MEASUREMENT AND CFD ANALYSIS OF OPEN AIR INVASION PHENOMENON AT OPENING OF AN AUTOMATIC SLIDING DOOR

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ABSTRACT

This paper describes the measurement of wind velocity and pressure difference between that inside and outside of a single sliding door at open–close operation, and describes CFD analysis using measured pressure difference, aiming at the development of a CFD analysis approach considering opening and closing of a sliding door. Comparison with measurements verified that the analysis can reproduce unsteady phenomena observed in measurement in general.

INTRODUCTION

Because an entrance door of a building is opened wide to the external atmosphere for traffic, the entrance space is apt to undergo heat loss by open air invasion. Particularly because negative pressure occurs attributable to internal and external pressure differences by the chimney effect at the first floor of a skyscraper, deterioration of the thermal environment and enhanced heat loss occur in the entrance space by open air invasion. The entrance layout that minimizes external atmosphere invasion also accommodates recent demands for CO_2 reduction, and is therefore an important subject for thermal environment discipline. Measures for suppressing external atmosphere invasion include double sliding doors with a wind shield room and revolving doors, which are considered better than a single sliding door.

In Japan, a fatal accident in 2004 at a building with a revolving door decreased their new installment, and double doors are employed in many cases in skyscrapers (Fig. 1, Kimura, 2010). However, the depth of a wind shield room (distance between doors) is often insufficient, being only 4 m or less, and open air invasion accompanying the simultaneous opening of two doors is a concern (Fig. 2, Sakai, et al., 2012).

Because the area of opening of a sliding door varies with open–close operation, open air invasion is presumably an unsteady phenomenon. In addition, open air invasion to an entrance space in the case of a double sliding door depends on the depth of the wind shield room and the number of people passing through, the opening time of the door, and the chimney effect, so that it is presumably a complex phenomenon.

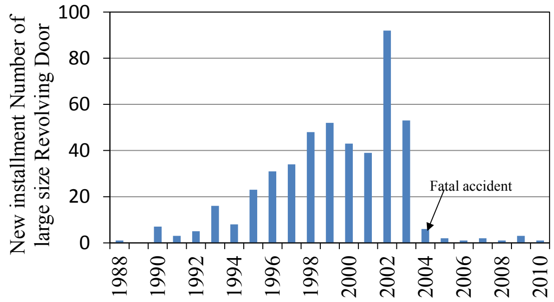


Fig. 1 New instalment number of large size Revolving Door in Japan

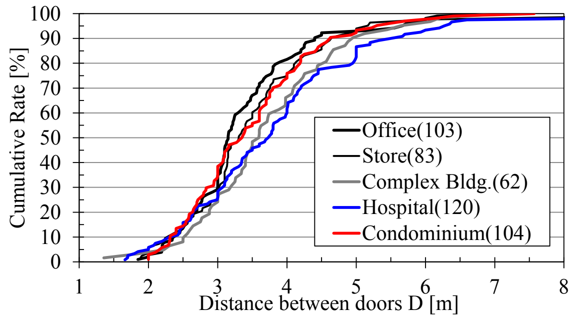


Fig. 2 Depth of wind shield room in Japan (Double sliding door)

It is necessary to comprehend an unsteady open air invasion phenomenon to the interior at open–close operation of a door to evaluate the thermal environment of entrance space with an automatic sliding door. Where parameter changes are simple, application of CFD analysis is desirable for elucidating open air invasion situations under various conditions.

This study is aimed at quantitative comprehension of open air invasion to entrance space in various automatic door layouts, and at evaluation of the thermal environment of the entrance space. The measurement of open air invasion situations for sliding doors or revolving door layouts is conducted along with unsteady CFD analysis (Ito, Ono, Sakai, 2012). This paper reports the results of measurement of wind velocity and pressure difference between that inside and outside a single sliding door at open–close operation and CFD analysis using the measured pressure difference, aiming at development of a CFD analysis approach considering the opening and closing of a sliding door.

