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Comparison of airflow homogeneity in Compost Dairy Barns with different ventilation systems using the CFD model

B. Fagundes[1], F.A. Damasceno[2,*], R.R. Andrade[3], J.A.O. Saraz[4], M. Barbari[5], F.A.O. Vega[4] and J.AC. Nascimento[2]

[1]Professional Faculty, Department of Climatization Engineering, Porto Alegre, Tocantins Street, 937, n. 8, BR91.540.420 Porto Alegre, Brazil
[2]Federal University of Lavras, Department of Engineering, BR37200-000 Lavras, Minas Gerais, Brazil
[3]Federal University of Viçosa, Department of Agricultural Engineering, Av. Peter Henry Rolfs, s/n Campus University of Viçosa, BR36570-900, Viçosa, Minas Gerais, Brazil
[4]Univeridad Nacional de Colombia, Agrarian Faculty, Department of Agricultural and Food Engineering, Carrera 65 n. 59A – 110, Bloque 14 - Oficina 430, Medellin, Colombia
[5]University of Florence, Department of Agriculture, Food, Environment and Forestry, Via San Bonaventura, 13, IT50145 Firenze, Italy
[*]Correspondence: flavio.damasceno@ufla.br

Abstract. In the pursuit of high milk productivity, producers are using confinement systems in order to improve performance and animal welfare. Among the housing systems, the Compost bedded-pack barns (CBP) stand out. In these barns a bedding area is provided inside, where cows move freely. Generally this area is covered with carbon source material (such as sawdust or fine dry wood shavings) which together with manure, thanks a regular mechanically stirring, ensures the aerobic composting process. The ventilation in these facilities has the function of dehumidifying the air, improving the air quality, drying the bedding, improving the thermal comfort conditions of the confined animals. This work aimed at validating a computational model using Computational Fluid Dynamics (CFD) to determine the best homogeneity of airflows generated by different forced ventilation systems used in CBP barns. Two CBP barns were compared with different ventilation systems: high volume low speed (HVLS) and low volume high-speed (LVHS) fans. The results showed that the proposed model was satisfactory to predict the flows generated by both types of fans. It was concluded that the use of HVLS fans produced a more homogeneous airflow when compared to LVHS fans. The use of mechanical ventilation in tropical conditions is necessary for the proper functioning of the system. In this study, the systems used promoted the increase in air speed to levels close to adequate.

Key words: airflow, animal housing, compost-bedded pack barn, dairy cows, simulation.

INTRODUCTION

In dairy cattle farming, one of the major concerns of producers is the effect that the breeding environment can have on animals during lactation, especially in summer. High air temperature values are included among the main stressors that negatively affect the performance of lactating cows, especially in temperate climates.

The housing system can affect dairy cow's welfare and performance and have a major influence on the ecological footprint and the consumers' perception of dairy farming. Since shifting from tie-stall to loose housing, many different systems have been developed (Leso et al., 2020). Among the housing systems, the Compost bedded-pack barns (CBP) stand out.

The CBP are a relatively new loose housing system for dairy cows that seem to offer improved cow comfort (Leso et al., 2013; Leso et al., 2019). In compost barns the cows are free to move in a bedding area used for resting and exercise. Usually a feeding alley is present in the barn, with concrete floor. There are no obstacles to the movement of the animals like individual stalls of freestall housing (Oliveira et al., 2019b).

The main characteristic of the CBP system is to have a compost bedded pack resting area, consisting of carbon source material, which together with the animal excreta, thanks to the regular turning of this material, guarantees the main feature of the system, the degradation of organic material through microbiological decomposition (Janni et al., 2007).

The choice of the proper ventilation system is very important for its correct functioning in the CBP system, as it allows creating a comfortable thermal environment for the cows and the elimination of gases, dust and other pollutants, the maintenance of the air temperature and relative humidity of the bedding at levels suitable for composting (Damasceno, 2012). The main types of fans found in the CBP are: high volume and low speed (HVLS), and low volume and high speed (LVHS).

