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Computational Fluid Dynamics Modeling of Environmental Conditions in A Naturally Ventilated Free-Stall Dairy Barn

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Abstract: An essential parameter for the design of a dairy barn is adequate ventilation. A well-ventilated barn benefits the environment and the animals by reducing stress and improving air quality. The aim of this study was to evaluate the spatial variability of environmental conditions in a free-stall dairy barn using computational fluid dynamics (CFD). Measurements of temperature and air velocity in the barn were made for comparison with the simulated results. The simulations were performed under steady-state conditions and considered the specific behavior of standing and lying cows and their distribution in the barn. The measured and predicted mean air temperatures in the barn were 21.50 ± 0.174 °C and 21.33 ± 0.213 °C, while the air velocities were 0.30 ± 0.196 m s^{-1} and 0.31 ± 0.197 m s^{-1}, respectively. In conclusion, this study demonstrated that CFD is a valuable tool for evaluating the spatial variability of environmental conditions in dairy barns and can be used as an alternative technique for analyzing barn environments.

Keywords: airflow, cow comfort, heat stress, numeric analysis, ventilation

Doğal Havalandırmalı Serbest Duraklı Bir Süt Sığırı Ahırında Çevre Koşullarının Hesaplamalı Akışkanlar Dinamiği ile Modellenmesi

Öz: Süt sığırı ahırlarının tasarımında yeterli havalandırmanın sağlanması önemli bir faktördür. İyi havalandırılmış bir ahır, hayvanlarda stresi azaltarak ve hava kalitesini iyileştirerek çevreye ve hayvanlara fayda sağlar. Bu çalışmanın amacı, hesaplamalı akışkanlar dinamiği (HAD) modelini kullanarak serbest duraklı bir süt ahırında çevresel koşulların mekânsal değişkenliğini değerlendirmektir. Simülasyondan edilen sonuçlarla karşılaştırmak için ahırda sıcaklık ve hava hızı ölçümleri yapılmıştır. Simülasyon, kararlı durum koşulları altında gerçekleştirilmiş ve ahırdaki hayvan dağılımlarının yanı sıra ayakta duran ve yatan ineklerin belirli davranışları da göz önünde bulundurulmuştur. Ahırda ölçülen ve tahmin edilen ortalama hava sıcaklıkları sırasıyla 21.50 ± 0.174 °C ve 21.33 ± 0.213 °C, hava hızları ise sırasıyla 0.30 ± 0.196 m s^{-1} ve 0.31 ± 0.197 m s^{-1} olarak elde edilmiştir. Sonuç olarak, bu çalışma, HAD'ın süt ahırlarındaki çevresel koşulların mekânsal değişkenliğini değerlendirmek için önemli bir araç olduğunu ve ahır iç ortam koşullarını analiz etmek için alternatif bir teknik olarak kullanılabileceğini göstermiştir.

Anahtar Kelimeler: Hava akışı, hayvan konforu, sıcaklık stresi, sayısal analiz, havalandırma

1. Introduction

Environmental stresses can negatively impact animal productivity and health, leading to considerable financial losses. Numerous factors affect livestock production, including geographic location, age, breed, diseases, management, nutrition, environmental conditions, etc. (Khalifa, 2003). Environmental conditions are undoubtedly the most important of these factors affecting livestock productivity. Of the environmental conditions, heat stress is the most harmful factor to livestock production (Rivington et al., 2009).

Heat stress in cattle has significant negative consequences on their nutrition and health and can even lead to death. Farmers need to pay special attention to this circumstance as it can have a significant impact on their income (Brown-Brandl et al., 2005). In addition, heat stress is one of the primary factors that can lead to low animal productivity in a hot, semi-arid environment (Martin et al., 2004). In hot weather, animals exert themselves more to eliminate their body heat, resulting in a higher respiration rate, body temperature, and heart rate (Marai et al., 2000). Animals suffering from heat stress show increased body temperature and respiratory rate (Al-Haidary, 2004). An increase in body temperature negatively affects reproduction and production of animals by decreasing feed intake, diverting blood flow, and altering endocrine function (Averós et al., 2008).

