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Comparison of different mechanical ventilation systems for dairy cow barns: CFD simulations and field measurements

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ABSTRACT

Proper ventilation in dairy cow barns in terms of volume flow rate and air velocity is important to avoid heat stress, which leads to reduced milk production and respiratory disease. In this study, three different ventilation systems for dairy cow barns were compared in terms of the airflow inside the barn using Computational Fluid Dynamics (CFD) simulations. The 3D steady simulations were validated against velocity point measurements in a dairy cow barn, with the average difference being within 15%. The first system (barn A) had four inlet fans, 36 sidewall inlet fans, and eight exhaust fans. The second system (barn B) had no inlet fans and ten exhaust fans. The third system (barn C) had six inlet fans and eight exhaust fans. In all three barns, circulation fans were located above the cows resting areas. The results showed that the percentage of the barn's total volume flow rate through the resting area in barn C was 50% and 10% higher than barns A and B, respectively. High air velocities between 3 and 5 m/s was obtained in barn C, the same was only obtained in half of barn B near the exhaust end, while barn A showed the lowest performance. It was shown that it is necessary to have fans on the inlet and exhaust ends of the barn (barn C) to obtain relatively sufficient and uniform air velocity along the barn. Furthermore, the results showed that inlet end fans and sidewall inlet fans (barn A) worked against each other, leading to low air velocity and volume flow rate through the animal occupied zones; therefore, their combination is not recommended.

1. Introduction

Poor ventilation of dairy cow barns can lead to a decrease in milk production, heat stress, and respiratory disease (Mandel et al., 2016; Polsky and von Keyserlingk, 2017). A properly designed ventilation system should remove heat, moisture, and gaseous emissions from a barn by bringing in fresh air at an adequate rate (Drewry et al., 2018b; Mondaca, 2019).

In temperate climates, natural ventilation systems are used in dairy cow barns (Firfiris et al., 2019). These systems are dependent on wind conditions and temperature differences between inside and outside air. However, in desert and semiarid climates, dairy cow barns are mechanically ventilated using fans. In terms of airflow direction, the main types of mechanical ventilation systems in dairy cow barns are tunnel and cross ventilation systems (Atkins et al., 2016). In tunnel ventilation systems, the airflow is parallel to the ridge of a barn's roof, while in cross ventilation systems, the airflow is perpendicular to the ridge. In terms of the created pressure inside the barn, the main types of mechanical ventilation systems are negative, positive, and neutral (Bickert et al., 2000). In a negative pressure system, air is blown out of a barn using exhaust fans. In a positive pressure system, inlet fans are used to blow air inside the barn. While in a neutral system, a combination of both inlet and exhaust fans are used; usually, the capacity or the size of the exhaust fans are a little larger than the inlet fans to create a somewhat negative pressure inside the barn.

To reduce the effect of heat stress during hot weather, evaporative cooling systems, utilizing sprinklers or misters, are used in dairy cow barns (Lin et al., 1998). It has been shown that increasing air velocity over the body of cows leads to a decrease in heat stress (Mondaca, 2019). If adequate ventilation is provided in a dairy cow barn, air velocities above 3 m/s directed at a cow's body can reduce or alleviate heat stress (Shearer et al., 1991). However, when the air temperature is higher than the cow's skin surface temperature, misters and sprinkler systems have to be added in addition to increasing the air speed to cool the cow's body and reduce heat stress.

Assessing a ventilation system in terms of the obtained airflow pattern using field measurements, specifically in large structures like a dairy cow barn, is difficult. A main drawback of field measurements is that typically only point measurements are performed. An alternative is Computation Fluid Dynamics (CFD) simulations using validated models. The CFD simulations provide whole-field data, giving a complete representation of

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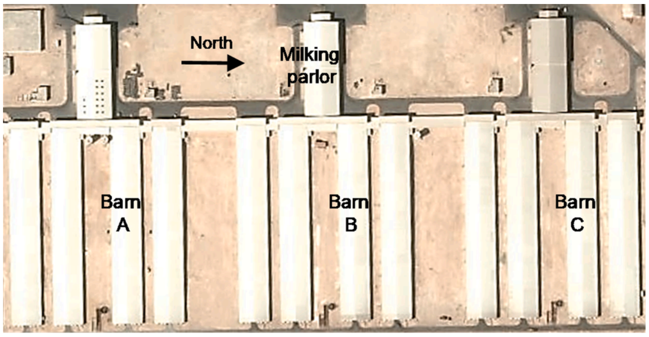

Fig. 1. Aerial view of the barns.

the airflow inside a structure. There has been a number of studies that used CFD simulations to assess and investigate ventilation systems in livestock buildings. In these studies, either the presence of cows was not considered (Ecim-Djuric and Topisirovic, 2010; Norton et al., 2010; Shen et al., 2012a, 2012b; Yi et al., 2019), the barn was assumed to be empty, or their presence was approximated using a porous media approach (Rong et al., 2015). In recent studies (Drewry et al., 2018a; Zhou et al., 2019), the 3D geometry of cows have been used.

In order to obtain proper ventilation in a dairy cow barn, attention should be given to both air change rate and airflow (Gooch and Timmons, 2000). In a study by Mondaca et al. (2019) using CFD simulations, it was shown that about 12.8% of the total cross-sectional airflow in a mechanically tunnel ventilated barn was flowing through the animal occupied zone while the rest was flowing through the overhead space. It was concluded that only by increasing the air change rate capacity of a barn, the obtained air velocity at cow level would not increase.

The objective of this paper is to compare three different mechanical ventilation systems for dairy cow barns in terms of the volume flow rate and air velocity through the animal occupied zones. The comparison was conducted using three-dimensional (3D) steady CFD simulations. The simulations were validated using velocity point measurements in one of the dairy cow barns. The results of this study can aid in the process of making an informed selection of ventilation systems for dairy cow barns.

The remainder of this paper is structured as follows. Section 2.1 outlines the experimental setup. Section 2.2 presents the details of the CFD simulations. The results are presented and discussed in Section 3, including the comparison of CFD simulations and field measurements (Section 3.1) and the comparison between the different ventilation systems in terms of the obtained volume flow rate and airflow (Section 3.2). Finally, the main conclusions of the study are presented in Section 4.