Fig. 3 Building for measurement and measurement situation.

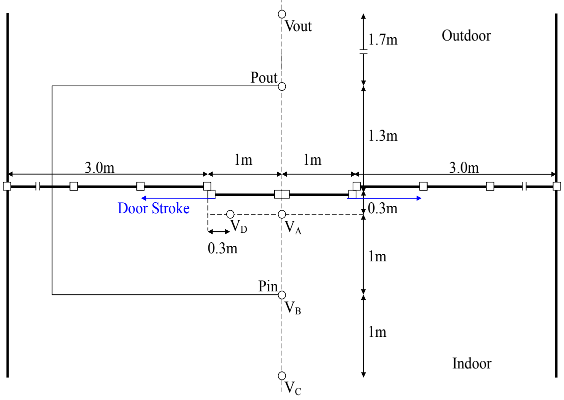


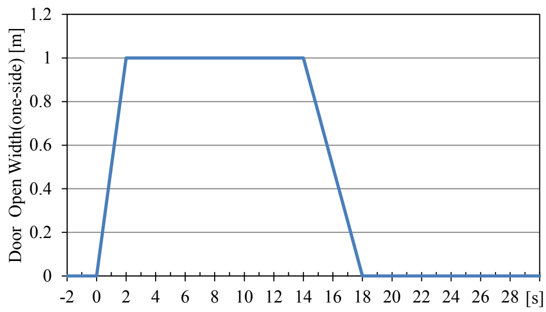
Fig. 4 Measuring points (horizontal projection).

OUTLINE OF MEASUREMENT

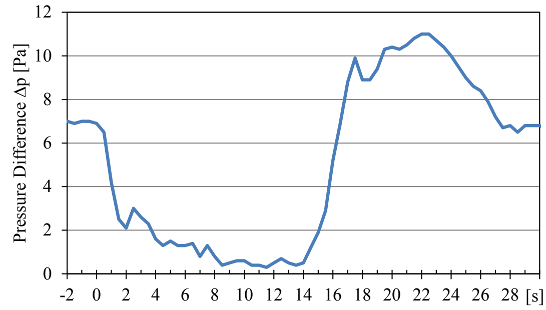
At the north side entrance of a six-story building having an enclosed atrium at the center section, the wind velocity and pressure difference between that inside and outside a door were measured during its open–close operation (December 16, 2012 13:00–16:00). The entrance has a single automatic door (1,970 mm width; 2,140 mm height). Figure 3 shows the appearance of the building and measurement condition, and Fig. 4 depicts the measuring points. Five hot-wire anemometers (0.1 m/s measurement accuracy, Model 6531; Kanomax Japan Inc.) were used for wind velocity measurements. A differential pressure gauge for micro-pressure (0.1 Pa measurement accuracy, DMP201N12; Okano Works, Ltd.) was used for measurement of the static pressure difference between inside and outside (Δp = Pout–Pin). The measurement interval was 1 s for wind velocity and 0.5 s for differential pressure. Indoor heating was suspended on the day of measurement. Indoor temperature was higher than ambient temperature by about 2 °C, and internal pressure was lower than that outside.

The automatic door was left open for 18 s assuming that four people passed continuously.

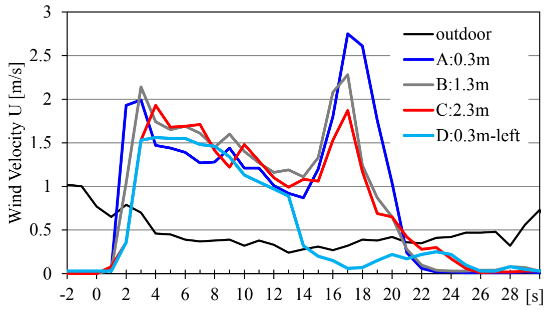
The door took 2 s from full close to full open and 4 s from full open to full close. In all, nine measurements were conducted. The result with the least effect of external wind was adopted for additional examination.



a) Door open width control with time.



b) Pressure difference change with time.



c) Wind velocity change with time.

