Wind Engineering Joint Usage/Research Center
FY2024 Research Result Report

Research Field: Indoor environment.
Research Year: FY2024
Research Number: 24242011
Research Theme: Study on accuracy evaluation and effectiveness of unsteady analysis during wind direction using RANS

Representative Researcher: Takashi Kurabuchi (Tokyo University of Science)

Budget [FY2024]: 290,000 Yen

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1. Research Aim

Although airflow analysis around buildings is generally conducted under steady-state conditions, the actual airflow inside and outside of buildings is considered to differ from the results of steady-state analysis because outdoor wind direction and velocity fluctuate from moment to moment. Therefore, in this study, indoor airflow was measured by rotating the wind tunnel rotating board to reproduce wind direction fluctuations. The results of the CFD analysis were compared with those of the wind tunnel experiment, and the validity of the unsteady analysis for wind direction fluctuation was examined.

2. Research Method

2.1 Experiment Summary

The experiment was conducted in an Eiffel-type wind tunnel at the Tokyo Polytechnic University. A plan view of the model is shown in Figure 1. The dimensions of the model are 300 mm wide, 300 mm deep, 150 mm high, and the wall thickness is 8 mm. An omni-directional anemometer was installed inside the model at 17 locations at a height of 15 mm above the top of the rotating board to measure the wind speed. The measurement interval was 0.1 s. The model aperture is shown in Figure 2. Two patterns were considered for the windward side: one at the center of the wall surface and the other in contact with the floor surface of the model. The model was placed in the center of the rotating board, and changes in the external wind direction were simulated by rotating the rotating board. The behavior of the rotating board is shown in Figure 3. The rotating board was rotated at 22.5°/s, but since the speed is reduced at the start and stop of the rotation, the actual rotation was 1.8 s from 0 to 22.5° and 2.8 s from 22.5° to -22.5°. The wind velocity profiles of the experiment are shown in Figure 4. The wind tunnel was set up so that winds of 6.0 m/s were blowing at the height of the model's top surface. The study cases of the experiments are shown in Table 1. For the steady-state experiment, the rotating board was fixed at a rotation angle of every 0.1 s in Figure 3, and the airflow velocity in the room was measured for 1 minute. In the unsteady experiment, the rotation of the rotating board was repeated 50 times, and the results were ensemble averaged. The rotation of the rotating board is performed after the airflow in the room has stabilized.

