Development of a straightforward method of estimating age-of-air using CFD

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Abstract

Ventilation is significant to keep internally optimum environmental conditions in agricultural facilities such as greenhouse and livestock house. Because of importance of ventilation, many related studies have been actively conducted to investigate ventilation performance of target structure. Among the various concepts of evaluating ventilation rate or efficiency, age-of-air concept such as local mean age (LMA) and local mean residual life time (LMR) can be one of indicators to examine the ventilation efficiency of agricultural facilities by estimating the abilities of fresh air supply and contaminants emission. The tracer gas experiment has been usually adopted to measure the values of age-of-air. This method has some limitations caused by characteristics of unstableness and invisibility of air flow. However, the application of Computational fluid dynamics (CFD) can be a solution to analyze the age of air values of the target structure. Bartak et al. (2001) computed value of LMA by solving the passive scalar transport equation using CFD simulation. However, more research are still needed to develop the method for computation of the concept of LMR. The aim of this study was to develop a straightforward method to evaluate LMA and LMR via CFD simulation. The main idea of estimating LMA and LMR was to solve the passive scalar transport equation in the CFD solver. Especially, to calculate the value of LMR, computed flow field was reversed compulsively by using user defined function (UDF). Then, the value of LMR was assessed at the value of virtual LMA computed to solve the passive scalar transport equation at the reversed flow field. This method could reduce the number of equations by solving only transport equation. Therefore, the calculation time in CFD simulation could be reduced and the process of calculating age-of-air values could be more simple and convenient. To validate the newly developed method of this study, the results computes in this study were compared with the experiment results of Kwon et al (2011)’s study. The estimated values of LMA and LMR by designed method in this study were shown in the range of about 10~40% errors with Kwon et al. (2011)’s experimental data. We also reduced the total computation time to estimate the values of age of air by about 75%. Especially, our method could overcome the complexity and laborious repetitive works on simulation process to compute LMR values.

Keywords: Age-of-air, Computational fluid dynamics, Local mean age, Local mean residual life time, Passive scalar transport equation

1. Introduction

Ventilation is important factor to control optimum environmental condition in agricultural facilities such as greenhouse and livestock house. In case of livestock house, various contaminants which are emitted from feed and feces are accumulated, and it has bad influences on stocks and farm workers (Zhaung et al., 2002). Especially in winter season ventilation systems of livestock house are usually operated at the minimal level to maintain proper thermal environment and save heating costs and energy. It causes the accumulation of
various pollutants and dust that are harmful to livestock and workers in livestock house. Thus, ventilation in agricultural facilities has grown in importance to satisfy the proper environmental conditions. Many researchers have studied to quantify and evaluate the ventilation performance. Various methods have been studied to quantify ventilation such as energy balance model (Boulard et al., 1993; Boulard, Draoui, 1995; Lee, Short, 2000), tracer-gas method (De Jong, 1990; Nederhoff et al., 1985), pressure difference model (Boulard et al., 1996), etc. Although, these traditional methods are useful in evaluating overall ventilation, these are still weak at evaluating local ventilation effect (Kwon et al., 2011). In recent researches by Hong et al. (2008) and Seo et al. (2009), the tracer gas decay method was used to analyze characteristics of local ventilation using CFD technology. However, this method also has limitations of not guaranteeing ventilation efficiency. Sandberg (1981) proposed the age-of-air concept for the first time to examine ventilation efficiency. In comparison to the mentioned methods, the age-of-air concept can evaluate not only overall ventilation efficiency but also local ventilation efficiency at all indoor point. Han (1992 and 1999) studied experimental method to estimate value of age-of-air following the tracer gas approach. However, this experimental method also has some limitations such as the acquisition of quantitative and qualitative data and uncertainties due to the unstable gas. Nevertheless, these limitations could be solved using CFD. Kwon et al. (2011) calculated the value of age-of-air using CFD. Kwon et al. (2011) solved various gas transport equations, because this method was based on the experimental procedure of tracer gas approach. This method needed much computing time to calculate the value of age-of-air. More researches are necessary to reduce the computing time and determine intuitionally ventilation efficiency. The main objective of this study was to develop straightforward method to evaluate the value of LMA and especially LMR by solving the passive scalar transport equation following the method suggested by Bartak et al. (2001).

2. Materials and methods

2.1 Age-of-air concept

Sandberg and Sjoberg (1983) used the terms “age” and “residence time” in his comprehensive theoretical framework of ventilation engineering. Age-of-air means the time that the inflow of fresh air from outside reaches to a designated point inside the structure. The inflow generally reaches to arbitrary point via various pathways; the statistically mean value of age-of-air is defined as the local-mean-age (LMA). In addition, the air or pollutants also reaches to outlet via various pathways; the mean value of residence time to reach the outlet from a designated point is defined as the local-mean-residual-lifetime (LMR). The conceptions of age-of-air are presented in Figure 1.

