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Analysis of convective heat transfer in dairy cattle via computational fluid dynamics

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Abstract This study aimed to evaluate convective heat transfer in dairy cattle during grazing in a tropical climate region through computational fluid dynamics (CFD) simulations. Furthermore, this study aimed to explore the relationship between an animal's orientation and airflow during grazing. To achieve these objectives, a virtual bovine model was developed, incorporating detailed physiological and morphometric parameters, and subjected to CFD simulations employing the k-ω SST model. Local meteorological data from Chapadinha, Maranhão, Brazil, were employed to characterize the micrometeorological profile, and physiological parameters from four adult dairy cattle were measured to define simulation boundary conditions. The study revealed an average convective heat transfer of 88.85 W/m². Furthermore, the results demonstrated a notable variation in convective heat transfer, with a 33.5% increase when the orientation was altered from 0° to 30°, followed by a slight reduction of 2.29% when the orientation was increased to 45°. Hence, by employing CFD with the k-ω SST model, it was possible to estimate the convective heat loss of dairy cattle. The orientation of the animal relative to the airflow in the pasture significantly influences convective heat loss and should be considered in strategies and infrastructures designed to optimize heat transfer.

Keywords: computational analysis, animal welfare, bioclimatology, thermal comfort

1. Introduction

In the current scenario of climate change, mitigating the deleterious effects of thermal stress on dairy cattle production has emerged as a central challenge for the dairy industry, especially in tropical regions (Sejian et al., 2022). Heat stress has been shown to increase body temperature and the respiratory rate, decreasing conception rates and dry matter intake in animals (Ji et al., 2020). Consequently, these factors impact the quantity of milk production as well as its quality, including parameters such as fat, casein, lactose, and total solids (Ouellet et al., 2019; Jeon et al., 2023).

The compression of thermal requirements and exchanges in dairy cattle, along with their adaptive responses, has become pivotal for the implementation and adaptation of sustainable production systems (Broom 2019; Ji et al., 2020). These findings emphasize the critical importance of unraveling heat transfer processes between animals and their environment, which is a fundamental aspect for adept thermal comfort management and the preservation of environmental quality (Machado et al., 2021a).

Computational fluid dynamics (CFD) has been instrumental in event forecasting and the assessment of agricultural products and processes (Zhang et al., 2018; Damasceno et al., 2020; Pinheiro et al., 2022; Qi et al., 2024; Machado et al., 2024). Its adoption is notably driven by cost reduction, enhanced processor performance, and advancements in computational simulation software (Pinheiro et al., 2021). CFD studies have explored convective heat exchange in animals such as pigs (Li et al., 2016a) and cattle (Cao et al., 2023). and broilers (Li et al., 2016b). There remains a gap in research concerning convective heat transfer under conditions simulating animal grazing in the field, a practice that is very common in ruminant farming in the state of Maranhão, Brazil. This gap is particularly noticeable when the orientation of the animals relative to the airflow is considered, especially in tropical climates.

This study aimed to assess the convective heat transfer of dairy cattle during grazing in a tropical climate region through fluid dynamics simulations. Additionally, it aimed to relate this to the effect of the animal's orientation relative to the airflow during grazing.

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2. Materials and Methods

2.1. Study site and dataset

The study was conducted at the Center for Sciences in Chapadinha, Federal University of Maranhão, located in Chapadinha, MA, Brazil (03°44'33" S, 43°21'21" W, and an altitude of 100 m). To define boundary conditions and generate more accurate and robust simulations of CFD, physiological parameters from four adult crossbred Holstein-Gir cows, aged seven years, with a body weight of 550±10 kg were used. The hair coat surface temperature (°C) was measured via infrared thermography with a Fluke TiS10 camera (Fluke Systems®, Everett, WA, USA). The thermographic camera was calibrated with the local temperature and emissivity (ε) indicated for the biological tissues of dairy cattle, with ε = 0.98 (Machado et al., 2021b). The images were captured at a fixed distance of 1 m from the animals to the thermographic camera (Sampaio et al., 2021). Analysis of thermographic images was performed via SmartView Classic 4.4® software. The internal body temperature of the animals was evaluated transrectally via a veterinary digital thermometer (Digital TH186, Incoterm, Porto Alegre, Brazil; measuring range 32.0–44.0°C, resolution 0.01°C, maximum error ± 0.1°C, self-checking system), at a depth where the bulb was in contact with the rectal mucosa (Araújo et al., 2024). Finally, the body surface area of the animals was estimated via the mathematical model developed by Simão and Maia (2016), as shown in equation (1).

$$BA = 0.1781 \times BW^{0.5534} \qquad (1)$$

where BA is the body area in m², and BW is the body weight in kg.

