Agronomy Research **17**(3), 890–899, 2019
https://doi.org/10.15159/AR.19.108

Computational fluids dynamics (CFD) in the spatial distribution of air velocity in prototype designed for animal experimentation in controlled environments

M.O. Vilela[1,*], R.S. Gates[2], M.A. Martins[1], M. Barbari[3,*], L. Conti[3], G. Rossi[3], S. Zolnier[1], C.G.S. Teles Jr.[1], H.H.R. Zanetoni[1], R.R. Andrade[1] and I.F.F. Tinôco[1]

[1]Federal University of Viçosa, Department of Agricultural Engineering, Av. Peter Henry Rolfs, s/n Campus University of Viçosa CEP: 36570-900, Viçosa, Minas Gerais, Brazil
[2]University of Illinois at Urbana-Champaign, Department of Agricultural and Biological Engineering, 1304 West Pennsylvania Avenue 61801, Urbana, USA
[3]University of Florence, Department of Agriculture, Food, Environment and Forestry, Via San Bonaventura, 13, IT50145 Firenze, Italy
[*]Correspondence: monique.vilela@ufv.br; matteo.barbari@unifi.it

Abstract. Maintaining a comfortable and productive thermal environment is one of the major challenges of poultry farming in tropical and hot climates. The thermal environment encompasses a number of factors that interact with each other and reflect the actual thermal sensation of the animals. These factors characterize the microclimate inside the facilities and influence the behaviour, performance and well-being of the birds. Thus, the objective of this study is to propose and validate a computational model of fluid dynamics to evaluate the spatial distribution of air velocity and the performance of a system designed to control air velocity variation for use in experiments with birds in controlled environment. The performance of the experimental ventilation prototype was evaluated based on air velocity distribution profiles in cages. Each prototype consisted of two fans coupled to a PVC pipe 25 cm in diameter, one at each end of the pipe, with airflow directed along the entire feeder installed in front of the cages. The contour conditions considered for the simulation of airflow inside the cage were air temperature of 35 °C at the entrance and exit of the cage; air velocity equal to 2.3 m s^{-1} at the entrance of the cage; pressure of 0 Pa. The model proposed in this study was representative when compared to the experimental measurements, and it can be used in the study of air flow behaviour and distribution for the improvement of the prototype design for later studies.

Key words: computational fluids dynamics, air velocity, ventilation, poultry farming.

INTRODUCTION

In the last decades, the Brazilian poultry industry has presented great advances and expressive numbers within the animal protein production complex. In view of all the modernization of the sector, quail breeding in Brazil is considered a very profitable activity for the producer who wishes to invest professionally in the exploitation of eggs and meat (Albino & Barreto, 2012).

One of the major challenges of poultry farming in tropical and hot climates is the maintenance of a comfortable and productive thermal environment for birds (Coelho et al., 2018), since, under unfavourable thermal conditions, animals need to adjust their behavioural and physiological patterns in order to perform the heat balance (Farag & Alagawany, 2018). Climatic elements such as temperature and relative humidity of the air, wind and solar radiation are preponderant factors as they directly affect the productive, reproductive and survival capacity of quails (Baêta & Souza, 2010; Leinonen et al., 2014; Nawab et al., 2018).

One of the most commonly used tools for the characterization of the animal breeding thermal environment is the development of mathematical models and the application of numerical simulations based on Computational Fluid Dynamics (CFD) (Curi et al., 2017; Saraz et al., 2017; Rojano et al., 2019). This methodology is an efficient way to predict the distribution of climatic variables inside a facility, because it reduces the time and the experimental costs and, consequently, it assists in the decision-making regarding the optimization of the installation design. Several thermal packaging configurations can be readily reproduced and evaluated in CFD simulations, as performed by Rojano et al. (2015), which evaluated the dynamics of a broiler facility analysing sensible and latent heat, mass transport and radiant energy transfer from the poultry rearing environment. Damasceno et al. (2014) adapted and validated a model for predicting temperature and air velocity of a heated air distribution system in chicken broiler houses. The authors verified that the validated model can be used to test different design configurations, different construction materials and other conditions of temperature and velocity of the incoming air. Osório Saraz (2010) also used the CFD to develop and validate a model to determine the distribution of ammonia concentrations in a broiler installation equipped with natural ventilation and without thermal insulation. The author states that the proposed model presented a good statistical correlation with the experimental data, and it can be used to predict the behaviour of the ammonia concentration within the house in real time.