The Methods of calculating LMA and LMR can be categorized as the method of injecting tracer gas technique; the pulse method, step-up method, and step-down method. Following equations explains how to compute age-of-air based on the step-down tracer gas approach.

\[
\text{LMA}_p = \int_0^\infty (1 - \frac{c_{p,\infty}(t)}{c_{p,\infty}}) \, dt \tag{1}
\]

\[
\text{LMR}_p = \int_0^\infty (1 - \frac{c_{p,\infty}(t)}{c_{p,\infty}(\infty)}) \, dt \tag{2}
\]

In the Eqs. (1) and (2), \(c_{p,\infty}\) is the tracer-gas concentration at the outlet which is introduced at a designated point p; \(c_{p,\infty}\) is the tracer-gas concentration at a designated point p coming through the inlet; \(c_{p,\infty}\) is the tracer-gas concentration when the space is filled with a homogeneous concentration of tracer-gas; LMA\(_p\) is the local-mean-age at a designated point p and LMR\(_p\) is the local-mean-residual-lifetime at designated point P.
2.2 Computational fluid dynamics simulation

Computational fluid dynamics simulation (CFD) is the analysis tool to obtain numerical solution about some systems such as fluid flow, heat transfer, and chemical reactions, etc. CFD simulations had significant advantages compared to field experiments. CFD simulation could easily simulate any conditions and illustrate airflow patterns. In this study, GAMBIT (ver. 2.4.6, Fluent Co. New Hampsher, USA) was used to design computational domain with meshes and establish the boundary conditions. ANSYS FLUENT (ver. 14.5, ANSYS Inc.) was used to solve the nonlinear differential Navier-Stokes equations based on the finite volume method. The model used in this study was same structure with that of Kwon et al. (2011)’s study to compare with the value of age-of-air computed in this study and experimented by Kwon et al. (2011). The value of LMA and LMR was estimated in three cases. The slot outlet for case 1 was located in the upper right section; that of case 2 was in the lower right section; that of case 3 was in the lower left section. The model is shown in Figure 2. Constant input values and boundary conditions for CFD simulation are shown in Table 1 and Table 2.

2.3 Development of the straightforward method of computing age-of-air using CFD technique

The value of LMA and LMR was calculated by solving the passive scalar transport equation based on the methodology suggested by Bartak et al. (2001). Eq. (3) is the formula used to calculate the LMA and LMR.

\[ \frac{d}{d\vec{x}_i}\rho u_i \phi - \vec{J} \frac{d\phi}{d\vec{x}_i} = \rho \left( \vec{J} = -\left( \rho D_m + \rho D_t \right) \frac{d\phi}{d\vec{x}_i} \right) \]  

Eqns. (3) was performed by using user-defined function (UDF) at FLUENT. In Eq. (3), \( \rho \) and \( \vec{u} \) are density and velocity of the fluid; \( \vec{J} \) is component of diffusion flux; \( D_m \) and \( D_t \) are molecular and turbulent diffusivity; \( (\rho D_m + \rho D_t) \) is a turbulent Schmidt number and its value was assumed 0.7.

After the flow field was solved in CFD simulation, the values of LMA were estimated by solving this equation. Because the equation for LMR calculation hasn’t still been developed, the indirect method which used the Eq.(3) was devised to calculate the value of LMR. It was assumed that the pathways from some arbitrary point to outlet are equal to the reversed pathways from outlet to mentioned arbitrary point. In other word, the value of LMA from the outlet to some arbitrary point with inversed vector field was theoretically same with the value of LMR from mentioned arbitrary point to the outlet. The concept of estimating the value of LMR was shown in Figure 3. To calculate the value of LMR, all directions of vector field were reversed compulsively by UDF which programmed by C language after calculating the flow equation. Then, by the same procedure for LMA calculation, the value of the travel time from outlet to some arbitrary point represented LMR. The calculation procedure of LMR is explained in Figure 4. This method only need to one calculation regardless of a number of measuring points; Because of calculation of the value of LMR using CFD based on tracer gas approach, many case calculations were required, however, calculation of LMR based on newly developed method in this study required only one case calculation. Therefore, it can be concluded that newly designed method in this study have powerful advantages in aspect of time efficiency and calculation convenience.