To establish the local micrometeorological profile for CFD simulations, data on air temperature, relative humidity, and wind speed were obtained from the National Institute of Meteorology of Brazil (INMET) station 82382, which considers a 15-year historical series (2008–2022). Furthermore, the average shortwave irradiance was derived from the Brazilian Solar Atlas, assuming 12 hours of sunlight per day for the historical series.

2.2. Virtual bovine model parameters and simulation setup

The virtual model of dairy cattle was virtually constructed via Solid Edge ST10 software at the true scale. Within the virtual model, specific parameters were defined to mirror real-world conditions. These included a 1 cm layer of subcutaneous fat, a body surface area of 6.10 m², a core coat temperature of 39.1°C, and a skin emissivity of 0.98. The computational domain, with dimensions of 31.63 × 60.68 × 62.51 m (length, width, and height), incorporated unstructured meshes, utilizing tetrahedral and prism cells (Figure 1). To enhance precision, the mesh density was increased near the virtual animal. Boundary conditions were intricately designed to faithfully replicate the environmental exposures encountered during grazing.

The commercial CFD code ANSYS Fluent 15 (Ansys Inc.) was employed for the simulations. Turbulence modeling was achieved via Reynolds-Averaging Navier–Stokes (RANS) methods. Given the complex geometry characterized by pronounced curves and sharp edges, which are poorly understood aerodynamically, the k-ω SST model was chosen because of its high performance in such scenarios (Li et al., 2016). A coupled scheme was adopted in the solution model to increase precision, coupled with high-quality spatial discretization.

The atmospheric conditions simulated included an adopted pressure of 998.68 mB, an average air temperature of 28.30°C, an average relative humidity of 71.14%, and an average wind speed of 1.21 m/s. The shortwave solar energy input was set at 6.8 kWh, which was aligned with the Brazilian Solar Atlas data. In Chapadinha, MA, the daily average irradiance was recorded at 5.49 kWh/m². Considering 12 hours of sunlight per day and considering half of the total body surface area of the virtual animal (equivalent to 3.05 m²), the estimated average solar irradiance incident on the dairy cow was determined to be 1395.4 W.

To guarantee the precision of our simulations, we incorporated viscous models within the steady-state regime and devised meticulous error criteria to assess accuracy. Employing a stringent threshold, we permitted a maximum error of 10–4% for energy values and 0.1% for velocity and density components. The analysis of convective heat transfer in dairy cattle via CFD was carried out in three different orientations in the pasture in relation to the air flow: 0°, 30° and 45°. Additionally, the average convective heat transfer coefficient or h_c (W m^{-2} K^{-1}) was calculated via Equation 2, according to Li et al. 2016.

$$h_c = \frac{Hc}{A \times (T_s - T_\infty)} \qquad (2)$$

where hc is the convective heat transfer coefficient (W m^{-2} K^{-1}), Hc is the convective heat rate (W); in this study, Hc is derived from the surface heat flux in the fluid, A is the surface area of the animal (m^2), Ts is the surface temperature of the animal (K), and T_∞ is the ambient temperature (K).

3. Results

The convective heat flow and convective coefficient in the virtual bovine model at different orientations are presented in Table 1. The simulation results revealed an average convective heat transfer of 88.855 W/m² in dairy cattle during grazing. When the dairy cattle were virtually oriented at 0°, 30°, and 45° relative to the airflow, the recorded convective heat transfer values were 73.045 W/m², 97.264 W/m², and 95.027 W/m², respectively. Thus, a significant increase of 33.15% was observed when the orientation was varied from 0° to 30°, followed by a slight reduction of 2.3% when the orientation was changed from 30° to 45°.

In this study, the average convective heat transfer coefficient was determined to be 8.22 W K^{-1} m^{-2} in the virtual bovine model. Specifically, when the virtual bovine model was oriented at 0°, 30°, and 45° in relation to the airflow, the convective heat transfer coefficients were measured at 6.801, 9.005, and 8.798 W $K^{-1}m^{-2}$, respectively (Table 1). Therefore, these values highlight a notable increase of 32.8% when the orientation is varied from 0° to 30° and a slight reduction of 2.4% when the orientation is altered from 30° to 45°. Figure 1 offers a visual representation of these variations, obtained through numerical simulations in various animal orientations, along with different airspeed levels.