The evaluation of different ventilation systems in dairy cattle facilities, whether naturally or mechanically, were carried out through field studies by some authors (Endres et al., 2011; Lobeck et al., 2012; Oliveira et al., 2019a). However, there are limitations to carry out these studies, such as the difficulty in finding similar facilities in the same location and the high costs that must be paid for the experiments, among other factors. So, validated computer simulations can be carried out in the first phase of the study. Field tests of variables of interest are performed in a second phase.

The application of Computational Fluid Dynamics (CFD) in animal production is becoming increasingly important. The versatility, precision and ease of use offered by CFD makes it suitable to solve problems related to thermal environment in animal production facilities (Norton et al., 2007). Spatial and temporal solutions for air speed, air temperature, relative humidity and air pressure can be easily reproduced through the use of CFD simulations, reducing the number of field experiments.

The aim of this study was to evaluate and validate a computational model, using CFD, to determine the best homogeneity of air flows generated by different forced ventilation systems used in CBP.

MATERIALS AND METHODS

Characterization of the evaluated CBP barns

The experimental study was carried out in two CBP systems during the months of September and October 2018. One of the dairy farm was located in the Sete Lagoas, Minas Gerais, Brazil (CBP_{LVHS}). The other animal facility was located in the Piracicaba, São Paulo, Brazil (CBP_{HVLS}).

The evaluated CBP barns had dimensions of 20.0 m wide × 80.0 m long × 5.0 m side height. Both CBP barns had different ventilation systems and open sides. One CBP barn had six High Volume Low Speed (HVLS) fans, placed horizontally, with a diameter of 7.3 m, speed of 50 rpm, power of 2.0 hp and a flow rate of 478,500 m^3 h^{-1} each. The HVLS fans were distributed along the length of the CBP barn at a distance of 12.0 m at a height of 3.0 m.

The other CBP barn had twenty Low Volume High Speed (LVHS) fans, with a diameter of 2.0 m, rotation of 360 rpm, a power of 3.0 hp and a flow rate of 120,000 m^3 h^{-1} each. The LVHS fans were distributed, in pairs, along the length of the CBP barn at a distance of 8.0 m at a height of 3.0 m.

The stirring of the bedding in the two CBP barns occurred twice a day, during the milking periods (5:00 am and 4:00 pm), with a modified cultivator on small tractor.

Holstein cows were housed in both CBP barns with an average production of 32 kg of milk per day. The stocky densities were 12 m^2 $head^{-1}$ in CBP_{LVHS} and 15 m^2 $head^{-1}$ in CBP_{HVLS}. Sawdust was used in the bedding area of the CBP_{HVLS} and peanut shell in CBP_{LVHS}.

Field data collection

For the test and validation of the computational model, dry bulb temperature (T_{db}), relative humidity (RH), air speed and direction (V_{air}) and bed surface temperature (T_{bed}) data at two-second intervals, for two days consecutive at each CBP barn, were collected. The data were collected at 27 distributed points, in a 3×9 equidistant grid along the compost pack resting area at 0.50 m high (Fig. 1). For this, a portable digital thermo-hygrometer (Instrutherm®, mod. TI-400, with accuracy of ± 1.0%) was used. In the case of V_{air}, a hot wire anemometer was used (Highmed®, mod. HM-385 with an accuracy of ± 5.0%). The wind direction was checked with a windsock. An infrared thermometer (Highmed®, mod. HM-88C with ± 2.0% accuracy) was used to measure T_{bed}.

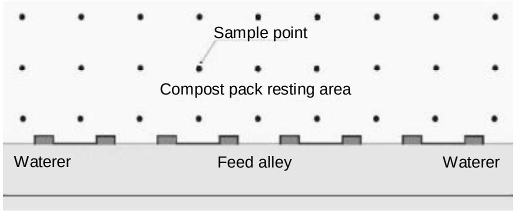

Figure 1. Spatial layout used for data collection.