Fig. 5 Measurement results.

MEASUREMENT RESULTS

Figure 5 presents the wind velocity measurement result obtained at each measuring point, which demonstrates a tendency by which the pressure difference declined and the inflow wind velocity was enhanced when the door opened.

Wind velocity became high, reaching the maximal values in door-open operation (at 2 s) and door-closing operation (at 14–18 s). Invasion of open wind of about 1–1.5 m/s was observed at the full open state (2–14 s).

Chronologically speaking, as the door starts to open, the static pressure difference dropped abruptly from 7 Pa to about 2 Pa, and wind velocity near the door V_A increased to about 2 m/s.

Pressure difference and wind velocity reduced monotonously at 2–16 s during the door opening operation. V_B and V_C far from the door were slightly greater than V_A.

V_D at the door end was greater than V_A at 4–8 s. The pressure difference increased to about 10 Pa at 14 s and later, after the door started to close, and settled at about 7 Pa after 28 s. This apparently occurred because the wind flowing toward the room from the outside collided with the closed door, so that the pressure difference rose.

Wind velocity peaked at 16–18 s, and V_A increased to about 2.7 m/s. A similar peak was observed also for V_B and V_C. It is assumed that a measurement interval of 1 s made the peak detection of wind velocity difficult. The authors are considering re-measurement using an anemometer with quicker response.

Wind velocity fell after 18 s entering full closed state, below 0.5 m/s after 20 s. V_B and V_C attenuate quicker than V_A. Wind velocity at measuring point D fell below 0.5 m/s at 14 s, presumably because the door edge passed D in closing operation.

CFD ANALYSIS OVERVIEWS

CFD analysis was conducted using the measured pressure difference between inside and outside, aiming at detailed comprehension of the open air invasion phenomenon at the open–close operation of a sliding door and development of a CFD analysis approach considering opening and closing. OpenFOAM 2.1.1 was used for analysis.

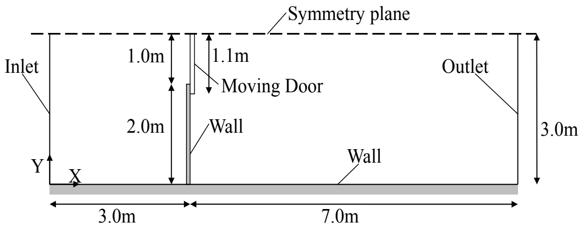
Figure 6-a) shows the computational region, which only covers a half region considering symmetry. Two-dimensional isothermal analysis was conducted, although the actual phenomena are expected to obey three-dimensional non-isothermal conditions. That is true because this analysis aims at examining a CFD analysis method considering opening and closing of a door.

Figure 6-b) shows the computational grid. The region contained 26,696 cells, each from 2.5 cm square (door neighborhood) to 5 cm square.

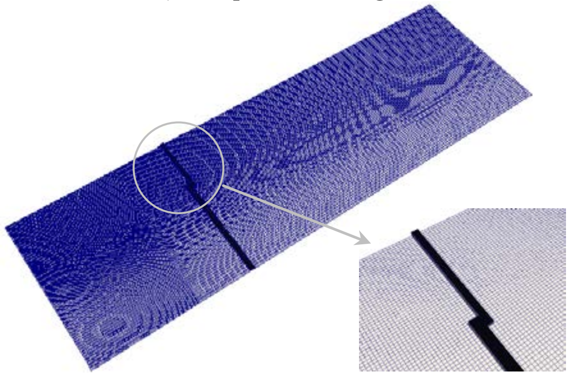
Computational conditions are presented in Table 1. The standard k–ε model was used for a turbulence model. PISO was adopted as an analytic algorithm, and transient analysis was conducted (Versteeg et al., 2007). Time interval Δt was 0.005 s. The computation was conducted for 0–20 s of actual measurements.

