

COMPUTATIONAL FLUID DYNAMICS (CFD) APPLICATION FOR VENTILATION STUDIES IN BROILER HOUSES

Doi:<http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v37n1p1-12/2017>

THAYLA M. R. DE C. CURTI^{1*}, DANIELLA J. DE MOURA², JULIANA M. MASSARI², MÁRCIO MESQUITA³, DANILO F. PEREIRA⁴

^{1*}Corresponding author. Faculdade de Engenharia Agrícola - UNICAMP/ Campinas - SP, Brasil.
E-mail: thaylamrcarvalho@hotmail.com

ABSTRACT: With the recent increase in the number of acclimatized broiler houses in Brazil, design and adaptation of facilities to withstand the tropical weather conditions enabling the maintenance of ideal conditions without increasing costs have been major challenges. The aim of this study was to evaluate the ventilation system in solid-wall broiler houses using computational fluid dynamics (CFD). The research was carried out in the city of Amparo - SP (Brazil). The facility consisted of a broiler house enclosed by masonry sidewalls with tunnel ventilation equipped with exhaust fans (air outlet) and cooling pads (air inlet). The following variables were collected: wind speed and dry bulb temperature over 27 equidistant points inside the house at bird height (0.30 m above the floor), wind speed in inlet – cooling pad, and static pressure in the outlet (exhaust fans) as a boundary condition. The data were monitored at the most critical time of the day – 2 pm during the final rearing stage in summer. The CFD technique allowed visualizing the air flow according to each running condition for exhaust fans, as well as determined the best setting of exhaust fans, avoiding a low air area renewal and turbulence.

KEYWORDS: Broiler house, computational modeling, environmental control, poultry, thermal comfort.

INTRODUCTION

The challenge of agricultural production in tropical and subtropical countries, such as Brazil, arises because of high temperatures that negatively affect broiler production, especially at the final rearing stage. This problem causes economic losses and animal suffering, which is inconceivable since producers own technological tools in broiler houses and regulations to ensure the welfare of broiler production (BUSTAMANTE et al., 2013).

Thus, the thermal environment condition (temperature, relative humidity, wind speed and solar radiation) is very important to animal production, because it can affect broiler homeothermy responsible for guaranteeing the welfare and productive responses (AMARAL et al., 2011). Broilers under heat stress present significant decreases in food consumption and growth index (RAZUKI et al., 2011), as well as feed efficiency (KHAN et al., 2011). Studies found that poultry exposed to heat stress conditions have a high risk of production loss, and at critical cases can lead to animal death (SALGADO & NÄÄS, 2010).

The deleterious effect of high temperatures can be mitigated using ventilation systems with negative pressure and adiabatic evaporative air-cooling. This system aims to reduce the temperature inside facilities. The ventilation is responsible for cooling the inlet air (evaporative panel), reducing the environmental temperature in the building. A negative ventilation system is equipped with exhaust fans, foggers, and evaporative panels, accountable for air exchange and air-cooling inside the broiler house. The system also presents other functions as i) sanitary function - removing moisture, dust and gas; ii) thermal function - removing animal-produced heat load, equipments, solar radiation and lighting; and iii) production index function - ensuring uniformity and thermal comfort (CURTI et al., 2014; SILVA et al., 2013). On the one hand, such mechanical system requires

² Faculdade de Engenharia Agrícola - UNICAMP/ Campinas - SP, Brasil.

³ Escola de Agronomia - UFG/ Jataí - GO, Brasil.

⁴ Faculdade de Ciências e Engenharia - Universidade Estadual Paulista/ Tupã - SP, Brasil.

Received in: 4-19-2016

Accepted in: 8-18-2016

a great amount of energy and high investments in technology. On the other hand, the broiler production is affected by periodic problems of mortality related to heat stress.

In short, both ventilation system with its components (exhaust fans, evaporative panel, sensors, controller and operator inference) as the broiler houses (type, construction materials, insulation materials – roofs and side curtains) become important factors to determine the environmental quality, influencing the success of poultry production (MOORE et al., 2011; MILES et al., 2013; CURI et al., 2014, DA SILVA et al., 2015).

Many studies have been conducted to evaluate ventilation system operation in commercial broiler houses to determine whether the environmental conditions were appropriate by means of different mathematical and computational methods such as fuzzy logic, data mining, geostatistics and Computational Fluid Dynamics - CFD (MOSTAFA et al., 2012; BUSTAMANTE et al., 2013).

Recently, the CFD modeling has been successfully used for building rural facilities, playing an important role in ventilation system optimization, positioning of the exhaust fans, assessment of system changes, analysis of system air flow and thermal exchanges for each type of animal facility (BLANES-VIDAL et al., 2012; BUSTAMANTE et al., 2013, 2015; ZHAO et al., 2013; NORTON et al., 2013; ABID et al., 2013; GUERRA-GALBO et al., 2015. RAHMAN et al., 2014). Therefore, this study aimed to evaluate the ventilation system in a broiler house by computational modeling of fluid dynamics (CFD), using the software ANSYS CFX v. 14.0, and then propose new settings of exhaust fan activation.

MATERIAL AND METHODS

The experiment was conducted in a broiler house located in Amparo city, São Paulo State, Brazil (22°42'04" S latitude, 46°45'52" W longitude, and altitude of 674 m). According to the Köppen's climate classification, the prevailing climate in this region is of Cwa type (hot climate with dry winters: air average temperature of 22 °C in summer and 18 °C in winter). Broiler chickens of *Cobb Vantruss* 500 strain in the final rearing stage (i.e. 40 days old), during the summer of 2013.