Air velocity in animal facilities is one of the main factors to be considered, especially in Brazil, where the constructive typology of aviaries is largely open. Thus, it is of paramount importance to plan the design of animal facility projects according to the environmental needs of the species, the type of management and the climatic characteristics of each region (Biaggioni et al., 2008; Coelho et al., 2015), including the direction and speed of the air, so that it can be controlled as required. In view of the relevance of more studies relating the influence of air velocity on the well-being and performance of farmed animals, and considering the practical difficulty often encountered to perform this type of experiment under field conditions, it is of paramount importance the development of control prototypes of this variable, which can be used in experiments with animals in controlled environments. An example of this is the system developed by Yanagi et al. (2002) for the control and measurement of dry bulb temperature, relative humidity and air velocity in a research evaluating the effect of heat stress on birds.

Thus, the present work aims to propose and validate a model using computational fluid dynamics (CFD) to be used in the study of the spatial distribution of air velocity and in the evaluation of the performance of a system designed to control the variation of air velocity for use in experiments with birds in a controlled environment.

MATERIALS AND METHODS

Experimental Design

The present research was carried out in a climatic chamber located in the Experimental Area of the Center for Research in Ambience and Engineering of Agroindustrial Systems (AMBIAGRO) in the Agricultural Engineering Department of the Federal University of Viçosa. The climatic chamber has dimensions of 3.2 m in length, 2.44 m in width and 2.38 m in height and is equipped with heating, humidification and cooling system. Setpoints of temperature and relative humidity were established by electronic micro controllers (Model MT-513R plus, Full Gauge Controls, Canoas, RS, BR), installed inside the climatic chambers, with temperature control in the range of -10 to 70 °C and resolution of 1 °C, and relative humidity control from 20 to 85%, with resolution of 0.1%.

The designed air velocity control system consists of Micro Motor fans (Elgin 1/25 MM-20B Bivolt, 60 Hz frequency, 11.93 W and 25 cm diameter). The set consists of two fans coupled in a PVC pipe, one at each end, with the outflow of air directed to the cages. The maximum volumetric flow rate of the system, according to the manufacturer's specifications, is 950 $m^3\ h^{-1}$. Thus, by adjusting the power frequency, the air velocities of the fans could be manipulated and adjusted at different levels, according to what was predetermined for the experiment.

The experimental ventilation prototype was installed in front of the cage (Fig. 1), with possibility to adjust different air velocities at the level of the birds.

Figure 1. Inside view of the climatic chambers, where 1: air conditioning; 2: air humidifier; 3: electronic temperature and relative humidity controller (MT-531R plus); 4 and 5: ventilation tubes; 6: air heater; 7 and 8: cages; 9 and 10: feeders; 11 and 12: water tanks.

To validate the simulation, air velocity data were collected at 275 points uniformly arranged along the three dimensions (width, length and height) of the whole cage. The thermoanemometer Testo 425, used for the trials, has the following specifications: probe head 7.5 mm in diameter, measuring range 0.0 to 20.0 m s^{-1}, resolution of 0.01 m s^{-1} and range for the 2-second moving average. The data were collected during the period of 1 minute, totalling 30 samples per point, and finally the average was recorded in the display.

Computational Model

The geometry (Fig. 2) was developed in software ANSYS S® Workbench™ 18.2 Academic using the DesignModeler™ and the mesh was developed in Meshing. The three-dimensional geometry was conceived in the actual dimensions of the cage used in the experiment, the area being modelled 0.38 x 0.33 m, considering only half-length in order to reduce the computational domain.

