A numerical study on natural ventilation promotion and control in experimental house with fluid diode window

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Abstract. The objective of this study is to investigate the effects of installing a fluid diode window (FDW) in buildings to promote natural ventilation by controlling ventilation paths. An FDW is a porous plate with an internal structure that provides varying resistance to airflow depending on the flow direction. An FDW was installed in the bathroom of an experimental house to prevent polluted air from flowing into the adjacent multipurpose room during ventilation. Computational fluid dynamics simulations with a steady Reynolds-averaged turbulence model and tracer gas method were performed to evaluate the performance of the FDW. The results show that an open window or FDW in the bathroom reduced the concentration and increased the ventilation rate. In the same wind direction at which the airflow exits through the window or FDW, it flows out at almost the same volumetric flow rate. In the cases where the airflow enters the bathroom through the window or FDW, the effect of preventing backflow from the bathroom window to the multipurpose room can be observed when the FDW was utilised, resulting in a reduction or even prevention of the gas entering the multipurpose room.

1 Introduction

The use of natural ventilation in buildings can reduce the workload of mechanical ventilation, conserve energy, and improve indoor air quality. However, when natural ventilation is realised via a general opening, controlling the ventilation path is difficult because of changing wind directions, which may reduce the air quality of the adjacent room. Therefore, to utilise natural ventilation to achieve efficient ventilation with a low environmental load, openings capable of controlling the wind direction are required.

The objective of this study is to investigate the effects of installing a porous plate, called the fluid diode window (FDW), in buildings to promote natural ventilation while controlling the ventilation paths. The FDW has an internal structure that can provide varying resistance to airflow depending on the flow direction. Utilising an FDW enables both passive and automatic ventilation path control without the need to install additional moving or mechanical parts on the window. The internal structure of the FDW includes a novel fluid diode plate that is optimised based on the Tesla valve. The Tesla valve structure is shown in Fig. 1 [1]. This structure has been studied and applied to heat transfer [2], microfluidic control [3], gas decompression [4], etc. In the field of building ventilation, Cao et al. [5] conducted wind tunnel tests and numerical simulations to determine the effects of the fluid diode plate on airflow under different influencing factors, and optimised this structure. They reported on potential building ventilation applications in the field. However, no reports have been found in the literature on a method to install an FDW in a real building and its performance.

Therefore, we conducted a series of computational fluid dynamics (CFD) simulations on the ventilation performance of an activated fan in the bathroom of an experimental house. The ventilation performance was compared between cases with three different window settings: closed window, open window, and FDW, for two characteristic wind directions. The performance of the FDW was examined by comparing the airflow in and out of the bathroom between cases. This was quantified by the ventilation rate of the rooms, and the volumetric flow rate and concentration flux at all the openings of the bathroom.

2 Target house and fluid diode window

2.1 Experimental house

The experimental house is located at the Kashiwa Campus of the University of Tokyo (Institute of Industrial Science, Chiba Experiment Station) [6]. A schematic of the building is shown in Fig. 2. It has an area of approximately 60 m^2 and three rooms: a multipurpose room, measurement room, and equipment laboratory (bathroom). The multipurpose room has two openings on the east and west walls, and two doors connecting it to the bathroom and measurement room,

Fig. 1 Schematic diagram of fluid diode by Tesla structure [1] (flow resistance changes between forward and reverse flow)

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respectively. In this study, we only considered multipurpose room and bathroom. The measurement room stayed closed.

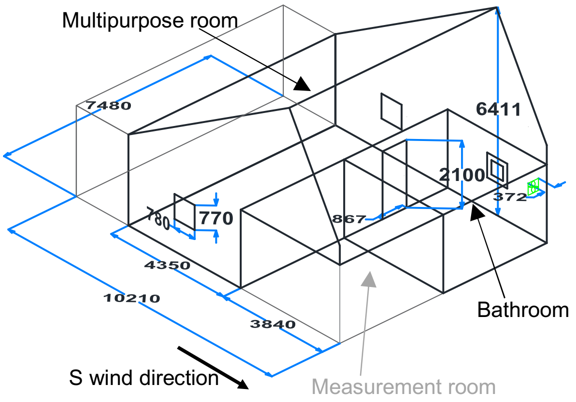

Fig. 2. Schematic diagram of the experimental house (unit of length: mm)

2.2 Fluid diode window

The FDW was installed in the bathroom of the experimental house to investigate whether it can prevent the polluted air in the bathroom from flowing into the adjacent multipurpose room during natural ventilation. The size of the FDW was set as 0.77 × 0.78 m^2, which matches the window size of the experimental house. The characteristics of the FDW were based on the fluid diode plate verified experimentally by Cao et al. [5]. The porosity of the FDW was set as 0.33. According to the pressure difference between the forward and reverse flows, the porous inertial resistance factor was set as 9 for the forward flow from indoor to outdoor, and 31 for the reverse flow, i.e., from outdoor to indoor.