The solid-wall broiler house (SW) is located in Amparo-SP (22°45'37" S latitude, 46°46'42" W longitude, and altitude of 706 m). It has a north-south cartographic orientation, with dimensions of 20 × 120 × 3 m (width × length × height) and density of 13 birds per m². The cooling system is composed of an artificial negative-pressure ventilation. It comprises sixteen exhaust fans with 1.38 m diameter (six at the front and five on each side – Figure 1a) with three-blade propellers and a 1.0 HP engine and nominal flow rate of 41,100 m³ h⁻¹ (at 0 AP), using evaporative panel made in cellulose and masonry sealing with a wall built of concrete blocks (Figure 1b).

| | | | | | | | | |
|----|----|----|----|----|----|----|----|----|
| 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 |
| 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 |

(a)



(b)

FIGURE 1. Layout of the environmental data sampling points (a) and studied broiler house photograph (b).

Dry bulb temperature (DBT, °C) and wind speed (WS, m s⁻¹) were recorded by a hot-wire anemometer (VelociCalc, TSI Inc., St. Paul, MN), within a reading range between -18 and 93 °C (0.1°C) for temperature, and within 0 to 30 m s⁻¹ (0.01 m s⁻¹) and accuracy of ± 0.015 m s⁻¹ for wind speed. The equipment registered both parameters in 27 points in a row as shown in Figure 1(a). The measurements were carried out using the method proposed by Blanes-Vidal et al. (2008) that requires a six-minute permanence of the wind speed sensor at each point since there was only

one sensor. The static pressure was measured using an MN 2150 manometer (ICEL[®]), with an amplitude of 0 to 100 psi and a precision of $\pm 10\%$.

The CDF was used through simulation results by Ansys[®] CFX version 14.0. This software is based on the numerical solution of Navier-Stokes equations, i.e. mass, momentum and energy conservation equations. Precision and quality of the results are strongly associated with physical quantities derived from boundary conditions in the flow domain, knowledge degree and ability of users in the simulation process, as well as the number of mesh elements to represent space and the proper refinement thereof.

Equation 1 is known as “momentum equation”; it stands for the mass conservation principle, while [eq. (2)] represents the general feature of mass equations, that is, the temporal fluid variation equals the resultant force acting thereon.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial}{\partial x_i} p + \frac{\partial}{\partial x_j} \tau_{ij} + \rho g_i + F_i \quad (2)$$

where,

ρ – fluid density (kg m^{-3});

t – time (s);

x, x_i, x_j – length of the components (m);

u_i, u_j – speed of the components (m s^{-1});

p = pressure (AP);

τ – stress tension (AP);

g_i – gravity acceleration (m s^{-2}), and

F_i – body external forces towards i direction (N m^{-3}).

In this study, simulation involved four basic steps: problem definition, preprocessing, solving and post-processing. The preprocessing step includes geometry creation and meshes generation.

Geometry was created in Ansys Workbench 14.0 design modeler using a scale of 1:1 in relation to the broiler-house actual size, including the entire volume of air within it, except for the air volume in the attic (Figure 2). At this stage, the air inlets were designed (by the evaporative panel), as well as the air outlets (exhaust fans).

The area of air inlets was sectioned into 0.10 m rectangles along the panel length with a 0.001-m spacing between them (evaporative panel length of 10.55 m in the back, and 18.60 m in the laterals), to assist boundary conditions since air inlet opening was altered every 0.10 m by the ventilation control system.

The ultimate goal of geometry is drafting the area of the fluid involved in the problem domain.

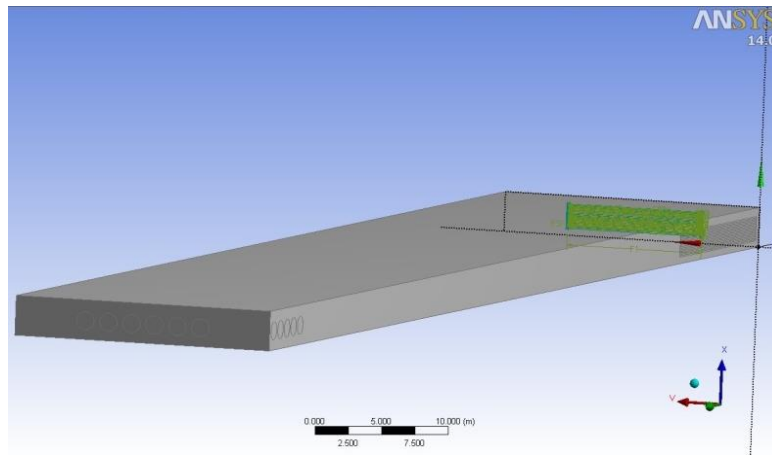


FIGURE 2. Geometry design of the broiler house.

The computational mesh was generated by dividing the air volume within the poultry house into small volumes. Then, we calculated mass, heat, and momentum conservation. The smaller the mesh dimension, the more accurate the results and the greater the time and the processing power necessary for simulation (CÓSTOLA & ALUCCI, 2011).

Different dimensions were used for the mesh building, of which the smaller one was equal to the thickness of air inlet and outlets (0.001 m), and the larger measuring 0.230 m. The chosen type of mesh was hexahedral because tetrahedral meshes require greater computational effort and a larger quantity of elements to the same number of nodes (JOAQUIM JUNIOR et al., 2007). Furthermore, tetrahedral meshes provide a poor solution representation in wall-adjacent layers. The mesh was evaluated regarding the number of elements and nodes, aspect ratio, besides element quality. The latter should not be less than 0.75, and skewness not exceeding 0.8 for a good mesh quality (GAMBIT, 2001).

