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NUMERICAL EVALUATION OF AERODYNAMIC DEVICES IN MITIGATING HEAT STRESS IN PIGS DURING TRANSPORT

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KEYWORDS

animal welfare, computational modeling, precision livestock farming.

ABSTRACT

Improving natural ventilation during animal transportation is a promising approach for promoting animal well-being and reducing losses. The objective of this study was to evaluate in silico the efficiency of devices (airfoils and deflectors) used for cooling trailers during the transportation of pigs. Device performance was assessed using computational fluid dynamics (CFD) simulations and 3D modeling of the enthalpy profile of a trailer, and adaptive mesh generation was employed to construct a computational mesh. Turbulence treatments were performed using RANS model and k-ω SST models. The results revealed that compared with the conditions observed in commercial transportation, the use of an airfoil increased the airflow and reduced the enthalpy within the assessed trailer (-5.4%). Likewise, the use of deflectors resulted in a reduction in enthalpy (-3.04%), although their use led to a translocation of the thermal core to the front region of the upper floor of the trailer. Nevertheless, the use deflectors has been proven to be more efficient when combined with an airfoil. In conclusion, the results obtained from our CFD simulations provide evidence to indicate that it is possible to optimize ventilation within transport containers using aerodynamic devices.

INTRODUCTION

Heat stress, resulting from the high heat load in the compartments of the truck during the transportation of live animals, emerges as a matter of significance for the well-being and survival of these animals during transportation operations (Dalla Costa et al., 2019; Alambarrio et al., 2022; Machado et al., 2022). A complexity of this issue is notable due to the significant influence of the interaction between various environmental variables during the journey (Melo et al., 2023), particularly the accumulation of relative humidity and inadequate ventilation, resulting in the development of 'thermal cores' within the cargo (Barbosa-Filho et al., 2009; Machado et al., 2021a).

Conceptually, the term 'thermal core' describes the most critical region in terms of moisture accumulation in the cargo intended for animal transportation. This is the area where enthalpy values reach their highest levels, making them particularly susceptible to heat stress and, consequently, production losses (Gilkeson et al., 2016; Spurio et al., 2015). To better understand this issue, it is important to consider that pigs weighing around 100 kg emit approximately 160W of heat (Kettlewell et al., 2001). Furthermore, the primary heat dissipation method for these animals is through evaporative means (Rioja-Lang et al., 2019), a mechanism that can be seriously compromised by the accumulation of moisture in the environment where the animals are placed.

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Understanding this scenario allows us to hypothesize that aerodynamic devices designed to increase ventilation inside the cargo could be an effective solution to reduce water vapor accumulation and dissipate heat from the trailer during the transportation of pigs. Studies using computational fluid dynamics (CFD) techniques are being conducted worldwide to characterize the ventilation profile of the cargo during the transportation of live animals (Gilkeson et al., 2016; Romero et al., 2022; Pinheiro et al., 2022). Likewise, the aim of this study was to assess the efficiency of aerodynamic devices for mitigating the enthalpy of pig transportation *in silico*.

MATERIAL AND METHODS

Ethic

This experiment was approved by the Ethics Committee for Animal Use at the Center for Agricultural Sciences of the Federal University of Ceará (Process number 9871250719).

Data set

A database related to commercial pig transportation was acquired through monitoring four trips covering a distance of 170 km, occurring between a farm located in Maracanaú – CE, Brazil (3°54'46.4"S 38°39'19.2"W and 43 m of altitude) and the slaughterhouse in the city of Morada Nova – CE, Brazil (5° 06’ 24” S 38° 22’ 21” W and 52 m of altitude). These trips took place on paved highways, with a cargo density of 290 kg/m², during the period from February 16 to 28, 2020, always in the afternoon shift (2:30 PM to 5:40 PM).

The transportation was carried out using a Ford® truck model Cargo 1519, equipped with a Triel® – HT model body, which had two fixed floors containing six compartments, totaling twelve compartments, with a loading capacity of 13 tons. Further detailed information about the handling and infrastructure available for pre-slaughter operations is available in previous studies (Machado et al., 2021a; Machado et al., 2022), see supplementary file.