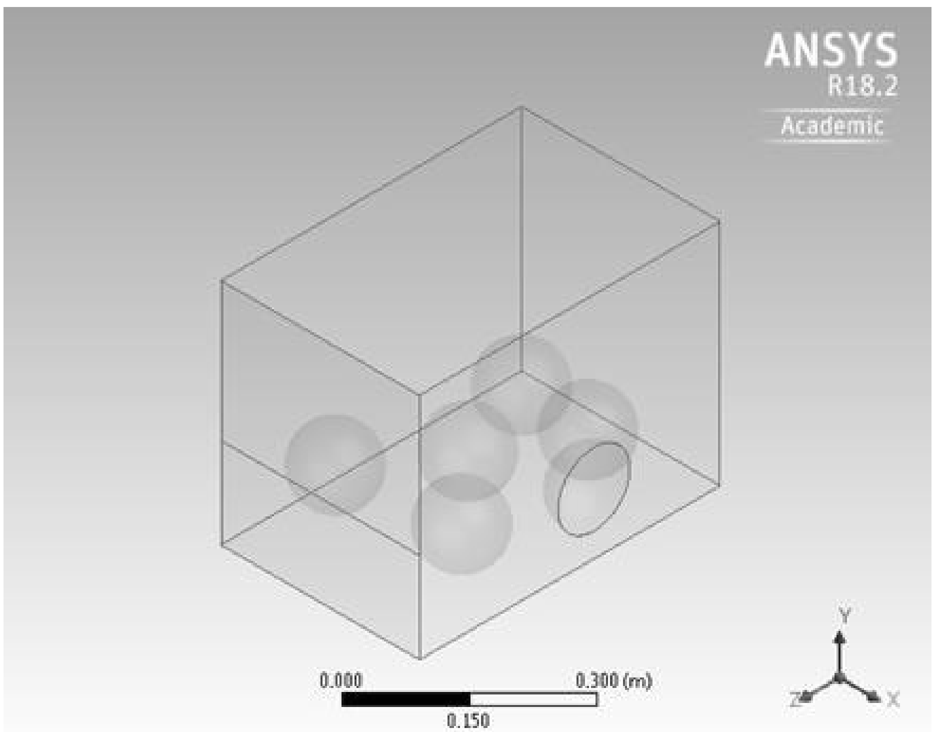

Figure 2. Cage's geometry in ANSYS software 18.2.

The CFD technique was used to solve the Navier-Stokes equations and energy equation, discretizing the fields of velocity, temperature and pressure by the finite volume method. The set of governing equations is given by the equations of continuity, conservation of momentum and energy.

The considerations assumed were: permanent regime, incompressible and turbulent flow. The model of turbulence adopted was the Shear Stress Transport model, where the High Resolution option in Turbulence Numerics was selected.

Quail was considered as a source of heat, and its estimate of heat production (q) was calculated by Eq. 1, proposed by International Commission of Agricultural and Biosystems Engineering - CIGR (2002).

$$q = (6.28m^{0.75} + 1.25) \cdot (1 + \frac{20(20 - T)}{1,000}) \quad (1)$$

where m = bird weight (approximately 0.15 kg); T = environment temperature (°C).

Spheres distributed randomly in the cage represented the birds, in order to evaluate the airflow distribution and the influence of the animals in the heat transfer process. The boundary conditions of the domain are shown in Table 1.

Table 1. Boundary conditions adopted for the simulation of the airflow inside the cage

	Boundary condition	Type	Properties
Cage	Inlet	Inlet	External air temperature = 35 °C
			Air velocity = 2.3 m s^{-1}
	Outlet	Outlet	Pressure = 0 Pa
			External air temperature = 35 °C
	Opening	Opening	Pressure = 0 Pa
			External air temperature = 35 °C
	Wall	Wall	No slip wall
Quail			Heat source = 2144.4 W m^{-3}

The thermophysical properties considered for quails in this study were: a) thermal conductivity: 0.45 W m^{-1} K^{-1} (Pereira et al., 2013); b) specific heat: 3,340 J kg^{-1} K^{-1} (Neves Filho, 1978); c) density: 1,075 g cm^{-3} (Pereira et al., 2013).

