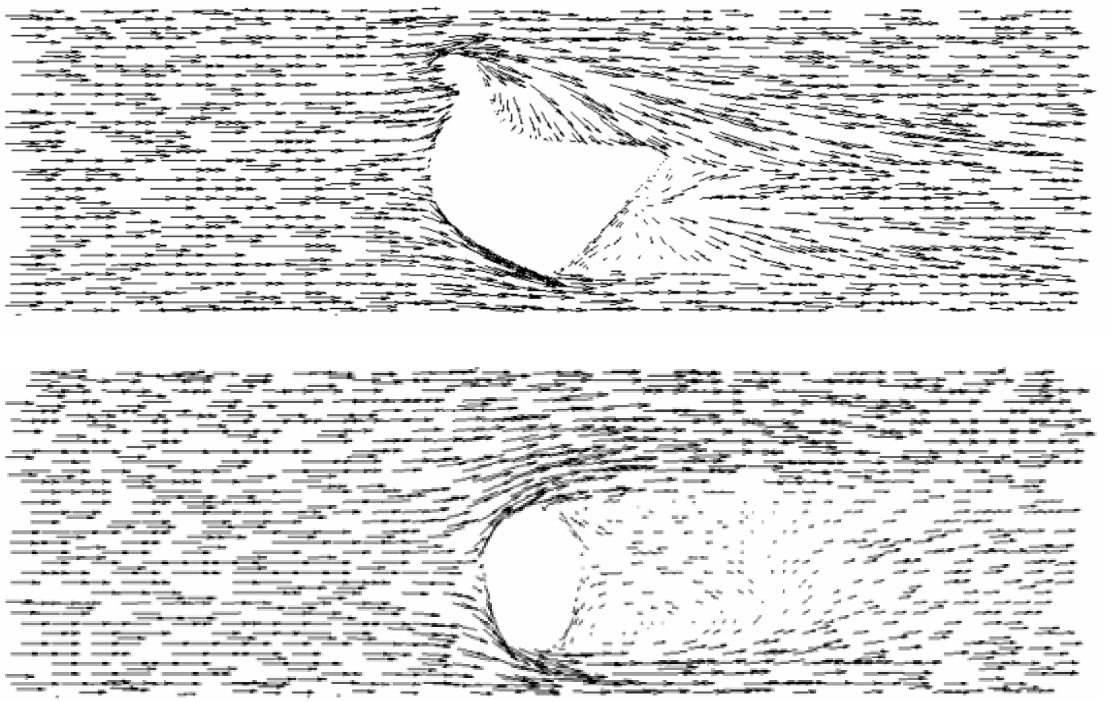
MID-TERM REPORT: COMPLEX VENTILATION AND MICRO-ENVIRONMENTAL CONTROL IN **LIVESTOCK HOUSING**

Civil and Architectural Engineering
Technical Report CAE-TR-2



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Abstract: Micro-complex ventilation involves integrating precision local ventilations in animal zones. In order to gain knowledge about air motion and temperature distribution in animal occupied zones, the project will investigate an integrated micro ventilation concept in livestock housing. Data will be gathered by using both Computational Fluid Dynamics (CFD) simulations and scale experiments in wind tunnel. After the establishment of the system, optimisations are also needed. Then, to validate the optimal system, varied techniques including local cross ventilation, tunnel ventilation, low pressure ventilation and heat exchange will be investigated. The proposed system combines the advantages of natural, mechanical and displacement ventilation, making it a technology with great efficiency and potential.
So far, parts of the experiment about the heated body have already been conducted in the wind tunnel. A CFD simulation about heat convection from chicken have already been finished and written into a manuscript. This report contains introduction of the project of Complex Ventilation and Micro-Environmental Control in Livestock Housing. This report contains activities, courses, and manuscript was presented. There is also a plan for further work.

Keywords: Ventilation, Climate control, Thermal condition, Experimental fluid dynamic, Computational fluid dynamic

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COMPLEX VENTILATION AND MICRO-ENVIRONMENTAL CONTROL IN LIVESTOCK HOUSING

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Abstract

Micro-complex ventilation involves integrating precision local ventilations in animal zones. In order to gain knowledge about air motion and temperature distribution in animal occupied zones, the project will investigate an integrated micro ventilation concept in livestock housing. Data will be gathered by using both Computational Fluid Dynamics (CFD) simulations and scale experiments in wind tunnel. After the establishment of the system, optimisations are also needed. Then, to validate the optimal system, varied techniques including local cross ventilation, tunnel ventilation, low pressure ventilation and heat exchange will be investigated. The proposed system combines the advantages of natural, mechanical and displacement ventilation, making it a technology with great efficiency and potential.
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Complex Ventilation and Micro-Environmental Control in Livestock Housing

Hao Li

Summary

Micro-complex ventilation involves integrating precision local ventilations in animal zones. In order to gain knowledge about air motion and temperature distribution in animal occupied zones, the project will investigate an integrated micro ventilation concept in livestock housing. Data will be gathered by using both Computational Fluid Dynamics (CFD) simulations and scale experiments in wind tunnel. After the establishment of the system, optimisations are also needed. Then, to validate the optimal system, varied techniques including local cross ventilation, tunnel ventilation, low pressure ventilation and heat exchange will be investigated. The proposed system combines the advantages of natural, mechanical and displacement ventilation, making it a technology with great efficiency and potential.

So far, parts of the experiment about the heated body have already been conducted in the wind tunnel. A CFD simulation about heat convection from chicken have already been finished and written into a manuscript. This report contains introduction of the project of Complex Ventilation and Micro-Environmental Control in Livestock Housing. The work progress including activities, courses, and manuscript was presented. There is also a plan for further work.

1. Introduction to the field of research

Research on animal behaviour and welfare have showed that both thermal and airflow parameters have strong influence on the procedures of livestock breeding. A poor thermal environment results in a negative spiral of development for animals, personnel, environment, economy and food quality prompted by reduced hygiene, increased risk of diseases, increased ammonia evaporation, reduced air quality and increased daily labour requirement for pen cleaning. While on the other hand ventilation and airflow at animal zone could have large effects on ammonia and greenhouse gas emission from livestock buildings.

The purpose of the ventilation system is to maintain a desired indoor thermal condition while controlling levels of humidity and removing gaseous contaminants introduced by the animal and their waste (Saha et al., 2010). Houses can be acclimated through either forced or natural ventilation. Natural ventilation is one of the techniques for lower energy consumption compared with the energy consumption of forced ventilation (Ecim-Djuric, 2009). However, at certain circumstances, only depending on natural ventilation is not enough to meet the requirement of air motion in animal buildings. Then the mechanical ventilation is needed. There are many different kinds of ventilation system in a mechanical ventilated animal building, e.g. tunnel ventilation, low pressure ventilation, and cross ventilation. These ventilation systems could be installed either singly or integratedly in animal buildings. All these lead to a complex both air velocity and temperature distributions in animal occupy zone, and the control of the indoor environment become correspondingly complex. That is the basic complex ventilation idea. It derives from a study on a pig building conducted by Farm Building Division of Danish Building Research Institute in 1990s (Strøm and Zhang 1989; Zhang et al. 1992). Until now many researches have been done on complex ventilation system. However, there are still many conceptions are unclear.

2. Hypothesis/Aim of the project

Different control strategies could result to different indoor environments and have varied cooling potentials during the hot period. The integral impact from environment will affect animal comfort on varied degrees. To provide a friendly environment to the animals, it is necessary to find a reliable parameter to represent animals' comfort first and then try to reach the set environment through different strategies. The research then could be separate into two parts, one is to explore the thermal index for animal, and the other is to study indoor climate parameters results from different ventilation systems.

The aims of the project are 1) to introduce a new concept for monitoring the thermal and airflow conditions in the animal zone, 2) and then to set up a dynamic predictive model to provide a precision environment control strategy at individual animal or defined zone level and consequently to improve animal welfare and to reduce environmental impact, 3) to generate knowledge on cooling effectiveness of different kinds of cooling and ventilation systems.