To monitor the internal conditions of the cargo, twelve thermo-hygrometer dataloggers (Onset, U23-001 HOBO Pro v2, with TA accuracy of ±0.2°C and RH ±2.5%) were installed at the center of each compartment of the bodywork, at the animal height. These dataloggers recorded temperature (TA, °C) and relative air humidity (RH, %) data every 10 minutes throughout the journey. Consequently, specific enthalpy (H, kJ/kg of dry air) was calculated using equation 1, as proposed by Rodrigues et al., 2011, to characterize the micro-meteorology of the cargo. To complement the analysis, information on radiation incidence was obtained from the weather stations 82397 – Fortaleza (3º49'12" S, 38º32'24" W and 29.89 m of altitude) e 82588 – Morada Nova (5º8'24"S, 38º21'36"W and 45.02 m of altitude) from the National Institute of Meteorology of Brazil (INMET).

$$H = 1.006.TA + \frac{RH}{Pb}.10^{7.5TA(237.3+TA)^{-1}}.(71.28+0.052\ TA) \quad (1)$$

Where:

TA is the air temperature in °C;

RH is the relative humidity in %, and

Pb is the local barometric pressure in mmHg.

Treatments

We conducted a numerical evaluation of two aerodynamic devices designed to mitigate thermal stress in pigs during transportation. The first device, an airfoil (BR 10 2020 013584 8), was designed to be attached to the top of the truck cabin. This device consists of a support base, a semi-spherical shaped cover device installed at the rear region of the support base, and a fixing plate for the top part of the airfoil support base, as illustrated in Figure 1. The second device, a deflector (BR 10 2021 005211 2), was designed to be attached to the sides of the truck body. It consists of a semi-spherical shaped piece and two clips for connection to the side of the body, as shown in Figure 2. The detailed description of these devices is available in the supplementary file. In this computational study, we conducted a performance analysis *in silico* using virtual models of the truck equipped in three different ways: (1) with the airfoil, (2) with the deflector, and (3) with both devices, as illustrated in Figure 3.

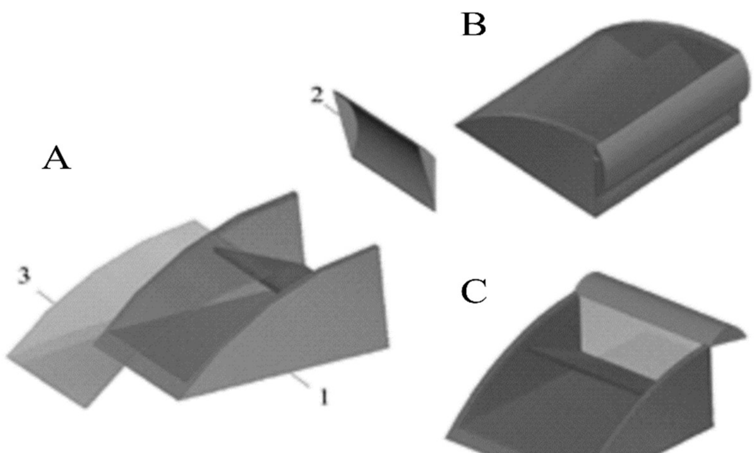

FIGURE 1. General view with explosion (A) and without explosion of the parts in the rear (B) and front (C) views of the airfoil.