The mesh independence test was performed with different levels of refinement. Nine different mesh sizes were tested, ranging from 0.005 to 0.015 m. As convergence criterion, the mean square error type was adopted, with a value less than 10^{-5}, maximum number of iterations equal to 500 and Physical Timescale of 1s. The selected advection scheme was Specified Blend Factor, with Blend Factor of 0.8.

Model validation

The results obtained by the CFD model were compared with the real corresponding experimental data by means of the normalized mean square error (NMSE) (Eq. 2).

$$\text{NMSE} = \frac{(V_{CFD} - V_m)^2}{(V_{CFD} \cdot V_m)} \quad (2)$$

RESULTS AND DISCUSSION

Several types of tetrahedral meshes were used, and after the previous evaluation of different levels of refinement, a mesh with 170,502 nodes and 891,715 elements was selected. The result of the mesh test is presented in Table 2 and Fig. 4. The test was performed from the data obtained at the measurement points located near the air outlet of the cage (Fig. 3), 8 cm in height of the floor. Line 1 refers to the location of the points used in the mesh independence test.

A reduction in the difference of the values of air velocity between the meshes was observed and, therefore, mesh independence from the mesh size 0.006 m was verified.

Table 2. Air velocity at the positions of the X-axis (m) at the air outlet of the cage

Mesh size (m)	Number of nodes	Elements	X-axis position (m)			
			0.05	0.10	0.20	0.30
0.005	265,558	1,404,140	2.63	0.69	1.31	2.00
0.006	170,502	891,715	2.62	0.69	1.19	2.00
0.007	117,205	607,156	2.54	0.68	1.13	1.94
0.008	85,055	436,239	2.44	0.71	0.95	1.87
0.009	67,592	346,822	2.36	0.70	0.84	1.83
0.010	52,405	267,013	2.26	0.68	0.75	1.77
0.013	27,709	137,899	1.97	0.66	0.61	1.59
0.015	19,622	95,867	1.70	0.63	0.51	1.43

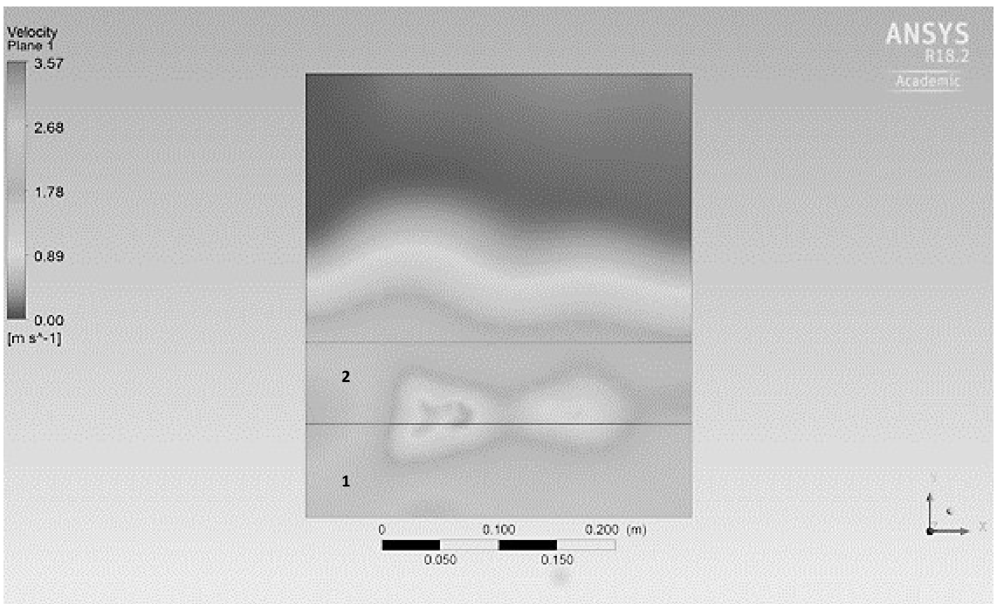

Figure 3. Air velocity profile in cross section of cage.