3. Results and Discussions

In this study, the values of age-of-air were computed by solving the scalar transport equation in the CFD solver, ANSYS FLUENT. Computation of values of LMA and LMR was executed by designed UDF linked in FLUENT. The value of LMA at the cell represented the final time-scalar value at every computation domains. For the calculating the value of LMR, general user-defined-scalar (UDS) and its transport equation embedded in FLUENT package were modified to represent the time scalar. Computed flow field at process of computing the value of LMA was reversed compulsively by using UDF. The values of LMR were estimated by the value of...
virtual LMA computed at the reversed flow field. Finally, the results of these calculation were compared with former research; Kwon et al. (2011) performed a computing age-of-air values by laboratory experiments and CFD simulations based on the tracer gas method. The computed values of LMA and LMR at the experimental points are presented in Figure 5. The average errors of LMA and LMR values also compared with lab experiment and result of CFD simulation conducted by Kwon et al. (2011) are shown in Table 3. The tendency of the value of age-of-air computed in this study was similar to Kwon’s results. The average errors of LMA and LMR values between experimental results and CFD simulation results were in the range of about 10~40%, implying that the errors had relatively big differences. Especially, there were some experimental points that were relatively large differences of the value of age-of-air; those were P2-2, P2-3, P2-4, P3-2, P3-3, P3-4. There were several reasons why large errors were computed. These results could be explained by that effect of diffusion coefficient between solving transport equation and tracer gas approach was different in the region of low velocity. Actually, the average errors of LMA and LMR values between experimental results and CFD simulation results were reduced at 25% in case of excepting the those points. Another reason is the experimental error generated by difficulty of setting equivalent condition during repetitive experiment. Also, standard k-ε turbulence model used in study couldn’t consider small eddy. Although the errors of LMA and LMR between experiment and CFD simulation results were relatively large, the results of age-of-air computed in this study were effective on estimating qualitatively congested areas. Also, the newly developed method in this study could evaluate air flow and reduce the errors generated from following the tracer gas approach.

4. Conclusions

In this study, the improved calculation method of age-of-air was suggested. As a result, the tendency of LMA and LMR showed good agreement with results of Kwon at al.(2011). Furthermore the computational time was significantly reduced compared with Kwon et al.(2011)’s study. This calculation method of age-of-air will contribute to various ventilation researches in respect of not only its accuracy but also its efficient computational cost. Finally, while this study used standard k-ε turbulence model, another study should be conducted by applying another turbulence models that are proper to analyze the small eddy and congested areas. Also studies about diffusion coefficient should be conducted to enhance the reality of model in CFD simulation.

5. References


<table>
<thead>
<tr>
<th>Content</th>
<th>Value</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Operating temperature</td>
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</tr>
<tr>
<td>Gravitation acceleration</td>
<td>9.81</td>
<td>ms^{-2}</td>
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<tr>
<td>Specific heat of air</td>
<td>1006.43</td>
<td>J kg^{-1}K^{-1}</td>
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<tr>
<td>Density of air</td>
<td>1.225</td>
<td>kg m^{-3}</td>
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<tr>
<td>Velocity Magnitude at Inlet</td>
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<td>ms^{-1}</td>
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<td>Viscosity of air</td>
<td>1.86\times10^{-5}</td>
<td>kg m^{-1}s^{-1}</td>
</tr>
<tr>
<td>Molecular weight of air</td>
<td>28.966</td>
<td>g mol^{-1}</td>
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Table 2 Boundary Conditions for the CFD simulation model

<table>
<thead>
<tr>
<th>Case</th>
<th>Wall</th>
<th>Inlet</th>
<th>Outlet1</th>
<th>Outlet2</th>
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<tr>
<td>Case 1</td>
<td>Wall</td>
<td>Velocity inlet</td>
<td>Pressure outlet</td>
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<tr>
<td>Case 2</td>
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<td>Velocity inlet</td>
<td>Wall</td>
<td>Pressure outlet</td>
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</tr>
<tr>
<td>Case 3</td>
<td>Wall</td>
<td>Velocity inlet</td>
<td>Wall</td>
<td>Wall</td>
<td>Pressure outlet</td>
</tr>
</tbody>
</table>

Table 3 Average error of LMA and LMR values between lab experiment and CFD simulation (Exp means the values of LMA and LMR from lab experiment (Kwon et al., 2011), Kwon means the value of LMA and LMR from simulation results based on tracer gas approach (Kwon et al. 2011) and Park means the values of LMA and LMR from this study)

<table>
<thead>
<tr>
<th>Case</th>
<th>Average error of LMA</th>
<th>Average error of LMR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp VS Kwon</td>
<td>Exp VS Park</td>
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<tr>
<td>Case 1</td>
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</tr>
<tr>
<td>Case 2</td>
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<tr>
<td>Case 3</td>
<td>19.94</td>
<td>39.24</td>
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</table>

Figure 1 The concepts of LMA and LMR based on the age-of-air (Line means average value of various courses of air and dotted line means various courses of air or contaminants.)
Figure 2 The structure of model used in this study and the designated study points for the CFD simulation

Figure 3 The concept of estimating the value of LMR using hypothetical LMA

Figure 4 The calculation procedure of LMR
Figure 5 LMA / LMR values computed by three method: measuring the experiment approach, using CFD based on tracer gas method (Kwon, 2011), using CFD based on passive scalar transport equation (this study). ( experiment and Kwon means the result of study (Kwon, 2011), park mean the result of this study )