Numerous studies have shown that dairy cows are more likely to stand than lie down in a high-temperature environment (Chen et al., 2016; Cook et al., 2004; Mattachini et al., 2017; Tucker et al., 2008; Zähner et al., 2004). Cows stand more in hot weather than in cold weather, for unknown reasons, but it could be due to thermodynamic rules (Nordlund et al., 2019).

Radiation, animal heat production and the barn's inadequate size can cause the building's temperature to rise. Ventilation plays a significant role in controlling airflow and provides adequate air exchange within the building so that environmental conditions are at the right level. A well-constructed building provides a more productive environment for animals and a healthier one for the people who work in it. Therefore, it is crucial to analyze the characteristics, airflow, and air distribution in the barn (Yani et al., 2007).

In animal production systems, many phenomena and information are required to determine and analyze the environmental variables. Therefore, computational fluid dynamics (CFD) is a suitable approach to solve this problem. CFD provides a simulation technique that includes spatial and temporal field solutions of fluid pressure, temperature, and velocity.

Many phenomena and information are required inside the animal production systems to determine and analyze the environmental variables. Thus, the CFD can solve fluid-related problems and allows visual analysis of the results (Norton et al., 2007). This method is advantageous because it saves time, labor, and cost compared to experimental studies. However, experimental studies are urgently needed to validate CFD simulations (Küçüktopcu & Cemek, 2019a, 2019b).

The CFD technique has already been successfully used in a variety of applications in agricultural buildings such as poultry houses (Blanes-Vidal et al., 2008; Bustamante et al., 2013; Chen et al., 2021; Du et al., 2019; Küçüktopcu et al., 2022; Rojano et al., 2018, 2019; Yang et al., 2022), pig barns (Gautam et al., 2021; Lee et al., 2022; Tabase et al., 2020; Xin et al., 2022; Yeo et al., 2019), and cow barns (Bustos-Vanegas et al., 2019; Doumbia et al., 2021; Mondaca et al., 2019; Pakari & Ghani, 2021; Saha et al., 2020). These studies have contributed significantly to our understanding; however, to our knowledge, no comprehensive research has been conducted to simulate the exact conditions of animal behavior in the barn and analyze their effects on environmental conditions in the barn.

To fill the gaps in our knowledge about the environmental conditions of cows in barns, we used a CFD simulation that considers the specific behavior (standing and lying), the number and distribution of cows in the barn, and their effects on the environment.

2. Materials and Methods

2.1. Barn design

Measurements were taken in a dairy barn with natural ventilation in Konya, Turkey, on October 24 between 11:00 and 12:00h. The barn had an east-west orientation, a length of 60 m, a width of 26 m, and a height of 6 m (Figure 1). The barn, designed in a free-stall system, consists of 150 cattle and 70 dairy cows. A summary of the barn characteristics is listed in Table 1.

Table 1. Barn characteristics
Çizelge 1. *Ahırın özellikleri*

Barn type	**Freestall system**
Cattle capacity	150
Dairy cow capacity	70
Stall width	1.15 m
Stall length	2.30 m
Feeding length	0.82 m/cow

2.2. CFD model and boundary conditions

The Fluent (Ansys13, Fluent Inc., Lebanon, NH, USA) was used to simulate the barn environmental conditions (Figure 2). The 3-D building geometry was created using SolidWorks software (SolidWorks Corporation, Waltham, MA, USA). The Holstein cow (Anderson, 2014) geometry was simplified to a six-cylinder geometry to reduce computation time and avoid elements with high skewness. Previous studies have shown that this geometry produces nearly identical results compared to a highly detailed polygonal cow model (Mondaca & Choi, 2016). The cow was modeled in two positions, standing (Figure 3a) and lying (Figure 3b). At the time of measurement, there were a total of 84 cows in the barn, of which 30 were lying and 54 were standing.