This process demonstrates the model geometrical information in discrete nodal points, in a process known as discretization. CFD simulation should be independent of the results obtained for each mesh density. To ensure this, a mesh independence test has to be carried out (BJERG et al., 2013). Thus, simulation results will be able to guarantee non-interfere of the mesh with the simulations. However, mesh refining major problem is related to increasing computational costs thereby has to be carefully regarded. An improperly refined mesh, i.e. “thick”, shows as main symptom lack of simulation convergence. The tested meshes consisted of standard (*default*) with 0.40 m, 0.30 m, 0.25 m, 0.23 m and 0.20 m, at a growth rate of 1.10.

A proper use of CFD technique involves defining boundary conditions so that the model is as close to reality as possible. Conversely, boundary condition determination and quantification in broiler houses can be difficult in practice. For this reason, we sought studies on ventilation systems of commercial broiler facilities that used as boundary conditions the air speed in inlets and static pressure in the outlets (VAN WAGENBERG et al., 2004; BLANES-VIDAL et al., 2008). Given the above, we opted to use air speed in inlets, the temperature in the outlets, fluid density and viscosity as internal boundary conditions of the facility; in this case, atmospheric air and static air pressure both in the outlets (Figure 3 and Table 1). For simulations, we considered the walls as isothermal. Figure 3 shows how the model was simulated, taking into account the wind speed perpendicular to the air inlets at the building back, as well as the static pressure in each of the turned on exhaust fans at the sampling time.

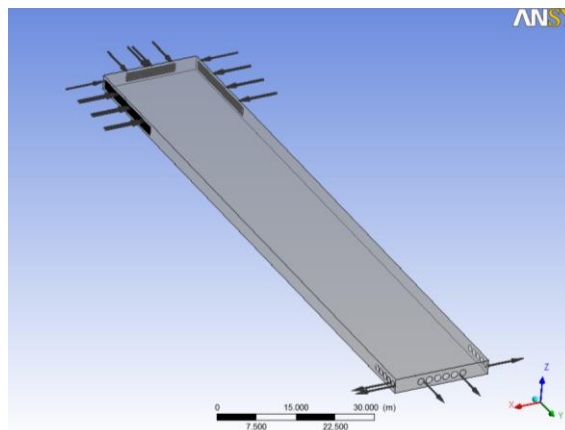


FIGURE 3. CFD model boundary conditions for validation.

TABLE 1. Experimental data boundary conditions for model validation.

| Location | Variable | Value |
|-------------------|-----------------|---|
| Air inlet | Air speed | Face 1 (Figure 4): 1.10 m s ⁻¹ |
| | | Face 2 (Figure 4): 1.02 m s ⁻¹ |
| | | Face 3 (Figure 4): 2.03 m s ⁻¹ |
| Facility interior | Air speed | Average: 1.23 m s ⁻¹ |
| | Air temperature | 25.00°C |
| | Specific heat | 1006 J kg ⁻¹ K ⁻¹ |
| | Air density | 1.16 kg m ⁻³ |
| Air outlets | Static Pressure | 0 Pa |

The first order *standard* k- ϵ model (CFX, 2013) was chosen for considering turbulence effects on average flow in accordance with turbulence kinetic energy (k) and dissipation rate (ϵ).

This model was chosen for being widely used in studies of air flow in poultry ventilation system (BLANES-VIDAL et al., 2008; ZHAO et al., 2013). CFD simulations using first-order closing models, such as the k- ϵ standard, have been successfully validated for various applications in studies in interior environment of broiler houses (LEE et al., 2007; PAWAR et al., 2007; MOSTAFA et al., 2012; BUSTAMANTE et al., 2013). In other words, isotropic models, in some circumstances, might provide valid results, depending on the relationship between result quality and small processing capacity required.

The choice of the domain and the mesh is important since seriously interferes with the results. Therefore, the following considerations were taken: a stationary regime, flow incompressibility and turbulence. As convergence criterion, we also adapted the maximum residue of the solution to a value lower than 10^{-4} , between a minimum of 50 and a maximum of 300 iterations.

Model validation was performed based on the CFD modeling results, being thereafter verified and compared with the corresponding experimental data. The correlation between measured and CFD predicted values was evaluated by calculating the normalized mean square error (NMSE) (ANDERSON et al., 1992; SARAZ et al., 2011), as described in Equations 3 and 4. For this purpose, air speed measurements were taken, for six minutes, at all 27 points (Figure 4) and air inlets inside the building following procedures adapted from Blanes-Vidal et al. (2008). These records were taken for five consecutive days just for model validation, by the time birds were 28 days old. NMSE values below 0.25 were deemed as good correlation indicators.

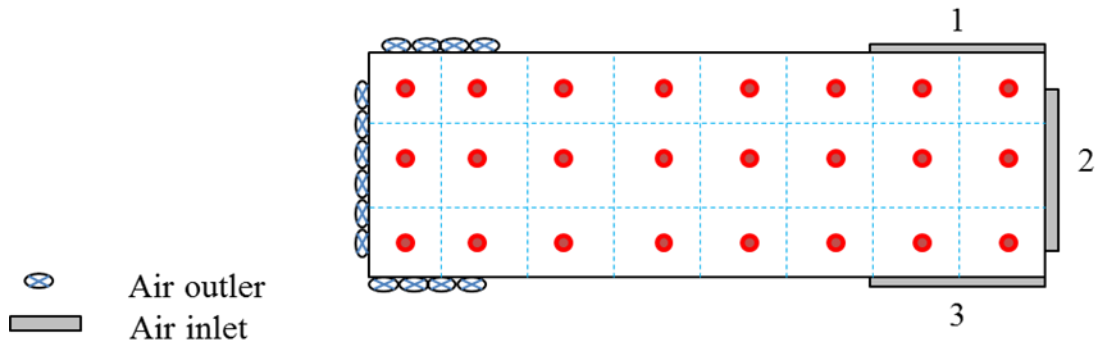


FIGURE 4. Record points for CFD model validation.