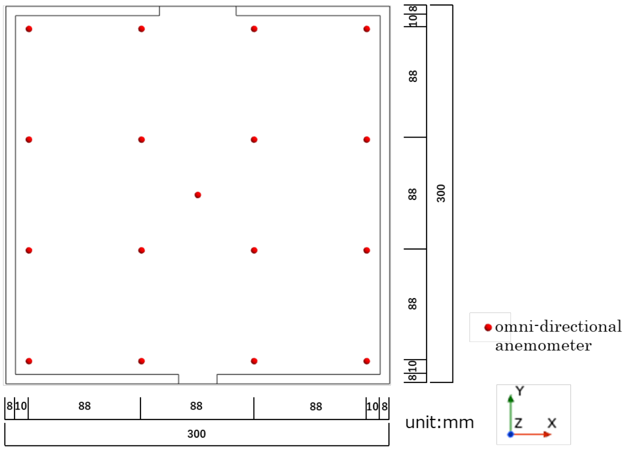


Figure1 Plan view of the model

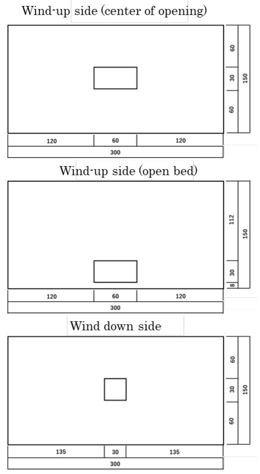


Figure 2 Model aperture

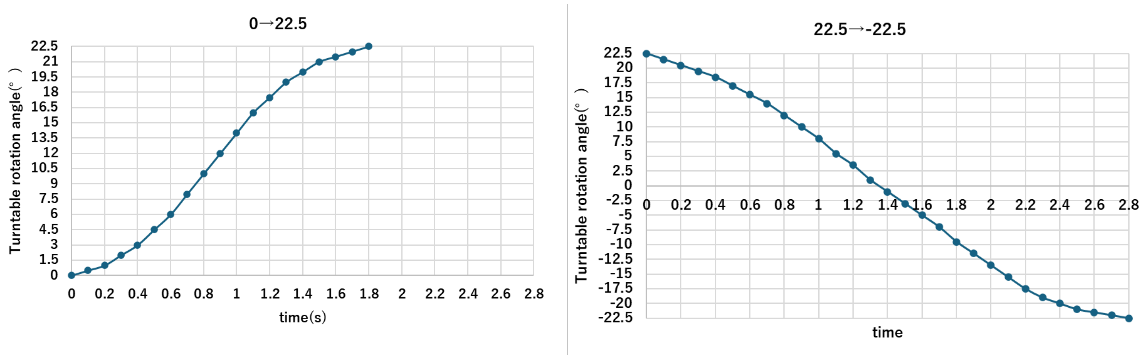


Figure 3 Behavior of a turntable

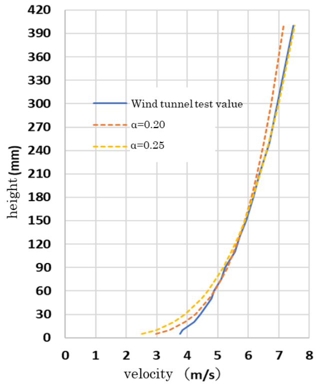


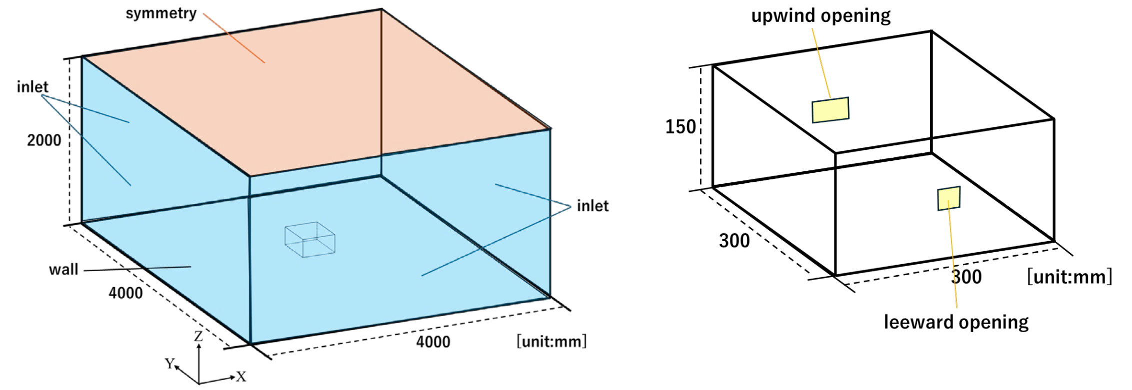
Figure 4 Wind velocity profile

Table 1 Experimental cases

Case Name	Experimental Details	Aperture requirement	Rotation conditions
case1-1	steady state	aperture center	0° →22.5°
case1-2	unsteady state		
case2-1	steady state	above the opening floor	
case2-2	unsteady state		
case3	unsteady state	aperture center	22.5° →－22.5°
case4	unsteady state	above the opening floor	

2.2 CFD overview

In order to compare in detail the indoor airflow structure under steady and unsteady conditions, we attempted to reproduce what we studied in the wind tunnel experiments by CFD analysis. The analytical model is shown in Figure 5. The analytical model consists of a model of the same dimensions as in the experiment set up in the center of the analysis space, which is 4000 mm wide × 4000 mm deep × 2000 mm high. The boundary conditions are shown in Table 2. Four surfaces of the analysis area were set as inlets so that the boundary conditions do not need to be rearranged according to the wind direction angle when the wind direction is varied. The top surface was set as the target surface, and the ground and the wall of the model were set as the wall boundaries. The analytical conditions are shown in Table 3. The standard k-ε model was used as the turbulence model for both the steady and unsteady analyses. The SIMPLE method was used for the steady-state analysis. The unsteady analysis used the implicit unsteady analysis, and the implicit scheme was SIMPLEC. The time step was 0.1 s, the same as the measurement interval of the omni-directional anemometer in the wind tunnel experiment. The calculation was terminated when the residuals at each time step met the convergence criterion or when the number of iterations reached 500, and the next time step was used. The vertical air velocity distribution was given based on the wind velocity profile from the wind tunnel experiment shown in Figure 4, and the turbulence energy k and dissipation rate ε were calculated from the vertical wind velocity with a power index of 0.20 to give the inflow boundary conditions. In the unsteady analysis, the inflow boundary condition was changed every 0.1s time step to obtain the wind direction variation shown in Figure 3.



outside inside

Figure 5 Analysis model

Table 2 Boundary conditions

boundary surface	boundary condition	
inflow surface	inlet	Profile based on 1/5 power law H=150mm Wind speed 6m/s
top side	symmetry	free slip
ground	wall	Wall functions on generalized logarithmic laws
model		

Table 3 Analysis conditions

Analysis Method	Steady-state analysis	Implicit non-stationary analysis
Analysis Software	SimcenterSTAR-CCM+2406	
turbulence model	Standard k- ε model	
implicit-dissolution scheme	SIMPLE	SIMPLEC
time step		0.1s
Analysis Area	4000㎜×4000㎜×2000㎜	
Number of meshes	198234	

3. Research Result

3.1 experimental results

The wind speed transition at each point in the unsteady experiment is shown in Figure 6. The time constant of the omni-directional anemometer is 3 seconds, so it cannot be said to represent instantaneous wind speed. However, for the purpose of comparing steady and unsteady conditions, the analysis was conducted this time by considering the point at which the wind speed value changed to be the start of rotation. It can be seen that before the rotation of the rotating board, there is almost no change in the indoor air velocity because of the steady state. The rotation stops 1.8 s after the rotation of the rotating board starts, and the indoor airflow velocity changes until around 3.0 s. After that, the airflow velocity ceases to change and becomes stationary again.

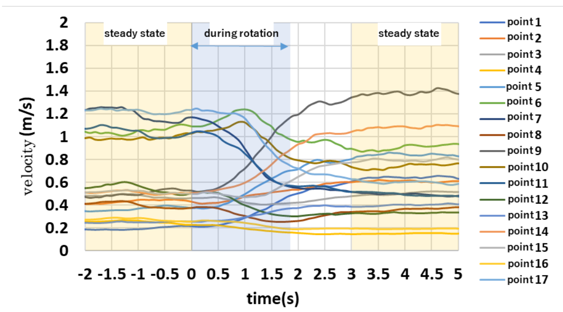
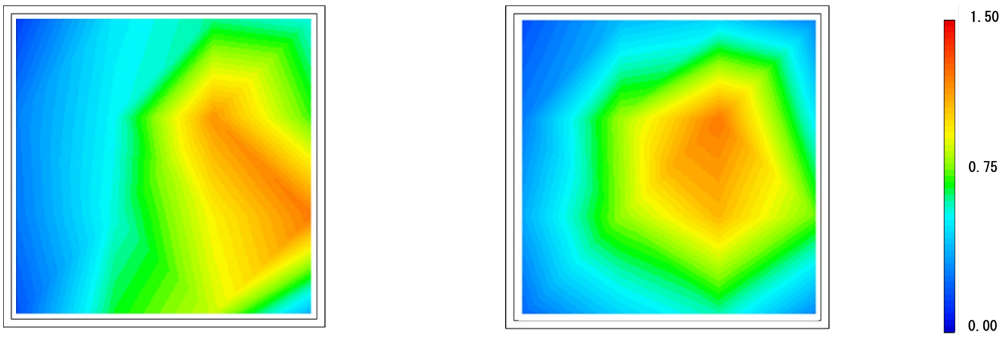