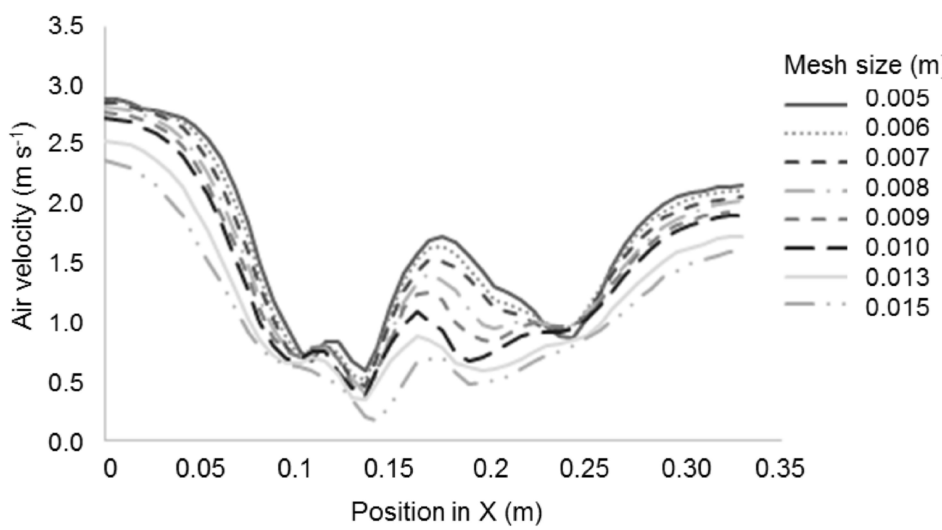

Figure 4. Mesh independence test, with mesh size ranging from 0.005 to 0.015m.

To validate the simulation, air velocity values obtained by CFD at different positions (A: 0.05 m; B: 0.10 m; C: 0.20 m; D: 0.30 m) were compared with the real values measured by means of NMSE. The NMSE was calculated at the entrance Z = 45 cm) and air outlet of the cage (Z = 3 cm). The results found are shown in Table 3.

It is observed that in position A, both in the entrance and in the air outlet of the cage, the NMSE found was superior to the level considered ideal to indicate the agreement between the values simulated and measured experimentally. However, in the other positions, the values found indicated good agreement between the measured and simulated data.

Table 3. Normalized Mean Square Error (NMSE) between the air velocity values obtained in the simulation and experimentally

	Position (m)	NMSE
Air Inlet	A	1.532
	B	0.001
	C	0.000
	D	0.019
Air Outlet	A	5.619
	B	0.051
	C	0.070
	D	0.026

Mostafa et al. (2012) state that NMSE values below 0.25 are considered good indicator of agreement between simulated and field values. Corroborating with our findings, Padavagod Shivkumar et al. (2016) evaluated the performance of a poultry engineering chamber complex by direct flow testing and CFD, and they found NMSE of 0.007, indicating a good agreement of simulated results with measurements. Saraz et al. (2016) evaluated the environmental conditions in a natural ventilation system in broiler chickens by means of the computational fluid dynamics and verified NMSE values of 0.024 to 0.099 between the ammonia concentration obtained in the simulation and the experimental measurements. The values considered in the study indicate that the model is able to predict the concentration of ammonia inside the aviary. Similarly, Mostafa et al. (2012), studying different configurations of ventilation systems of broiler chickens by means of CFD, obtained NMSE values of 0.2 between the simulated and measured values for ammonia concentration, being considered satisfactory for the prediction of the concentration of gas.

After validation of the model, the behaviour of airflow and velocity distribution was observed. Fig. 5 shows the airflow behaviour from the streamlines in the three dimensions of the cage (x, y and z). Fig. 6 shows that air velocity decreases as affected by the presence of the quails but increases on the sides of the birds due to the principle of mass conservation, which leads to air velocities greater than the velocity of entry, which is 2.3 m s^{-1}.