Simulations were performed by testing five exhaust fan settings, being turned on at the same time to achieve the best combination of effective air exchanges, based on the standard operating setting thereof (Figure 5).

Inlets beforehand installed in the aviary were disregarded in the simulations. This happened because they were unused at the time of data collection for validation and evaluation of the system, in which case the external air entered the building through the evaporative panel to the building back.

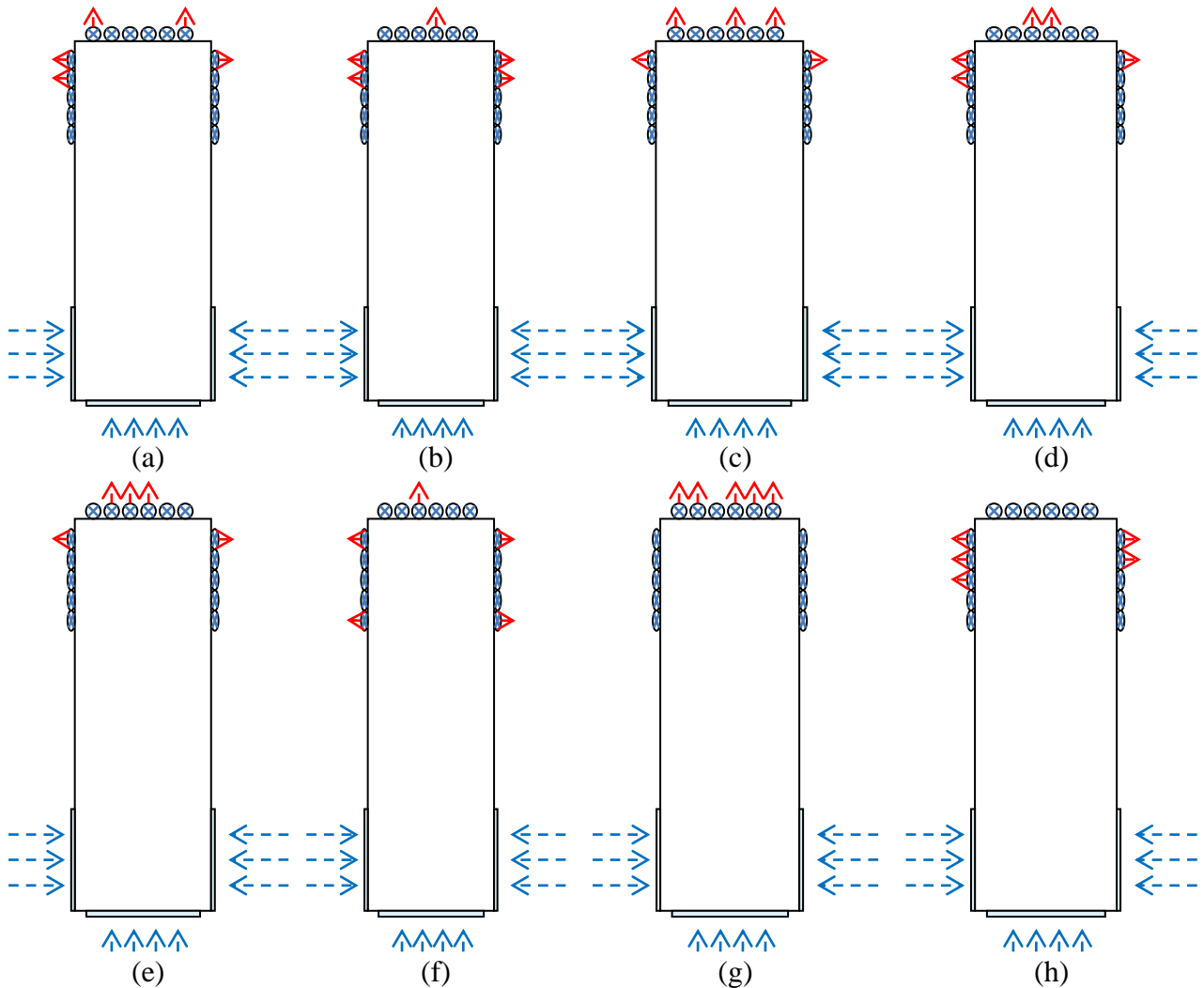


FIGURE 5. Simulations for determination of the best exhaust fan setting: original operating mode (a), simulation 1 (b), simulation 2 (c), simulation 3 (d), simulation 4 (e), simulation 5 (f), simulation 6 (g) and simulation 7 (h).

RESULTS AND DISCUSSION

Table 2 shows the characteristics of the tested meshes, featuring the number of elements, the number of nodes and other mesh parameters (element quality, aspect ratio, and skewness). All tested meshes showed skewness value lower than 0.80 and element quality above 0.75, as recommended by GAMBIT (2001).