2. Methods

2.1. Experimental setup

The selected barns in this study were located near Al Khor municipality, Qatar, latitude 25.6912° N and longitude 51.4106° E (Fig. 1). The

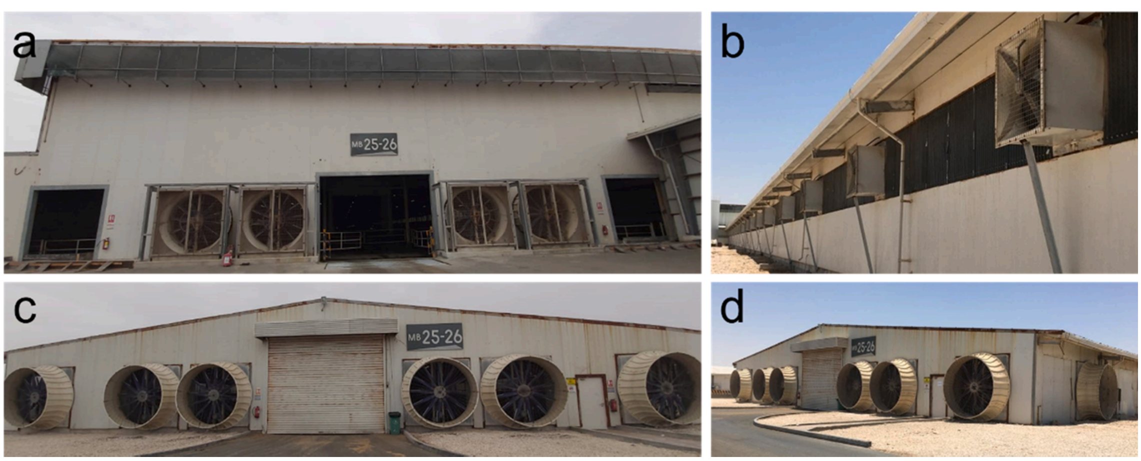

Fig. 2. Pictures of barn A: (a) inlet end, (b) side of the barn showing the sidewall inlet fans, (c) exhaust end, and (d) exhaust end side view.

Fig. 3. Pictures of barn B: (a) inlet end, (b) inlet end side view, (c) exhaust end, and (d) exhaust end side view.

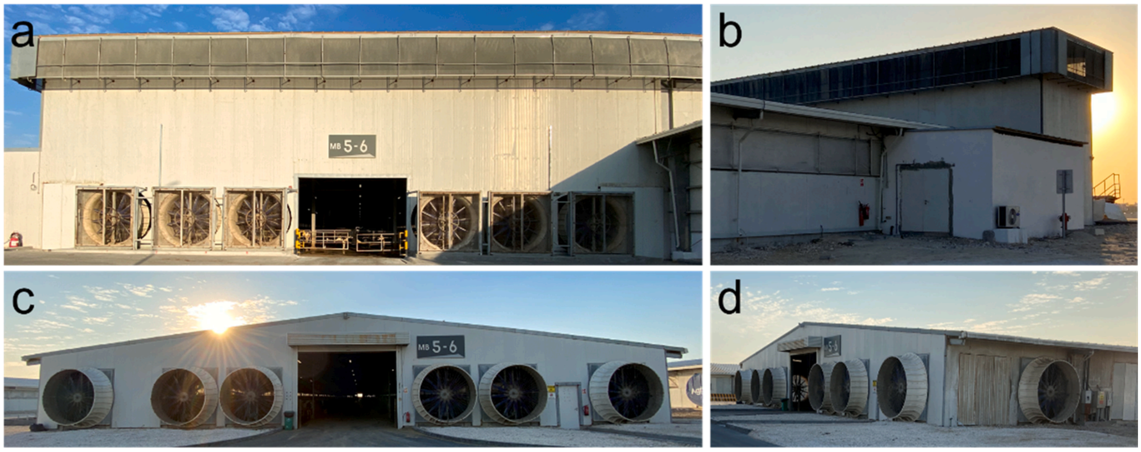

Fig. 4. Pictures of barn C: (a) inlet end, (b) inlet end side view, (c) exhaust end, and (d) exhaust end side view.

Table 1
Fans specifications in Barns A, B, and C.

Location	Manufacturer	Diameter (m)	Flow rate (m^3/s)	Power (kW)	Quantity		
					Barn A	Barn B	Barn C
Inlet end	Agpro	2.44	49.5	5.59	4	0	6
Exhaust end	Agpro	2.44	49.5	5.59	8	10	8
Sidewall	VES	0.91	5.6	0.37	36	0	0
Overhead	VES	1.83	37	2.24	40	40	40

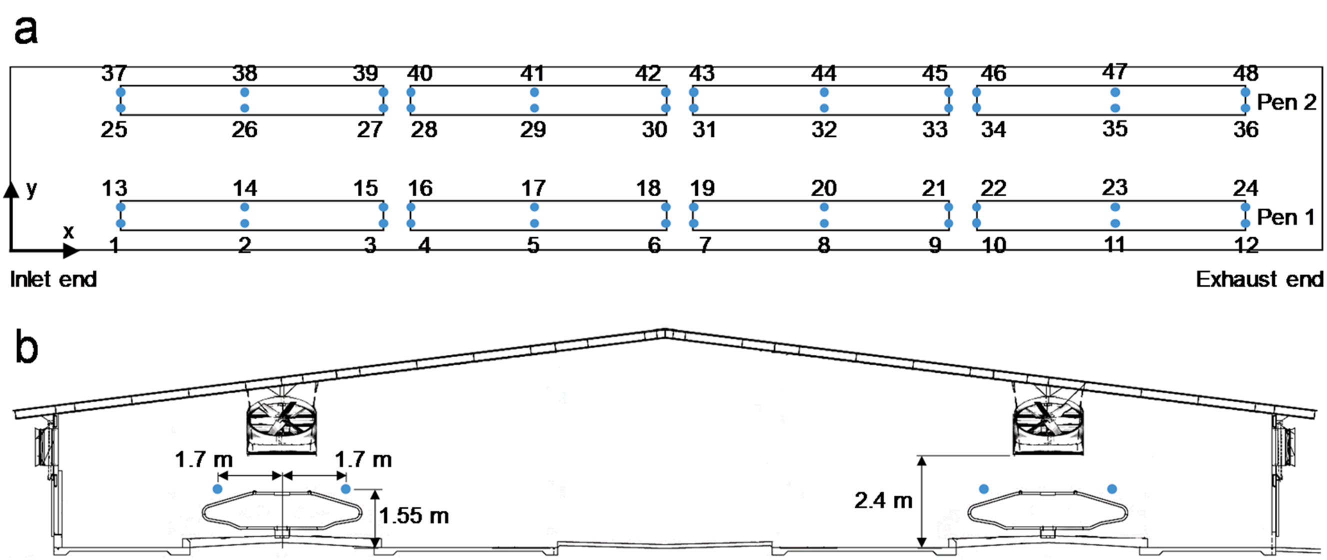

Fig. 5. Schematic showing the experimental setup: (a) top view of the barn and (b) cross-sectional front view of the inside of the barn showing the locations of the air velocity measurements in the resting areas.

barns had an east–west orientation (the exhaust end faces east), with a length of 228.2 m and a width of 31.9 m. Each barn can house about 600 dairy cows. Pictures of the three different mechanically ventilated dairy cow barns are shown in Fig. 2, Fig. 3, and Fig. 4. The barns were identical except for the ventilation systems. The first barn, barn A, which was selected for the validation of the CFD simulations, had four inlet fans located on the inlet end, eight exhaust fans, and 36 sidewall inlet fans (18 on each side). At the inlet end, there was one main door and two side doors that remain permanently open, also it included a wind tower that was open on all four sides. In all three barns, at the exhaust end, the main door remains closed and only opens for the feed truck. The second barn, barn B, had no fans on the inlet end and ten exhaust fans. The third barn, barn C, had six fans on the inlet end and eight exhaust fans. At the inlet end, there was only one door that remains permanently open.