3. Description of methods

The project will apply both numerical modelling method and full scale experiments to investigate the effectiveness of the system for an optimal thermal environment and air quality for both animal and workers with high effectiveness and low energy consumption.

Models of heated bodies which are so-called artificial pig and poultry will be made and test in wind tunnel in Air Physics Lab, Aarhus University, Denmark. This wind tunnel has a large range of turbulence boundary layers and dimensions height ×width ×length=6.00m×1.38m×1.55m. This low-speed-type wind tunnel can produce a maximum flow with a wind speed of 3.8m/s.

Computational Fluid Dynamics (CFD) can effectively model airflow in both spatial and temporal fields, and it was proved the potential to model livestock buildings and can provide concrete flow information. Therefore, in this project, CFD is used to analyse the air motion and thermal condition in AOZ and heat boundary of animals.

4. Progress of the project

Two heated body with different sizes have been built. Heat convective coefficients of the cylinders on different air velocities and orientations have been generated through experiment. That data could be used as basic data to develop the effective temperature of animals.

CFD simulation on a model chicken was also conducted to test the feasibility of using CFD method to study heat transfer convective coefficient from animals. Great potential have been showing in the research. The results have been arranged in a manuscript.

Both the simulation and experiment will focus on more complex geometry in future research.

5. Dissemination

5.1. Publications

Li, H., Zhang, G., 2015. A numerical approach to study forced convection from animal: simulation with a real geometry. Manuscript for publication in a scientific journal.

Zong, C., **Li, H.**, Zhang, G., 2014. Ammonia and greenhouse gas emissions from fattening pig house with two types of partial pit ventilation systems. Agriculture, Ecosystems & Environment, Revised version submitted in Oct. 2014.

Zong, C., **Li, H.**, Zhang, G., 2014. Airflow characteristics in a pig house with partial pit ventilation system: an experimental chamber study. Prepared submitting to a peer review journal.

Zong, C., Zhang, G., **Li, H.**, Rong, L. 2014. Investigation on ventilation effectiveness in a full-scale model pig house with partial pit ventilation system. Proceedings International Conference of Agricultural Engineering, Zurich, 06-10.07.2014.

Yan, Z., Wang, C., Li, B., Zhang, G., Shi, Z., **Li, H.**, Wang, H. Yuan, Y. Influence of water temperature and spraying interval on cooling effect of sprinkler system in dairy barns. Applied Engineering in Agriculture, Vol. 30(4): 611-617.

5.2. Activities

Experiment, report and discussion with VSP (pig research center) on design of ventilation systems for point extraction, from 01/10/2013 to 05/03/2014, in Denmark

Seminar on application of CFD in agriculture, 09/04/2014, in Korea

Workshop on the CFD simulation for ventilation system, 19/05/2014, in Korea

Seminar on hot climate control in Pig & poultry house, 16/10/2014, in Denmark

Seminar on heat balance model in animals, 27/10/2014, in Denmark

Seminar on hot climate control and technology in Pig & poultry housing, 14/01/2015, in Denmark

5.3. Courses

Course title	Institution	ECTS	Status
Fundamentals of Ventilation, Indoor Air Quality, Air Motion and Emissions (MD 1)	Aarhus University	5	Completed
Science Teaching -Module 1:Introduction to Science Teaching	Aarhus University	3	Completed
Academic English for non-Danish Speaking PhD Students	Aarhus University	3	Completed
Fundamental of computational fluid dynamics (CFD)	Aalborg University	3.5	Completed
Computing with data using R	Aalborg University	4	Completed
Introduction to R	Aarhus University	1	Completed
Basic Statistical analysis in Life and Environmental Sciences	Aarhus University	4	Ongoing
Fundamentals of Ventilation, Indoor Air Quality, Air Motion and Emissions (MD 2)	Aarhus University	5	Planned, June 2015
The World of Research	Aarhus University	2	Planned, May 2015

Completed Courses: 20.5 ECTS; Ongoing: 4 ECTS; Planned: 7 ECTS; In total: 31.5 ECTS.

5.4. Study abroad:

I spent 3 months in the lab of Prof. In-bok Lee in Aero-Environmental & Energy Engineering, College of Agriculture and Life Sciences, Seoul National University. There I developed my CFD simulation skills and communicated research status with peers.

6. Plan for remaining study period

6.1. Conference

I plan to join two international conferences. The first one is the ASABE annual conference 2015 in New Orleans, Louisiana, US. And the second one is CIGR conference 2016 in Aarhus, Denmark. I will make oral presentations there.

6.2. Working plan on research

For the next half period for my PhD study, I plan to do the research in two different levels – the housing level and animal level. On the housing level the core of research is to study the effectiveness of different ventilation and cooling system. On the animal level, the goal is to develop the index that could represent real feeling of animal in different thermal conditions.

Working title in housing level:

1. *Modelling indoor environment and cooling potential with different cooling strategies in closed animal housing (expect to be started from March 2015 and finished in June 2015)*
2. *Economic analysis on the cooling strategies in different climate zones (air conditioner, natural ventilation and mechanical ventilation) (expect to be started from April 2015 and finished in August 2015)*

Working title in animal level:

1. *Scale effect on convective heat loss – a study based on heated bodies (expect to be finished in March 2015)*
2. *Comparison of convective coefficient between pig model with real and simplified shapes (expect to be finished in March 2016)*
3. *A numerical approach to study forced convection from animal: simulation with a fur layer (expect to be finished in June 2016)*

It is planned that each working title will produce one publication.

Appendix A: Manuscript “A numerical approach to study forced convection from animal: simulation with a real geometry”

A numerical approach to study forced convection from animal: simulation with a real geometry

Hao Li, Guoqiang Zhang

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Abstract

Convective heat transfer is an important parameter to judge animal thermal comfort. Computational Fluid Dynamics (CFD) method was employed to study convective coefficient from animal. In order to achieve accurate result, several RANS (Reynolds averaged Navier-Stokes) turbulence models were tested on a sphere model for the feasibility to study forced convection using CFD method. RSM model showed the best agreement with theoretical calculation and therefore was adopted for further calculation. The results of simulation showed the CFD method had a strong potential in studying convective coefficient of animal. Based on the simulation result, convective coefficient of chicken was predicted over a broader range of air velocity compared with former research. A relationship between model with a chicken geometry and sphere was also discussed in the paper.

1. Introduction

Thermal comfort is an important factor for farm animal. Poor thermal condition may lead to stress of animals and even to death of animals, and poor production. The thermal comfort of animal is highly dependent on heat transfer from animal to the environment. The heat transfer from animal is including evaporation, conduction, convection and radiation. Among all these four kinds of heat transfer avenues convection is one of the most important, since it is highly relevant to the control of the ventilation air speed in animal occupied zone.

Many researches have been conducted using varied artificial animal models to study the thermal condition of animals. Most study in those works, Spheres and cylinders were employed for physical modelling (Bakken, 1976; Bakken and Gates, 1975; Campbell and Norman, 1998; Monteith and Unsworth, 2013; Norton et al., 2010; Porter and Gates, 1969) . The oversimplification of the geometry will undoubtedly lead to discrepancy on the results. Wathes and Clark (1981) tested heat transfer from a copper model in a chicken model and Mitchell (1985) tested the convective coefficient of a real chicken using a wind-tunnel calorimeter. However, both of the experiment had some limitations. They were not conducted in a very high wind speed. The air pattern around animals could not get due to the limitation of the equipment.

CFD has become a useful and powerful tool to predict airflow characteristics and mass and energy transfer across wide research areas: airflow distribution in greenhouses (Bartzanas et al., 2002); ammonia emission from pig houses(Rong et al., 2010); dynamic flux chamber methodology (Saha et al., 2011); pit exhaust system of a cow building; remove ratio of gases (Wu et al, 2012); Air flow pattern inside a small cow room (Gebremedhin and Wu, 2005); the indoor environment of a pig building (Seo et al, 2011).