Figure 6

case1-2 Wind speed at various points

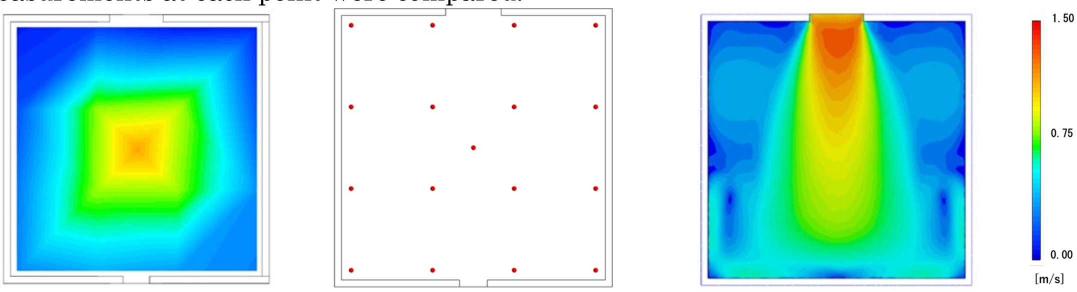
Figure 7 shows the indoor air velocity distribution at 1.1s (16.0°) after the start of the wind direction variation for the steady and unsteady results of case1 with the aperture in the center. In the steady state (case1-1), the inflow airflow from the aperture seems to collide with the sides of the room, while in the unsteady state (case1-2), the inflow airflow does not collide with the sides of the room, and is located in the center of the room compared to the steady state, confirming that there is a time delay before the wind direction variation affects the indoor airflow in the unsteady experiment. In the unsteady experiment, there is a time delay before the wind direction fluctuation affects the airflow in the room.



(a)case1-1 (b)case1-2

Figure 7 Experimental results case1 indoor air velocity distribution (1.1s 16.0°)

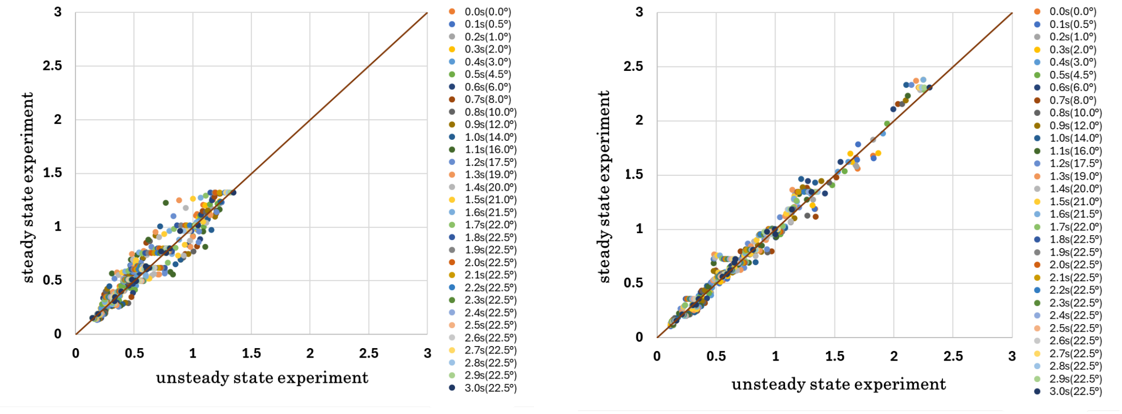
Case 2, in which the windward opening was located on the floor, did not have an anemometer installed near the opening, which was thought to be the maximum value of incoming airflow from the opening, and the incoming airflow was not captured. Therefore, instead of comparing indoor air velocity distributions, the corresponding wind velocity measurements at each point were compared.



Case2 Measurement position CFD Analysis Results

Figure 8 Experimental results case2 indoor air velocity distribution (0.0s 0.0°)

The correspondence between the experimental results and measured wind speed is shown in Figure 7. The horizontal axis shows the unsteady results of the experiment and the vertical axis shows the steady results of the experiment.



(a)case1 (b)case2

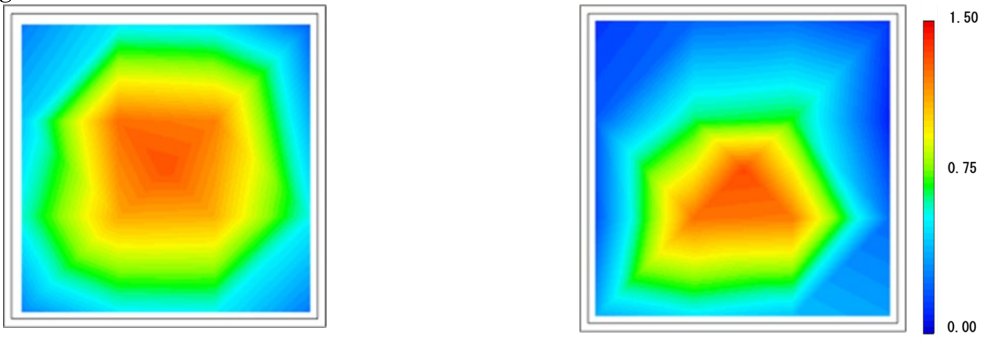
Figure 9 Actual measurement results Corresponding wind speed measurements