Geometry

The definition of the domain geometry represents the first stage of the simulation in CFD.

Domain geometry for this study was generated with the software SolidWorks® (Fig. 2). The simulations were carried out by means of software ANSYS® version 17 (available at the Federal University of Rio Grande do Sul, Mechanical Engineering).

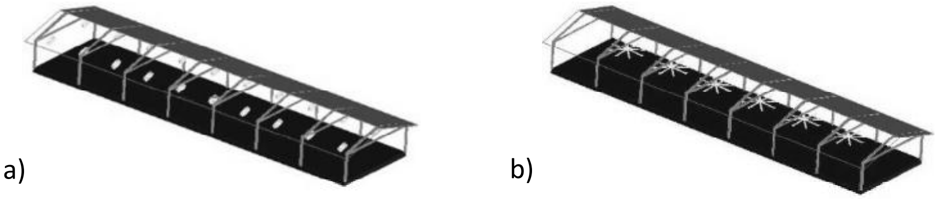

Figure 2. Geometries of CBP barns with different domains: a) LVHS and b) HVLS.

Computational mesh

Due to the complexity of the geometry and the dimensions of the fans, we chose to use the software ANSYS ICEM CFD® for designing a computational mesh with tetrahedral cells.

Tests with different mesh sizes were conducted until there were no significant differences between measured and simulated data ($p < 0.05$). As a result, a mesh of 3,805.719 tetrahedral elements (Fig. 3) was designed and used as the computational domain, which consisted of a system with 696,322 nodes. The Reynolds number for the proposed problem was 2.0917×107, which indicated a turbulent flow inside the CBP barns.

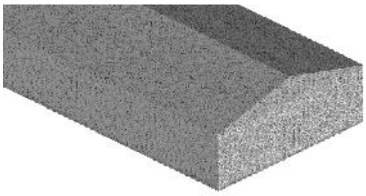

Figure 3. Mesh generated for implementation of the CFD model.

Numeric modelling

In this study the solution of the Reynolds number average system extracted from the Navier – Stokes equations allowed to define the CFD technique.

The model concerning the non-isothermal fluid flow is defined by equations of continuity, momentum and energy. The equations are simplified as suggested by Fluent (2004) and Ahmadi & Hashemabadi (2008):

$$\nabla.(\rho U) = 0 \tag{1}$$

$$\nabla.(\rho UU) = \nabla p + [\mu_\tau(\nabla U + \nabla U^T] \tag{2}$$

$$\nabla.(-k\nabla T + \rho C_p TU) = Q \tag{3}$$

P – density, kg m^{-3}; U – velocity vector; p – static pressure, N m^{-2}; T – tensor transposition; μ_τ – fluid dynamic viscosity, kg m^{-1} s^{-1}; κ – turbulent kinetic energy, m^2 s^{-2}; C_p – specific heat, W kg^{-1} K^{-1}; Q – term related to source, W m^{-3}.

The k-ε standard model was used to model the turbulent flow. The viscosity (μ_t) is calculated as relationship between turbulent kinetic energy (κ) and dissipation of turbulent kinetic energy ε.

$$\mu_\tau = C_\mu \rho \frac{\kappa^2}{s} \tag{4}$$

Eqs 5 and 6 allow to calculate k-ε values:

$$-\nabla.\left[\left(\eta + \rho \frac{C_\mu}{\sigma_k}\frac{k^2}{\varepsilon}\right)\nabla_k\right] + \rho U.\nabla_k = \rho C_\mu \frac{k^2}{\varepsilon} + (\nabla U + \nabla U^T)^2 - \rho\varepsilon \tag{5}$$

$$-\nabla.\left[\left(\eta + \rho \frac{C_\mu}{\sigma_\varepsilon}\frac{k^2}{\varepsilon}\right)\nabla_\varepsilon\right] + \rho U.\nabla_\varepsilon = \rho C_{\varepsilon 1} C_{\mu k}(\nabla U + \nabla U^T)^2 - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{6}$$

ε – dissipation of turbulent kinetic energy, m^2 s^{-3}; η – ratio between mean flow and temporal scale; $C_\mu = 0.09$; $C_{\varepsilon 1} = 1.44$; $C_{\varepsilon 2} = 1.92$; $\sigma_\varepsilon = 1.3$; $\sigma_k = 1.0$.