To determine convective coefficient of a bluff body in a ventilated air space, it is depending on the modelling results in both the air velocity field and the temperature field. The accuracies of both aspects have influence on the final result. And the two aspects could have interaction for the simulation of the convective coefficient. Zhang, Zhai et al. (2007) tested different turbulence models in enclosed space, the predictions on temperature, velocity and turbulence are in different accuracy levels. From this point, turbulence models need to evaluated for the prediction of convective coefficient.

Therefore, the objective of this study is 1) to assess the feasibility of using CFD (computational Fluid Dynamic) to study forced convection from animals, 2) to use CFD model to make prediction of convective coefficients on higher air velocity, 3) to explore the relationship between sphere and the model in a chicken shape.

2. Materials and Methods

2.1. Geometry and calculation domain

Firstly, a model chicken was made based on real geometry of chicken by Sketchup (Google Inc., USA). However, too detailed model could result to increasing of difficulty in mesh establishment and burden in calculation afterwards. Therefore, the model was rebuild and appropriately simplified in Rhino (Robert McNeel & Assoc Inc., USA); the comb and legs were removed, and beak and wings were moderately smoothed (Fig. 1). The model was rescaled to a size with a surface area of 0.0769m^2 which is the calculated surface area of chicken in a former experiment (Mitchell, 1985) .

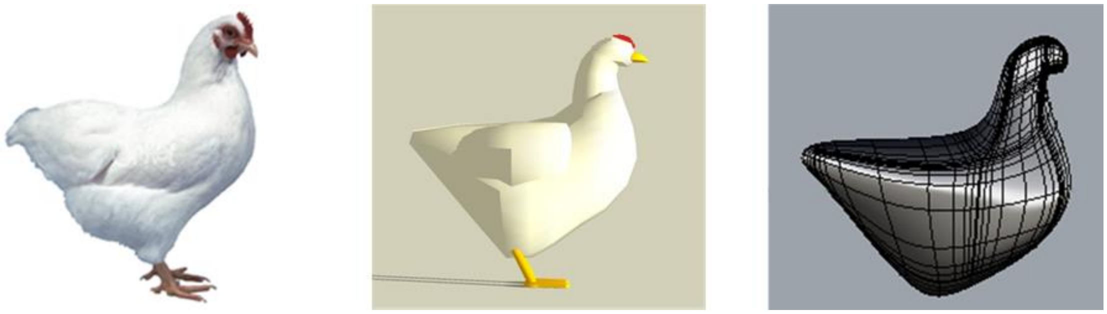


Fig. 1 The process of generating the model chicken

The simulated wind tunnel was following the dimensions in Mitchell's experiment as well, the length was 1m, and the cross section was 0.31m*0.31m. Model chicken was placed in the middle with a height of 0.06m from floor. That height was corresponding length of leg in that growing period. Four chicken orientations respect to the wind were set in the simulation, 0^o (Fig. 2 a), 45^o (Fig. 2 b), 90^o (Fig. 2 c) and 180^o (Fig. 2 d), respectively.

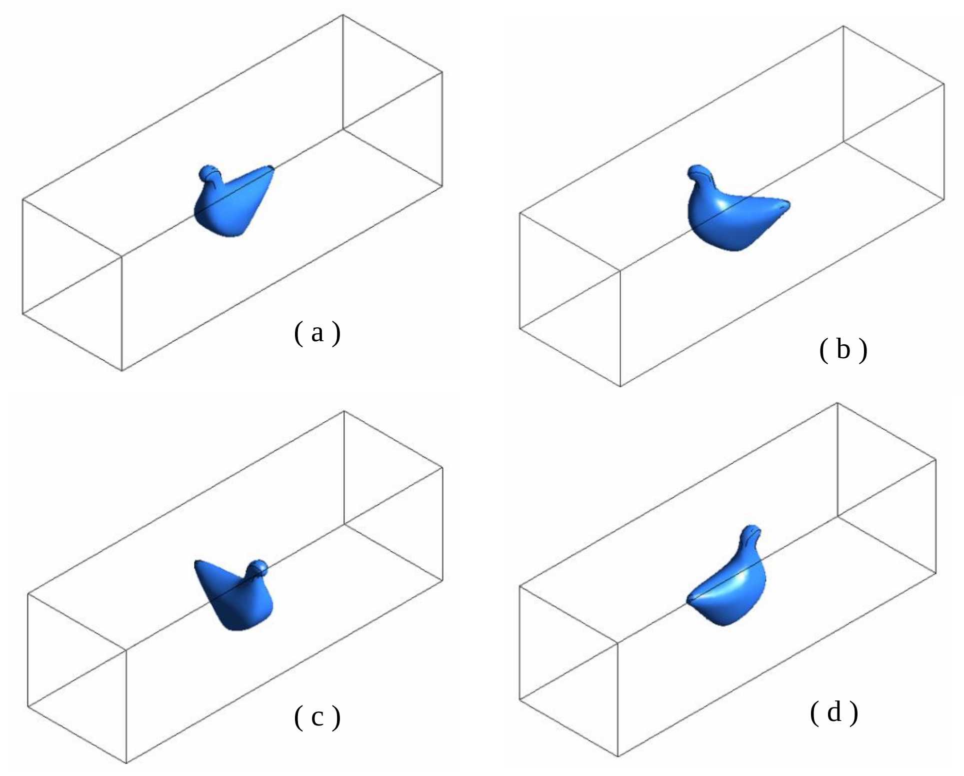


Fig. 2 Schematic of the calculation domains with four chicken orientations to the wind: (a) 0°, trunk axis parallel to the wind direction with head facing the wind; (b) 45°, trunk axis 45° angle to the wind direction; (c) 90°, Trunk axis perpendicular to wind direction; (d) 180°, trunk axis parallel to the wind direction with posterior end facing the wind.

In order to study scale effect on the results, the calculation domain was scaled into two other sizes by factors of 0.6 and 1.3. The corresponding areas of chicken surface were 0.0276 m^2 and 0.1300 m^2, respectively. In all the three scales, the body weight was calculated from the surface area from the relationship below (Walsberg, 1978):

$$M = \sqrt[0.667]{S / 0.081}$$

The corresponding body weights were 0.2kg, 0.9kg, and 2.0kg, respectively, which respected the whole growth process of a chicken.

In order to test the accuracy of CFD method in studying forced convection, a simple geometry of sphere was examined in a same virtual wind tunnel. The sphere had a diameter of 15.6cm and the area was 0.0769 m^2, as same as the virtual chicken in this study. The sphere was arranged in the middle of virtual tunnel.

2.2. Basic concept of CFD and software

The fundamental bases of almost all CFD problems are to solve governing equations like the Navier-Stokes and continuity equations. All these governing equations mentioned above can be written in a general form as:

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho\boldsymbol{u}\phi) = div(\Gamma grad\phi) + S$$