3 Simulation setup

3.1 Simulation conditions

The CFD simulation was performed using the STAR-CCM+ 12.02.010 software to obtain the time-averaged distributions of the wind speed and concentration. The internal and external flow fields in the experimental house were solved simultaneously. Fig. 3 shows the simulation domain with the full-scale target building. A steady Reynolds-averaged Navier–Stokes (RANS) model with a realisable k-ε two-layer model that provides accurate results in a cross-ventilation simulation [7] was applied to evaluate the performance of the FDW. According to the results of studies on the grid independence of the hexahedral mesh, the calculation must be performed with a mesh containing approximately 5.58 million grids. Table 1 provides the simulation details. To reproduce the wind flow in the suburban area where the target building is located, the mean velocity of the approaching flow under the inflow boundary condition was set to follow the power law (α = 1/7) of the wind profile. The reference velocity (U_H = 1.86 m/s), defined as the velocity at approximately the roof height of the experimental house (Z_H = 6 m), is the five-year average wind speed obtained from the closest meteorological station in Abiko City, Chiba Prefecture. To verify the performance of the FDW in both forward and reverse flows, two wind directions (SE and NW) were considered and simulated separately, as shown in the upper left of Fig. 3.

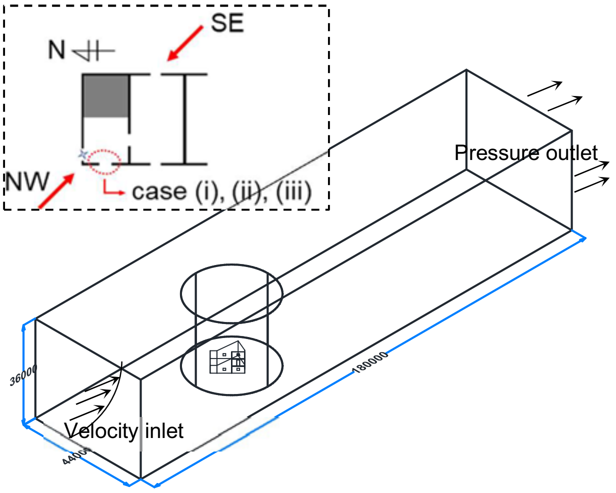

Fig. 3. Simulation domain and wind direction for the experimental house (unit of length: mm).

Table 1. Simulation conditions

Items	**Contents**
Simulation model	Steady Reynolds-averaged Navier–Stokes (RANS)
Turbulence model	Realizable k-ε two-layer model
Simulation domain	180 (x) × 44 (y) × 36 (z)
Simulation mesh number	Approximately 5.58 million
Time marching	SIMPLE
Discretisation scheme for advection term	Second-order upwind difference scheme
Discretisation scheme for diffusion term	Second-order central differencing
Inlet boundary condition	Velocity inlet [8]: $U_z = U_H \left(\frac{z}{Z_H}\right)^{\alpha}$ $k_z = \left[0.1 \left(\frac{z}{Z_G}\right)^{-\alpha-0.05} \times U_z\right]^2$ $\varepsilon_z = C_\mu^{0.5} \times k_z \times \frac{U_H}{Z_H} \times \alpha \left(\frac{z}{Z_H}\right)^{\alpha-1}$ Where Z_G (= 350 m) is the atmospheric boundary layer height.
Outlet boundary condition	Pressure outlet (Pressure = 0 pa)
Sources	Two kinds of independent tracer gases are released constantly and uniformly within the multipurpose room and bathroom, respectively, with an emission rate of 1 ppm/s.

3.2 Case settings

The multipurpose room has two openings on the east and west walls, and a door connecting it to the bathroom. A ventilation fan was activated in the bathroom, and three different conditions were considered for the bathroom window (Table 2): (i) a closed window, (ii) open window, and (iii) FDW. For a better comparison, the area of the open window was set to be one-third that of the FDW because the porosity of the FDW is 0.33. The FDW was set to provide a larger resistance to the airflow entering the bathroom and less resistance to the airflow leaving the bathroom. Two types of independent tracer gases were constantly and uniformly emitted throughout the multipurpose room and bathroom, whose concentrations were simulated as passive scalar quantities. The flow rate of the fan was set as 284 m^3/h. In the absence of natural ventilation, the ventilation rate of the experimental house is once per hour.