3.2 CFD Analysis Results

3.2.1 Wind direction 0° steady comparison

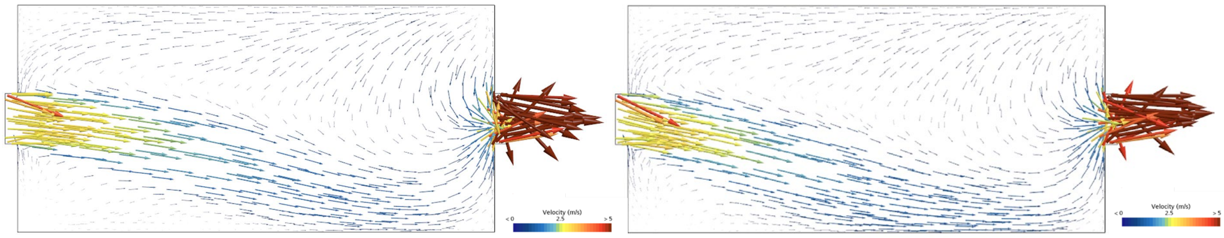
Figure 10 shows a comparison of the indoor airflow velocity distribution between the experimental steady-state results and the CFD steady-state results for a wind direction of

0° in case 1, where the aperture is placed in the center and the wind direction changes from 0° to 22.5°. It can be seen that the experimental steady-state result shows a large area of wind velocity in the center, while the CFD steady-state analysis result shows a large area of wind velocity from the center to the downwind side. The wind velocity vector distribution at the center cross-section of the opening is shown in Figure 11. The standard k-ε model is used in this study because Realizable k-ε is known to make it difficult for the jet of incoming air to fall and to fall backward.



(a) Experimental steady state (b) CFD steady-state analysis

Figure 10 case1 indoor air velocity distribution (0.0s 0.0°)

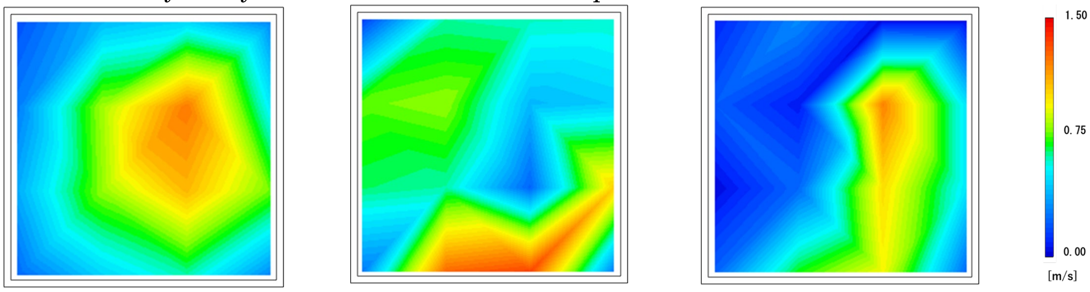


(a) Realizable k-e (b)標準 k-e モデル

Figure 11 Wind velocity vector in the center section of the aperture (0.0s 0.0°)

3.2.2 Comparison of CFDs in each case

Figure 12 shows the indoor air velocity distribution of the experimental unsteady, CFD steady-state, and CFD unsteady analyses of Case 1 after 1.1s. In the steady-state analysis, it can be seen that the incoming airflow hits the side wall and goes around the downwind wall, while in the unsteady analysis, it can be seen that the incoming airflow does not reach the side wall, indicating that the unsteady analysis result is closer to the unsteady experiment. The results of the CFD unsteady analysis gradually approaches the results of the CFD steady analysis after the rotation is completed in 1.8s.

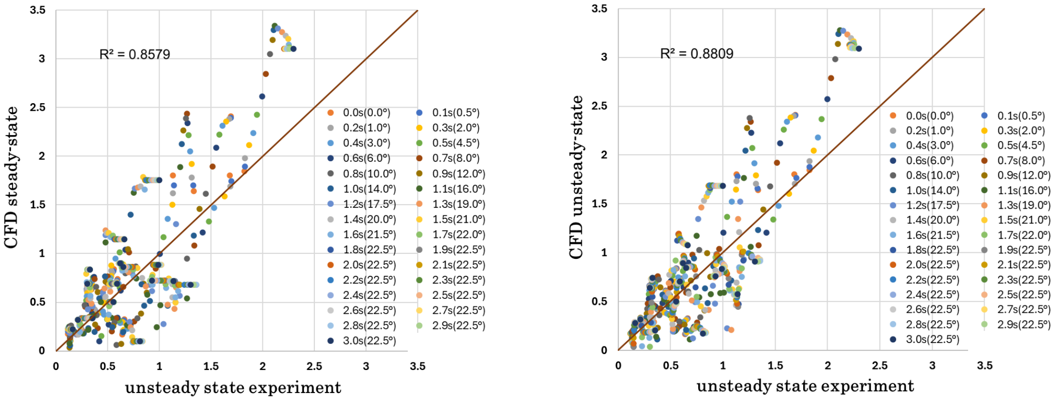


(a) experimental unsteady (b) CFD Steady-state analysis (c) CFD unsteady-state analysis

Figure 12 case1 Comparison of indoor air velocity distribution 0°→22.5° (1.1s 16.0°)

The correspondence between the unsteady experiment and the steady-state analysis (Figure 13(a)) and between the unsteady experiment and the unsteady analysis (Figure 13(b)) of the wind speed at the location of the omni-directional anemometer when the opening is located on the floor and the wind direction changes from 0 to 22.5° (case 2). It can be seen that the variation is larger than that of the experimental results shown in