Figure 2 shows the flow profile in the virtual bovine model oriented at 0° in relation to the wind flow. The head and front paws are the regions where there is a higher intensity of heat exchange through convection, as they form zones of recirculation. Nonetheless, the wind speed is dampened by the animal's aerodynamics. In general, the wind speed in these areas does not reach values greater than approximately 1.46 m/s under the wind conditions established by the simulation. When the virtual bovine model was positioned at 30° relative to the airflow direction, a notable increase in ventilation in the lateral region of the animal was observed, as indicated by the streamline patterns in Figure 3. The wind speed in this area ranges between 1 and 1.6 m/s, indicating a significant increase in heat transfer. When orienting the virtual animal model at 45° relative to the direction of airflow, recirculation zones near the animal's head were identified, albeit with more limited effectiveness along the body (Figure 4).

Table 1 Convective heat flow and convective heat transfer in different orientations of the virtual bovine model.

	0°	30°	45°	Average
Convective heat flow (W/m²)	73.045	97.264	95.027	88.855
Convective coeficiente (W $K^{-1}m^{-2}$)	6.801	9.005	8.798	8.220

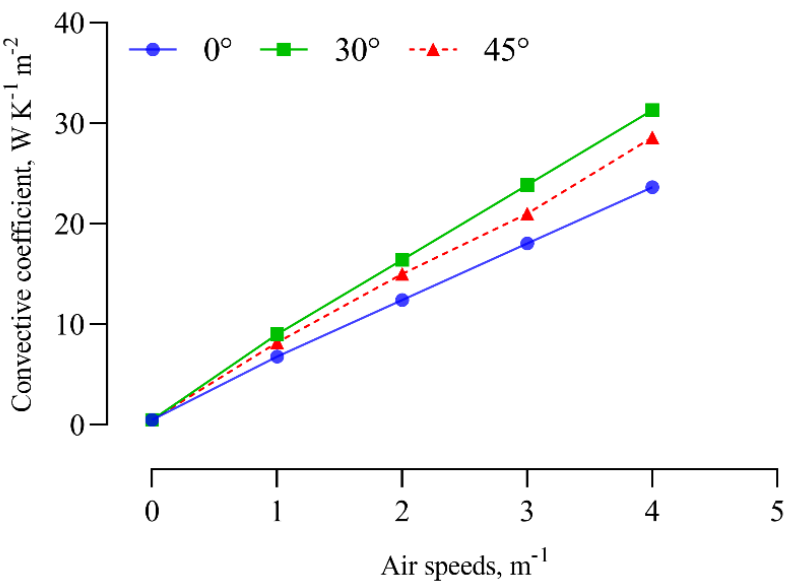

Figure 1 Comparison of the convective heat transfer coefficient on different dairy cattle orientations.

4. Discussion

The application of fluid dynamics simulation techniques enabled the analysis of convective heat transfer in dairy cattle during grazing in tropical conditions. The results obtained indicated an average convective heat transfer rate of 88,85 W/m², which aligns with the reported findings of 160 W/m² for Holstein cattle in similar environments by Maia et al (2005), thus reinforcing the coherence of our results. In support of the hypothesis that the orientation of cattle with respect to wind direction is a deliberate thermoregulatory behavior rather than a mere passive response, our study presents compelling evidence. Specifically, we observed a significant increase in convective heat flow of approximately 33.15% when the orientation shifted from 0° to 30°, followed by a slight reduction of 2.3% when the orientation was adjusted to a 45° angle. Similarly, the convective coefficient exhibited comparable increases of approximately 32.41% at a 30° orientation and approximately 29.36% at a 45° orientation compared to the baseline condition where the animal was aligned parallel to the airflow.