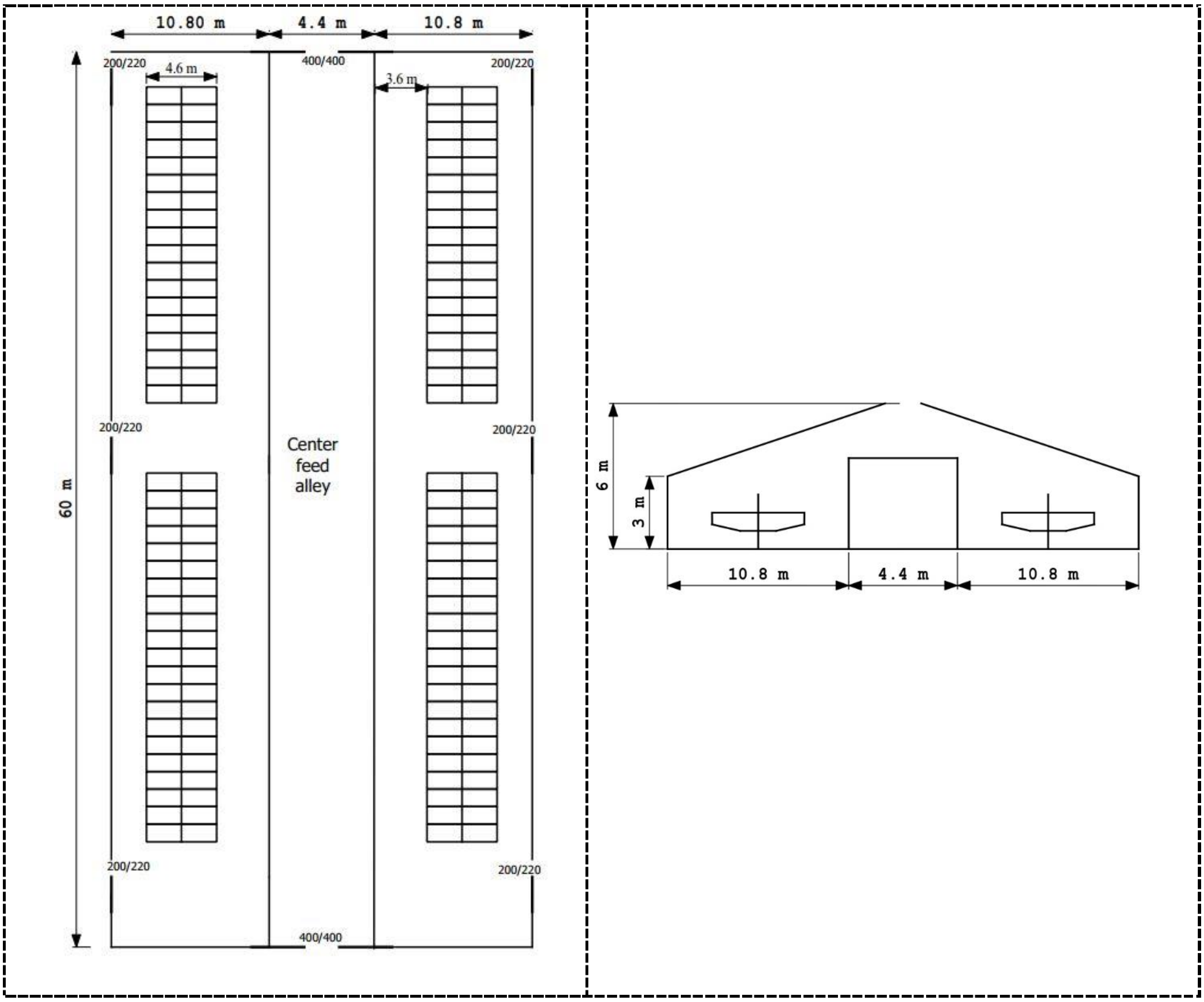


Figure 1. The cross section and plan view of barn
Şekil 1. *Ahırın kesit ve plan görünümü*