Written in expansion,

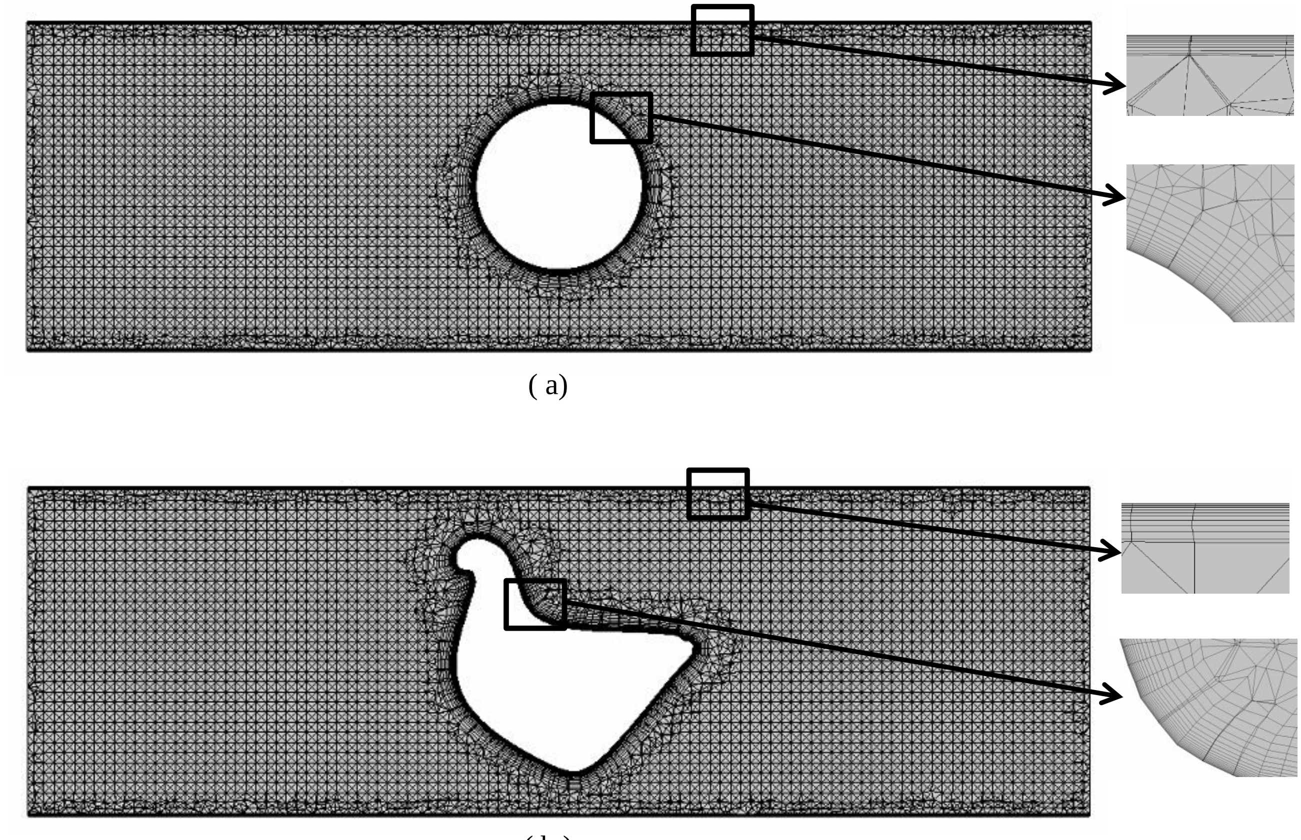
$$\frac{\partial(\rho\phi)}{\partial t} + \frac{div(\rho u\phi)}{\partial x} + \frac{div(\rho v\phi)}{\partial y} + \frac{div(\rho w\phi)}{\partial y} = \frac{\partial}{\partial x}(\Gamma\frac{\partial\phi}{\partial x}) + \frac{\partial}{\partial y}(\Gamma\frac{\partial\phi}{\partial y}) + \frac{\partial}{\partial z}(\Gamma\frac{\partial\phi}{\partial z}) + S$$

where, ϕ represents variables, Γ the effective diffusion coefficient, and S the source term of an equation. The terms are transient term, convective term, diffusive term, and source term, respectively in equation.

In this research, commercial software Fluent 15.0 (Ansys Inc., USA) was used to solve the equations on the basis of finite volume method. Standard k-ε, RNG k-ε, low Re k-ε, transition SST and RSM turbulence models were tested in this work. Velocity and turbulence terms for convection were all approximated using second order upwind scheme. Diffusion terms were discretised using central difference scheme. SIMPLE method was employed for the pressure-velocity correction.

2.3. Mesh

To solve the boundary layer around the virtual chicken, continuously layers of prism cells were created both on the surface of the virtual chicken and wall with an initial height of 0.1mm to keep the $y^+<1$. Tetra-meshes were then arranged from the outside of the boundary layer to the other side walls in the analytical space. After the grid independence test, a total number of computational cells of 1.5 million were used for the mesh of sphere and virtual chicken.



(a)

(b)

Fig. 3 Schematic of the mesh in the calculation: (a) the mesh of the sphere; (b) the mesh of the virtual chicken.

2.4. Boundary conditions

The inlet was set as velocity inlet with air speeds ranged from 0.3m/s to 3m/s, turbulence intensities of the inlet air was 5%. Outlet was set as pressure outlet. The no-slip condition was adopted as the wall surface boundary condition for the velocity and hence the flow pattern and detailed temperature gradient inside the viscous sublayer could be precisely analysed. The skin surface temperatures of the virtual chicken were fixed at a constant value, 24.7^{o}C, which was the average temperature derived from literature. For the sphere, the surface temperature was set as a constant value of 42^{o}C. The environment temperature in the simulation was set as 20^{o}C, both for the wall and air inside.

2.5. Calculation of convective coefficient

Convective heat transfer from skin or feather results from an airstream perturbing the insulating boundary layer of air clinging to the surface of the body. The convective heat loss can be written in equation below:

$$H_c = A \times h_c \times (T_s - T_\infty)$$

Where, A is the surface area (m^2), h_c is the convective heat transfer coefficient (W/m^2 K^{-1}), T_s is the averaged surface temperature of the chicken (K), T_∞ is the ambient temperature (K).

Correspondingly, h_c can be calculated based on the equation above, given total convective heat loss, surface area, and temperature difference between environment and surface of animal:

$$h_c = \frac{H_c}{A \times (T_s - T_\infty)}$$

The convective coefficient of the sphere and virtual chicken in the simulation in this research was calculated based on the equation above.

The convective coefficient h_c is related to the thickness of the boundary layer, which could be expressed in a dimensionless form using is Nusselt number, Nu. It can be calculated based on this equation:

$$h_c = \frac{k}{d} Nu$$

Where k is the conductivity of the fluid (W/m K^{-1}), d is the characteristic dimension (m), Nu is Nusselt number.

For a sphere, Holman (2008) recommended to use the relations developed by Achenbach (1978) applicable for air with Pr = 0.71:

$$\mathrm{Nu} = 2 + \left(0.25\ \mathrm{Re} + 3 \times 10^{-4}\, \mathrm{Re}^{1.6}\right)^{1/2} \text{ for } 100 < \mathrm{Re} < 3 \times 10^5$$

The theoretical calculation of the sphere was based on the method above.

In addition, all the velocities in the simulation of the sphere were corrected due to blocking effect using the method suggested by some researchers(Kowalski and Mitchell, 1976). For the simulation of chicken, the velocities were taken from average velocity of the middle section in the virtual tunnel.

3. Results

3.1. Effectiveness of different turbulence models

Table.1 shows the convective coefficient calculated using different RANS turbulence models and those obtained from theoretical calculation. The agreement between convective coefficient predicted by CFD and measurement values varied with different turbulence models. For Standard k- ε and RNG k- ε models, both of them overestimated convective coefficients in all the air velocity ranges compared with theoretical calculation. The discrepancies between simulation and calculation were small with a relative error around 1%, and then increased with air velocity. At 1.05m/s, the relative errors were 3.4% and 6.6% for Standard k- ε and RNG k- ε models, respectively. Low Re k- ε model had much higher values in all the air speed scales with relative errors ranging from 8.5% to 48.3%. However, SST k-ω underestimated the convective value in all the air speeds from 0.3 m/s to 1.05m/s, and the discrepancies decreased with air speeds from -22.7% to -1.4%. Transition SST underestimated the values at low air speed of 0.3m/s and 0.45m/s, and overestimated those at relative higher air speed. The convective coefficient calculated by RSM model had lower results at low air speeds, and the relative errors were relatively small in all the air speed range in this study. In this study, In order to get more precise results in following simulation, RSM model was employed in all the following simulation.