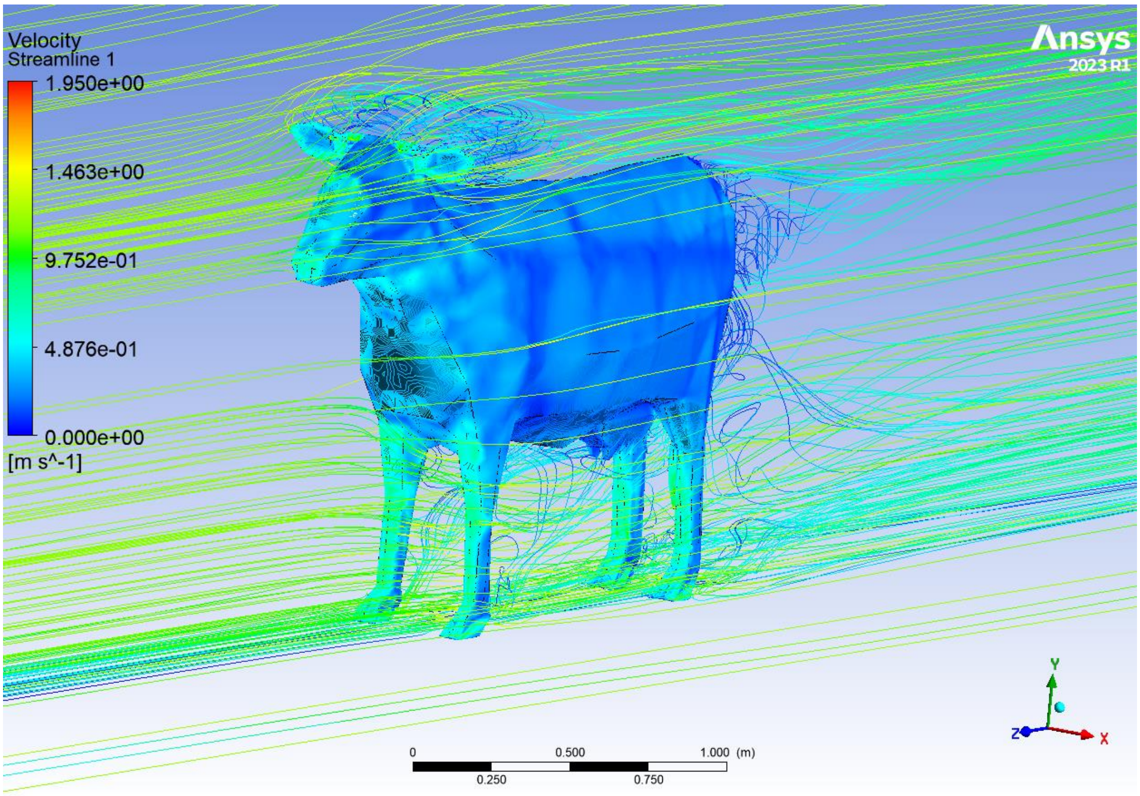

Figure 2 Treamlines from CFD simulation for dairy cattle orientation at 0°.