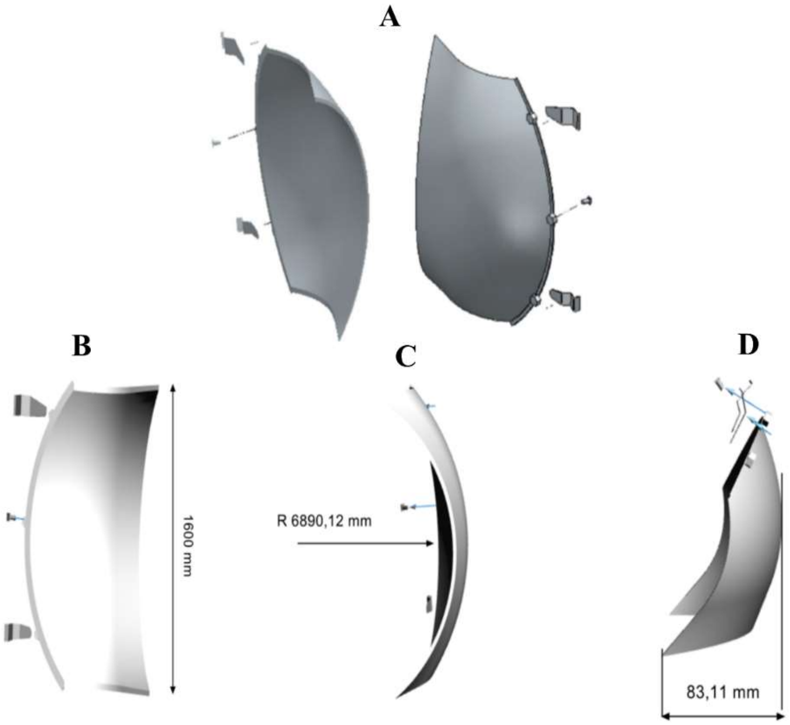

FIGURE 2. General view with explosion (A), and without explosion on the parts in the front (B), side (C) and auxiliary (D) views of the deflector.

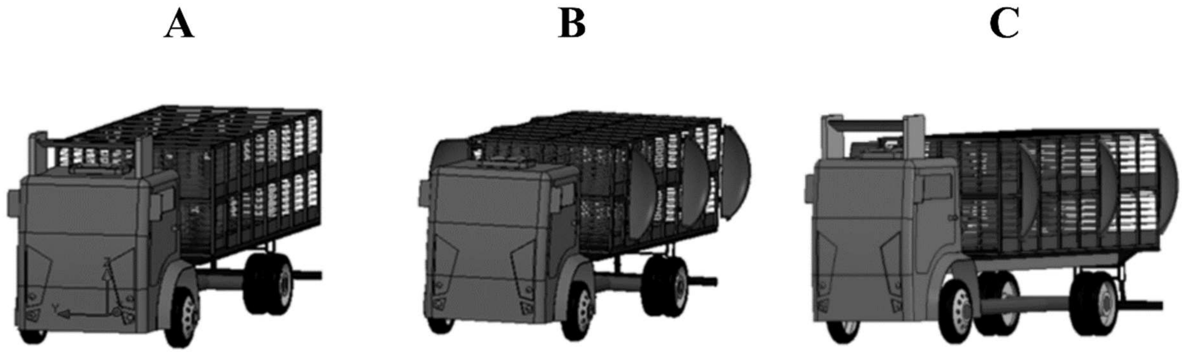

FIGURE 3. Virtual models: the virtual model with airfoil A), virtual model with deflector (B), and a virtual model with both devices (C).

Description of the performance evaluation

To assess the performance of the devices, numerical simulations were conducted through computational fluid dynamics (CFD) tests. In the study, SolidWorks Flow Simulation software, version 2020, was utilized. The construction of the computational mesh employed adaptive mesh generation, where the SolidWorks software provided an automatic mesh generator. This process resulted in a computational mesh primarily composed of structured hexahedral cells throughout the domain, except in the area near the truck, where tetrahedral cells with refinement along the vehicle surface were employed.

The computational domain used had dimensions of 45.82 meters in length, 23.50 meters in width, and 40.45 meters in height. To ensure accurate results, viscous models in the steady-state regime were adopted. Turbulence treatment was conducted using the Reynolds Averaging Navier-Stokes (RANS) model, and due to the complex geometry of the truck, which included sharp curves and areas less known from an aerodynamic perspective, the k-ω shear stress transport (SST) model was chosen, because widely recognized for its effectiveness in such scenarios (Li et al., 2016). Menter's SST model comprises equation the specific turbulent kinetic energy (2) and equation the specific turbulent dissipation rate (3), as described by Menter (1993).

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(U_i \rho k)=\frac{\partial}{\partial x_j}\left(\mu_k \frac{\partial}{\partial x_j} k\right)+\tilde{P}k-\beta p w k, \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(U_i \rho \omega)=\frac{\partial}{\partial x_j}\left(\mu_\omega \frac{\partial}{\partial x_j} \omega\right)+\tilde{P}w-\beta p \omega^2+2p(1-F1)\ \frac{1}{\omega}\ \frac{1}{\sigma_{\omega,2}} \frac{\partial}{\partial x_j} k \frac{\partial}{\partial x_j} \omega \tag{3}$$

Where:

k is the specific turbulent kinetic energy in $m^2 s^{-2}$;

ω is the specific turbulent dissipation rate in s^{-1};

β is the turbulence modeling constant;

$\widetilde{\mathbf{P}}\mathbf{k}$ is the effective rate of production of k in kg $m^{-1} s^{-3}$;