Table.1 Comparison of measured convective coefficients with that calculated from different turbulence models

Turbulence models and measurement	Convective coefficient (w/m2-k) and relative error compared with theoretical calculation (%)											
	Varied air speeds of inlet (m/s)											
	0.3		0.45		0.6		0.75		0.9		1.05	
Standard k- ε	5.90	1.1%	7.39	2.6%	8.67	3.2%	9.81	3.5%	10.86	3.5%	11.83	3.4%
RNG k- ε	5.90	1.2%	7.46	3.6%	8.82	4.9%	10.03	5.7%	11.15	6.3%	12.19	6.6%
low re k- ε	6.33	8.5%	8.71	20.9%	10.92	30.0%	13.01	37.2%	15.02	43.2%	16.96	48.3%
SST k-ω	4.51	-22.7%	6.07	-15.8%	7.49	-10.9%	8.81	-7.1%	10.07	-4.0%	11.27	-1.4%
Transition SST	5.59	-4.3%	7.14	-0.9%	8.50	1.2%	9.73	2.6%	10.87	3.6%	11.93	4.3%
RSM	5.58	-4.3%	7.04	-2.2%	8.31	-1.1%	9.44	-0.5%	10.48	-0.1%	11.45	0.1%
Theoretical (Achenbach, 1978)	5.84		7.21		8.40		9.49		10.49		11.44	

3.2. Effects of Animal orientation

No significant difference (*P>0.05*) was found between the two conditions in which chicken trunk axis was parallel to the wind direction with head or posterior end against wind. The convective coefficients (h_c), increased with air velocity (v) and can be described by the relationship: $h_c = 12.14v^{0.5747} \left(R^2 = 1\right)$ and $h_c = 11.958v^{0.5726}$ $(R^2 = 0.9996)$ .The cases with trunk axis inclining to wind direction at 45 degree and 90 degree showed obvious higher prediction values than that of the other two orientations. The simulated convective coefficients ranged from 6.00 w/m^2 k^{-1} to 13.58 w/m^2 k^{-1}. The relationship between convective coefficient and air velocity are $h_c = 13.216v^{0.557}$ $(R^2 = 1)$ and $h_c = 12.85v^{0.5555}$ $(R^2 = 0.9999)$, respectively.

The cases with trunk axis parallel to the wind with head towards wind were similar to the experiment done by Wathes and Clark (1981). The CFD simulation results showed that the convective coefficients were underestimated at lower air speeds but overestimated at higher air speeds. The relative errors ranged from -8.8% to 5.2%. ANOVA analysis showed that the difference between these two group data was not significant ($P>0.05$).The cases that with lateral orientation to the air flow were in the same conditions with the experiment done by Mitchell (1985). The mean deviation between simulation and experiment was -8.42% with the largest discrepancies occurring at the very lowest and very highest air velocities. ANOVA analysis showed a significant difference between these two group data ($P<0.05$).

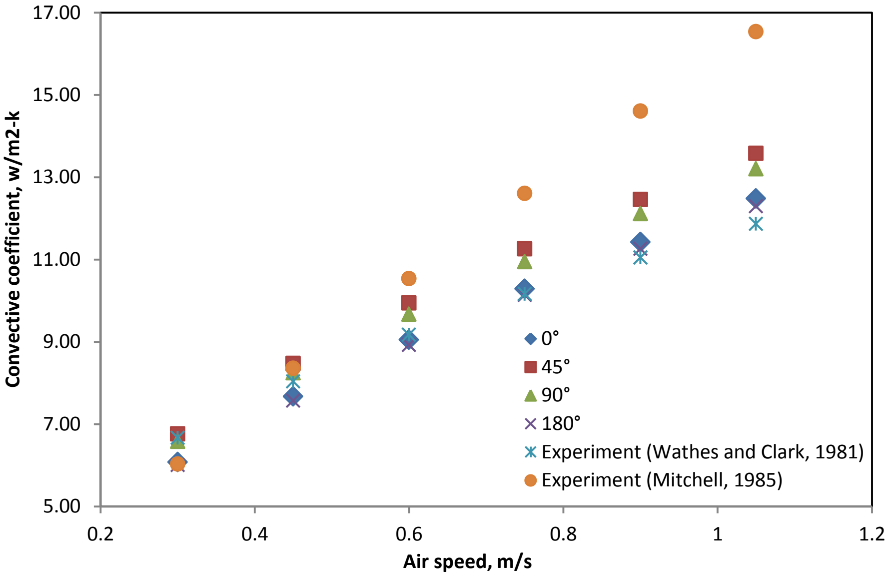


Fig. 4 Relationship between air speed and convective coefficient with different orientations

3.3. Effects of the model scale

Fig.5 shows the convective coefficient of chicken models with different scales calculated over the range of air speeds in simulation. It is obviously that the models with smaller scale have higher convective coefficient compared larger scale models in the same air velocities. The model with 0.9kg corresponding weight was the same model as the model with lateral orientation to the wind direction. The relationship between convective coefficient and air velocity of the other two models can be described as $h_c = 16.138v^{0.5446}$ ($R^2 = 0.9999$) and h_c=11.464$v^{0.5621}$ (R^2 = 0.9998) for models in 0.2kg and 2kg, respectively.

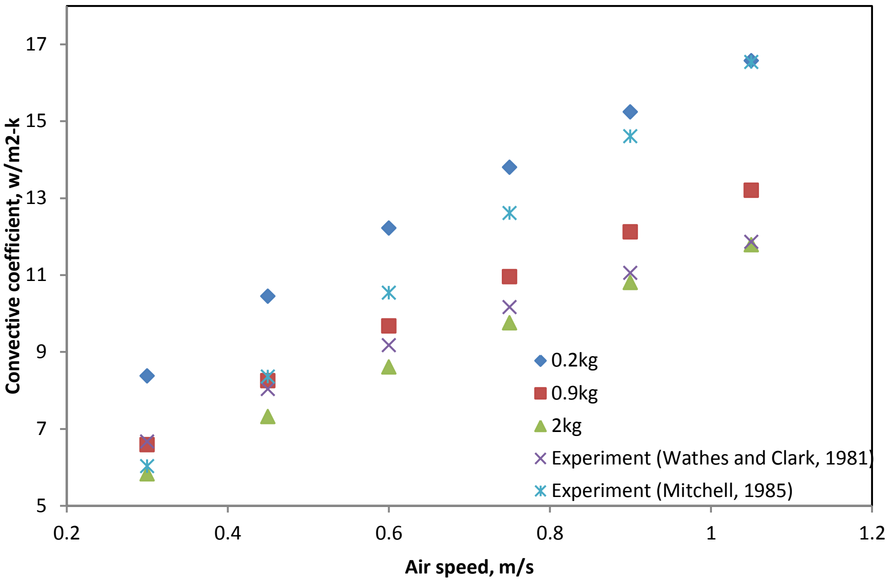


Fig.5 Relationship between air speed and convective coefficient with different scales

3.4. Velocity field and airflow pattern around animals

Symmetry plane in calculation domain was employed to demonstrate the velocity field and airflow patterns. Examples for velocity field are showed in Fig for 0° and 90° orientation to the airflow with inlet air speeds of 0.3m/s and 1.05m/s.

In the cases of chicken head facing the wind, as showed in Fig.6 (a) and Fig. 6 (b), higher air velocities appeared at the top and the bottom of the chicken body. There were low air velocity zones just behind the neck and trunk of the chicken. In the cases that chicken were laterally orientating to the airflow, as showed in Fig. 7(a) and Fig. 7(b), higher air velocities were observed also at the top and bottom position of the virtual chicken. Obvious low air velocity zones were found downwind side of the body. They had a much larger affected area compared with the cases with chicken head orientating to the wind. The velocity contours were almost same in condition with 0.3m/s inlet air speed and 1.05m/s inlet air speed. The air velocities were proportionate to the inlet air velocities.

Airflow patterns were demonstrated in Fig. 8. Small vortexes were found downwind side of the neck and body in cases that chicken head orientating to the wind with inlet air velocity of 0.3m/s (Fig. 8 a) and 1.05m/s (Fig. 8 b) . No significant difference of air pattern was found in these two cases. Large vortex zones were found behind the body along wind direction in the cases that trunk axis perpendicular to wind direction in the two velocities working conditions (Fig. 8 c and d). The vortex zones were the place where were the low air velocity zones.