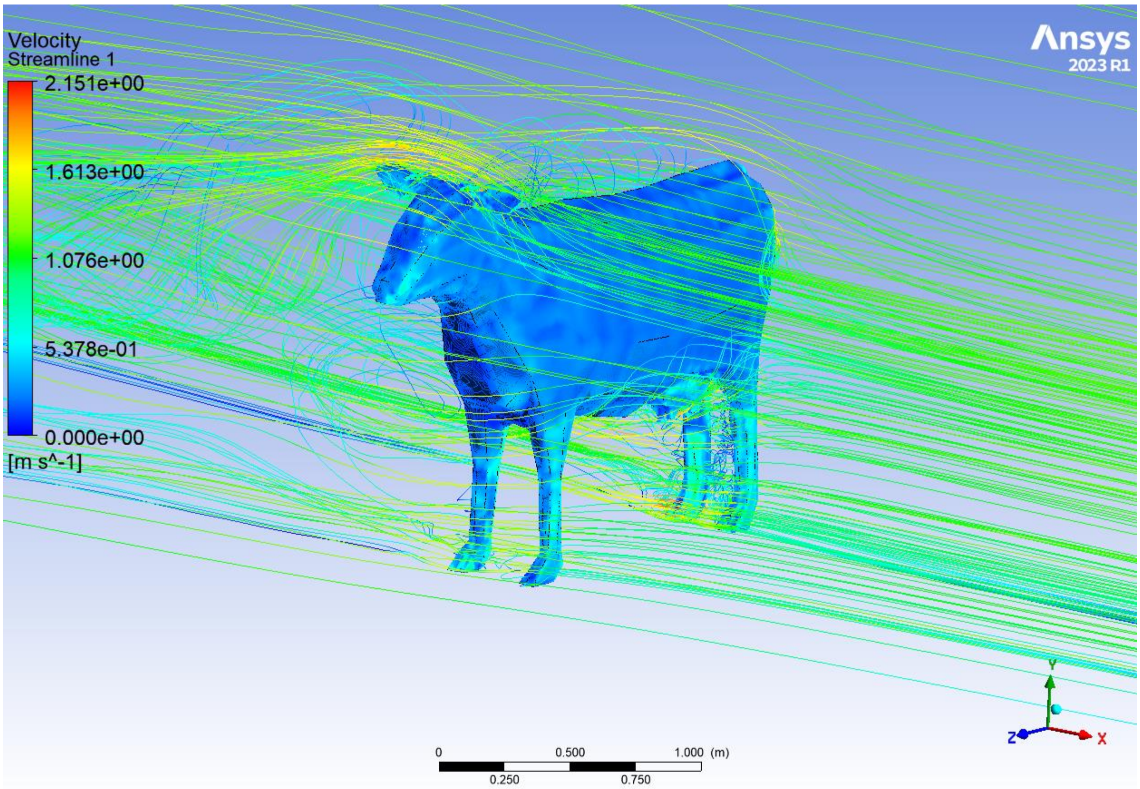

Figure 3 Treamlines from CFD simulation for dairy cattle orientation at 30°.

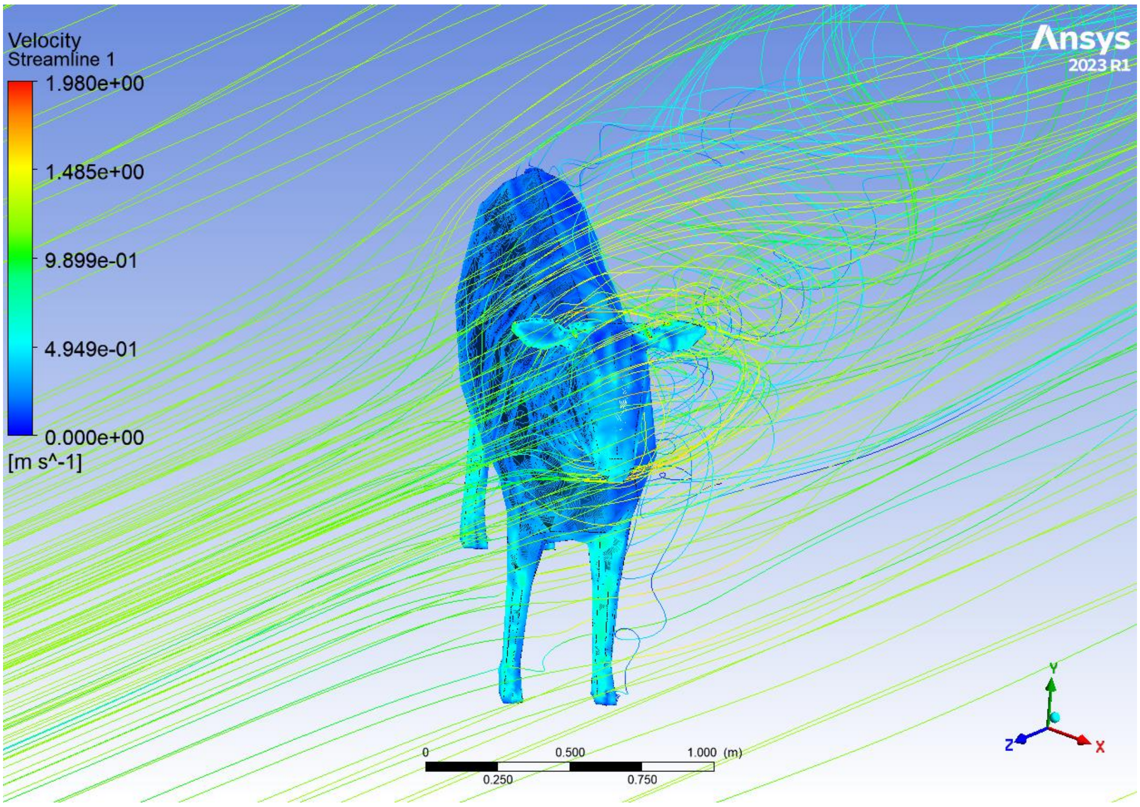

Figure 4 Treamlines from CFD simulation for dairy cattle orientation at 45°.