TABLE 2. Characteristics of the tested meshes.

| Mesh dimensions | 0.20 m | 0.23 m | 0.25 m | 0.30 m | 0.40 m |
|------------------------|---------|--------|--------|--------|--------|
| Number of elements | 1014595 | 706390 | 585619 | 389829 | 214623 |
| Number of nodes | 1055529 | 729949 | 590374 | 396666 | 208855 |
| <i>Element Quality</i> | 0.940 | 0.914 | 0.890 | 0.850 | 0.790 |
| <i>Aspect Ratio</i> | 1.680 | 2.020 | 2.290 | 2.620 | 3.880 |
| <i>Skewness</i> | 0.065 | 0.100 | 0.140 | 0.160 | 0.250 |

The mesh independence test is presented as a graph in Figure 6. Each bar length stands for the air speed found in the simulations, inside the poultry house, towards the X coordinate direction of the area (Figure 6). Such test is important to ensure lack of interference of the chosen mesh with the simulation results (BRAGA et al., 2015; SANT'ANNA et al., 2015; JUNIOR et al., 2015).

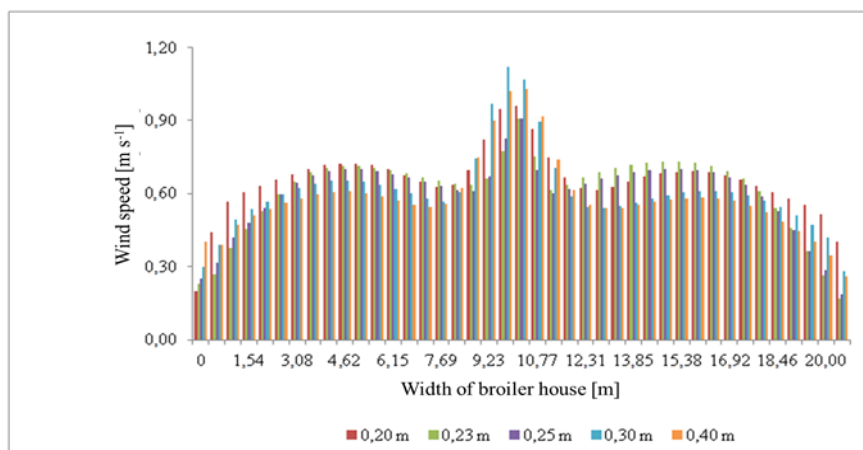


FIGURE 6. Comparison of the simulations for the evaluated mesh sizes.

We can see the difference (of up to 107.48%) of the length of the bars between the most and least refined mesh, showing that refining caused major changes in the results. The lowest difference is between the mesh of 0.23 m and the one of 0.20 m, signaling the independence of the results in regards to the mesh. As a result, the mesh dimension of 0.23 m should be chosen to obtain results as good as the 0.20-m mesh, but with less computational costs. In this sense, the mesh chosen had 706,390 elements, 729,949 nodes and a skewness equal to 0.10. The skewness in the results of the less refined mesh (size 0.40 m) is of 0.25, which is a clear indication of mesh adequacy. As the mesh was refined, skewness decreased. These values are based on residual errors of the numerical solution of the moment and continuity equations suggested in the literature for transport quantity maintenance. Therefore, the convergence of the solution was carefully verified by monitoring the transport equation residuals throughout the simulation.

The model was validated by correlating the measured values and the CFD simulated ones, using the mean square of standardized errors, obtaining an NMSE value of 0.1936 (RÁCZ et al., 2013; DAMASCENO et al., 2014; SARAZ et al., 2012). Since values below 0.25 are taken as good indicators of correlation, the model was considered valid concerning the adopted boundary

conditions. In this regard, the air inlets were dimensioned for being added to the boundary conditions and thereby increasing the accuracy of the results.

All the simulations (from 1 to 7) were differentiated by positioning five turned on exhaust fans, which made part of the original simulation (Figure 5). Table 3 shows the maximum and minimum values of air speed found in each simulation according to the scale.

TABLE 3. Comparison of the wind speed (m s^{-1}) distribution inside the broiler facility for CFD simulations.

| Wind speed (m s^{-1}) | Maximum | Minimum | Mean | Difference |
|----------------------------------|---------|---------|------|------------|
| Original/Standard Simulation | 2.80 | 0.04 | 1.42 | 2.76 |
| Simulation 1 | 2.78 | 0.03 | 1.40 | 2.75 |
| Simulation 2 | 2.78 | 0.04 | 1.41 | 2.74 |
| Simulation 3 | 2.78 | 0.03 | 1.40 | 2.75 |
| Simulation 4 | 2.89 | 0.04 | 1.46 | 2.85 |
| Simulation 5 | 2.78 | 0.03 | 1.40 | 2.75 |
| Simulation 6 | 2.86 | 0.09 | 1.53 | 2.86 |
| Simulation 7 | 3.10 | 0.03 | 1.56 | 3.07 |

The advantage of CFD simulations comes from its graphical representation providing an easy understanding of the air flow, with parameters represented by different colors or vectors of the simulations (Figure 7a). The simulations of the various exhaust fan settings aimed to provide a homogeneous distribution of air speed, seeking for values close to the ideal ones found in the literature, which in this case are between 1.5 and 2.5 m s^{-1} (YAHAV et al., 2001).

Studies have reported that a suitable ventilation system promotes beneficial effects on poultry production factors, such as bird weight (SILVA et al., 2013). There has been also a few attempts to reduce areas of low air exchange, in other words, when air speed values are near 0.0 m s^{-1} . In this sense, broiler house building type directly influences the environmental conditions, which, in turn, are influenced by external climatic conditions where it is built, emphasizing the need for a ventilation system and facility type that are appropriate to the local microclimate (SILVA et al., 2015).