The importance of studying the intensity and distribution of airflow, especially in the area near the feeder, is associated with its influence on the ingestive behaviour of the animals. Thus, Yahav et al. (2001) studying the effect of air velocity on the performance of broilers subjected to heat stress (35 °C), concluded that birds exposed to higher air velocities (2.5 and 3 m s^{-1}) obtained better results in terms of weight gain, feed intake and feed conversion when compared to birds submitted to air velocity of 0.5 m s^{-1}. At air velocities of 2.3 m s^{-1}, there are very low values, generally less than 1 m s^{-1}, and the highest values are very close to 3 m s^{-1}, which implies averages always below the nominal speed expected for the treatment. Such amplitude can be explained due to the effect of the turbulence present in this flow.

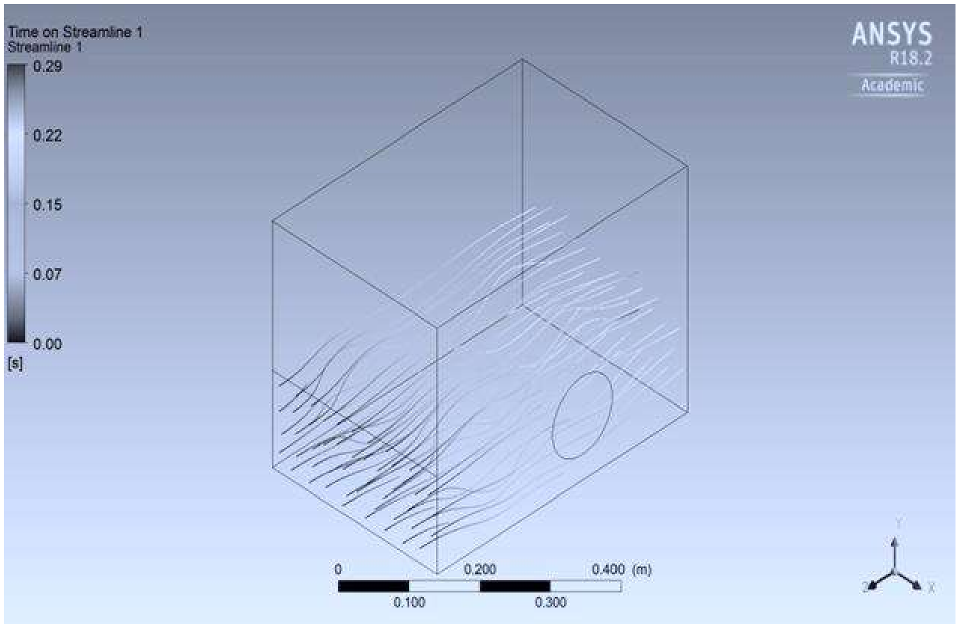

Figure 5. Behaviour of airflow demonstrated by streamlines.