The porous media method was applied to the moving door. The porous media has expressed by resistance value Si at source term of momentum equations. The power law was used for the resistance model Si (Table 1). Resistance value C_0 as moving door's cell is set to 500000 of the infinity equivalent. It was regard to be an imitative wall. Si of the cells except for the door is set to 0. Cell position as moving door part was calculated in advance (Figure 6-c), and has been listed in the every Δt step. The list of the door cell was read in the every Δt step, and the resistance value has been set. The open–close operation of the door was conducted at the same timing as the measurement.

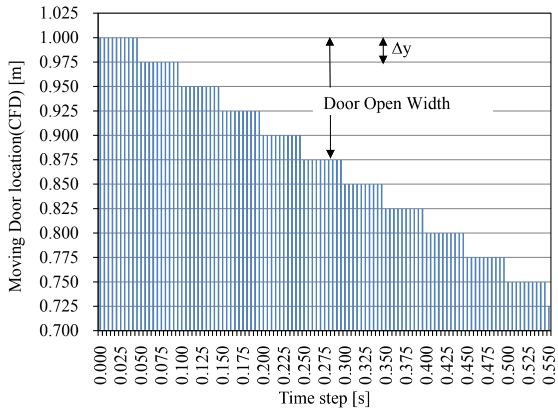
The generalized log law was applied to wall boundary condition. In this simulation, the minimum value of turbulent kinetic energy k was set to be $0.0007 m^2/s^2$, and it would become over $y^+>11.53$.



a) Computational region.



b) Computational grid.



c) Moving door position.

Fig. 6 Computational region.

Table 1 Computational conditions.

Turbulence Model : Standard k-ε model.
Algorithm : PISO method.(corrector step=2)
Scheme of Convective term: Gauss limitedLinear.
Boundary conditions :
Inlet: Pressure=100,000+Δp_{exp}[Pa], kin=0.00325[m^2/s2]
Outlet:Pressure=100,000[Pa]
Wall: Generalized log law (y^+>11.53) . No-slip (y^+<11.53).
Simulation Time:0 – 20[s]. Δt=0.005[s], Courant No.=0.5
Mesh: 26,696cell. Max size=5cm, Min. size=2.5cm(nearby door).
Porous media method:
Moving Door cell :

$$Si = (-\rho C_0 \cdot |U_i| \wedge ((C_1 - 1)/2))U_i$$

Si : Source term of Momentum eq. ρ: density
C_0=500000, C_1=0.
Other cells : *Si*=0

The value of y^+ after door release 1 seconds was almost 30 in all wall surfaces.

Outlet pressure was set to 1,000 hPa. The inlet pressure was set to the measured static pressure difference in addition to 1,000 hPa. Because the differential pressure measurement was performed with a 0.5 s interval, the actual measurement was linearly interpolated for every Δt step.