We observed that air speed has the largest values close to the turned on exhaust fans and also in the region where there is a simultaneous inlet of air through sides 1, 2 and 3 (Figure 4) through the evaporative panels, which increases air speed values above the recommended by the literature.

The air flow convergence produces a turbulence zone in the center of the broiler house near the air inlets, at bird height, which may interfere with poultry behavior during regular activities, affecting performance, feed conversion and water consumption (AMY et al., 2000).

At the edges of the building, points of low air exchange could be observed, near the air inlets and close to the exhaust fans turned off during the simulation. This result suggests that a better distribution of exhaust fans may decrease the occurrence of these zones. These differences in air speed throughout the facility may result in uneven flocks, interfering with the final production (poultry activity and body weight), since air speed influences convective heat loss and, therefore, hindering thermal comfort condition (TAO & XIN, 2003; BARACHO et al., 2013).

Given the above background, we noted that regions surrounding air inlets and outlets are critical, whereas the intermediary zone shows a smooth and homogeneous air flow. Therefore, the

existing demands for uniform environmental conditions inside broiler houses can be met by an effective control of the ventilation system (CALVET et al., 2011; HUMBERT et al., 2014.).

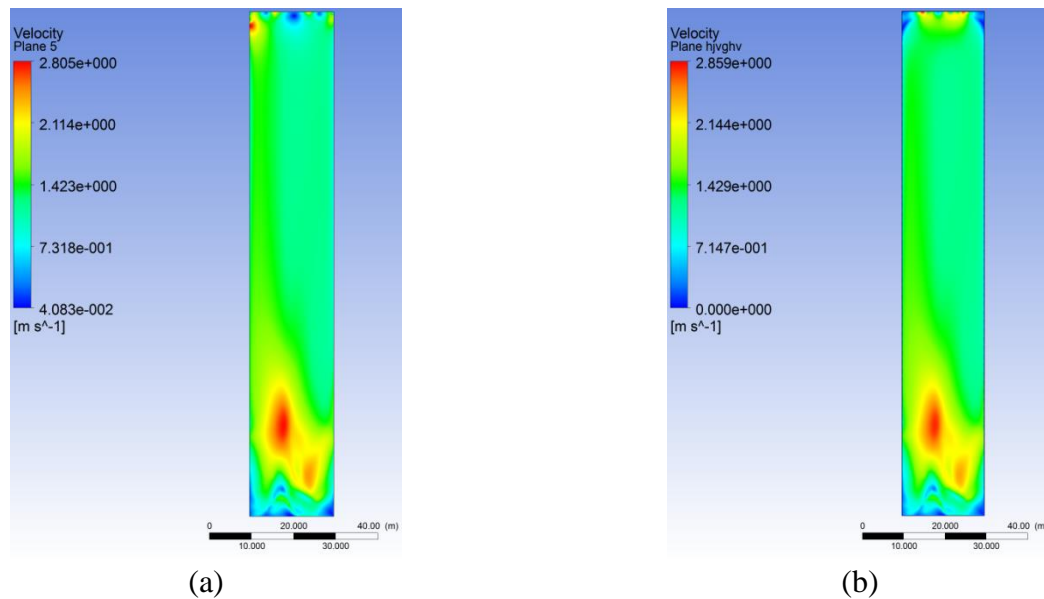


FIGURE 7. Wind speed pattern at the bird height inside the broiler house for Original Simulation (a) and Simulation 6 (b).

Thus, among the various provisions of the exhaust fans, Simulation 6 (Figure 7b) (five exhaust fans turned on at the front of the broiler house) showed the best performance regarding homogeneity, reductions of low air-exchange and turbulence zones, presenting values deemed as appropriate by the literature (YAHAV et al., 2001).

CONCLUSIONS

The Computational Fluid Dynamics technique is an efficient and reliable method for predicting air flow displacements under different operating conditions of exhaust fans, as well as for determining the best turn-on setting of exhaust fans, avoiding low air-exchange and turbulence zones. In this sense, the ventilation system controller is capable of defining the most suitable setting for air exchange.

ACKNOWLEDGMENTS

FAPESP (Process FAPESP n° 2011/07545-7) and CNPq to support the research and scholarship.

REFERENCES

- ABID, M.; WAJID, H.A.; KHAN, N.D.; AKHTAR, S.; ZAHID, M. A.; USMAN, M. Optimization of ventilation system for existing environmentally controlled poultry sheds in Pakistan. **World Applied Sciences Journal**, Faisalabad, v.24, n.9, p.1221-1233, 2013.
- AMARAL, A.G.; YANAGI JUNIOR, T.; LIMA, R.R.; TEIXEIRA, V.H.; SCHIASSI, L. Effect of the production environment on sexed broilers reared in a commercial house. **Arquivo Brasileiro de Medicina Veterinária e Zootecnia**, Belo Horizonte, v.63, n.3, p.649-658, 2011.
- ANDERSON, M.P.; WOESSNER, W.W. **Applied groundwater modeling simulation of flow and advective transport**. 2nd ed. New York: Academic Press, 1992.
- BARACHO, M.S.; CASSIANO, J.A.; NÄÄS, I.A.; TONON, G.S.; GARCIA, R.G.; ROYER, A.F.B.; MOURA, D.J.; SANTANA, M.R. Ambiente interno em galpões de frango de corte com cama nova e reutilizada. **Revista Agrarian**, Dourados, v.6, n.22, p.473-478, 2013.