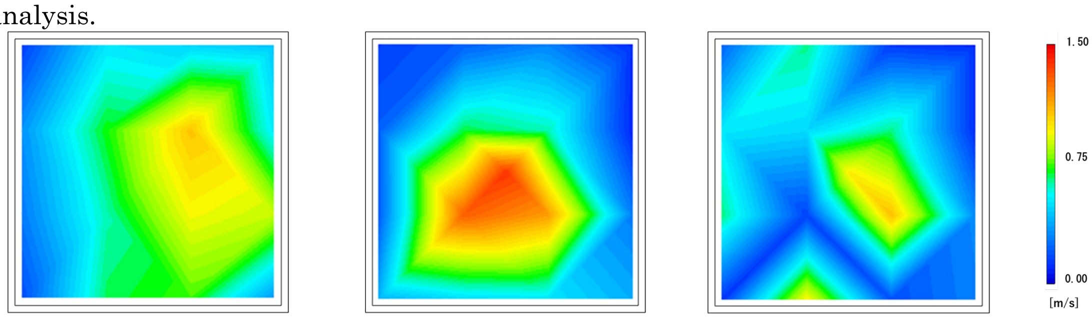
Figure 9. In the correspondence between the unsteady experiment and the steady-state analysis (Fig. 13(a)), the points plotted in the graph are lined up horizontally. This can be attributed to the fact that the results of the steady-state analysis do not change after 1.8s, while the values of the non-steady experiment change toward the steady state.



(a) CFD Steady-state analysis　　(b) CFD unsteady-state analysis

Figure 13 Actual measurement results Corresponding wind speed measurements

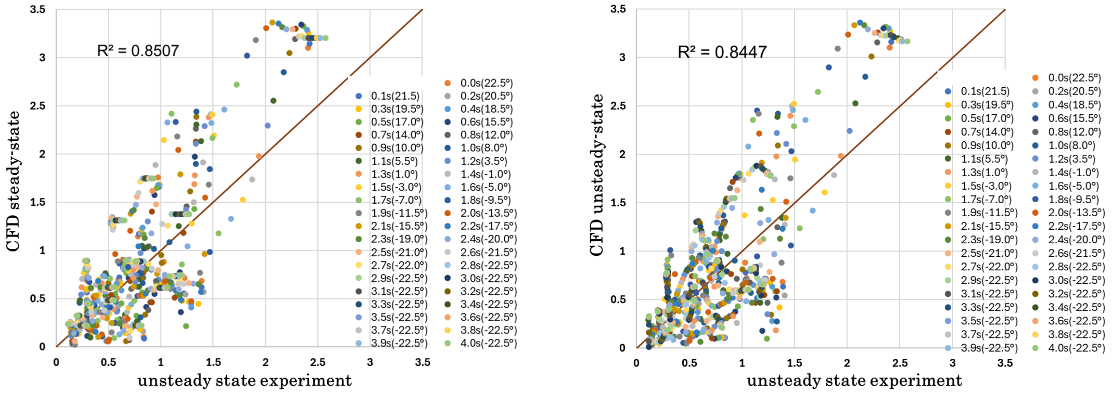
The indoor air velocity distributions of the experimental unsteady and CFD steady-state and CFD unsteady analysis after 1.4s in case 3, where the aperture is placed in the center and the wind direction changes from 22.5° to -22.5°, are shown in Figure 14. At 1.4s after the start of rotation, the wind direction exceeds 0° and becomes negative. Since the steady-state analysis does not consider the effect of the previous wind direction, the indoor air velocity distribution is formed by the airflow that flowed in with the outdoor wind direction of -1.0°. On the other hand, the unsteady result is affected by the previous time step in both the experiment and the CFD analysis, and a time delay in the indoor air velocity distribution can be seen. In addition, the CFD unsteady analysis resulted in the indoor air velocity distribution changing about 0.2s earlier than the experimental unsteady analysis.



(a) experimental unsteady　　(b) CFD Steady-state analysis　　(c) CFD unsteady-state analysis

Figure 14 case1 Comparison of indoor air velocity distribution 0°→22.5°(1.1s 16.0°)

Figure 15 shows the correspondence of wind speed measurements for case 4, where the opening is placed on the floor and the wind direction changes from 22.5° to -22.5°. As in case 2, the steady-state analysis shows some points plotted side by side on the graph, but compared to case 2, both steady-state and unsteady-state analyses show a poor correspondence with the unsteady experiment. The measured wind speeds in each case were determined. Table 4 compares the coefficients of determination of wind speed measurements for each case, and shows that the coefficients of determination for the steady and unsteady cases from case1 to case3 are higher for the unsteady case. The coefficient of determination for the unsteady analysis result of case 2 is the highest, which can be attributed to the fact that the aperture is located above the floor, so the jet of incoming airflow does not descend, resulting in a two-dimensional flow.



(a) CFD Steady-state analysis (b) CFD unsteady-state analysis

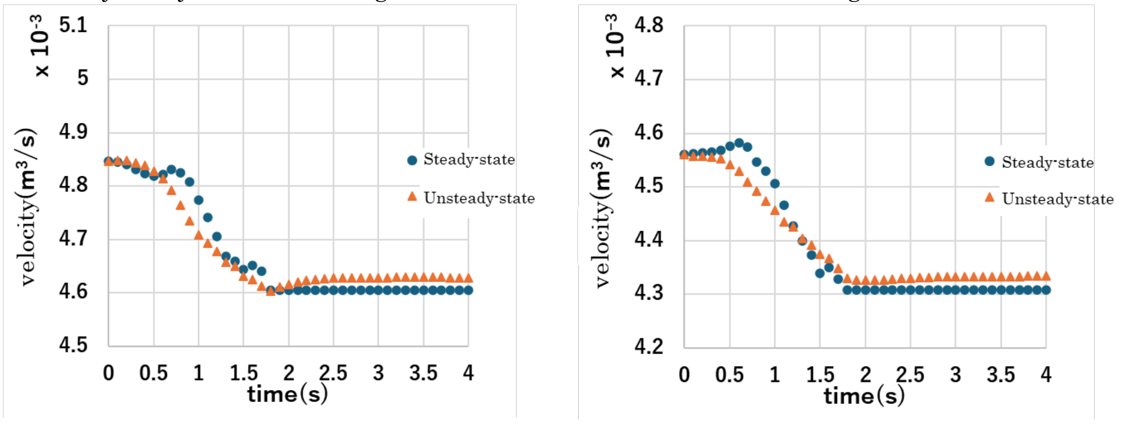
Figure 15 Actual measurement results Corresponding wind speed measurements