The fans on the inlet and exhaust ends were Agpro, 96 in. (2.44 m) in diameter, the manufacturer-stated maximum airflow rate was 105,000 cfm (49.5 m^3/s). The sidewall inlet fans were VES, 36 in. (0.91 m) in diameter, the manufacturer-stated maximum airflow rate was 12,000 cfm (5.6 m^3/s). Inside the barn over the cow resting areas, 72 in. (1.83 m) in diameter cyclone VES fans tilted downwards at 45° angle were located, the manufacturer-stated maximum airflow rate was 78,000 cfm (37 m^3/s). The exact locations of the overhead and sidewall fans are shown in Fig. 16 in the appendix. A summary of the fans location in the barns and their specifications are listed in Table 1.

Each barn contained two pens, each having four resting areas. To validate the CFD simulations, air velocity was measured at multiple locations in barn A. During the measurements, the barn was empty and no cows were present. The measurements were carried out on February 1st,

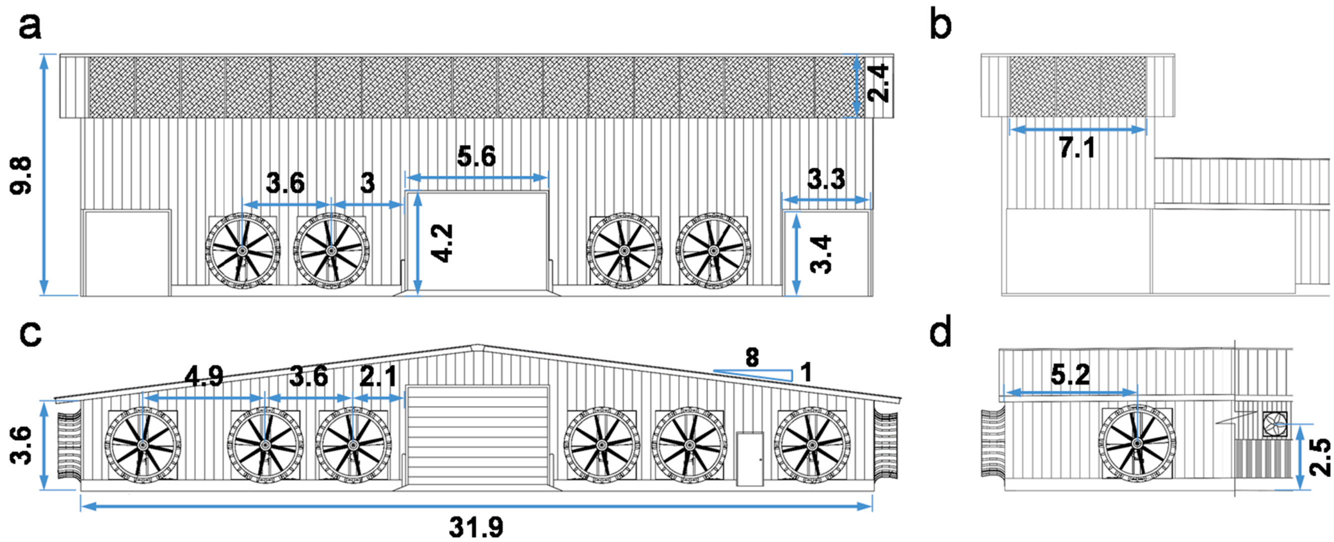

Fig. 6. Dimensions of barn A: (a) inlet end, (b) side view of the inlet end, (c) exhaust end, and (d) side view of the exhaust end. Dimensions are in meters.

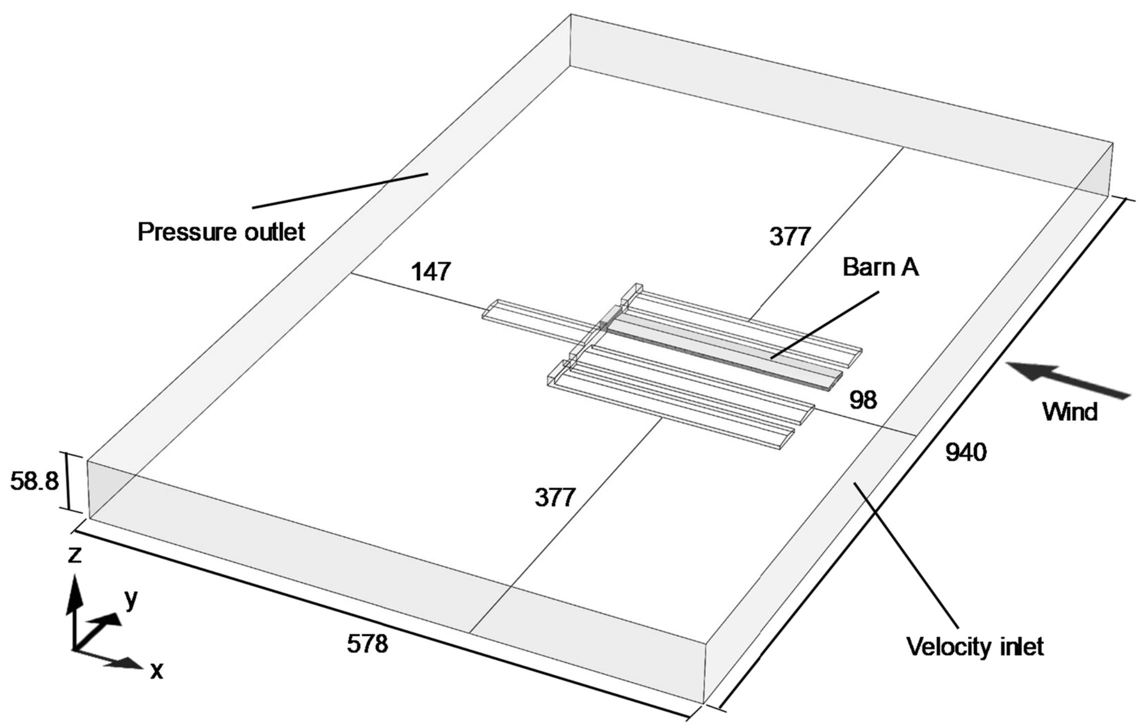

Fig. 7. Perspective view of barn A and the surrounding barns in the computational domain showing the inlet and outlet locations of the domain. Dimensions are in meters.

2020. Fig. 5 illustrates the location of the measurement points in the barn. Air velocity was measured at 48 points at the resting area of the cows at a height of 1.55 m, which is approximately equal to a resting-cow height, and a horizontal distance of 1.7 m from the center of the resting area. The measurements were performed with air flow sensors (Kestrel Meter 5400 Heat Stress Tracker). The uncertainty of the air velocity measurements, as reported by the sensor manufacturer, was the larger of ± 3% of the reading or ± 0.1 m/s. At each point, the air velocity was measured for about 60 s, at a rate of one measurement every two seconds (31 data points), and the time-averaged value was used for comparison with the CFD predictions. Given that the fans were running for a long time before performing the measurements, it was assumed that the flow has reached a steady-state. According to measured data form a nearby weather station, at the time of measurements, the wind direction was east and the wind speed was about 3 m/s at a height of 10 m.