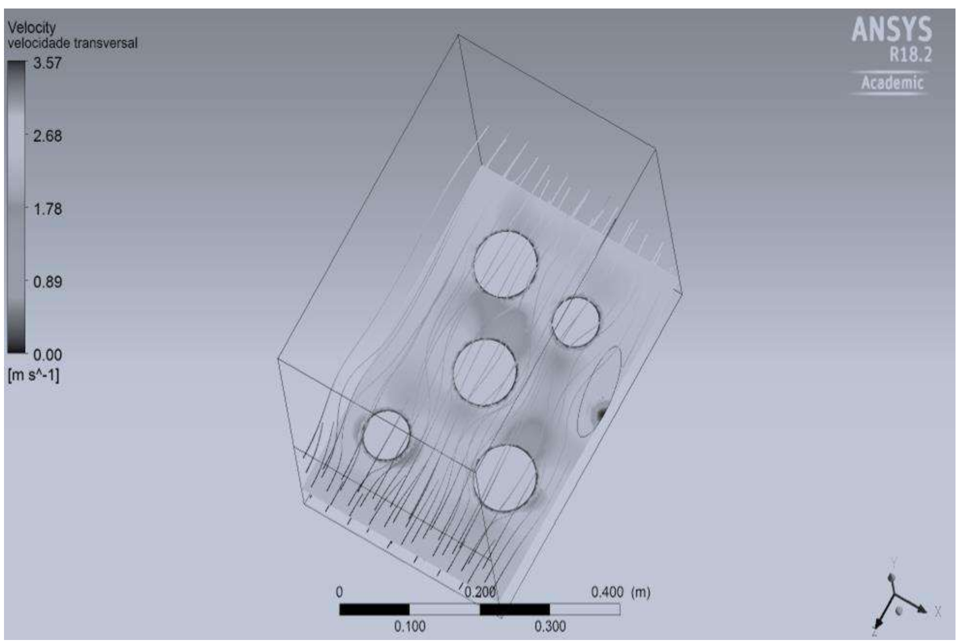

Figure 6. Simulated results visualization for the air velocity in the XZ plane.

According to Bustamante et al. (2013), CFD technique gives a more general view of indoor climate conditions of poultry farms through the graphics than direct measurements, making it a more complete and informative tool. Saraz et al. (2012) affirm that the studies carried out in recent years demonstrate the CFD technique advantages to deepen the studies of the heat and mass transfer phenomena, as well as to improve and optimize the structures designs seeking to obtain a better animal thermal comfort.

CONCLUSIONS

The proposed CFD model presented a good agreement with the real air velocity data obtained by the anemometer, i.e., the air velocity was not influenced by the methodology (real measurements or CFD). Thus, it can be a good tool to help researchers in creation, development and analyses of a system designed to control and adjust the air velocity, for the study of air velocity in controlled environments, as in climatic chambers.

The variation of air velocity observed inside the cage was substantially due to the opening design, since part of the incoming airflow is lost along the way through side and upper openings. In spite of this, higher velocities in the entrance of air were reached at the feeder zone, showing that the constructed prototype can be used in studies related to environment and ingestive behaviour of birds.

ACKNOWLEDGEMENTS. To FAPEMIG, CNPq, CAPES, Federal University of Viçosa, University of Illinois and University of Florence.

REFERENCES

Albino, L.F.T. & Barreto, S.L.T. 2012. *Quails for egg and meat production*. Viçosa: Aprenda Fácil, 268 pp. (in Portuguese).

Baêta, F.C. & Souza, C.F. 2010. *Environment in Rural Buildings*. 2nd ed. Viçosa: Editora UFV, 269 pp. (in Portuguese).

Biaggioni, M.A.M., De Mattos, J.M., Jasper, S.P. & Targa, L.A. 2008. Thermal performance in layer hen house with natural acclimatization. *Semina: Ciencias Agrária*s **29**(4), 961–972.

Bustamante, E., García-Diego, F., Calvet, S., Estellés, F., Beltrán, P., Hospitaler, A. & Torres, A.G. 2013. Exploring ventilation efficiency in poultry buildings: The validation of computational fluid dynamics (CFD) in a cross-mechanically ventilated broiler farm. *Energies* **6**(5), 2605–2623.

CIGR. 2002. *Climatization of Animal Houses – Heat and Moisture Production at Animal and House Level*. 4th Report of CIGR Working Group. Horsens, Denmark, 46 pp.

Curi, T.M.R.C., de Moura, D.J., Massari, J.M., Mesquita, M. & Pereira, D.F. 2017. Computational Fluid Dynamics (CFD) application for ventilation studies in broiler houses. *Engenharia Agrícola* **37**(1), 1–12.

Coelho, D.J.R., Tinôco, I.F.F., Vieira, M.F.A., Mendes, M.A.S.A., Sousa, F.C. & França, L.G.F. 2015. Mapping the thermal environment of aviaries of open posture in vertical creation system. *Revista Brasileira De Engenharia Agrícola e Ambiental* **19**(10), 996–1004.

Coelho, D.J.R., Sousa, F.C., Baptista, F., Cruz, V.F., Tinôco, I.F.F. & Souza, C.F. 2018. Use of analysis and processing of digital images for evaluation and control of animal behavior in hot climates. *Agricultural Engineering International: CIGR Journal*, 2018 (Special Issue).