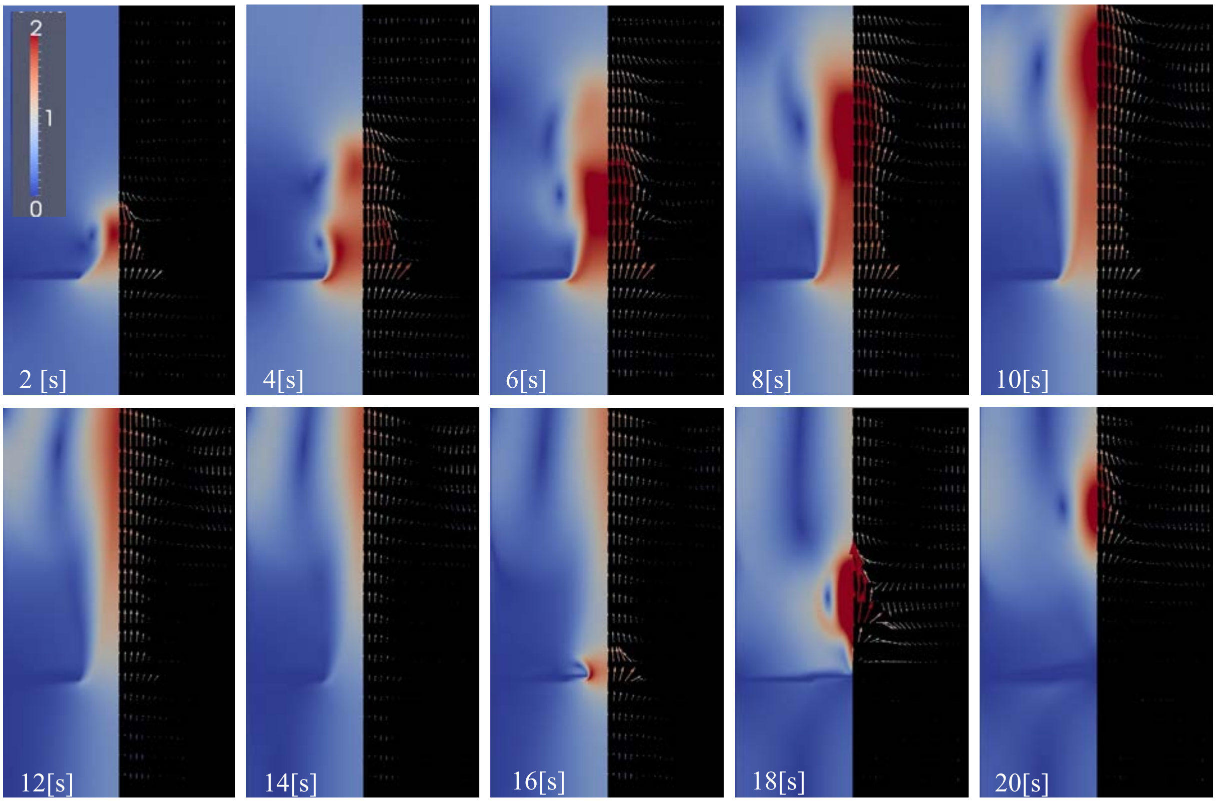


Fig. 7 Analytical result (scalar wind velocity and velocity vector distribution [m/s]).