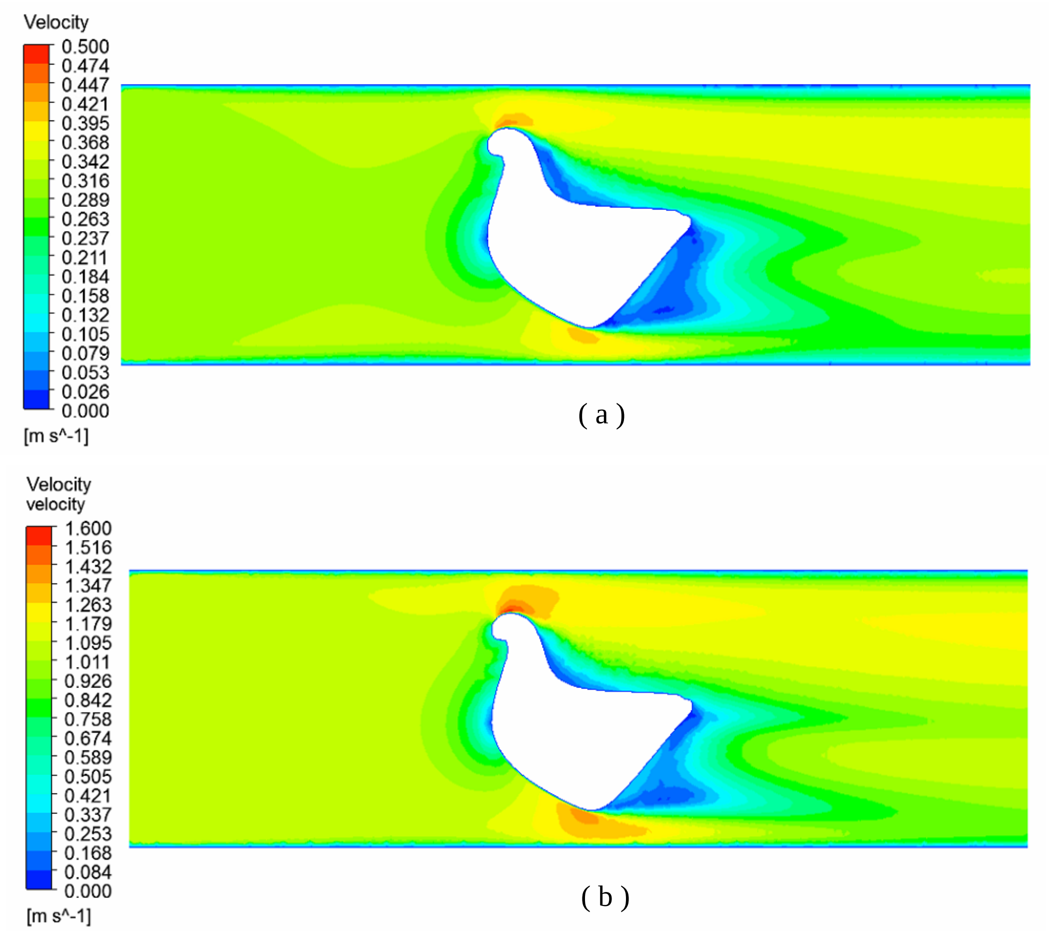


Fig.6 Velocity field around chicken with 0° to the wind direction while the inlet velocity of: (a) 0.3m/s; (b) 1.05m/s.

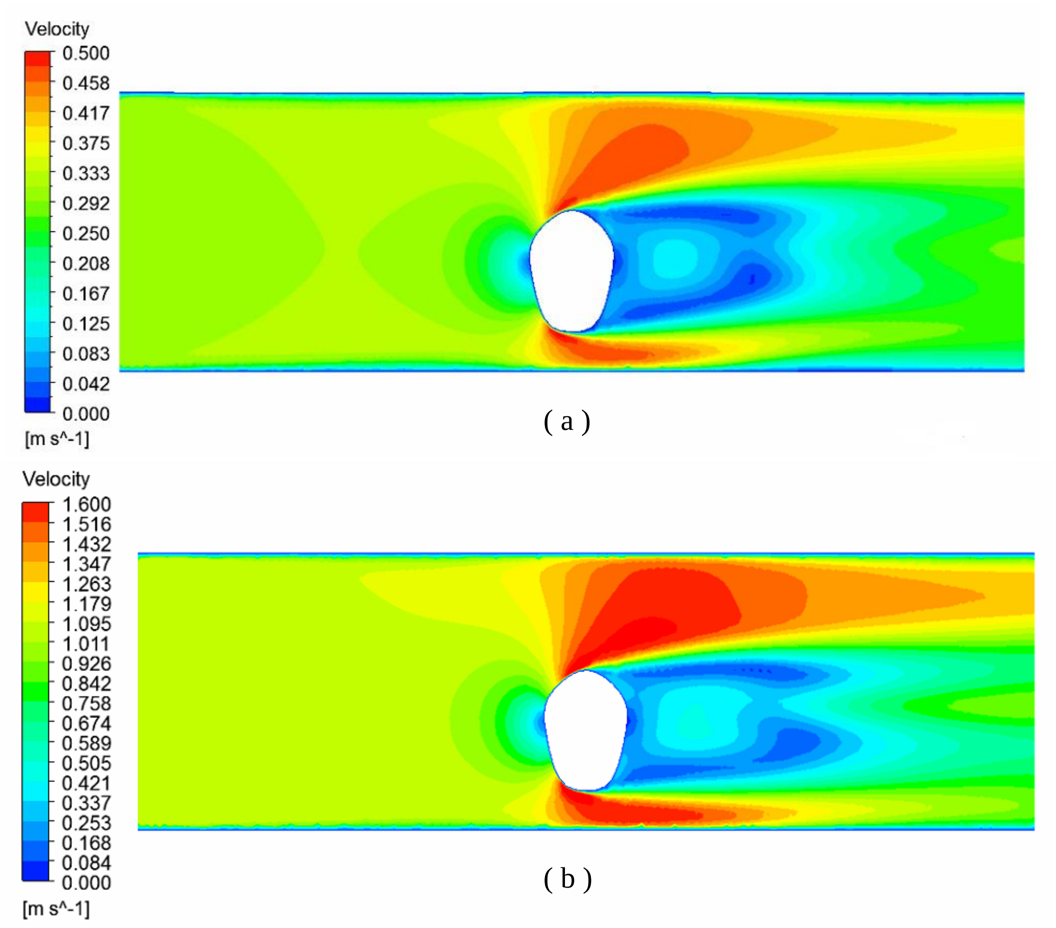


Fig.7 Velocity field around chicken with 90° to the wind direction while the inlet velocity of: (a) 0.3m/s; (b) 1.05m/s.