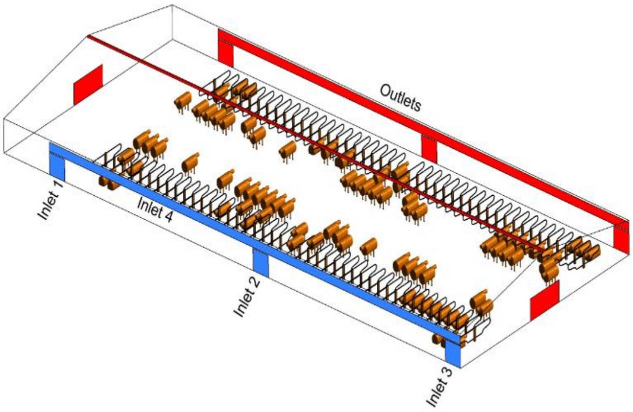
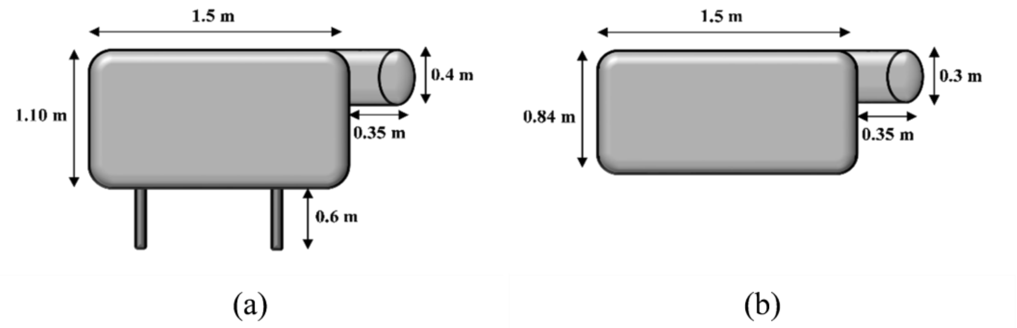


Figure 2. The positions of inlets and outlets
Şekil 2. *Hava giriş ve çıkış açıklıklarının konumları*

The simulations were performed under steady-state conditions. The buoyancy was considered with the Boussinesq approximation. Due to its high accuracy, the renormalization group (RNG) k-ε turbulence model was used to predict the indoor climate of the barn (Küçüktopcu & Cemek, 2019a). The continuity, momentum, and turbulence equations were calculated with a convergence criterion of 10^{-4}, while the energy equations were calculated with a convergence criterion of 10^{-6}. Table 2 gives the initial boundary conditions for the numerical solution. The optimum mesh distribution and the number of cells were set in proximity and curvature in size function, fine relevance center, high smoothing, slow transition, and fine span angle center. The skewness of the mesh was 0.799.

Table 2. Boundary conditions for CFD simulation
Çizelge 2. *HAD simülasyonu için sınır koşulları*

Element	**Air velocity (m s^{-1})**	**Temperature (°C)**
Inlet 1	1.10	20.50
Inlet 2	1.15	20.60
Inlet 3	1.20	21.60
Inlet 4	1.15	20.90



(a) (b)

Figure 3. Simplify the geometry of the cow: (a) standing cow; (b) lying cow
Şekil 3. *İneğin geometrisinin basitleştirilmesi: (a) ayakta duran; (b) yatan*

2.3. Field measurement

To validate CFD simulation, air temperature and air velocity were measured at twenty locations in the barn (Figure 4). Measurements were taken at an average adult human height (1.80 m). A digital temperature meter (Onset Computer Corporation, Bourne, MA, USA) with an accuracy of ±0.3 °C was used to monitor the indoor air temperature distribution. The air velocity distribution was determined with an anemometer (PCE-423, PCE Instruments, Jupiter, FL, USA) with an accuracy of ±5%. Air temperature and air velocity measurements were taken simultaneously, and the instruments were calibrated before use.

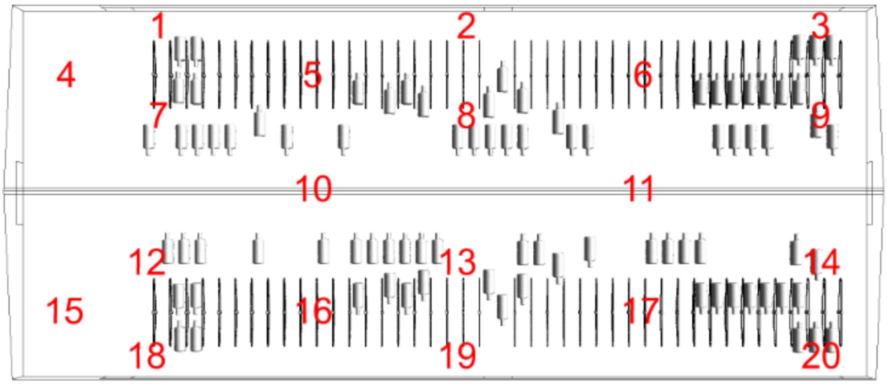


Figure 4. Measurement locations for air temperature and velocity in the barn
Şekil 4. *Ahırdaki hava sıcaklığı ve hızı için ölçüm konumları*