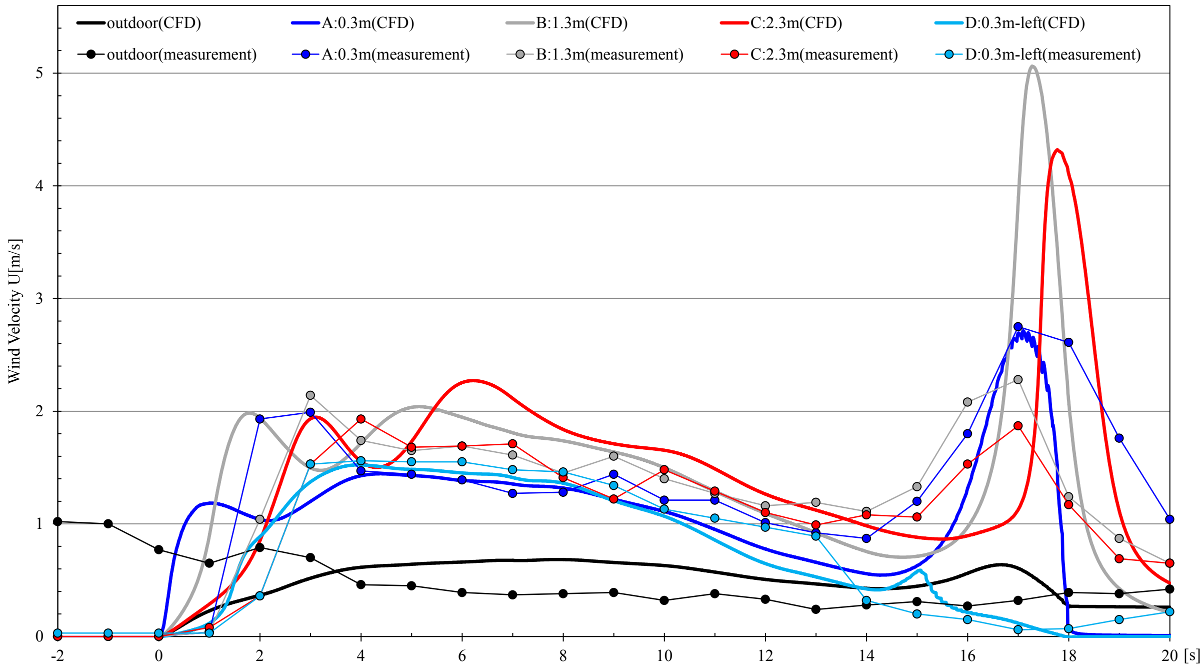


Fig. 8 Wind velocity change with time (CFD & Measurement).

Although the external wind velocity of about 0.5 m/s was observed in the actual measurement, external wind (dynamic pressure) was not examined in this analysis.