Boundary conditions

The purpose of the CFD simulations was to carry out an evaluation of the flow homogeneity, that is, to verify the flow behaviour and its distribution in the compost pack resting area.

In simulations ANSYS CFx software was used assuming four conditions (a: steady state; b: single-phase flow; c: thermal energy condition; d: incompressible and turbulent flow).

The simulated solution was validated using experimental data. The mean residue for linear systems technique (RMS, Root Mean Square) was considered with a tolerance of 10^{-4} as convergence criterion and a limit of 100 interactions.

Additionally, to create the CFD model, dimensions and operating conditions of the air velocity distribution in CBP barns model were used. Then, the measured values coming from the experimental CBP barn for boundary conditions were averaged out and implemented to the computational model as presented in Table 1.

Table 1. Average of input values used as the boundary conditions

Fan speed (LVHS)	360 rpm
Fan speed (HVLS)	50 rpm
Air dry bulb temperature	25.0 °C
Bed surface temperature	25.0 °C
Atmospheric pressure	0 Pa

The geometry of the fans was suppressed, due to the high computational cost that would be involved in the complete modelling of the fans. To represent the fans, the condition (Momentum Source) was applied to the cylinders representative of the fans. This condition is an adequate approach for the evaluation in question, since it correctly represents the flow and velocities obtained experimentally.

The condition of source of moment makes use a determined force per unit of volume. The force in Newtons generated by the fan in the volume that it occupies was estimated. In addition, the rotation speed of each fan was properly used for the cylinders.

A comparison of data coming from CFD model and data obtained in experimental trials was carried out. As recommended by ASTM (2002) (Eq. 7 and 8), the normalized mean square error (NMSE) was used to verify the agreement between experimental and model data. The same procedure and has been followed to validate the computational model in several studies with CFD (Zhao et al., 2007; Saraz et al., 2012). In this study a sample size of 160 data points was considered to calculate the NMSE. A high degree of agreement between measured and predicted values yields in an NMSE that is equal to 0. However, NMSE values lower than 0.25 are considered good indicators of agreement.

$$NMSE = \frac{\left(\overline{Cp - Co}\right)^2}{\left(Cpm \cdot Com\right)} \qquad (7)$$

$$\left(\overline{Cp - Co}\right)^2 = \frac{\sum_{n} \left(Cpi - Coi\right)^2}{n} \qquad (8)$$

C_{pi} – predicted value; C_{oi} – observed value; C_{pm} – average predicted value; C_{om} – observed value; n – number of measurements.

RESULTS AND DISCUSSION

For validation, a comparison between CBP_{LVHS} and CBP_{HVLS} of the data found by the CFD model and by experimental trials points out that the mean values of air velocity coming from the experiments show NMSE values of 0.12 and 0.10, respectively. Therefore, a good agreement between the results is reached. As conclusion, the average behaviour of air velocity inside the CBP barns with different ventilation systems can be predicted by means of the developed CFD model (Table 2).

Table 2. Comparison between model and experimental data for air velocity (m s^{-1})

Data	CBP_{LVHS}		CBP_{HVLS}	
	Experiment	CFD Model	Experiment	CFD Model
Mean	3.98	4.11	2.07	1.97
NMSE	0.12		0.10	

The relationship between air velocity data coming from experimental tests and from the model is illustrated in Fig. 4. Results of the application of a simple t-test for the null hypothesis (H_o) that the difference between model and experimental values of air velocity inside the CBP_{LVHS} is equal to 0, were in favour of H_o ($p = 0.877$). When fit to a linear model the correlation coefficient between experimental and model data is 0.949. So, the regressed model gives a good explanation of the change in this variable (F test, $P < 0.0001$), with 2.5 m s^{-1}average error (Fig. 4, a).