- BJERG, B.; CASCONI, G.; LEE, I.B.; BARTZANAS, T.; NORTON, T.; HONG, S.W.; ZHANG, G. Modelling of ammonia emissions from naturally ventilated livestock buildings. Part 3: CFD modelling. **Biosystems Engineering**, London, v.116, n.3, p.259-275, 2013.
- BLANES-VIDAL, V.; GUIJARRO, E.; BALASCH, S.; TORRES, A.G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. **Biosystems Engineering**, London, v.100, n.1, p.105-116, 2008.
- BLANES-VIDAL, V.; SUH, H.; NADIMI, E.S.; LØFSTRØM, P.; ELLERMANN, T.; ANDERSEN, H.V.; SCHWARTZ, J. Residential exposure to outdoor air pollution from livestock operations and perceived annoyance among citizens. **Environment international**, New York, v.40, n.1, p.44-50, 2012.
- BRAGA, E.; MORAES, C.; MEDRONHO, R. Estudo do escoamento de gás natural e formação de enxofre elementar em uma válvula redutora de pressão. **Blucher Chemical Engineering Proceedings**, São Paulo, v.1, n.2, p.11486-11493, 2015.
- BUSTAMANTE, E.; GARCÍA-DIEGO, F.J.; CALVET, S.; ESTELLÉS, F.; BELTRÁN, P.; HOSPITALER, A.; TORRES, A.G. Exploring ventilation efficiency in poultry buildings: The validation of computational fluid dynamics (CFD) in a cross-mechanically ventilated broiler farm. **Energies**, Basel, v.6, p.2605-2623, 2013.
- BUSTAMANTE, E.; GARCÍA-DIEGO, F.J.; CALVET, S.; TORRES, A.G.; HOSPITALER, A. measurement and numerical simulation of air velocity in a tunnel-ventilated broiler house. **Sustainability**, Basel, v.7, n.2, p.2066-2085, 2015.
- CALVET, S.; ESTELLÉS, F.; CAMBRA-LÓPEZ, M.; TORRES, A.G.; VAN DEN WEGHE, H.F.A. The influence of broiler activity, growth rate, and litter on carbon dioxide balances for the determination of ventilation flow rates in broiler production. **Poultry Science**, Savoy, v.90, n.11, p.2449-2458, 2011.
- CÓSTOLA, D.; ALUCCI, M.P. Aplicação de CFD para o cálculo de coeficientes de pressão externos nas aberturas de um edifício. **Ambiente Construído**, São Paulo, v.11, n.1, p.145-158, 2011.
- CURI, T.M.R.C.; VERCELLINO, R.A.; MASSARI, J.M.; SOUZA, Z.M.; MOURA, D.M. Geoestatística para a avaliação do controle ambiental do sistema de ventilação em instalações comerciais para frangos de corte. **Engenharia Agrícola**, Jaboticabal, v.34, n.6, p.1062-1074, 2014.
- DA SILVA, T.P.; PANDORFI, H.; GUISELINI, C.; DE ALMEIDA, G.L.; GOMES, N.F. Typology of poultry houses in the Agreste region of Pernambuco. **Engenharia Agrícola**, Jaboticabal, v.35, n.4, p.789-799, 2015.
- 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. **Revista Facultad Nacional de Agronomía**, Medellin, v.67, n.2, p.7355-7363, 2014.
- GAMBIT. **Gambit user's Guide, version 6.0**. Lebaro: Fluent, 2001.
- GUERRA-GALDO, E.H.; SANZ, S.C.; BARBER, F.E.; LÓPEZ-JIMÉNEZ, P.A. CFD model for ventilation assessment in poultry houses with different distribution of windows. **International Journal of Energy and Environment**, Al-Najaf, v.6, n.5, p.411-424, 2015.
- HUMBERT, U.; WESSELS, G.J.C.; SMIT, J.E.; UBBINK, O. Improving broiler lifestyle: a CFD approach. In: SOUTH AFRICAN CONFERENCE ON COMPUTATIONAL AND APPLIED MECHANICS, 9., 2014, Somerset West. **Proceedings...** Somerset West: South African Association for Theoretical and Applied Mechanics, 2014.
- JOAQUIM JR., C.F.; CEKINSKI, E.; NUNHEZ, J.R.; URENHA, L.C. **Agitação e mistura na Indústria**. Rio de Janeiro: LTC Editora, 2007.