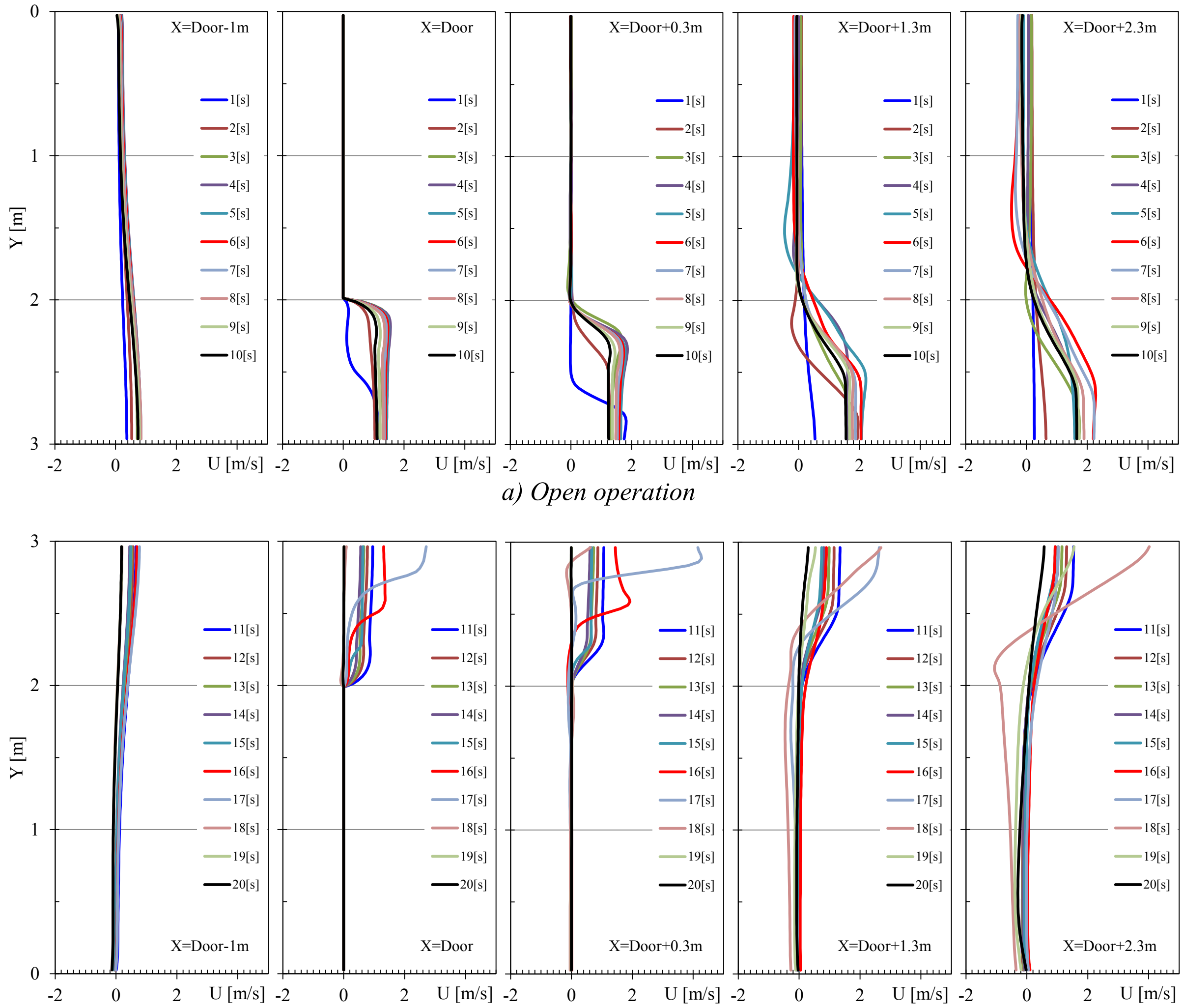
CFD ANALYSIS RESULTS

Figure 7 exhibits scalar wind speed distribution at every 2 s, which clearly reveals the manner of open air invasion according to door opening and closing.

Wind velocity in the door part was slightly greater at the wall edge than at the door center at 4–12 s.

Wind velocity at the tip of the invading air flow was greater than at the door part at 6–10 s.

Presumably, the wind velocity was exaggerated because the invading air flow from the door was contracted to the center section. Circular vortices created by the invading air flow moved in the surrounding air.



a) Open operation

b) close operation

Fig. 9 Profiles of wind velocity of X direction.

The width of the invading wind became narrow and wind velocity at the center section was enhanced at 18 s when the opening space of the door shrank. Wind velocity was high at some measuring points near the atrium center at 20 s.

Figure 8 depicts a change in computed wind velocity with time at the identical positions as measurement. The tendency of wind velocity and its fluctuation for 4–14 s showed general agreement with the actual measurement.The peak of V_A at 0–2 s was smaller than the measurement, whereas those of V_B and V_C were comparable. However, V_A was comparable as the measurement whereas V_B and V_C were about twice at 16–20 s. The discrepancy at open operation might result from the effect of external wind: only the static pressure difference was given as a boundary condition in CFD. Disagreement at close operation is considered because of the coarse measurement interval.

Figure 9 shows the wind velocity U_x profile in the Y direction. The upper and lower panels express results for 0–10 s and 11–20 s, respectively, at 1 s intervals.

Wind velocity at the edges of opening (near Y = 2 m) was greater than that at the center near the door, whereas winds concentrated into the center section and wind velocity were exaggerated away from the door.

The results presented above verified the analysis showing that modeled door opening and closing with the porous media method can reproduce unsteady phenomena observed in the actual measurement in general, in spite of discrepancy in wind velocity peaks.

CONCLUSION

This manuscript describes the measurement of wind velocity and pressure difference between that inside and outside a single sliding door at open–close operation and CFD analysis using measured pressure difference, aiming at the development of a CFD analysis approach considering opening and closing of a sliding door. The obtained results are presented below.

The measurement results verified that pressure and wind velocity varied unsteadily with open–close operation of the door.

Movement of the door was modeled using the porous media method, and unsteady CFD analysis was conducted. Comparison with measurements verified that the analysis can reproduce unsteady phenomena observed generally when taking measurements.

The authors seek to elucidate phenomena using more highly precise measurements in the future.

A double sliding door is scheduled to be analyzed based on this single sliding door analysis.

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