The mean air velocity at the CBP_{HVLS} calculated with the CFD model was 1.97 ± 0.9 m s^{-1}. The difference with the experimental mean air speed (2.07 ± 0.83 m s^{-1}) is not significant (simple t-test, $p = 0.718$). The linear model allowed explaining the variability of air velocity between model and experiment data (F test, $P < 0.0001$; R^2: 0.937) (Fig. 4b).

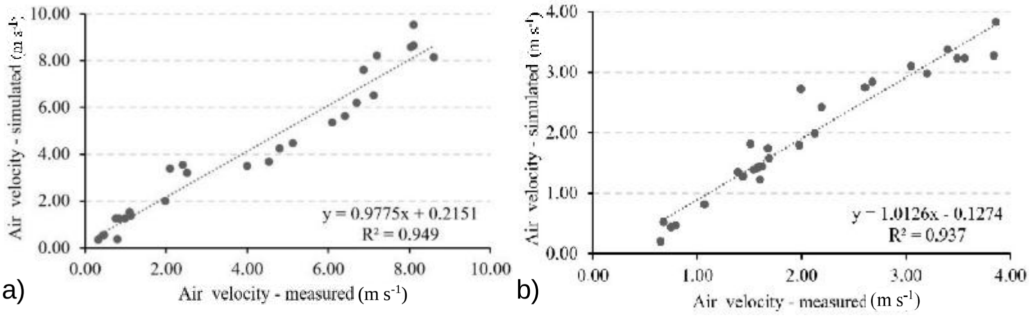

Figure 4. Relationship between model and experiment data for air velocity in CB barns with different ventilation systems: a) LVHS and b) HVLS.

The airflow lines and velocity distribution on the surface of compost pack resting area in the modelled CBP_{LVHS} barn can see in Fig. 5. The results demonstrate the current air flow lines for the HVLS fan (Fig. 5, a) that may undergo small variations. These variations are of small magnitude and do not significantly affect the results. The current air flow lines, through an HVLS fan, coming from the fan, close to the bed surface, is oriented in all directions. Below each fan, specifically in the centre, is a region of lower speeds (Fig. 5, b). Higher speeds are developed around this centre of the barn (ranging from 2.5 to 3.8 m s^{-1}).

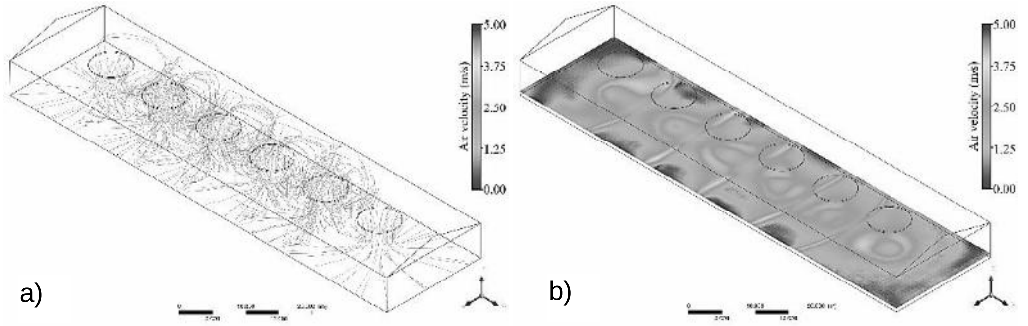

Figure 5. Results of CFD simulation of CBP barns with HVLS ventilation system: a) air flow lines and b) air velocity distribution on the surface of compost pack resting area.