- JUNIOR, I.P.; DUARTE, C.R.; DOS SANTOS, D.A. Estudo experimental e de simulação da fluidodinâmica de um leito de jorro operando em fase diluída (“Jet Spouted Bed”). **Horizonte Científico**, Uberlândia, v.9, n.1, p.1-21, 2015.
- KHAN, R.U.; NAZ, S.; NIKOUSEFAT, Z.; TUFARELLI, V.; JAVDANI, M.; RANA, N.; LAUDADIO, V. Effect of vitamin E in heat-stressed poultry. **World’s Poultry Science Journal**, Wallingford, v.67, n.3, p. 469-478, 2011.
- LEE, I.; SASE, S.; SUNG, S. Evaluation of CFD Accuracy for the Ventilation Study of a Naturally Ventilated Broiler House. **Japan Agricultural Research Quarterly**, Tokyo, v.41, n.1, p.53-64, 2007.
- MAY, J.D.; LOTT, B.D.; SIMMONS, J.D. The effect of air velocity on broiler performance and feed and water consumption. **Poultry Science**, Savoy, v.79, p.1396-1400, 2000.
- MILES, D.M.; BROOKS, J.P.; MACLAUGHLIN, M.R.; ROWE, D.E. Broiler litter ammonia emissions near sidewalls, feeders, and waterers. **Poultry Science**, Savoy, v.92, n.7, p.1693-1698, 2013.
- MOORE, P.A.; MILES, D.; BURNS, R.; POT, D.; BERG, K.; CHOIF, I.H. Ammonia emission factors from broiler litter in barns, in storage, and after land application. **Journal of Environmental Quality**, Madison, v.40, n.5, p.1395-1404, 2011.
- MOSTAFA, E.; LEE, I.B.; SONG, S.H.; KWON, K.S.; SEO, I.H.; HONG, S.W.; HAN, H.T. Computational fluid dynamics simulation of air temperature distribution inside broiler building fitted with duct ventilation system. **Biosystems Engineering**, London, v.112, p.293-303, 2012.
- NORTON, T.; KETTLEWELL, P.; MITCHELL, M. A computational analysis of a fully-stocked dual-mode ventilated livestock vehicle during ferry transportation. **Computers and electronics in agriculture**, New York, v.93, p.217-228, 2013.
- PAWAR, S.R.; CIMBALA, J.M.; WHEELER, E.F.; LINDBERG, D.V. Analysis of poultry house ventilation using Computational Fluid Dynamics. **Transactions of the ASABE**, St Jopseph, v.50, n.4, p.1373-1382, 2007.
- RÁCZ, N.; KRISTÓF, G.; WEIDINGER, T. Evaluation and validation of a CFD solver adapted to atmospheric flows: Simulation of topography-induced waves. **Időjárás**, Budapest, v.117, n.3, p.239-275, 2013.
- RAHMAN, M.M.; CHU, C.M.; KUMARESEN, S.; YAN, F.Y.; KIM, P.H.; MASHUD, M.; RAHMAN, M.S. Evaluation of the Modified Chimney Performance to Replace Mechanical Ventilation System for Livestock Housing. **Procedia Engineering**, v.90, p.245-248, 2014.
- RAZUKI, W.M.; MUKHLIS, S.A.; JASIM, F.H.; HAMAD, R.F. Productive performance of four commercial broilers genotypes reared under high ambient temperatures. **International Journal of Poultry Science**, Faisalabad, v.10, n.2, p.87-92, 2011.
- SALGADO, D.D; NÄÄS, I.A. Avaliação de risco à produção de frango de corte do estado de São Paulo em função da temperatura ambiente. **Engenharia Agrícola**, Jaboticabal, v.30, n.3, p.367-376, 2010.
- SANT’ANNA, M.C.S.; TAVARES, M.; SARMENTO, S.M.; SILVA, G.; MEDRONHO, R.; LUCENA, S. Estudo da dinâmica de fluidização de um sistema composto areia-gás-biomassa. **Blucher Chemical Engineering Proceedings**, São paulo, v.2, n.1, p.751-589, 2015.
- SARAZ, A.O.J.; TINÔCO, I.D.F.F.; ROCHA, O.; SULLIVAN, K.; MARTINS, M.A.; DE PAULA, M.O. Modeling and experimental validation to estimate the energy balance for a poultry house with misting cooling. **Dyna**, Medellin, v.78, n.170, p.167-174., 2011.

- SARAZ, O.; ALEXANDER, J.; TINOCO, I.D.F.F.; ROCHA, O.; SULLIVAN, K.; MARTINS, M.A.; DAMASCENO, F.A. Validation of a cfd model for prediction of the efficiency of evaporative cooling in porous panels. **Revista UDCA Actualidad & Divulgación Científica**, Bogotá, v.15, n.1, p.209-217, 2012.
- SILVA, E.G.D.; SANTOS, A.C.D.; FERREIRA, C.; SOUSA, J.P.L.D.; ROCHA, J.M.L.D.; JÚNIOR, O.S. Variabilidade espacial das características ambientais e peso de frangos de corte em galpão de ventilação negativa. **Revista Brasileira de Saúde e Produção Animal**, Salvador, v.14, n.1, 2013.
- SILVA, R.C.; RODRIGUES, L.R.; RODRIGUES, V.P.; ARRUDA, A.S.; SOUZA, B.B. Análises do efeito do estresse térmico sobre produção, fisiologia e dieta de aves. **Agropecuária Científica no Semiárido**, Campina Grande, v.11, n.2, p.22-26, 2015.
- TAO, X.; XIN, H. Acute synergistic effects of air temperature, humidity, and velocity on homeostasis of market-size broilers. **Transactions of the ASAE**, St Joseph, v.46, n.2, p.491-497, 2003.
- VAN WAGENBERG, A.; BJERG, B.; BOT, G.P.A. measurements and simulation of climatic conditions in the animal occupied zone in a door ventilated room for piglets. **Agricultural Engineering International: the CIGR Journal of Scientific Research and Development**, Tsukuba, v.6, p.1-19, 2004.
- YAHAV, S.; STRASCHNOW, A.; VAX, E.; RAZPAKOVSKI, V.; SHINDER, D. Air velocity alters broiler performance under harsh environmental conditions. **Poultry Science**, Savoy, v.80, p.724-726, 2001.
- ZHAO, Y.; XIN, H.; SHEPHERD, T.A.; HAYES, M.D.; STINN, J.P. Modelling ventilation rate, balance temperature and supplemental heat need in alternative vs. conventional laying-hen housing systems. **Biosystems Engineering**, London, v.115, n.3, p.311-323, 2013.