorpe, Meden Vale, Mansfield, Nottingham NG20 9PF, UK
[c] Animal & Veterinary Sciences, SRUC, Roslin Institute Building, Easter Bush, Midlothian EH25 9RG, Scotland, UK

ARTICLE INFO

Article history:
Received 6 November 2012
Received in revised form 11 February 2013
Accepted 20 February 2013

Keywords:
Livestock transportation
Animal welfare
CFD analysis

ABSTRACT

Concerns relating to animal transport in general, and specifically to the thermal conditions to which animals are exposed, have led to the development and implementation of regulations, legislations and codes of practice in a number of countries seeking to impose limits on journey times, stocking densities and thermal conditions inside the transport space of vehicles. In the current study, computational fluid dynamics (CFD) was used to analyse the influence of a wind-free environment, such as that presented when the vehicle is transported on the car-deck of a RO–RO ferry, on the ventilated performance of livestock transport vehicle. The livestock transporter under investigation had two decks, the top deck of which was naturally ventilated container and its lower deck was mechanically ventilated container. Using CFD the level of environmental heterogeneity was studied in both the mechanically and naturally ventilated decks. It was found that the naturally ventilated container was hotter and more humid than the mechanically ventilated container. However, the environmental variables were much more evenly distributed in the naturally ventilated container.

1. Introduction

Most farm animals are transported at least once during their lives, due to either the transfer of ownership to a different producer, the need for better environmental/feeding conditions, or because they need to be taken to the abattoir. However, the handling, loading, transporting, and unloading of animals can have detrimental effects on their well-being, as they are exposed to a variation of stressors (Rostagno, 2009). Stressors include increased human contact, vibration and an unfamiliar climatic environment, all of which may disturb the animal's homeostatic state, and the subsequent regulatory responses necessary to restore balance may have inhibitory or adverse effects on the animals at high doses (Mattson, 2008; Rostagno, 2009). While all stressors can affect the welfare of the animals during transportation, it is generally accepted that the thermal micro-environment of the transport container otherwise referred to as the "bio-load" poses the greatest challenge (Fisher et al., 2004, 2009; Kettlewell et al., 2001; Mitchell and Kettlewell, 2008). Consequently, concerns relating to animal transport in general, and to the thermal conditions to which animals are exposed, have led to the development and implementation of regulations, legislations and codes of practice in a number of countries, as they seek to impose limits on journey times, stocking densities and thermal conditions inside the transport space of vehicles (Mitchell and Kettlewell, 2008).

The main determinants of the internal thermal micro-environment in livestock containers are the external climatic conditions, the ventilation regime, internal air flow patterns and the total heat and moisture production of the animals. Past research into livestock vehicles, as well as studies into the effects of transportation on animals, have generally focussed on naturally ventilated transport (Hoxey et al., 1996; Baker et al., 1996; Dalley et al., 1996). These studies confirm that the main difficulty with natural ventilation is due to the variability of outdoor climate conditions, the travelling speed and geometry of the vehicle, as well as the non-linear relationship between the airflow through the openings and the ventilation efficiency at animal level.

As well as the experimental research, some research on the computational modelling of livestock transporters research has been previously carried out. Dalley et al. (1996) developed a three dimensional computational model of heat and mass transfer in a poultry transporter. The model formed a reasonable representation of the distributed climate but its accuracy was limited by the coarse gridding method used due to available computer power. Gilkeson et al. (2009) are among the first works looking at the ventilation efficiency of passively ventilated livestock through experimental and CFD modelling, focussing on the important case of opening design and location. The work of Gilkeson et al. (2009)

---

* Corresponding author. Tel.: +44 (0)1952 815357.
E-mail address: tnorton@harper-adams.ac.uk (T. Norton).

0168-1699/$ - see front matter Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.compag.2013.02.005

has been the first to demonstrate how potentially useful CFD could be for this application. On the other hand, Randall and Patel (1994) developed a simple model to study the effects of the stationary environment induced by animal transportation on ferries. While their model captured the main physics within the ventilated container, it was not able to provide information on the distributed environment. However no CFD work is available in the literature on truck-based livestock transportation, even though this is the main mode of animal transportation over long distances. As a result, the conditioning effect of the incoming airflow on the animal's distributed micro-climate in these transporters is not yet fully understood.

To provide a more consistent, predictable internal climate, mechanically ventilated livestock transport vehicles have been designed and studied (Kettlewell et al., 2001; Mitchell and Kettlewell, 2008). In such vehicles, ventilation is induced by fans, rather than the movement of the vehicle, which ensures that enough air will pass through the livestock container during both the total transit and stationary periods of a journey. This is particularly important for the lower levels of multi-tiered transport vehicles, as the studies of Hoxey et al. (1996) and Baker et al. (1996) have shown that the pressure distribution over the sidewalls is almost uniform and equal, and may result in inadequate natural ventilation during forward motion. Kettlewell et al. (2001) took a holistic approach in forming a solution to this issue by designing a dual-mode ventilated multi-tier livestock transport vehicle, which employed natural ventilation on the upper deck and mechanical ventilation on the lower deck (Fig. 1a). With this design it was found that the top deck could be ventilated adequately via natural ventilation, as the continuous sidewall openings were positioned in the vicinity of strong local pressure gradients when moving. On the other hand, a negative pressure mechanically ventilated system was designed for and implemented on lower tiers of the transport vehicle so that all the animals can be exposed to the fresh incoming air, without dealing with the known issues of natural ventilation.