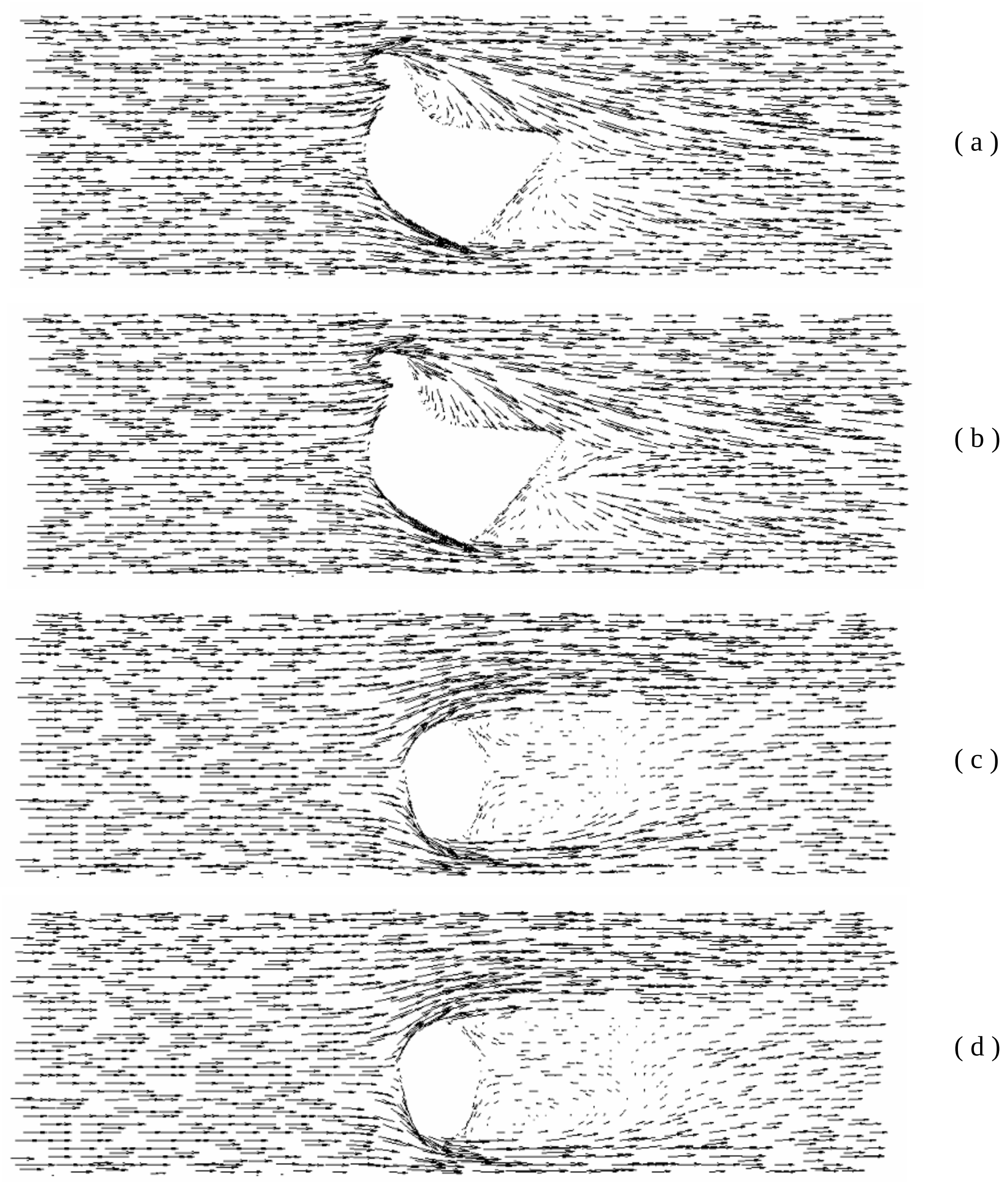
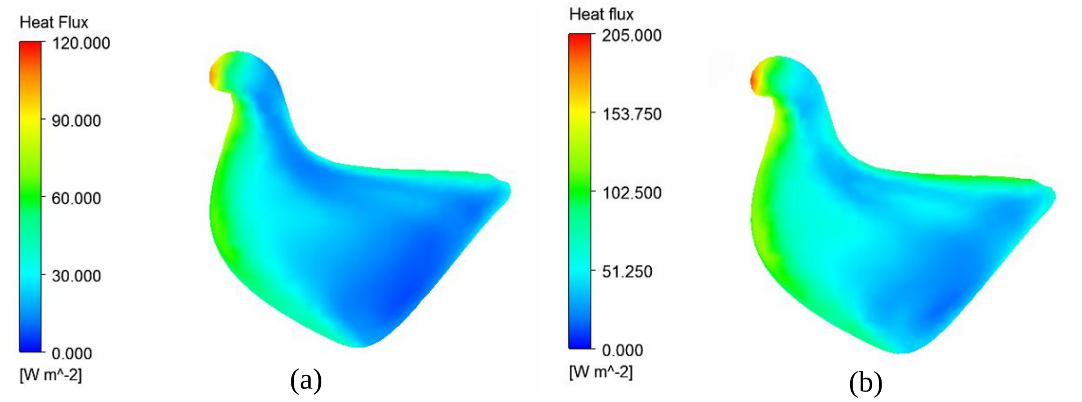


Fig.8 Airflow pattern around chicken with: (a) 0° to the wind direction while the inlet velocity of 0.3m/s; (b) 0° to the wind direction while the inlet velocity of 1.05m/s; (c) 90° to the wind direction while the inlet velocity of 0.3m/s; (b) 90° to the wind direction while the inlet velocity of 1.05m/s;

3.5. Heat flux on the surface

Fig.9 shows that the heat flux from the surface of body in the cases with inlet air velocities of 0.3m/s (Fig. 9 a) and 1.05m/s (Fig. 9 b) while chicken was facing the wind. Highest heat flux were found on the beak, the values were approxmately 111w/m^2 and 203w/m^2, respectively, for the two velocity 0.3m/s and 1.05m/s. The heat flux were relatively higher on the windward side, and lower on the rest of body. The average heat flux from the body surface were 30.4 w/m^2 and 62.5w/m^2 in these two velocity cases.

Fig. 10 shows that the heat flux from the chicken surface in the two velocity conditions with trunk axis perpendicular to the wind. Higher heat flux were found on 2 locations, beak and tail on the leeward side, on both the velocity working conditions. Hihgest value reached to around 105w/m^2 and 195w/m^2 for 0.3m/s (Fig. 10 a) and 1.05m/s (Fig. 10 b) inlet velocity. The downwind sides of the surfaces were found to have significant lower heat flux on both of the velocity cases.The mean heat flux from the whole surface of body were 36.6w/ m^2 (Fig. 10 c) and 73.5w/ m^2 (Fig. 10 d) in the two cases.



(a) (b)

Fig.9 Heat flux from the surface of body when the chicken was 0° to the wind direction in the cases with inlet air velocity: (a) 0.3m/s and (b) 1.05m/s.

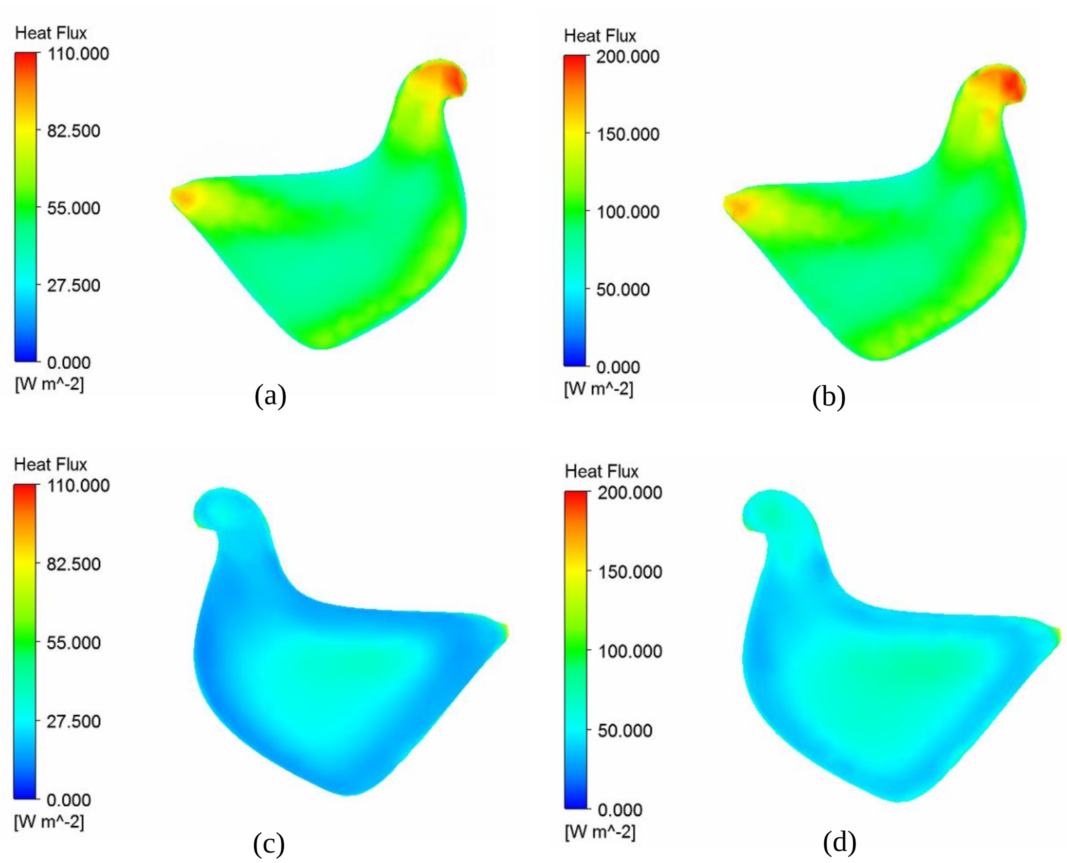


Fig.10 Heat flux from surface with trunk axis perpendicular to the wind in inlet air velocity of: (a) 0.3m/s on windward side; (b) 1.05m/s on windward side; (c) 0.3m/s on leeward side; (d) 1.05m/s on leeward side.