2.2. CFD simulations

The commercial code Ansys Fluent 18 was used to perform the CFD simulations. The 3D steady Reynolds-averaged Navier–Stokes (RANS) equations were solved in combination with the standard k–ε turbulence model. Since the measurements were taken in an empty barn, the presence of the cows was not considered in the CFD simulations.

2.2.1. Computational domain and boundary conditions

Fig. 6 shows front and side views of the inlet and exhaust ends of barn A, showing the location of the fans, the wind tower, and the main dimensions of the barn.

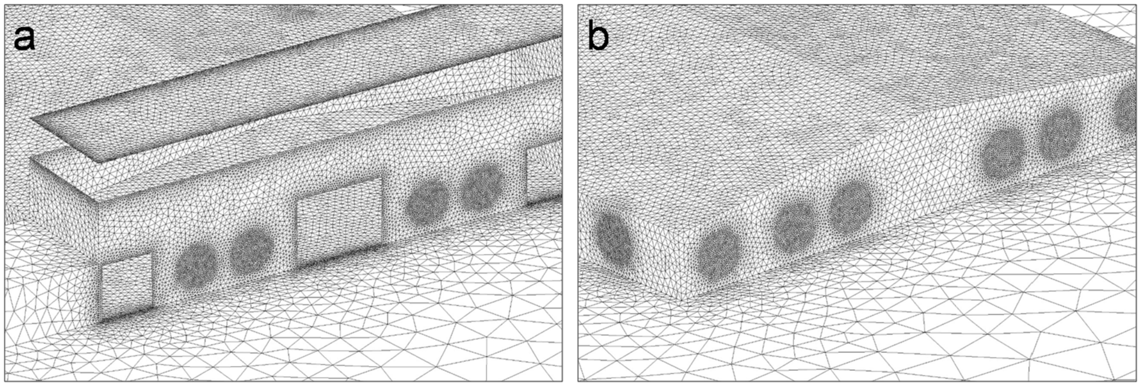

Fig. 8. Perspective view of the computational grid at (a) the inlet end, and (b) exhaust end of the barn.

The computational domain is shown in Fig. 7. Given that the barns include relatively large openings (main door, side doors, and wind tower openings), a coupled approach was used that includes both the wind flow around the barn and the airflow inside the barn in a single computational domain. The size of the computational domain was determined so that the blockage ratio, defined as the ratio of the frontal area of the buildings to the cross sectional area of the domain, would be less than 3%. Therefore, the sides of the domain were extended far enough to avoid artificial acceleration of the flow. Four barns and one milking parlor were included in the computational domain. The distance between adjacent barns is about 13 m, while the width and length of the milking parlor is about 32 m and 105 m, respectively.

Given that during the experimental measurements the wind direction was east, the east facing side of the computational domain was set as a velocity inlet, while the opposite face of the domain was set as a pressure outlet with zero static gauge pressure. At the top and lateral sides of the domain, symmetry conditions were applied. For the ground and buildings surfaces, the standard wall functions by Launder and Spalding (1974) were used. The inlet wind velocity profile was defined according to the logarithmic law:

$$U(z) = \frac{u^*_{ABL}}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \tag{1}$$

where U is the wind velocity at height z, u^*_{ABL} is the atmospheric boundary layer (ABL) friction velocity, κ is the von Karman constant, 0.42, and z_0 is the ground surface roughness length. According to the surrounding area, a roughness length of 0.03 m, corresponding to a flat terrain with few obstacles was selected (Wieringa, 1992). The value of the ABL velocity was determined using the measured wind velocity at a height of 10 m, which was 3 m/s. The turbulent kinetic energy, k, and turbulent dissipation rate, ε, were defined as (Richards and Hoxey, 1993):

$$k = \frac{{u^*_{ABL}}^2}{\sqrt{0.09}} \tag{2}$$

$$\varepsilon = \frac{{u^*_{ABL}}^3}{\kappa(z+z_0)} \tag{3}$$

The Iterations are stopped and convergence is assumed to be reached when all the scaled residuals, as defined in the Ansys Fluent 18 user guide, have leveled off and reached a minimum value of 10^{-5} for $\times$,y, and z velocity, and 10^{-4} for continuity, k, and ε. In addition, the ventilation flow rate and the velocity at several points along the length of the barn were monitored to ensure convergence. The fans were modeled using the fan boundary condition by setting a constant pressure jump across the fan, determined from the fans specifications. The pressure jump for each fan type was defined so that the corresponding airflow rate listed in Table 1 was obtained.

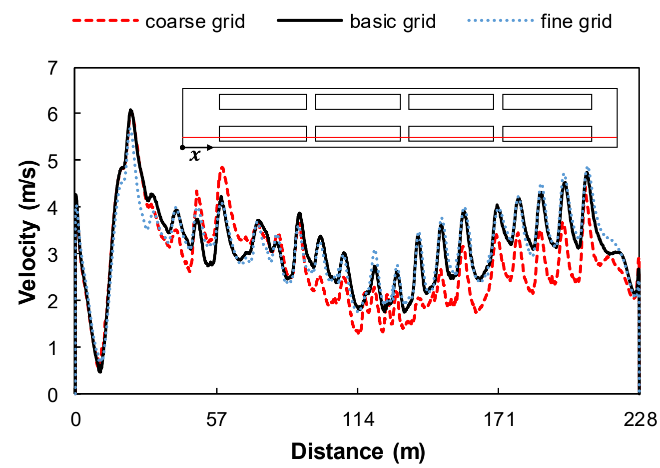

Fig. 9. Grid sensitivity analysis, air velocity magnitude along a horizontal line at a height of 1.55 m through pen 1, obtained using three different grids.

2.2.2. *Computational grid and grid sensitivity analysis*

The computational grid was created using a non-uniform mesh as shown in Fig. 8. The basic grid had 13,361,394 elements and the grid resolution resulted from a grid sensitivity analysis. The grid sensitivity analysis was performed by coarsening and refining the basic grid. The coarse and fine grids had 9,526,116 elements, and 18,710,922 elements, respectively. The coarse and fine girds were created by coarsening and refining the basic grid by a factor of about $\sqrt{2}$.

Fig. 9 shows the results of the grid sensitivity analysis, the air velocity magnitude along the length of barn A at a height of 1.55 m is plotted for the three grids. As shown in the figure, the results obtained from the basic and fine grids were almost identical, while the coarse gird results showed clear deviations from the basic grid results. In terms of the ventilation flow rate, the difference between the coarse and basic grids relative to the fine grid were 1.0% and 0.2%, respectively. Therefore, the basic grid was considered to provide grid-independent results and was used in conducting the remaining simulations.