2.4. Model validation

The CFD model results were compared to field measurements in the barn. For model validation, statistical parameters such as fractional bias (FB), normalized mean squared error (NMSE), geometric mean bias (MG), geometric mean-variance (VG), and fraction of two (FAC2) were used. Models were considered valid if more than half of the parameters met the following requirements: FB <0.3, 0.7< MG <1.3, NMSE<0.25, VG<4, and 0.5<FAC2<2 (Chang & Hanna, 2004; Hanna & Chang, 2011).

$$FB = 2\frac{X_{m,avg} - X_{p,avg}}{X_{m,avg} + X_{p,avg}} \tag{1}$$

$$MG = \exp\left[\overline{\ln\left(\frac{X_m}{X_p}\right)}\right] \tag{2}$$

$$VG = \exp\left[\overline{\ln\left(\frac{X_m}{X_p}\right)^2}\right] \tag{3}$$

$$FAC2 = \frac{X_p}{X_m} \tag{4}$$

$$NMSE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\left(X_m - X_p\right)^2}{X_{m,avg}.X_{p,avg}}\right) \tag{5}$$

Where X_m and X_p are the measured and predicted values; $X_{m,avg}$ and $X_{p,avg}$ are the measured and predicted mean values.

3. Results and Discussion

3.1. Field measurement results

When examining the parameters measured inside the barn, the highest temperature values generally occurred in the areas with lower air velocities. The areas with higher air velocities were mainly located near the side openings. A slight decrease in temperature values occurred in these areas. The minimum, maximum, and mean air temperatures measured in the barn were 21.20, 21.70, and 21.50 °C, and the air velocities were 0.10, 0.70, and 0.30 m s^{-1}, respectively (Figure 5).

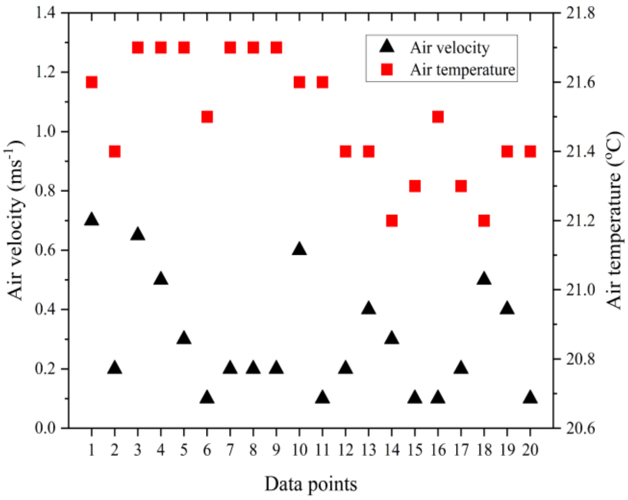


Figure 5. Measurement results for different data points
Şekil 5. *Farklı veri noktalarındaki ölçüm sonuçları*

During this measurement period (11:00-12:00 h), a significant proportion of cattle preferred to use the stalls (about 40%) and the feeding area (about 30%) rather than the courtyard area. According to the study by Uzal Seyfi (2013), stalls and courtyard area use increased when the feeding rate decreased.

3.2. Numerical simulation results

The mean values of air temperature and air velocity predicted by CFD simulations were 21.33 ± 0.213 °C and 0.31 ± 0.197 m s^{-1}, respectively. The simulations and experimental results agreed well with respect to air temperature and air velocity at each measurement position. Figure 6 shows the relative errors (%) of the measured versus predicted values for air temperature and air velocity. As a method of reducing the relative errors associated with low air velocity measurements, previous studies have generally compared measured and simulated air velocity as a percentage of the mean air velocity at the inlets (Blanes-Vidal et al., 2008; Du et al., 2019; Zhao et al., 2003). Considering relative error as a criterion, 15 out of 20 points for air velocity were less than or equal to -5% or 5%, while all points for air temperature were less than or equal to -5% or 5%. Air velocity measurements showed a discrepancy between measured and predicted values at points near the inlet and outlet openings, likely due to increased turbulence. Similar results were found by Küçüktopcu et al. (2022).