This variation can be attributed to the aerodynamic nature of the animal's body, as evidenced by fluid dynamics simulations. The simulations highlight that as the airflow reaches a more extensive part of the animal, increasing the contact zone with the body, more intense air recirculation occurs. This phenomenon significantly favors convective heat transfer. In their study, Pinheiro et al. (2022) assessed ventilation patterns during the transport of broiler chickens in different cargo layouts, such as the "central aisle" or air corridor, commonly used in Brazil. Using CFD simulations, the results showed that the layout with the "central aisle" promoted more efficient ventilation patterns, increasing air circulation between the crates. Machado et al. (2024) evaluated the efficiency of devices such as airfoils and deflectors for cooling trailers during the transport of pigs, using CFD simulations with the k-ω SST model. The results showed that the airfoil was effective in channeling the airflow, reaching an average speed of 10.50 m/s and redirecting it from the top of the cabin to the interior of the trailer. Both studies highlight the impact of aerodynamics on ventilation patterns and emphasize the potential of CFD as an effective tool for improving ventilation conditions and thermal control in animal production. In the present study, the influence of animal orientation is clearly observed, demonstrating how this variable affects heat exchange through conduction and convection.

Figures 3 and 4 illustrate how the virtual bovine model's orientation at 30° and 45° to airflow enhances the interaction between the animal's body and the moving air, facilitating efficient heat dissipation. In contrast, when the animal is oriented parallel to the airflow, the exposed surface area is minimized, limiting the efficiency of heat removal (Figure 2). In their study, Li et al. (2016a) reported that the orientation of pigs relative to airflow significantly influences convective heat transfer. When the pig's orientation was perpendicular to the airflow (90°), the convective heat transfer coefficient was greater than when the orientation was parallel to the airflow (0°). Additionally, the intensity of air turbulence had a considerable effect on convective heat transfer, with increases of up to 29.6% in the convective heat transfer coefficient observed at higher turbulence intensities. The specific in silico analysis of various animal orientations during grazing emphasizes the importance of maximizing the exposed surface area for effective convective heat dissipation. The practical implementation of these results can favor the design of more comfortable environments for dairy cattle in grazing systems, positively impacting thermal performance and, consequently, animal well-being.

Based on these findings, interventions in infrastructure design that promote better airflow circulation around the animals represent an optimization strategy for livestock systems. This is especially important for tropical regions, as it helps mitigate adverse climate impacts and enhances the thermal comfort of animals. Chen et al. (2024) compared the performance of a partition-mounted jet air supply (PJAS) with the commercially used ceiling jet air supply (CJAS) for mitigating thermal stress in lactating sows using CFD simulations. The PJAS, placed closer to the sows, significantly increased convective heat removal, requiring

45% less ventilation for the same heat flux. When ventilation rates were equal, the PJAS increased convective heat flux by up to 27.6%, making it an efficient and energy-saving cooling solution. In their study, Colombari et al. (2024) used CFD to assist in evaluating and designing ventilation systems for barns, simulating the thermal well-being of cattle. The fans were modeled using the OpenFOAM fan boundary condition, while the chimneys were simulated using uniformJumpAMI. The authors demonstrated that CFD simulations show good correlation with estimates from biophysical equations, particularly the Equivalent Temperature Index for Cattle (ETIC).

However, assumptions made in the simulation and simplifications of the virtual bovine model may introduce uncertainties. In the present study, the simulation was conducted considering a bovine with a smooth surface, thus disregarding the influence of the fur layer. In his study, Li et al (2016b), in evaluating chicken models with different masses (0.2 kg, 0.9 kg, and 2 kg), reported a correlation between the predicted convective heat transfer coefficients for a sphere and the tested chicken models, suggesting the feasibility of simplifying a chicken as a spherical model in future studies. Thus, future research could explore these uncertainties and further refine our understanding of convective heat transfer under grazing conditions via fluid dynamic simulations.

5. Conclusion

By applying fluid dynamics simulations, it was possible to estimate the convective heat loss of dairy cattle. This technology can assist technicians in quantifying the response to thermal stress in dairy cattle, serving as a supportive tool in the environmental management of dairy farms. The orientation of the animal relative to the airflow in the pasture has a significant influence on convective heat loss, emphasizing the need to consider this factor in strategies and infrastructures aimed at optimizing heat transfer.

Ethical Considerations

All experimental procedures followed guidelines and were approved by the Committee on Animal Care and Use of the Federal University of Maranhão (Process No. 23115.023701/2022-49).

Conflicts of Interest

The authors declare no conflicts of interest.

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