2.2.3. *Volume flow rate calculation*

The total volume flow rate of each barn is calculated by taking the surface integral of the velocity at the exhaust fans surfaces. In order to calculate the volume flow rate through the resting areas and the animal occupied zones, in post processing of the results, volumes corresponding to the resting areas and the animal occupied zones are created. The resting areas volumes are 5.2 m wide, 2 m high, and 196 long. While the animal occupied zones volumes are 13.1 m wide, 2 m high, and 196 m long. The volumes extend from the beginning till the end of the pens. The exact locations of the pens are shown in Fig. 16 in the appendix. The

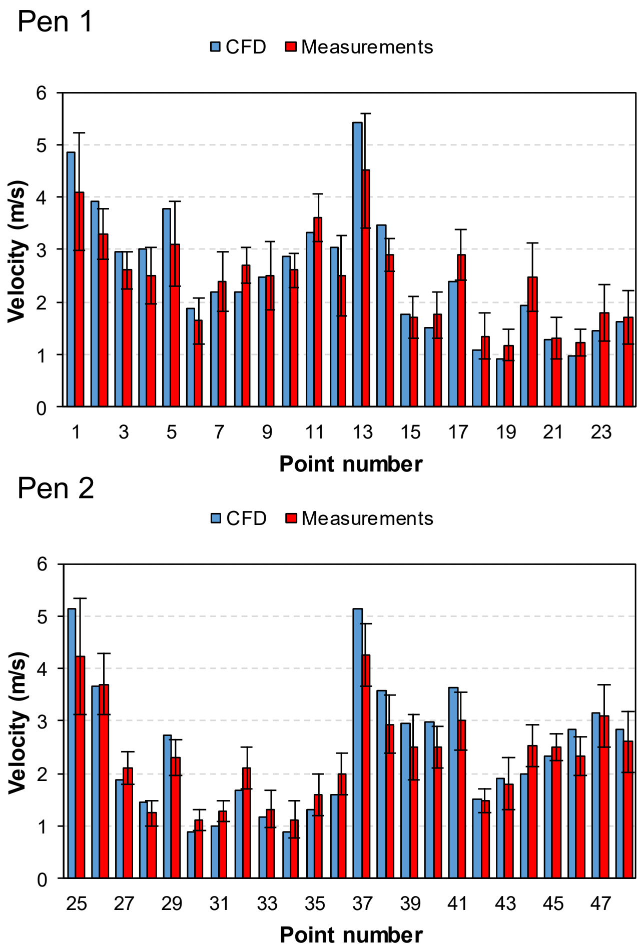

Fig. 10. Comparison of the CFD predictions and the field measurements of the air velocity in pen 1 and 2 in Barn A. The error bars represent the standard deviation of the measurements.

average volume flow rate through the resting areas and the animal occupied zones are obtained by multiplying the volume average of the × velocity by the frontal areas of their corresponding volumes, the frontal areas of the resting areas and animal occupied zones volumes are 10.4 m^2 and 26.2 m^2, respectively.

3. Results and discussion

This section consists of two parts. Section 3.1 presents a comparison between the velocity point measurements and CFD predicted results in barn A. The performance of the ventilation systems in barns A, B, and C are assessed in terms of the volume flow rate through the animal occupied zone, air velocity magnitude, and distribution in Section 3.2.

3.1. CFD simulation and field measurements comparison

Fig. 10 compares the CFD predictions and the point measurements of velocity in pen 1 and 2 in barn A. In general, good agreement between the measurements and simulations was found. The velocity measurements were over predicted in half the measurement points by the CFD simulation. Mostly, the over predictions were at the beginning of the resting areas. The average discrepancy (the relative discrepancy is calculated using the following formula $|\text{measured velocity} - \text{CFD predicted velocity}|/\text{measured velocity}$) between the point measurements and CFD predictions was about 15.3%, with a maximum of about 21.8% at point 14 and a minimum of about 0.5% at point 18. In terms of the absolute difference, the average was 0.4 m/s and the maximum was 0.9 m/s at point 13. Mainly, at higher air velocities (greater than 3 m/s), the CFD over predicted the measurements, while for lower velocities, the CFD under predicted the measurements.

3.2. Comparison of the ventilation systems

3.2.1. Volume flow rate

Fig. 11 (a and b) show the average volume flow rate through the cows resting area and the animal occupied zone in barns A, B, and C as a percentage of the corresponding barn total volume flow rate. The percentage of the total volume flow rate through the resting area in barn C was about 50% and 10% higher than barns A and B, respectively. Barns B and C had almost equal percentages of the total barn volume flow rate through the animal occupied zone (barn C was higher by about 2%), which were respectively higher than barn A by about 30% and 33%. In barn C, about 60% of the volume flow rate flowed through the animal occupied zone, while the rest flowed through the overhead space and the feed lane. Therefore, placing horizontal or vertical baffles above the animal occupied zone may result in an increase in the amount of volume flow rate through this zone.

3.2.2. Airflow pattern

Fig. 12(a–c) shows contours of the velocity magnitude in a vertical plane between the last two overhead fans in the first resting areas in

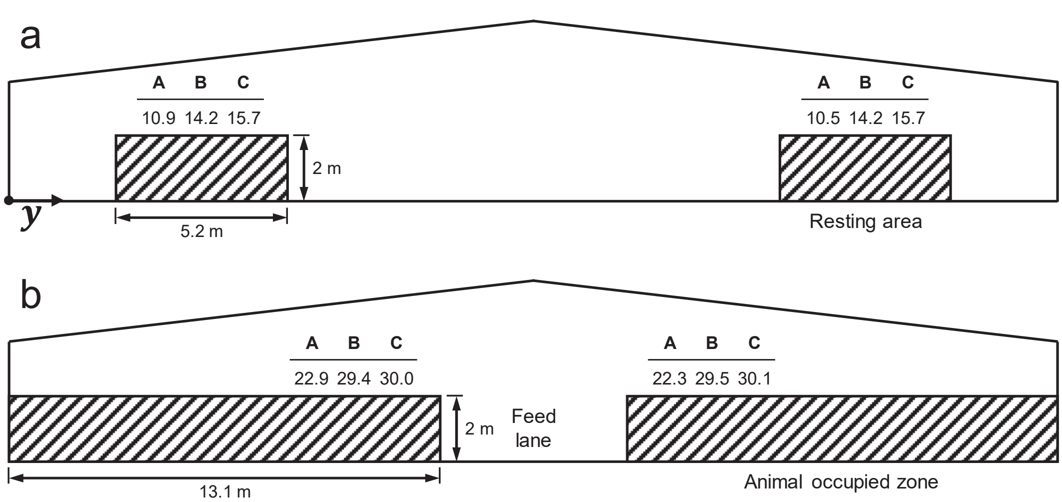

Fig. 11. Front view of the barn, showing the average volume flow rate through the (a) cows resting area and (b) the animal occupied zone for barns A, B, and C as a percentage of the total volume flow rate of the corresponding barns.