Pω is the rate of production of ω in kg $m^{-3} s^{-2}$;

p is the density in kg m^{-3};

F1 is the blending function;

i is the free-stream turbulence intensity in %,

U is the incident free-stream airflow in m s^{-1}.

$$\mu_k = \mu + \mu_t \frac{1}{\sigma k}$$

$$\mu_\omega = \mu + \mu_t \frac{1}{\sigma\omega}$$

Where μt is the modified eddy viscosity in kg $m^{-1} s^{-1}$, and σχ (χ = k;ω) are diffusion constants of the model. The Reynolds stresses τ_{ij} in kg $m^{-1} s^{-2}$ were calculated using two-equation models via the Boussinesq expression (Versteeg & Malalasekera, 2007; Costa-Rocha et al., 2014).

In this study, the virtual model of the trailer with an airfoil consisted of 13,720 mesh cells, achieving a maximum orthogonal quality of 82.60%. The virtual model of the trailer with a deflector had a mesh comprising 17,432 cells, with a maximum orthogonal quality of 83.20%. For the virtual model of the trailer equipped with both devices, the mesh consisted of 57,868 cells, resulting in an orthogonal quality of 89.30%. The boundary conditions were set up to simulate real wind flow conditions during transportation, as described in Table 1.

TABLE 1. Boundary conditions.

Variables	Values
Prescribed speed	18.00 m/s (64.80 km/h)
Temperature	27.50 °C
Relative humidity	68.00%
Radiation	460.00 kJ/m²
Atmospheric pressure	760.00 mmHg

For the simulations conducted in this study, a high-performance computer was used, configured with a 10-core i5 processor, 128 GB of DDR4 RAM distributed in four 32 GB modules, an RTX graphics card with 8 GB of VRAM, 512 GB of SSD storage, and an additional 1 TB hard drive. With this configuration, it was possible to perform the simulations with an average time of 36 hours per simulation.

To explore the spatial variability of enthalpy throughout the trailer, we employed geostatistical techniques, resulting in the creation of three-dimensional thematic maps using SGeMS® *software* (Remy et al., 2009). The construction of these thematic maps was based on the interpolation method known as ordinary kriging (4), and the spatial structure and dependence were established through the analysis of the semivariogram (5). Further information about this process can be found in the supplementary file.

$$\overline{Z}\ (S_o) = \sum_{i=1}^{N} \lambda_i * Z(S_i) \tag{4}$$

Where:

$Z\ (S_o)$ - is the interpolated value at position So;

λi - is the weight assigned to the i-th sampled value at position S_i;

$Z\ (S_i)$ - is the sampled assigned value;

N - is the number of neighboring locations used for point interpolation, and

the sum of weights λi must equal 1, and 0 ≤ λi ≥ 1.

$$\overline{\gamma}\ (h) = \frac{1}{2n_{(h)}} \sum_{i=1}^{N(k)} [Z(x_i) - Z(S_i + h)]^2 \tag{5}$$

Where:

$\overline{\gamma}$(h) - is the semivariogram;

h - is the separation distance between measurements;

N(k) - is the number of experimental pairs of measured data for Z(xi) and Z(si+h);

Z(si) - is the value of the variable for position si not estimated (true), considered as a random variable, a function of the sampling position x;

Z(si+h) - is the value of the same variable at position Si+h in any direction.

The simulated data of enthalpy inside the trailer, obtained through simulations, were exported, and subjected to the Shapiro-Wilk test to assess the normality of their distribution. Subsequently, an analysis of variance was conducted, and means were compared using the Tukey test. In all tests conducted, a significance level of 0.05 was adopted as the threshold.

RESULTS AND DISCUSSION

The use of the airfoil demonstrated a notable increase in the internal ventilation of the cargo, particularly in the front area of the upper compartment (SUP) of the trailer (Figure 4). This device effectively channeled the airflow with an average speed of 10.50 m/s, redirecting it from the upper region of the truck cabin to the interior of the trailer. This resulted in a significant improvement in air circulation within the compartments, which, in turn, led to a considerable reduction of 5.4% in the average enthalpy of the trailer, compared to the average enthalpy value of the trailer without devices recorded by Machado et al. (2021b), As shown in Table 2, as well as a more uniform distribution of heat (enthalpy) throughout the cargo, as evidenced in Figure 5.