3.6. Prediction of convective coefficient on higher air velocity

Convective coefficients at higher air velocities were predicted in cases with three orientations to the wind, i.e., chicken trunk axis 0°, 45° and 90° to the wind direction. New regression curves were made based on the simulated data in all the air velocities range from 0.3m/s to 3m/s. The relationships between convective coefficients and air velocities were $h_c = 2.417v^{0.6216}$ ($R^2 = 0.9983$), $h_c = 13.478\,v^{0.6015}$ ($R^2 = 0.9985$) and $h_c = 13.087\mathrm{v}^{0.6141}$ ($R^2 = 0.9975$), respectively, for the trunk axis of 0°, 45° and 90° to the wind direction. In addition, a regression that depicting the general condition of chicken between convective coefficient and air velocity was calculated based on the mean convective coefficient of the three orientations. The curve could be described as $h_c = 12.994v^{0.6121}$ ($R^2 = 1$).

4. Discussion

4.1. Selection of RANS turbulence models

In the preliminary study on the convective heat transfer from the sphere, Standard k- ε, Transition SST and RSM models had relatively low relative errors within 5% in the simulation in comparison with theoretical calculation. Compared with Standard k- ε model and Transition SST model, RSM model generated more accuracy results in a broad range. It was reported that RSM model made a accurcy results for velocity field(Wu et al., 2012). Since the convective coefficient is highly dependent on the velocity and boundary layer, the precise simulation of velocity is appreciable in simulating the convective coefficients. However, RSM model could take approximate five times more time in calculation than Standard k- ε (Zhang et al., 2007). In this study, Transition SST needed 1.5 times computing time longer than Standard k- ε. Taking computing time into consideration, Standard k- ε model is one of the most time saving turbulence model with relative high accuracy in calculating convective heat transfer. From this point, it is sufficient enough to carry out most of the calculation when the precision requirement is not that high.

4.2. Convective coefficient simulated by CFD

The results from CFD meet the measurement results from the smooth copper chicken model very well. It proved the feasibility of CFD to study the heat transfer from the heated body. However, there were deviations compared with the results from the measurement of real chicken. The discrepancy can be due to the uncertainty of the experiment method. The method was to measure the temperature difference between the upwind direction and downwind direction of the body with and without heat source, and then to recalculate the heat transfer based on the known power of heat source. In the preliminary experiment to study the convective heat loss from a copper sphere, a mean deviation 8% was found compared with theoretical calculation. When it came to a test for a real chicken, the uncertainty still existed.

Another reason of discrepancy between the simulation and the measurement of real chicken could be the chicken movement during the experiment. The chickens were allowed to stand or sit and extend neck and wings during the experiment. All that movement will lead to a higher blocking effect generating a higher velocity around the chicken and cause a higher heat loss. Higher air velocity will cause higher movement level of chicken. That could be the reason why measurement of real chicken got a higher convective coefficient compared with the static model in simulation. Besides, the blocking effect may also contribute the uncertainty in the experiment. The chicken was lateral orientated to the wind. The blocking effect was much stronger in that condition. Using characteristic diameter to calculate correct velocity could lead to underestimation of the actual air speed and overestimation of the convective coefficient.

The simplification of the geometry could be another reason that resulted to the deviation. A virtual chicken with smooth surface was employed in the simulation. The beak, legs and feather layer were all omitted. The simplification could have a strong effect on the simulation (Wu et al., 2012). Pelt or feather layer was reported for enhancing the convective heat transfer compared with the smooth body

(Mcarthur and Monteith, 1980). And the effect will increase with the air speed (Wathes and Clark, 1981) . The simulation results showed a good agreement with the experiment which used the smooth copper model also proved that the feather layer could be a very reasonable explanation for the discrepancy. In addition, there were unavoidable in CFD simulation. The uncertainty in the simulated air velocity and temperature will lead to a higher discrepancy when calculating the convective coefficients.

In order to validate the explanation, further research should be conducted in a condition with limitation of animal movement and without blocking effect. Since the CFD method showed strong promising in giving the detailed information. The CFD simulation considering the feather layer in a broad area is needed.

4.3. Simplification of model to a sphere

Many researchers have suggested or used sphere or cylinder as a model to study the thermal condition of animals (Gates, 1963; Mitchell, 1976; Norton et al., 2010; Porter and Gates, 1969). Based on the data with surface area of 0.0769m^2, which was calculated based on a chicken with 0.9kg weight, the convective coefficients of sphere and chicken model was found to have a relationship for $h_{c\_chicken}$=1.2221×h_{c_sphere} – 0.6267 (R^2=1) (Fig. 11). The relationship was applicable to the chicken with the weight of 0.2kg and 2kg also. The relative errors between calculated data and theoretical data were all below 3%. ANOVA analysis showed very high agreement in both of the groups. From this point, the relationship could be used to calculate the convective coefficient of a chicken based on a sphere with a same surface area.

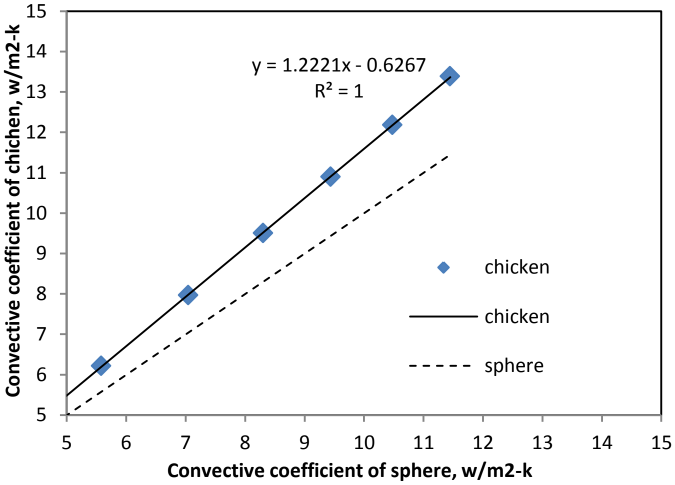


Fig.11 Convective coefficient of chicken (W/m^2-k) plotted against convective coefficient of sphere (W/m^2-k)

5. Conclusion

RSM (Reynolds Stress Models) was found to be the most accurate of the used RANS turbulence models in studying forced convection from geometry in wind tunnel, whilst it will take higher CPU usage. Considering accuracy and computing time, Standard k- ε is sufficient enough.

CFD method showed great potential in predicting the convective coefficient of animal. A prediction model for chicken with 0.9kg in a velocity range from 0.3m/s to 3m/s was generated as $h_c = 12.994v^{0.6121}$ ($R^2 = 1$). And the convective coefficient for the chicken could be calculated based on a sphere having a same surface area, the relationship is $h_{c\_chicken}=1.2221\times h_{c\_sphere} - 0.6267$ ($R^2=1$).

The simulation agreed the experimental data of smooth copper chicken model very well. However, when comparing the data of a real chicken, the discrepancy still existed. Future research could be done in both lab measurement and optimization of CFD simulation model. Block effect should be avoided in order to study the real situation in the field. From perspective of lab measurement, more precise experiment with higher air velocities is still needed. For CFD, simulation of a more complex geometry with feather layer could be conducted and simulated in a broader range of air velocities.

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