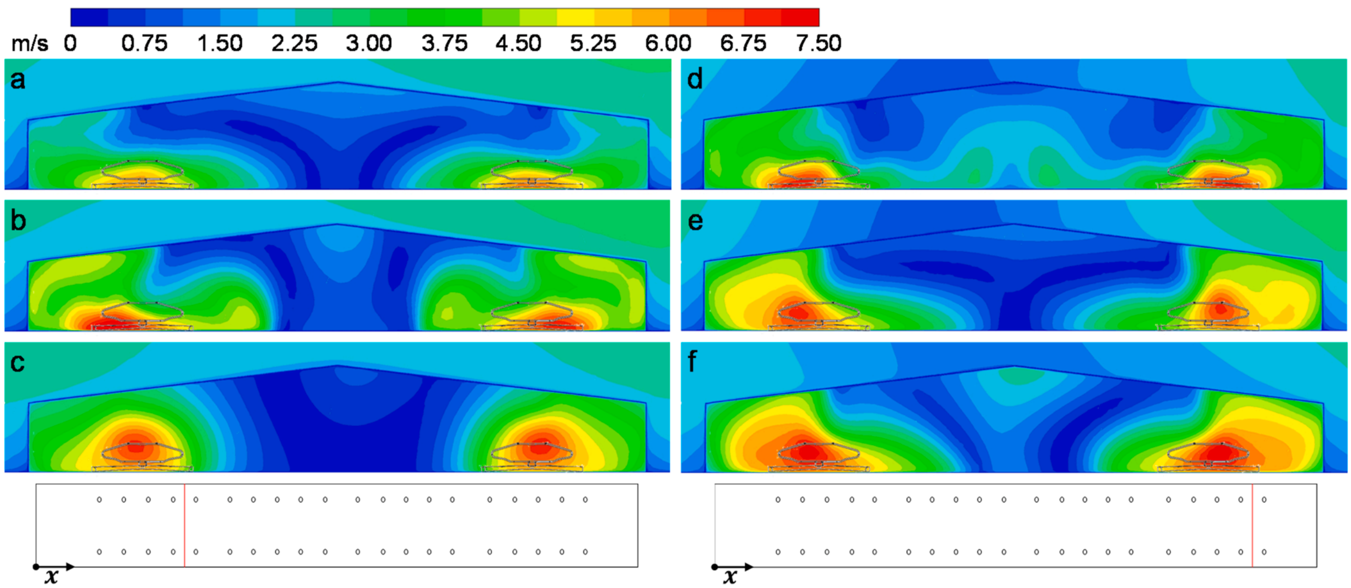

Fig. 12. Contours of velocity magnitude in a vertical plane between the last two overhead fans in the first resting areas in (a) barn A, (b) barn B, and (c) barn C and in a vertical plane between the last two overhead fans in the last resting areas in (d) barn A, (e) barn B, and (f) barn C. The insets illustrate the locations of the vertical planes.

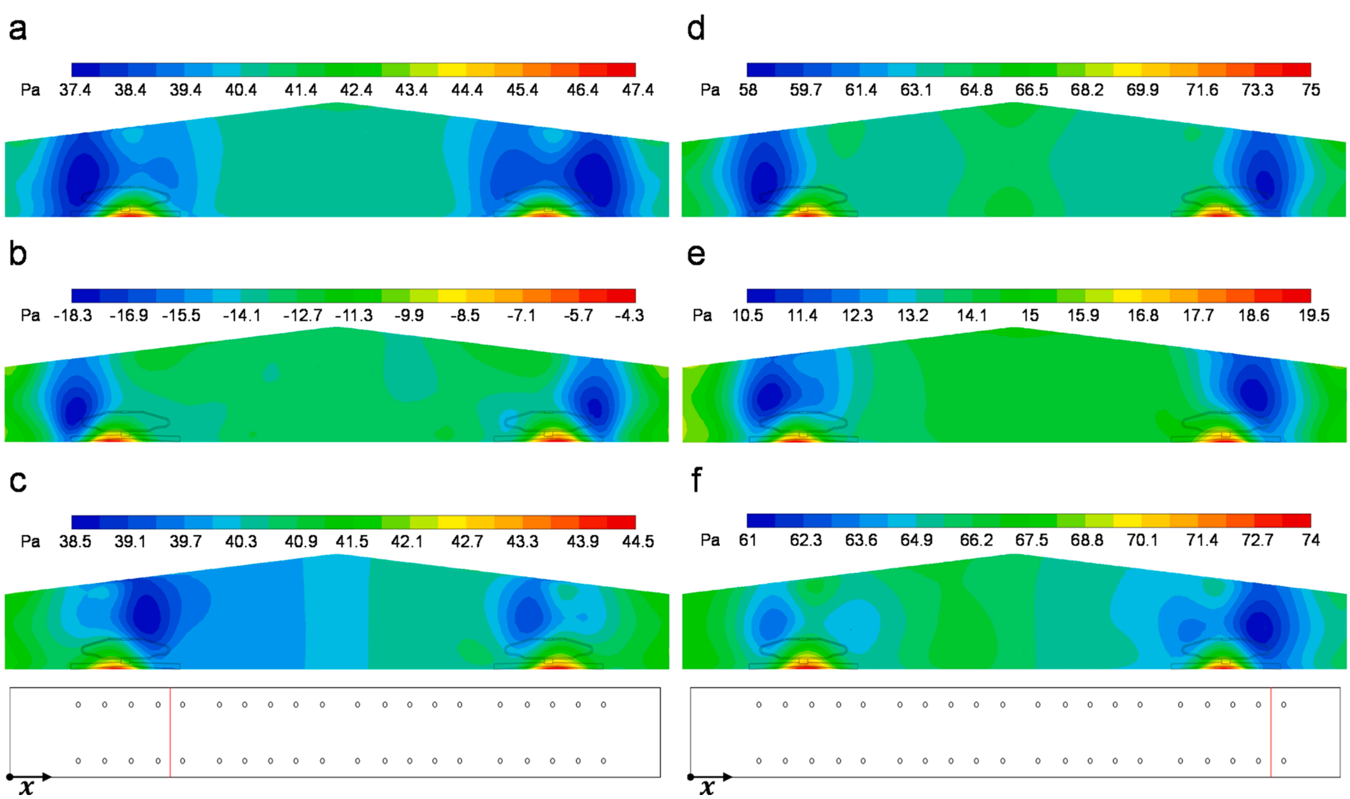

Fig. 13. Contours of pressure in a vertical plane between the last two overhead fans in the first resting areas in (a) barn A, (b) barn B, and (c) barn C and in a vertical plane between the last two overhead fans in the last resting areas in (d) barn A, (e) barn B, and (f) barn C. The insets illustrate the locations of the vertical planes.

barns A, B, and C, respectively, while Fig. 12(d–f) show the same between the last two overhead fans in the last resting areas. In all three barns, the air velocity was higher near the side walls, this might be attributed to the reduced cross sectional area of the barn on the sides given the slope of the barn's roof. In Fig. 12(d), barn A, the effect of the side intake fans on the airflow pattern can be seen with higher air velocities in the middle of the barn compared to the other two barns. There is a clear increase in the air velocity at the resting area in barn C relative to barns A and B. In barn C, the air velocity at the resting area was approximately greater than 5 m/s. In all three barns, high air velocities, exceeding 3 m/s, flow through the overhead space in the animal occupied zones, indicating the need for the placement of baffles to direct the air to lower heights and through the animal occupied zones.