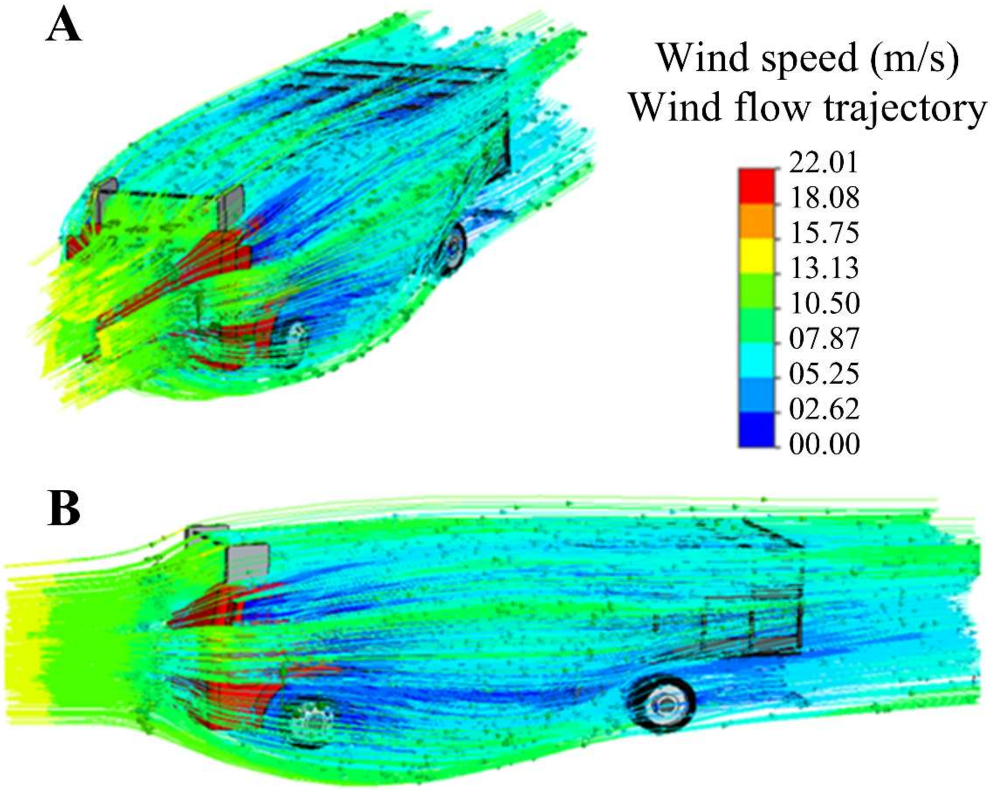

FIGURE 4. Wind flow of the virtual model of the load with the airfoil: front (A) and side (B) views of the truck.

TABLE 2. Averages (±SE) of the charge enthalpy of the evaluated virtual models.

Item	Enthalpic (kJ/kg dry air)
Virtual model of the trailer with airfoil	79.30±1.20[c]
Virtual model of the trailer with deflector	80.05±2.06[b]
Virtual model of the trailer with both devices	76.38±1.67[d]
Commercial transport[1]	82.56±2.86[a]
P-value	<0.001
CV (%)	6.73
Conventional trailer[1]	83.85

CV = coefficient of variation; SE = standard error of the mean. Means followed by the same letters (vertically) do not differ statistically from each other according to the Tukey test at P < 0.05. [1]Average values recorded by Machado et al., 2021b.

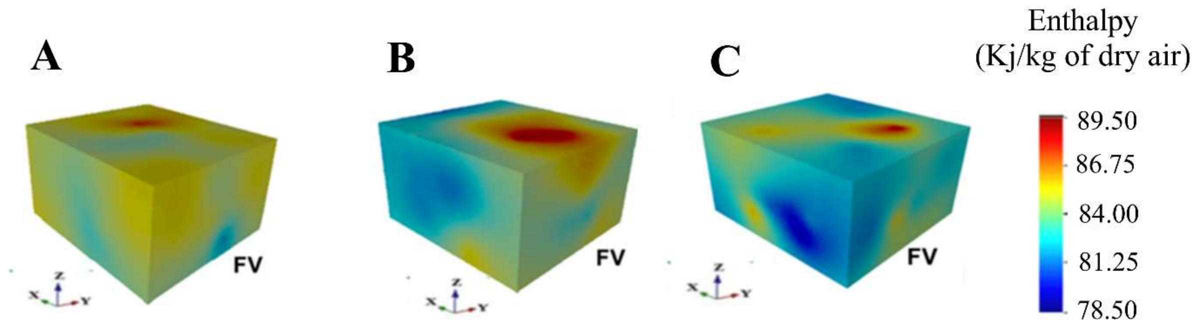

FIGURE 5. 3D load enthalpy maps virtual model of the truck with airfoil (A), deflector (B), with both devices (C). FV = Front of vehicle.