The results revealed that the CFD model met all criteria and accurately predicted indoor air temperatures and velocities. Despite some discrepancies between the simulated and measured values, the results of the experiments and the simulations generally agreed (Table 3).

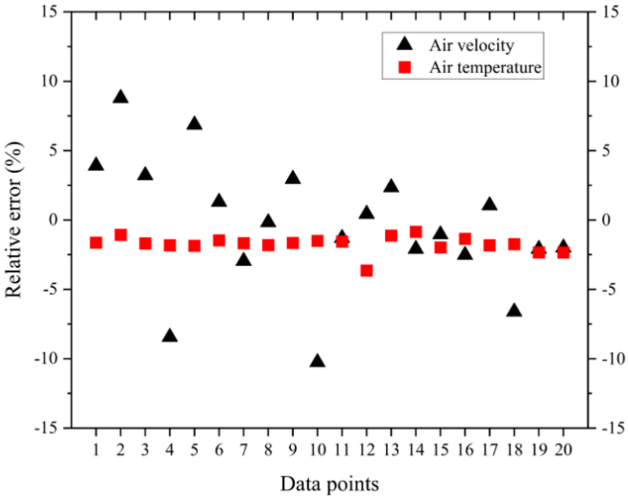


Figure 6. Relative errors (%) of air temperature and velocity values
Şekil 6. *Hava sıcaklığı ve hız değerlerinin bağıl hataları (%)*

Table 3. Statistical criteria for evaluating the performance of models
Çizelge 3. *Modellerin performansını değerlendirmede kullanılan istatistiksel kriterler*

Parameters	FB	MG	FAC2	VG	NMSE
Air temperature	0.018	1.018	0.983	1.000	0.001
Air velocity	0.016	1.049	0.985	1.035	0.031

3.3. Evaluation of indoor airflow pattern

Five planes were established for this study to explain the spatial changes within the barn. Planes 1-3 (Figure 7a) were designated as cross-sections of the barn (x_1=15 m, x_2=30 m, and x_3=45 m), while plane 4 (Figure 7b) was a longitudinal section of the barn (z = 13 m). Plane 5 (Figure 7c) was one meter above the ground (y =1 m)

The air temperature and velocity contours of the different sections are shown in Figure 8. From the air temperature contours, the air in the area where the animals were staying was warmer than the air in the barn. A lower volume of air flowing through the animal-occupied zone would explain this difference (Zhou et al., 2019). Heat was transported from the floor to the roof, as indicated by the vertical temperature distribution, and the heat was dissipated through the ridge opening. Similar findings were obtained by Wu et al. (2012).