According to Black et al. (2013), in CBP facilities, the ventilation should be provided such that the V_{air} is close to 1.8 m s^{-1} throughout the entire CBP, so that it can dry the bed, remove gases and favour the heat exchanges between the animal and the environment. Oliveira et al. (2019a), evaluating the spatial distribution of thermal conditions in CBP barns with different ventilation systems in Brazil, observed that in all facilities examined the V_{air} was lower (1.0 m s^{-1}) than the recommended. In this study, the systems used promoted the increase of such an attribute to levels close to adequate in most of the facilities. In addition, the results also show that the use of mechanical ventilation in tropical conditions is necessary for the proper functioning of the system, since only the natural ventilation was not sufficient to promote V_{air} values according to the recommendation for CBP barns.

The result of the CFD simulation in the CBP barn with the LVHS ventilation system is shown in Fig. 6. The air flow created by LVHS fans is distributed close to the surface of the compost bed, following the longitudinal direction of the barn (Fig. 6, a).

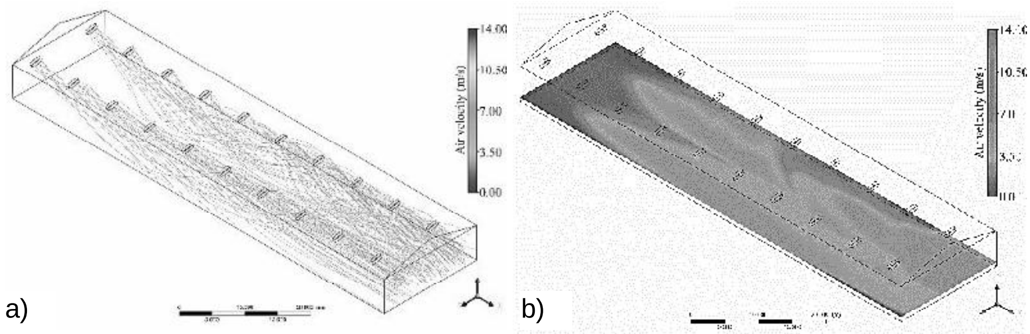

Figure 6. Results of CFD simulation of CBP barns with LVHS system: a) air flow lines and b) air velocity distribution on the surface of compost pack resting area.

Fig. 6, b shows the distribution of air velocity on the bed surface. At one end of the bedding area the air velocity values are very low. Two regions are observed at the opposite end of the CBP facility with higher speeds in the centre (around 4.0 m s^{-1}) and lower ones on the sides (around 2.5 m s^{-1}) of the compost bedding area. Air velocity values close to 5 m s^{-1} can be observed in the region of the right end of the compost bedding area due to the position of the LVHS fans and instability of air flow. The average air velocities caused an acceleration of the flow of air in this region.

Oliveira et al. (2019b) evaluating several CBP facilities in Brazil found that an artificial ventilation system was used by the compost barns in most cases (94.1%). They detected an air velocity at 0.05 and 1.50 m height of 1.3 ± 0.7 and 1.7 ± 0.8 m s^{-1}, respectively. The mechanical ventilation system in 76.4% of barns was realized by LVHS. Low Volume High Speed fans are spread in several parts of the world. In Kentucky 48.0% of CBP barns has LVHS fans as ventilation system (Damasceno, 2012).

CONCLUSIONS

The model was validated and could be used to predict the behavior in real time of air velocity distribution inside the CBP barns with differents ventilations systems.

The comparative analysis of the air flows generated by the HVLS and LVHS fans showed visual information that allows the evaluation to determine the best air flow homogeneity. The results indicate a better homogeneity in the CBP barn with HVLS fans with a smaller area with speed close to zero.

In all CBP barns evaluated, the air velocity (V_{air}) was higher than the recommended (1.8 m s^{-1}) in most of the bedding area, so that it can dry the bed, remove gases and favour the heat exchanges between the animal and the environment.

Nevertheless, in future studies, CFD models could be used to predict the distribution of heat within the CBP barns at different air speed and types of ventilations systems.

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REFERENCES

Ahmadi, A.H. & Hashemabadi, S.H. 2008. 3D CFD simulation and experimental validation of particle-to-fluid heat transfer in a randomly packed bed of cylindrical particles. *International Communications in Heat and Mass Transfer* **35**, 1183–1189.