Damasceno, F.A., Saraz, J.A.O., Mendes, L.B., Martin, S. & Martins, M.A. 2014. Evaluation of a heating system in poultry houses using a CFD model. *Rev. Fac. Nac. Agron. Medellín* **7**(2), 7311–7319.

Farag, M.R. & Alagawany, M. 2018. Physiological alterations of poultry to the high environmental temperature. *Journal of Thermal Biology* **76**, 101–106.

Leinonen, I., Williams, A.G. & Kyriazakis, I. 2014. The effects of welfare-enhancing system changes on the environmental impacts of broiler and egg production. *Poultry science* **93**(2), 256–266.

Mostafa, E., Lee, I.B., Song, S.H., Kwon, K.S., Seo, I.H., Hong, S.W. & Han, H.T. 2012. Computational fluid dynamics simulation of air temperature distribution inside broiler building fitted with duct ventilation system. *Biosystems Engineering* **112**, 293–303.

Nawab, A., Ibtisham, F., Li, G., Kieser, B., Wu, J., Liu, W., Zhao, Y., Xiao, M., An, L., Kieser, B., Nawab, Y. & Li, K. 2018. Heat stress in poultry production: Mitigation strategies to overcome the future challenges facing the global poultry industry. *Journal of Thermal Biology* **78**, 131–139.

Neves Filho, L.C. 1978. *Study of Some Variables in Chicken Immersion Continuous Cooling*. Thesis MSc in Food Engineering, FEA/UNICAMP, Campinas-SP, 164 pp. (in Portuguese).

Osório-Saraz, J.A. 2010. Measurement and CFD modelling of ammonia concentration, flux and thermal environment variables in open side broiler housing. *Thesis Doctorate* in Rural Constructions, UFV, Viçosa, MG, 136 pp.

Padavagod Shivkumar, A., Wang-Li, L., Shah, S.B., Stikeleather, L.F. & Fuentes, M. 2016. Performance analysis of a poultry engineering chamber complex for animal environment, air quality, and welfare studies. *Transactions of the ASABE* **59**(5), 1371–1382.

Pereira, T.E.D.J., Ströher, G.R., Turbiani, F.R.B. & Nicoleti, J.F. 2013. Thermophysical properties of white chicken meat: effect of temperature and moisture content. *Brazilian Journal of Food Technology* **16**(4), 278–284.

Rojano, F., Bournet, P.E., Hassouna, M., Robin, P., Kacira, M. & Choi, C.Y. 2015. Modelling heat and mass transfer of a broiler house using computational fluid dynamics. *Biosystems Engineering* **136**, 25–38.

Rojano, F., Bournet, P., Hassouna, M., Robin, P., Kacira, M. & Choi, C.Y. 2019. Modelling the impact of air discharges caused by natural ventilation in a poultry house. *Biosystems Engineering* **180**, 168–181.

Saraz, J.A.O., Martins, M.A., Marín, O.L.Z., Damasceno, F.A. & Velasquez, H.J.C. 2012. A review about the use of computational fluid dynamics (CFD) in broiler house. *DYNA* (Colombia) **79**(175), 142–149.

Saraz, J.A.O., Ferreira Tinôco, I.F., Oliveira Rocha, K.S., Barreto Mendes, L. & Norton, T. 2016. A CFD based approach for determination of ammonia concentration profile and flux from poultry houses with natural ventilation. *Revista Facultad Nacional De Agronomia Medellin* **69**(1), 7825–7834.

Saraz, J.A.O., Rocha, K.S.O., Damasceno, F.A., Tinoco, I.F.F., Osorio, R. & Tobón, J.C.A. 2017. A CFD approach to assess the effects of different opening combinations in poultry houses. *Revista Brasileira De Engenharia Agrícola e Ambiental* **21**(12), 852–857.

Yahav, S., Straschnow, A., Vax, E., Razpakovski, V. & Shinder, D. 2001. Air velocity alters broiler performance under harsh environmental conditions. *Poultry science* **80**(6), 724–726.

Yanagi, T., Xin, H. & Gates, R.S. 2002. A research facility for studying poultry responses to heat stress and its relief. *Applied Engineering in Agriculture* **18**(2), 55–60.