Table 4 Comparison of coefficients of determination for each case wind speed measurement

Coefficient of determination R^2	Steady-state analysis	Unsteady-state analysis
case1	0.7262	0.7934
case2	0.8579	0.8809
case3	0.7132	0.7597
case4	0.8507	0.8447

3.2.3 Comparison of airflow rate

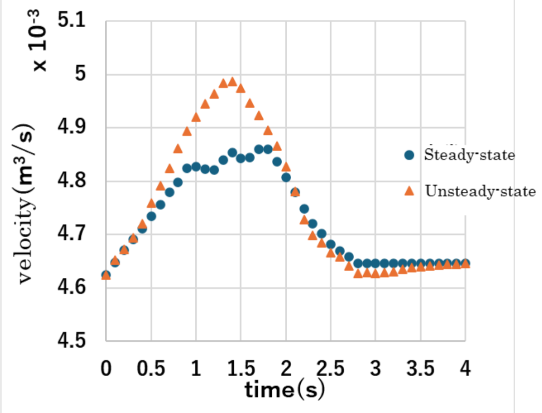
The airflow rates for the steady-state and transient analyses for case1 and case2, where the wind direction changes from 0° to 22.5°, are shown in Figure 16. Since the steady-state analysis is fixed at the wind direction angle at each time step, the airflow rate does not change continuously with the change in wind direction angle. On the other hand, the unsteady analysis shows changes similar to the behavior of a rotating board.



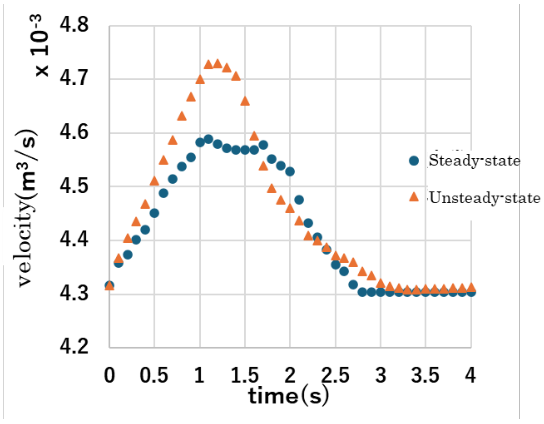
(a) aperture center (b) above the opening floor

Figure 16 Comparison of airflow rate 0° →22.5°

The airflow rates for steady and unsteady analysis are shown in Figure 17 for cases 3 and 4, where the wind direction changes from 22.5° to -22.5°. It can be seen that the steady-state analysis shows a nearly constant value when the wind direction is 0±10° regardless of the position of the upwind opening, while the unsteady analysis shows a maximum near 0°.



(a) aperture center



(b) above the opening floor

Figure 17 Comparison of airflow rate 22.5° →-22.5°

When the wind direction changes from 22.5° to -22.5° at a constant wind speed, the vector mean of the wind direction is 0°. The results show that the airflow rates are the same regardless of the position of the upwind aperture. From the above results, it is considered appropriate to evaluate the indoor airflow characteristics under non-steady state conditions, although the airflow rate may be evaluated by the average value of outdoor airflow direction.

Table 5 Comparison of airflow rate

	Constant Resolution 0.0° Ventilation Capacity (m^3/s)	Unsteady 0→2.8s average airflow(m^3/s)	difference(m^3/s)	difference(%)
aperture center	4.85×10^{-3}	4.80×10^{-3}	4.67×10^{-5}	0.97
above the opening floor	4.56×10^{-3}	4.51×10^{-3}	4.87×10^{-5}	1.08

4. Consideration of installing vertical sliding windows

4.1 Analysis conditions

Steady-state and transient analyses were performed by changing the opening size on the windward side to 30 mm x 30 mm, installing a vertical sliding window (hereafter WC) as shown in Figure 18, and varying the wind direction so that the angle of rotation was 45°. The analysis conditions are shown in Tables 2 and 3. The study cases are also shown in Table 6. Four study patterns were conducted with a fixed 45° rotation.

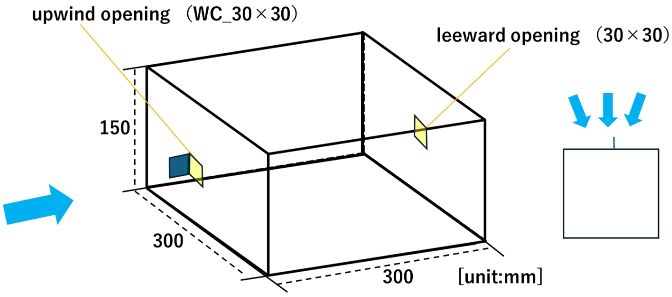


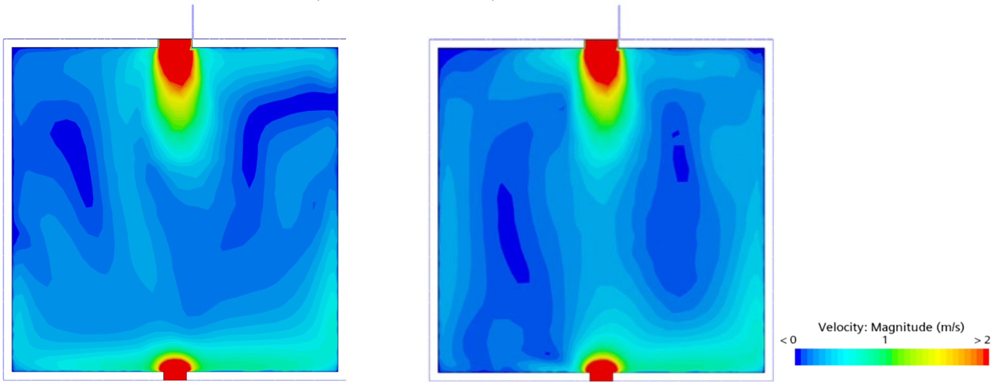
Figure 18 Analysis model for additional study