The use of the deflector device increased the airflow in the front region of the INF of the trailer, resulting in winds at approximately 15 m/s (Figure 6), where the thermal core (heat pocket) was concentrated during transportation under commercial conditions (Barbosa-Filho et al., 2009; Machado et al., 2021b). This resulted in a 4.5% reduction in the average enthalpy of the trailer with the deflector compared to the trailer without devices (Table 2). However, it was observed that the airflow in the front region of the SUP was compromised, leading to the development of a thermal core (heat pocket) in that area (Figure 6), which is not ideal for the thermal comfort of the pigs.

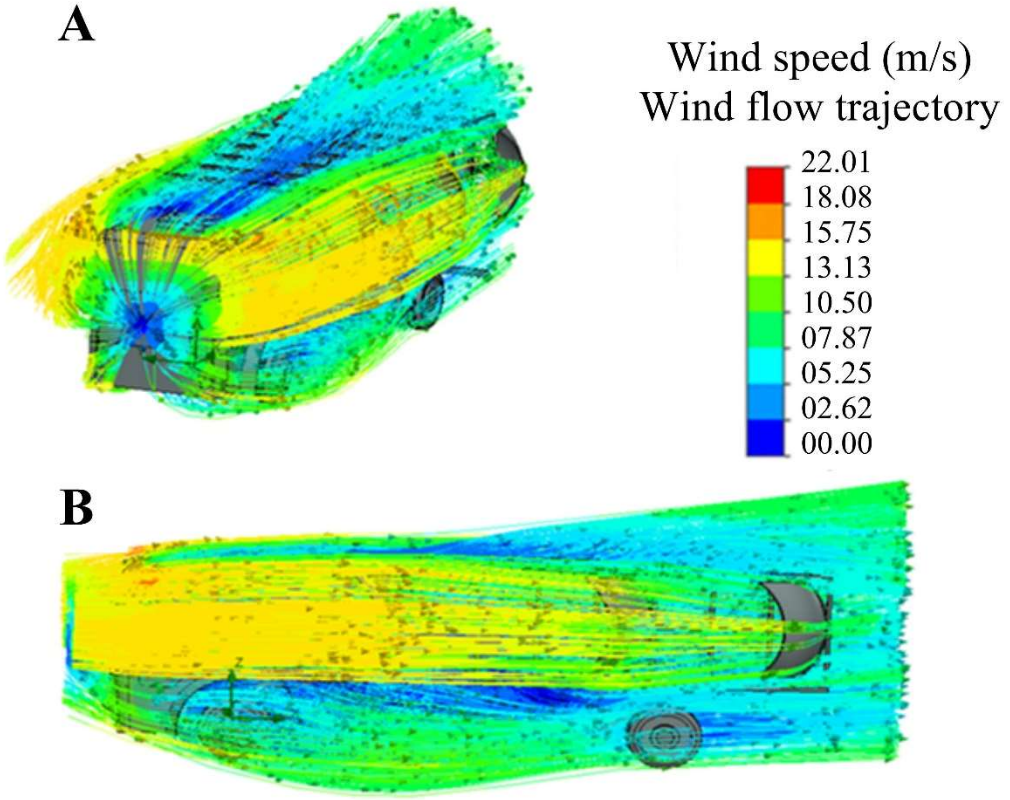

FIGURE 6. Wind flow of the virtual model of the load with the deflector: front (A) and side (B) views of the truck.

The combined use of the airfoil and deflector in the trailer resulted in a considerable increase in airflow within the body (Figure 7). The enthalpy of the cargo was significantly reduced (8.9%) compared to the conditions observed in commercial transportation (Table 2). This occurred because the upper airflow (from the airfoil) and lateral airflow (from the deflector) of the vehicle body are simultaneously directed into the cargo, which will undoubtedly improve thermal conditions and possibly reduce thermal stress on the pigs, consequently leading to reduced losses (Alambarrio et al., 2022; Machado et al., 2022). However, the combination of the airfoil with the deflector on the trailer will result in higher drag force during vehicle movement, suggesting increased fuel costs. This issue should be further investigated in future studies.