Ansys. 2016. Ansys Fluent 17.0 - Theory Guide - Ansys, INC. Canonsburg, PA, USA, 1236 pp.

ASTM. 2002. Guide for statistical evaluation of indoor air quality models (D5157-97). In: *American Society for Testing Materials. ASTM Standards on Indoor Air quality, 2nd edition.* West Conshohocken, pp. 68–71.

Black, R.A., Taraba, J.L., Day, G.B., Damasceno, F.A. & Bewley, J.M. 2013. Compost bedded pack dairy barn management, performance, and producer satisfaction. *J. Dairy Sci*. **96**, 8060–8074.

Damasceno, F.A. 2012. *Compost bedded pack barns system and computational simulation of airflow through naturally ventilated reduced model*. Thesis, Universidade Federal de Viçosa, Brazil, 404 pp.

Endres, M.I., Lobeck, K., Janni, K., Godden, S. & Fetrow, J. 2011. Barn Environment Study. *Minnesota Dairy Health Conference*. St. Paul. Minnesota, pp. 47–56.

Fluent. 2004 The manual of computational fluid dynamics (CFD), version 5.5. New Hampshire, USA, 625 pp.

Janni, K.A., Endres, M.I., Reneau, J.K. & Schoper, W.W. 2007. Compost dairy barn layout and management recommendations. *Appl. Eng. Agr.* **23**, 97–102.

Leso, L., Uberti, M., Morshed, W. & Barbari, M. 2013. A survey of Italian compost dairy barns. *J. Agr. Eng.* **44**(3), 120–124.

Leso, L., Pellegrini, P. & Barbari, M. 2019. Effect of two housing systems on performance and longevity of dairy cows in Northern Italy. *Agronomy Research* **17**(2), 574–581. https://doi.org/10.15159/AR.19.107

Leso, L., Barbari, M., Lopes, M. A., Damasceno, F.A., Galama, P., Taraba, J.L. & Kuipers, A. 2020. Invited review: Compost-bedded pack barns for dairy cows. *J. Dairy Sci.* **103**(2), 1072–1099.

Lobeck, K.M., Endres, M.I., Janni, K.A., Godden, S.M. & Fetrow, J. 2012. Environmental characteristics and bacterial counts in bedding and milk bulk tank of low profile cross-ventilated, naturally ventilated, and compost bedded pack dairy barns. *Appl. Eng. Agr.* **28**, 117–128.

Norton, T., Sun, D.W., Grant, J., Fallon, R. & Dodd, V. 2007. Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: a review. *Bioresource technology* **98**, 2386–2414.

Oliveira, C.E.A., Damasceno, F.A., Ferraz, P.F.P., Nascimento, J.A.C., Ferraz, G.A.S. & Barbari, M. 2019a. Geostatistics applied to evaluation of thermal conditions and noise in compost dairy barns with different ventilation systems. *Agronomy Research* **17**(3), 783–796. https://doi.org/10.15159/AR.19.116

Oliveira, V.C., Damasceno, F.A., Oliveira, C.E.A., Ferraz, P.F.P., Ferraz, G.A.S. & Saraz, J.A.O. 2019b. Compost-bedded pack barns in the state of Minas Gerais: architectural and technological characterization. *Agronomy Research* **17**(5), 2016–2028. https://doi.org/10.15159/AR.19.179

Saraz, J.A.O., Tinôco, I.F.F., Rocha, K.S.O., Martins, M.A. & Damasceno, F.A. 2012. Validation of a CFD model for prediction of the efficiency of evaporative cooling in porous panels. *Revista U.D.C.A Actualidad & Divulgación Científica* **15**, 209–217.

Zhao, J., Manbeck, H.B. & Murphy, D.J. 2007. Computational fluid dynamics simulation and validation of H_2S removal from fan-ventilated confined-space manure storages. *Trans. ASABE* **50**(6), 2231–2246.