Table 6 Additional study cases

Case Name	Wind Direction Condition	Average value of wind direction
caseA	22.5° →-22.5°	0°
caseB	45° →0°	22.5°
caseC	67.5° →22.5°	45°
caseD	90° →45°	67.5°

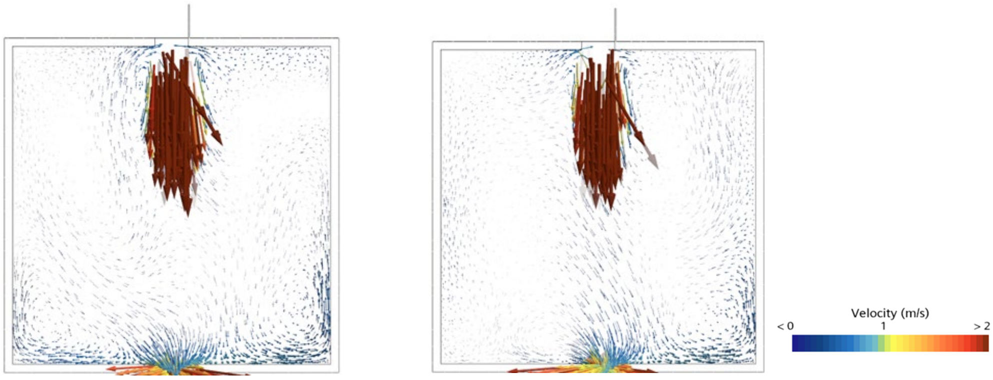
4.2 CFD Analysis Results

The room air velocity distribution in the center plane of the opening for the steady and unsteady analysis after 1.4s from 22.5° to -22.5° is shown in Figure 19. 1.4s is the moment of the next time step when the wind direction changes from 22.5° and exceeds 0°, and at first glance there appears to be no difference between steady and unsteady, but the steady analysis is At first glance, there does not appear to be that much difference between steady and unsteady, but the steady analysis shows that the incoming airflow is spreading to the left and right on the downwind side, while the unsteady analysis is influenced by the previous wind, and the wind is going mainly to the right side of the room only. The same is true for the case with WC on the upwind side, indicating that the air velocity distribution in the room differs between the steady and unsteady cases.



(a) CFD Steady-state analysis (b) CFD unsteady-state analysis

contour map



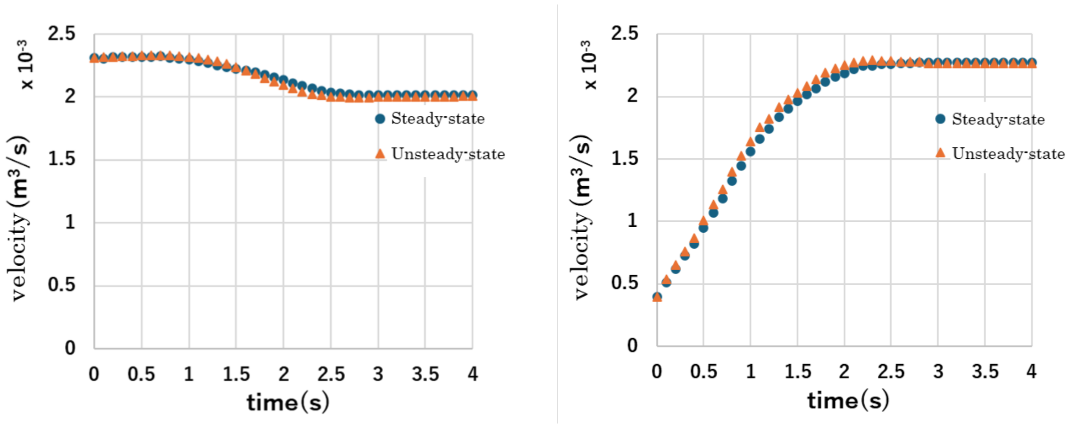
(a) CFD Steady-state analysis (b) CFD unsteady-state analysis

vector diagram

Figure 19

22.5° → -22.5°H=0.075 Comparison of indoor air velocity distribution (1.4s -1.0°)

A comparison of steady and transient airflow rates is shown in Figure 20. It can be seen that there is not much difference between the steady and unsteady airflow at each time step. The results of the unsteady analysis of the average airflow during wind direction variation and the airflow of the steady analysis at the average wind direction at this time are compared in Table 7. The difference is not large overall, but there is a difference of about 10% in the airflow rate for the 90°→45° case, and the reason for the larger difference for the 90°→45° case may be that the airflow rate fluctuates more in the 45° wind direction fluctuation range. In addition, it is desirable to perform an unsteady analysis in order to understand the airflow characteristics in a room with fluctuating wind direction, because a steady-state analysis may overestimate the effect of the WC.