Contours of the pressure inside the three barns is shown in Fig. 13. Given that there are only exhaust fans in barn B, the pressure inside the barn is negative, Fig. 13(b), causing air to be drawn inside the barn through the inlet end openings. As shown in Fig. 13(e), at the resting areas near the exhaust end, the pressure inside the barn is positive and

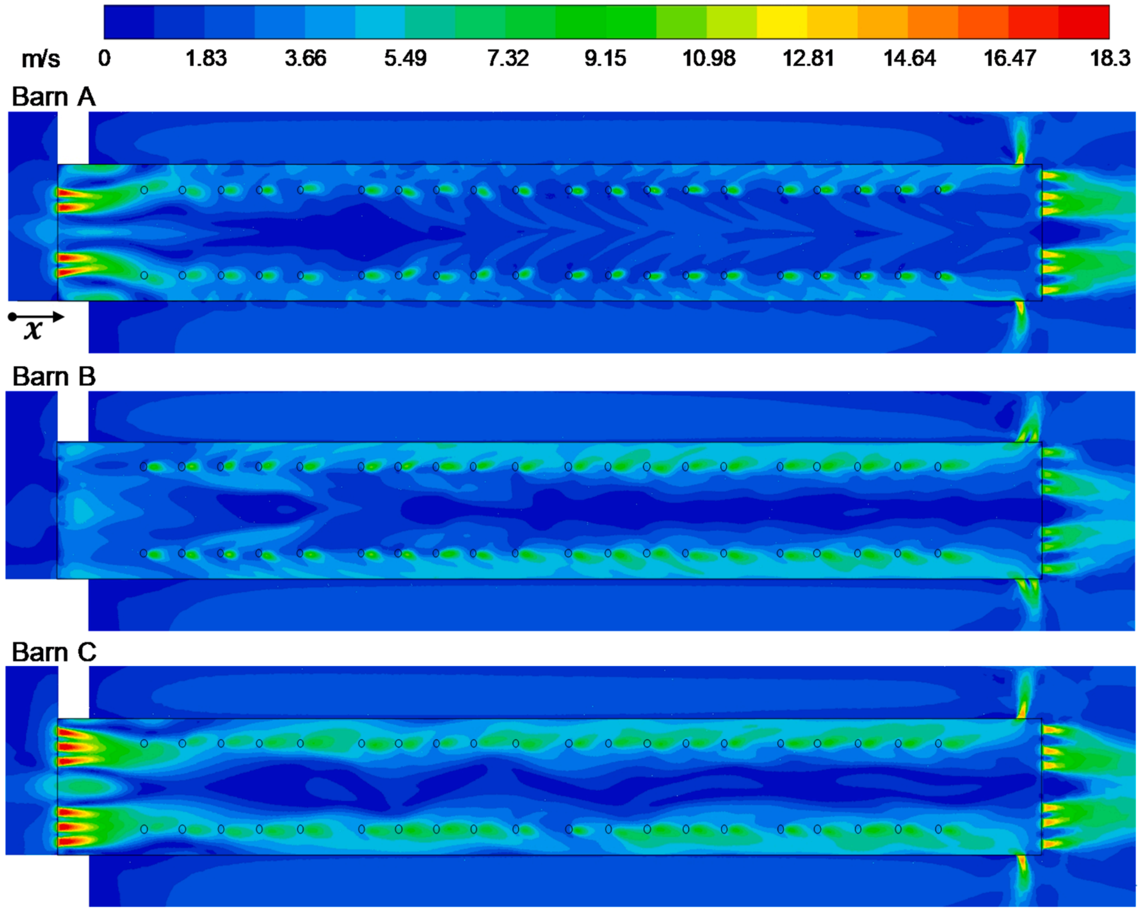

Fig. 14. Contours of velocity magnitude in a horizontal plane at a height of 1.55 m from the ground floor in barns A, B, and C. The oval shapes in the figure represent the overhead fans.

higher than the outside air, pushing the air out of the barn. While due to the use of inlet fans, there is a positive pressure inside barns A and C near the inlet end, Fig. 13(a and c), air is being pushed into the barns. At the resting areas near the exhaust end, Fig. 13(d and f), due to the exhaust fans, the positive pressure inside the barns has increased by about 60% compared to the resting areas near the inlet end.

Fig. 14 shows contours of the velocity magnitude in a horizontal plane at a height of 1.55 m from the ground floor in barns A, B, and C. To better understand the airflow patterns, the wireframes of the overhead fans are overlaid on the contours. The obtained air velocity in the resting areas in barn C was considerably higher than the other two barns. Comparing barns B and C, the air velocities near the exhaust end were similar, with a slight improvement in performance in barn C even though barn B had two additional exhaust fans. However, the air velocity values near the inlet end were considerably higher in barn C relative to barn B, demonstrating the effect of having inlet fans. Even though barn A, in addition to the inlet fans on the sidewalls, had fans on the inlet and exhaust ends, the obtained air velocities in the cow resting areas were considerably lower than barns B and C. High air velocity, more than 5 m/s, was only obtained near the overhead fans while the velocity in the areas between the fans was low, less than 3 m/s. It can be concluded that the sidewall inlet fans were working against the inlet end and exhaust fans, by pushing the air sideways rather than along the barn. This can be seen more clearly in Fig. 12 (d). In barns A and C, air was pushed out of the open doors on the inlet end of the barns. This is due to the positive pressure created in the barn next to the inlet fans. Therefore, positioning openings next to inlet fans is not recommended.

The air velocity along four horizontal lines at a height of 1.55 m in barns A, B, and C are shown in Fig. 15. The location of the lines correspond to the air velocity point measurements shown in Fig. 5. The lowest performing ventilation system, in terms of the air velocity along the resting areas, was barn A. Barns B and C had similar performance at half of the barn near the exhaust end with a slight advantage of barn C. However, at half of the barn near the inlet end, barn C have clearly outperformed barn B with the air velocity being at least 1 to 2 m/s higher. The air velocity along the lines near the sidewalls (Fig. 15(a and d)) was clearly higher than the inner lines (Fig. 15(b and c)) indicating the effect of the reduced cross sectional area of the barn on the air velocity.

The current study has some limitations. The presence of the cows was not considered in the CFD simulations. In future work, the effect of including the cows on the flow pattern and volume flow rate has to be considered.

4. Conclusions

This study compared the performance of three different mechanical ventilation systems for dairy cow barns. The comparison was performed using 3D steady RANS CFD simulations in terms of the volume flow rate and air velocity through the animal occupied zones. The presence of the cows was not considered in the CFD simulations. The simulations were validated against velocity point measurements in barn A. The main conclusions of this study are as follows:

- The air velocity through the cows resting areas was higher in barn C than barns A and B. The average volume flow rate (% of total volume flow rate of the barn) through the resting area in barn C was about 50% higher than barn A and 10% higher than barn B.