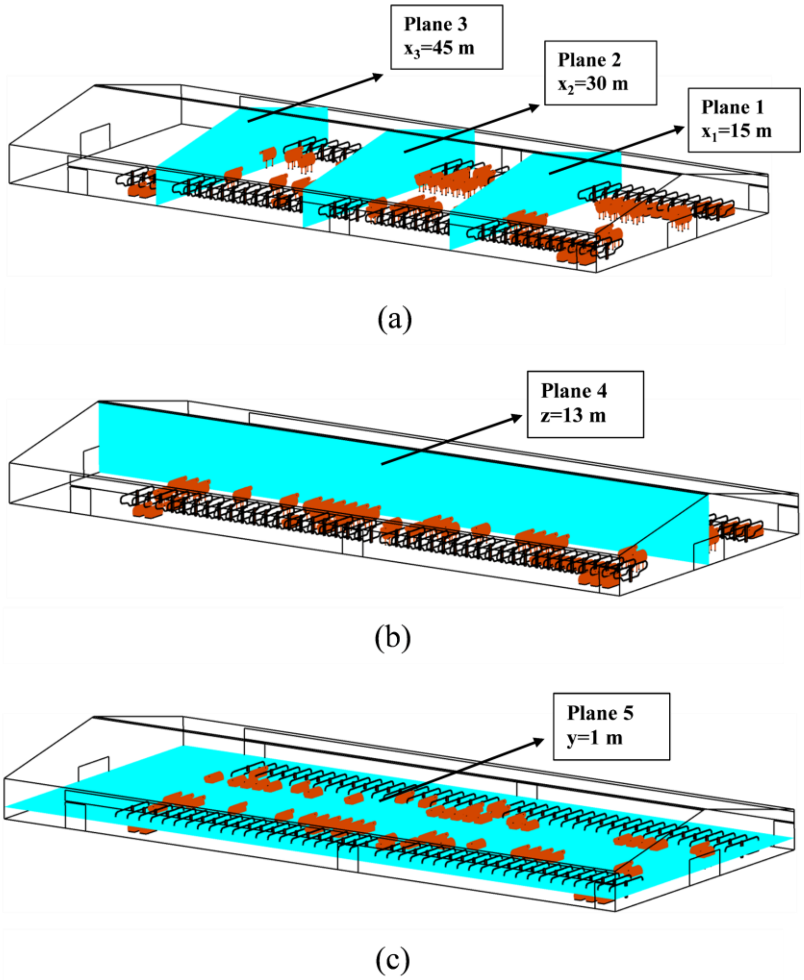


Figure 7. Locations of the planes: (a) x_1=15 m, x_2=30 m, x_3=45 m, (b) z=13 m, and (c) y=1 m to illustrate the spatial variations within the barn

Şekil 7. *Ahırdaki mekansal değişimleri göstermek için hazırlanan düzlemlerin konumları: (a)* x_1*=15 m,* x_2*=30 m,* x_3*=45 m, (b) z=13 m ve (c) y=1 m*

The air temperature and velocity contours of the different sections are shown in Figure 8. From the air temperature contours, the air in the area where the animals were staying was warmer than the air in the barn. A lower volume of air flowing through the animal-occupied zone would explain this difference (Zhou et al., 2019). Heat was transported from the floor to the roof, as indicated by the vertical temperature distribution, and the heat was dissipated through the ridge opening. Similar findings were obtained by Wu et al. (2012).

When the air velocity contours were examined, it was found that the fresh air entering through the sidewall openings was directed toward the ridge opening without adequate air circulation. In addition, the local air velocity increased, and the flow directed upward when the incoming air hit the surface of a cow. Similar flow paths and patterns were noted by Gebremedhin and Wu (2003).

Wang et al. (2018) applied a CFD modelling method, a virtual wind tunnel, and simplified geometric models representing a standing and a lying cow and analyzed the heat transfer of a typical cow. The authors recommended increasing airflow in the animal area to cool cows under hot conditions and encouraging the use of horizontal airflow in the animal area whenever possible. Tomasello et al. (2019) analyzed the air velocity distribution in a semi-open free stall barn and found that the proposed CFD model could be used to analyze the appropriate airflow distribution to determine the best configuration during the simulation of specific building design alternatives. Saha et al. (2020) studied the effects of different combinations of seasonal openings on airflow patterns and airflow rate of a naturally ventilated dairy barn using CFD models. They found that combinations of openings play a critical role in the distribution of fresh air in the barn.

In the present study, the combination of field measurements and numerical modeling revealed that CFD model could help identify environmental problems in dairy barns. As for future research, the main priority is to better understand the environmental conditions in a dairy barn by taking measurements at different times of the year. Once the environmental problems in the barn are identified, alternative solutions (design improvement in the CFD model) will be proposed to improve cow performance.