In order to ensure that this dual-mode ventilated livestock transport vehicle can represent the state-of-the-art in high-care animal transportation it is necessary to test and improve system design for both ventilation efficiency and animal comfort under limiting conditions. For the naturally ventilated deck, a limiting condition obviously occurs when ventilation must rely solely on natural convection. While such a condition rarely arises (as the vehicle is generally moving), it will inevitably occur when the livestock vehicle itself is transported in a confined space, e.g. within the car deck of a Roll-On Roll-Off (RO–RO) ferry. In such an environment, still conditions prevail and the passive ventilation rate will solely depend on the temperature difference between the inside and outside of the transporter. Therefore, it is essential that the environment of the ferry's car deck will always provide enough fresh air to the animals so as not induce thermal stress within the transport container. Also, for the mechanically ventilated deck, it has been observed that, given the position of the inlets relative to the outlets, a temperature gradient occurs longitudinally on the deck (Kettlewell et al., 2001). Consequently, it is of interest to determine and minimise the extent of this gradient so that a more uniform condition can be realised in the future, thereby reducing the potential for environmentally induced stress in some areas of the container.

Given this introduction to the state-of-the-art in livestock transport vehicle design, the objective of the current study is to use computational fluid dynamics (CFDs) to analyse the influence of a wind-free environment on the naturally ventilated environment of the transport vehicle (top deck) and compare this the environment and level of heterogeneity in the mechanically ventilated container in order to determine how justifiable the incorporation of mechanical ventilation systems are under such conditions.

2. Methods and materials

2.1. Details of the experimental livestock transport vehicle

As shown in Fig. 1a the livestock transport vehicle currently studied has two containers, a mechanically ventilated lower deck container and a naturally ventilated upper deck container. The mechanically ventilated system consists of four fans, one pair on each side of the vehicle, located at the front of the container. These fans extract air from within the container and were located in regions of low external pressure develop on the moving vehicle (Baker et al., 1996; Kettlewell et al., 2001). To operate on the vehicle 24 V DC powered axial flow fans were selected, each with a throughput of 0.25 $m^3\ s^{-1}$. The two rear openings, one on each side of the vehicle, were used as air inlets, each with an area of 0.76 m^2. All the other openings along the side of the vehicle were kept closed during its operation. The flow regime produced by the mechanically ventilated system results in air being drawn in from the rear of the vehicle, which then moves forward over all the animals before being extracted through the fans at the front sides of the container.

Combined temperature/relative humidity sensors were mounted near each rear air inlet and by each of the ventilating fans. These sensors were mounted within aspirated tubular housings, to protect them from direct solar radiation (Fig. 1b). Data collection on the middle deck was confined to temperature and humidity with an array of sensors at different locations, depending on the deck in which they were positioned. All sensors were attached at roof-level of the containers. Sensors were located, attached at roof level, on the nearside (i.e. passengers side), midline and offside (i.e. driver's side) of the vehicle to measure outside ambient temperature. The configuration of the sensor array in the two decks is shown in Fig. 1c. A total of 24 inputs of both temperature and relative humidity were available using combined probes (Vaisala type HMP 31 UT), with one measurement taken every minute. The manufacturer's quoted operational range for the temperature sensors was $-40\ ^\circ C$ to $80\ ^\circ C$ with an accuracy of $\pm 0.5\ ^\circ C$ and for the humidity sensors the range was 0–100% with accuracy of ±3%. The sensors inside the container did not incorporate any housing to protect for radiative effects, which may add additional uncertainty to the manufacturer's specifications. It was assumed however, that surface temperature gradients within the container can be deemed small as the environment was stable during the transportation period under analysis.

2.2. Details of the journey and experimental protocol

A total of 66 young cattle (approximately 12 months old, liveweight 300 kg) were exported from Ireland to Spain leaving from Rosslare port. The stocking density on both decks was the same at 1.2 $m^2\ animal^{-1}$ with 33 animals per deck. On the day of departure, the animals were loaded onto the transport vehicle and the vehicle was driven onto and parked in the car-park deck of the RO–RO ferry (Fig. 2). Once on the ferry, the lower deck's ventilation system was disconnected from the onboard generator and reconnected to the ship's power supply. Fans were fitted to the upper deck of the vehicle, but not used during the crossing. The vehicle was parked away from other vehicles on clear space, so no obstruction from other vehicles was encountered. The crossing from Rosslare to Cherbourg took 23 h (17:00–16:00) during which time the animals and the ventilation system were regularly inspected. Prior to arrival at Cherbourg, the ventilation system was shut down on the lower deck (to allow for the ship's power supply to be disconnected) and panels opened to convert to natural ventilation, thus matching the upper deck's configuration. The whole vehicle then