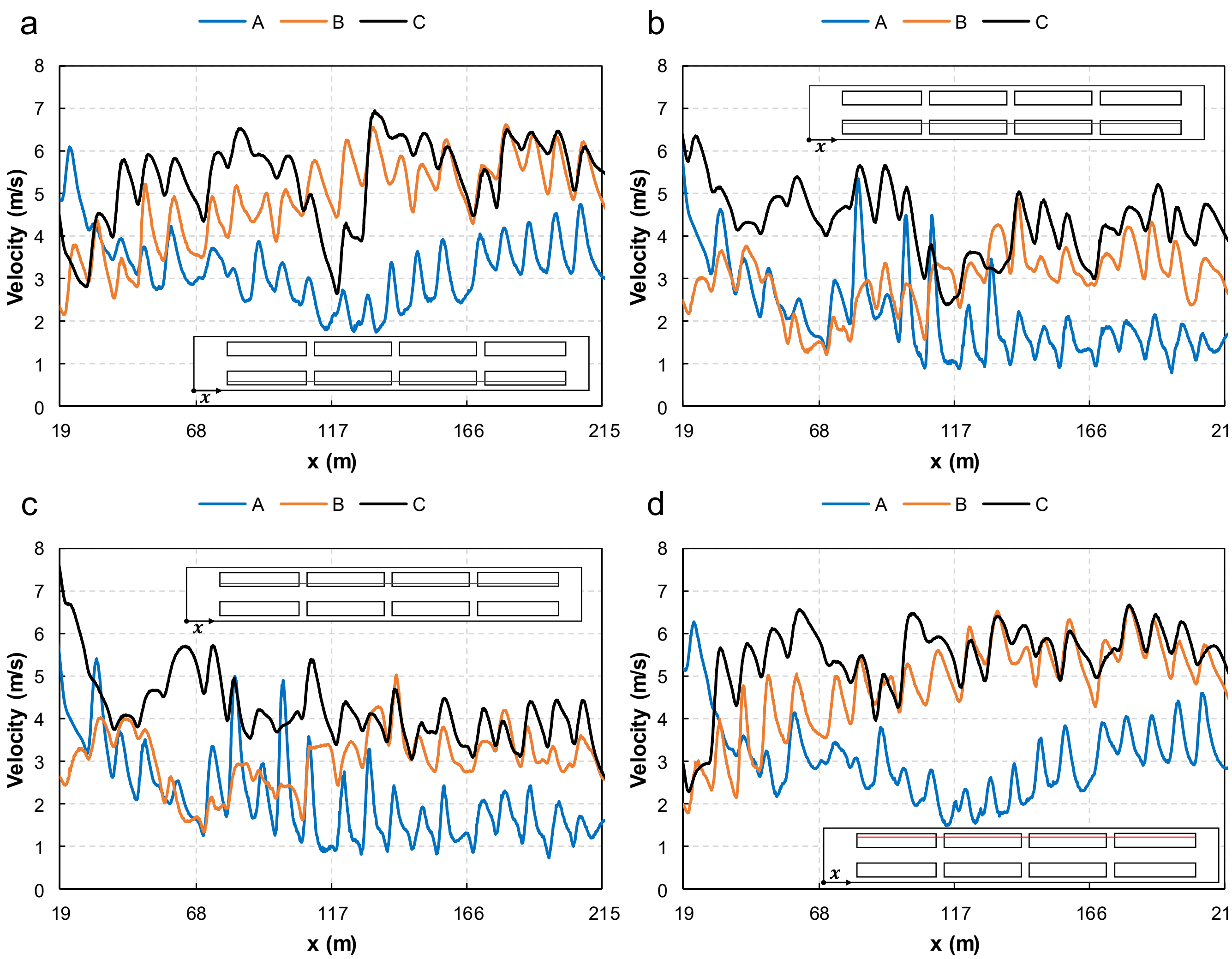

Fig. 15. Velocity magnitude along four horizontal lines at a height of 1.55 m in barns A, B, and C. The insets show a plan view of the barn illustrating the location of the horizontal lines.

- The average volume flow rate (% of total volume flow rate of the barn) through the animal occupied zone for barns B and C were respectively higher by about 30% and 33% than barn A, which showed the lowest performance.
- According to the results, it was shown that, given the length of the barn, it is necessary to have fans on the inlet end in addition to fans on the exhaust end of the barn (barn C) in order to obtain relatively sufficient and uniform air velocity along the barn.
- The combination of inlet fans located on the inlet end of the barn and sidewall inlet fans (barn A) is not recommended as it was shown that they work against each other, leading to low air velocity and volume flow rate through the animal occupied zones.
- Increasing the number of fans on the exhaust end without adding fans on the inlet end of the barn (barn B) would not increase the air velocity at the areas farthest from the exhaust end. Even though the use of a neutral pressure ventilation system in dairy cow barns is more expensive relative to the other types, in order to obtain a uniform and sufficient volume flow rate and air velocity through the animal occupied zones, both inlet and exhaust fans have to be used.
- Placing openings, for example, open doors, right next to inlet fans is not recommended, as it was shown that the created positive pressure inside the barn near the inlet fans pushed the air out of these openings.
- Even though the majority (about 60%) of the total volume flow rate of the barns (barns B and C) flowed through the animal occupied zones, airflow was provided in parts that were not required. Prompting the need to install horizontal or vertical baffles above the animal occupied zones to direct the flow into the parts that matters.

CRediT authorship contribution statement

Ali Pakari: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Saud Ghani:** Investigation, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Fig. 16

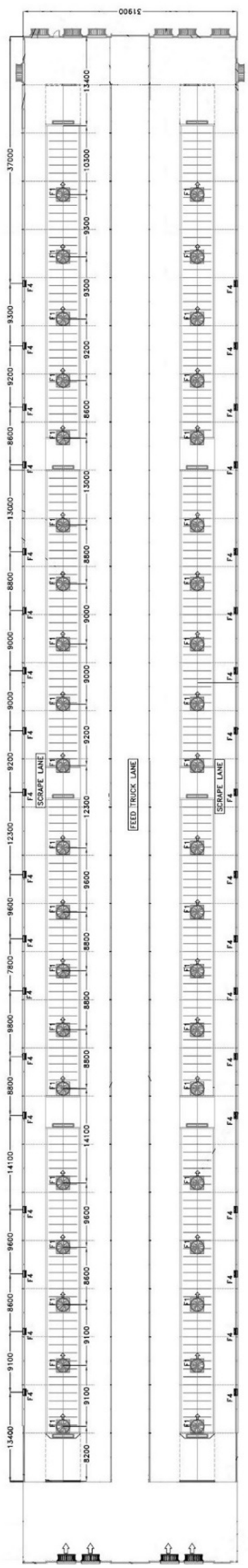

Fig. 16. Plan view of barn A, showing the locations of sidewall inlet fans (labeled as F4) and overhead circulation fans (labeled as F1). Dimensions are in mm.

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