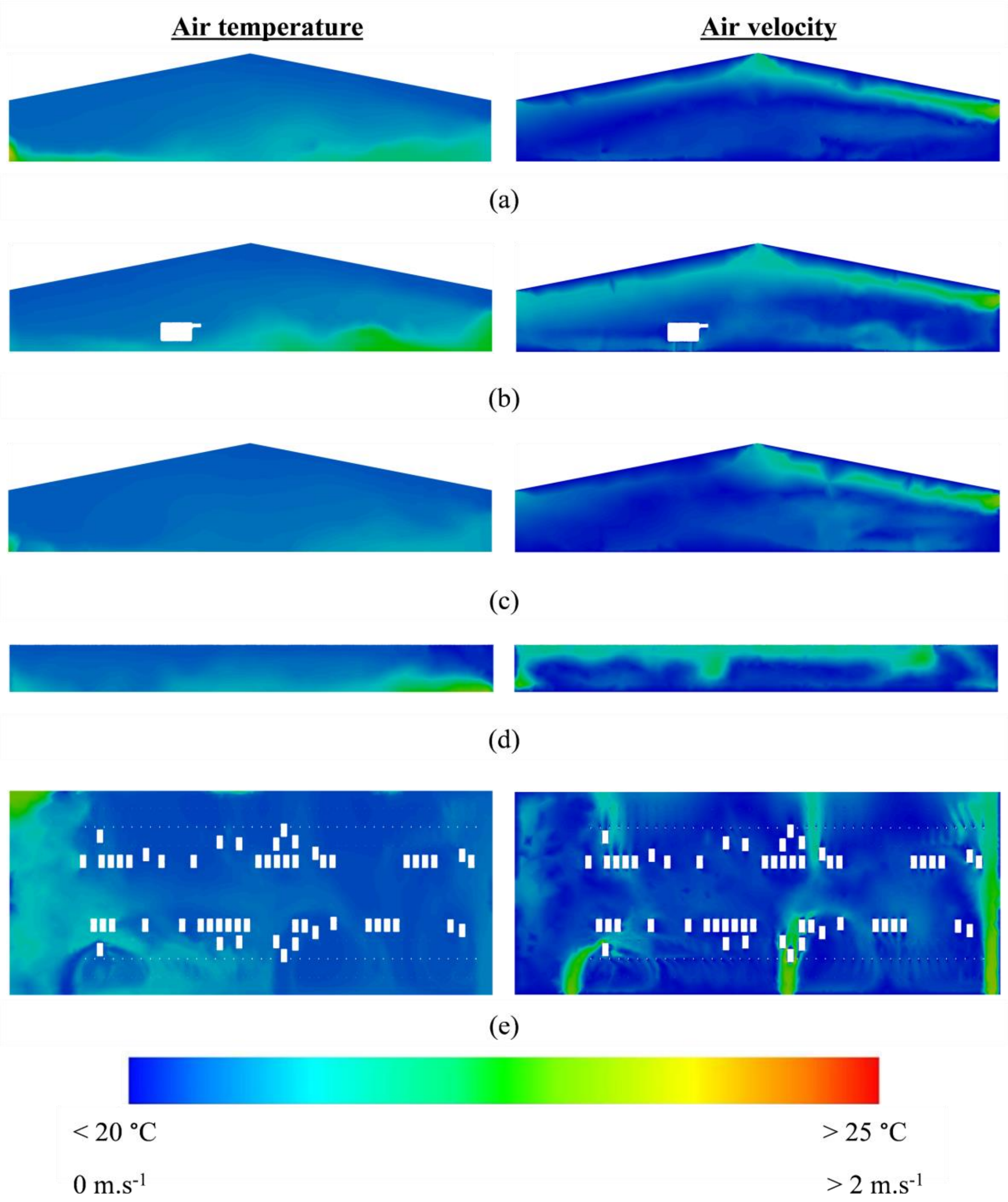


Figure 8. Air temperature and velocity contours of slice: (a) x_1=15 m, (b) x_2=30 m, (c) x_3=45 m, (d) z=13 m, and (e) y=1 m

Şekil 8. *Kesitlerdeki hava sıcaklığı ve hız dağılımları: (a) x_1=15 m, (b) x_2=30 m, (c) x_3=45 m, (d) z=13 m, ve (e) y=1 m*

4. Conclusion

This study simulated indoor conditions in a naturally ventilated dairy barn. The following conclusions were drawn from the findings.

The air in the zone occupied by animals was warmer than in the barn (more than 2 °C), as indicated by the temperature contours.

The measured and predicted mean air temperatures in the barn were 21.50 ± 0.174 °C and 21.33 ± 0.213 °C, while the air velocities were 0.30 ± 0.196 m s^{-1} and 0.31 ± 0.197 m s^{-1}, respectively.

High air velocities (>1 m s^{-1}) were noted, especially near the side openings. In these areas, there was a decrease in temperature values. Analysis of the air velocity contours showed that the fresh air entering through the openings in the side wall was directed into the opening of the ridge without sufficient air circulation.

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