(a) 22.5°→-22.5° (b) 90°→45°

Figure 20 Additional study Comparison of airflow

Table 7 Comparison of airflow by wind direction angle (upwind side WC)

Analysis Case	Average value of wind direction(°)	Constant Resolution Ventilation(m^3/s)	Unsteady 0→2.8s average airflow(m^3/s)	difference(m^3/s)	difference(%)
caseA(22.5° →－22.5°)	0°	2.25×10^{-3}	2.20×10^{-3}	4.38×10^{-5}	1.99
caseB(45° → 0°)	22.5°	2.32×10^{-3}	2.32×10^{-3}	3.80×10^{-6}	0.16
caseC(67.5° → 22.5°)	45°	2.26×10^{-3}	2.23×10^{-3}	2.72×10^{-5}	1.22
caseD(90° → 45°)	67.5°	1.88×10^{-3}	1.72×10^{-3}	1.56×10^{-4}	9.10

5. Summary

The following findings were obtained from this study.

1) Both the experimental and CFD analysis results show that in the unsteady state, the history of wind direction variation affects the indoor airflow structure, which is different from the indoor airflow structure in the steady state at each time step of wind direction.
2) The indoor airflow structure differs between steady and unsteady conditions when the wind direction fluctuates, and when a wind catcher or other device is installed, the airflow rate changes significantly depending on the wind direction angle, resulting in a large difference between steady and unsteady analyses.
3) Although this experiment confirmed the significance of evaluation under unsteady conditions, the anemometer readings include fluctuations during the three seconds immediately preceding the experiment, so it is necessary to conduct more detailed experiments in the future using an anemometer with a faster response speed.
4) There is a problem in reproducing the experimental results in CFD analysis, and it is necessary to continue to study the analytical model and analytical conditions.

6. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

[Presentations at academic societies]

[Published books]

[Other]

Intellectual property rights, Homepage etc.

7. Research Group

1. Representative Researcher

Takashi Kurabuchi — Professor, Tokyo University of Science

2. Collaborate Researchers

1. Akito Kono — Graduate Student, Tokyo University of Science
2. Minori Isikawa — Graduate Student, Tokyo University of Science
3. Toshihiro Nonaka — Professor, Tokyo University of Science
4. Jeongil Kim — Assistant Professor, Tokyo University of Science
5. Yosihide Yamamoto — Professor, Tokyo Polytechnic University

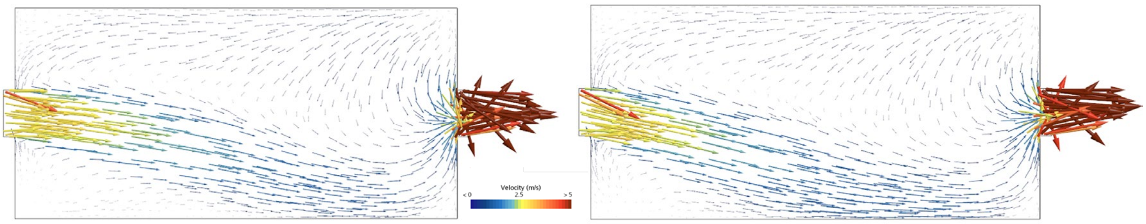
8. Abstract (half page)

Research Theme: Study on accuracy evaluation and effectiveness of unsteady analysis during wind direction using RANS.

Representative Researcher (Affiliation): Takashi Kurabuchi (Tokyo University of Science)

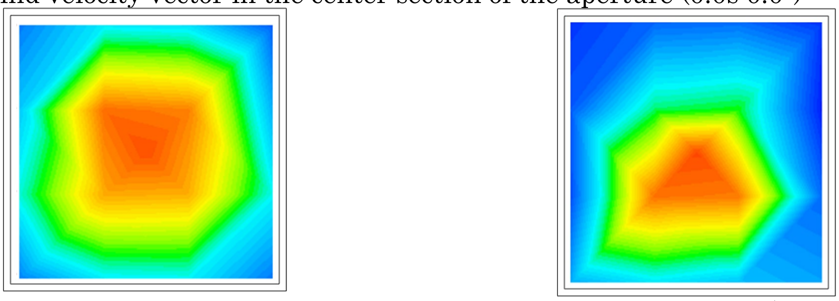
Summary・Figures

In this study, a rotating plate was rotated in a wind tunnel experiment to reproduce wind direction fluctuations, and indoor airflow measurements were taken. The consistency between the results of the wind tunnel experiment and the CFD analysis was confirmed, and the validity of the unsteady analysis during wind direction fluctuation was examined. The results showed that in the unsteady state, the airflow structure in the room is affected by the history of wind direction variation, and that the airflow structure in the room differs from that in the steady state for each time step of wind direction. There is a problem in reproducing the experimental results in CFD analysis, and it is necessary to continue to study the analytical model and analytical conditions.



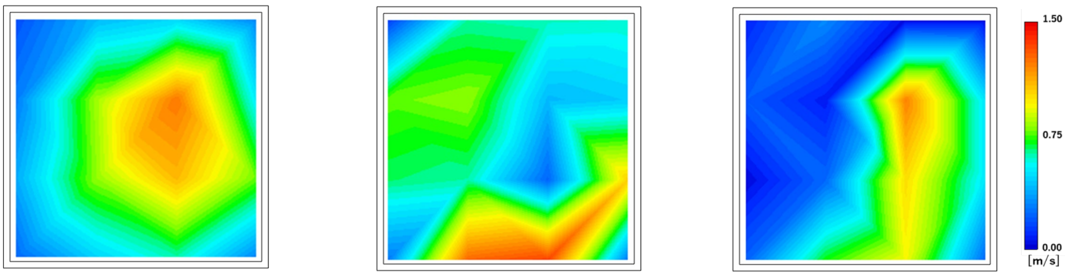
Realizable k-ε model Standard k-ε model

Wind velocity vector in the center section of the aperture (0.0s 0.0°)



Steady-state experimental results CFD steady-state analysis (standard k-ε)

case1 Comparison of indoor air velocity distribution (0.0s 0.0°)



experimental unsteady CFD Steady-state analysis CFD unsteady-state analysis

case1 Comparison of indoor air velocity distribution 0°→22.5°(1.1s 16.0°)