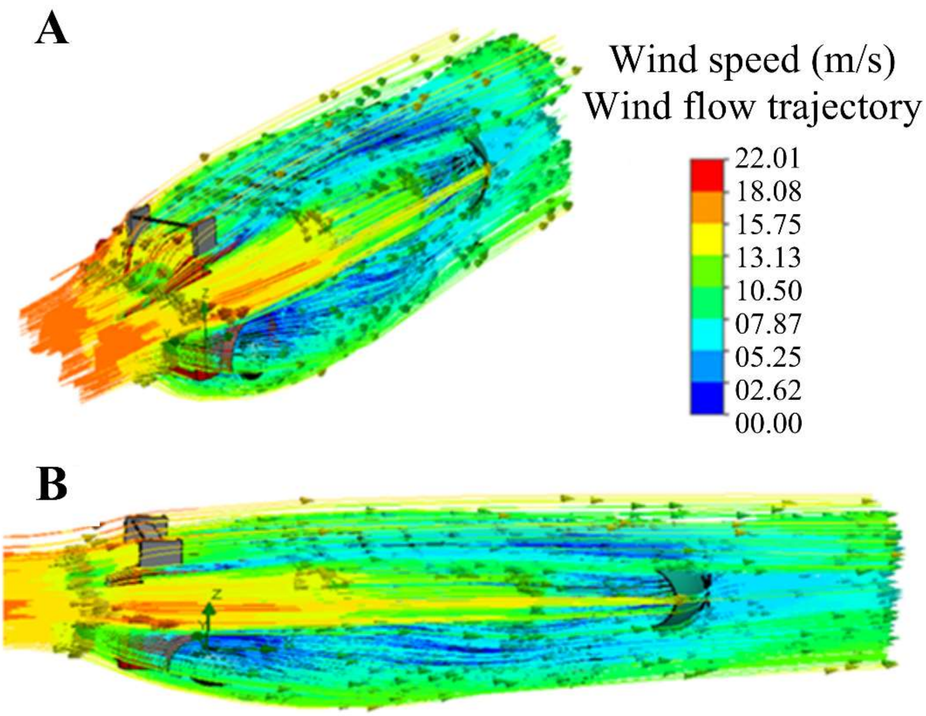

FIGURE 7. Wind flow of the virtual load model with the airfoil assembly and deflector: top (A) and side (B) views of the truck.

The results of this study prove promising for animal transportation, as they suggest that it is possible to alter the standard airflow dynamics, shifting the turbulence regime to other regions of the trailer. Under commercial transportation conditions, the airflow dynamics in the trailer are characterized by a significant dissipation of kinetic energy, followed by a turbulent stage that directs the air towards the upper and lateral regions of the trailer (Gilkeson et al., 2016).

The simulations demonstrated that the individual use of the airfoil and the deflector made it possible to direct the upper (airfoil) and lateral (deflector) airflow into the cargo, increasing internal air circulation. Therefore, these results support the hypothesis that it is possible to optimize natural ventilation to achieve a reduction in the trailer's enthalpy. It is reasonable to assume that the reduction in enthalpy is associated with increased ventilation, which reduces moisture accumulation inside the trailer. This could enhance animal welfare, reducing the incidence of losses and associated damages (Spurio et al., 2015).

Previous studies have shown that the presence of thermal cores (heat pockets) is directly related to points with inadequate ventilation throughout the cargo during commercial journeys (Barbosa-Filho et al., 2009; Machado et al., 2021b). This area was the most critical region for the well-being of transported pigs, associated with the highest average values of thermal stress indicators (Machado et al., 2022). In this research, the devices developed to direct the airflow into the cargo can be valuable tools for cooling it during the transportation of pigs in tropical climate regions, especially the airfoil.

CONCLUSIONS

Based on the simulations, it was observed the airfoil device enhanced airflow and reduced enthalpy by 5.5% compared to conditions without devices, while the deflector, despite reducing enthalpy by 4.5%, shifted the thermal core to the trailer's upper floor. Future studies should investigate different configurations of aerodynamic devices and evaluate their effects on fuel consumption and overall transport efficiency to enhance animal welfare and optimize transport conditions.

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