Table 2. Case settings

Case	Multipurpose room	Bathroom	
(i)	two windows	fan	closed window
(ii)	two windows	fan	open window
(iii)	two windows	fan	FDW

4 Simulation results

To determine the effect of the FDW in the bathroom of the experimental house with natural ventilation, the volumetric flow rate and concentration flux at the fan, door, and open window or FDW in the bathroom were analysed. Only the concentration flux driven by the mean flow was considered in this study. In addition, the ventilation rates of the multipurpose room and bathroom were calculated by the following equation:

$$n_i = \frac{3600k_i}{\bar{C}_i V_i} = \frac{3600}{\bar{C}_i},$$

where $i = 1$ or 2 denotes the two types of tracer gas emitted in the multipurpose room and bathroom, respectively; n_i (1/h) is the ventilation rate of the room; k_i (ppm·m^3/s) is the volumetric emission rate of the tracer gas; V_i is the volume of the room; and $\bar{C}_i$ (ppm) is the indoor average concentration of each room. In this study, $k_i = 1\ \mathrm{ppm}/(\mathrm{s\ m}^3) \times V_i$ because the tracer gas was constantly and uniformly released within the room at a rate of 1 ppm/ (s m^3).

Fig. 4 shows the concentration distribution inside and around the bathroom in the cross-section at the height of the opening centres for the SE wind direction. Table 3 lists the volumetric flow rates and concentration fluxes for each outlet of the bathroom, and the ventilation rates for the multipurpose room and bathroom. Positive values of the volumetric flow rate and concentration flux indicate outflows, while negative values indicate inflow. The concentration distribution results show that the concentration in the bathroom was significantly reduced by the installation of an open window or FDW. The ventilation rate of the bathroom increased from approximately seven times to 14 times per hour. The ventilation rate of the multipurpose room also increased by 0.4 times per hour. The results of the volumetric flow rate and concentration flux through the open bathroom window and the FDW to the outside are almost the same, indicating that the FDW functions as a typical open window when wind flows in the SE direction.

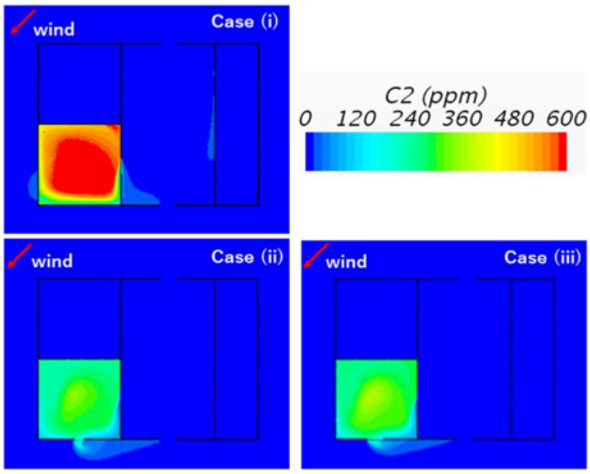

Fig. 4. Concentration (C$_2$) distribution inside and outside the experimental house at the height of 1.39 m for SE wind direction

Table 3. Volumetric flow rate, concentration flux, and ventilation rate results for the SE wind direction

SE	**Volumetric flow rate (m^3/s)**			
	Fan	**Door**	**Window**	**FDW**
(i)	0.078	-0.077		
(ii)	0.078	-0.203	0.125	
(iii)	0.078	-0.202		0.125

SE	**Concentration flux of C$_2$ (ppm・m^3/s)**			
	Fan	**Door**	**Window**	**FDW**
(i)	27.7	-6.9		
(ii)	12.5	-4.8	20.6	
(iii)	13.7	-5.1		19.5

SE	**Ventilation rate (1/h)**	
	Multipurpose room	**Bathroom**
(i)	6.6	6.7
(ii)	7.0	14.2
(iii)	7.0	13.3

Fig. 5 shows the concentration distribution for the NW wind direction. Table 4 lists the volumetric flow rates and concentration fluxes for each outlet of the bathroom, and the ventilation rates for the multipurpose room and bathroom. The concentration distribution results indicate that the concentration in the bathroom was

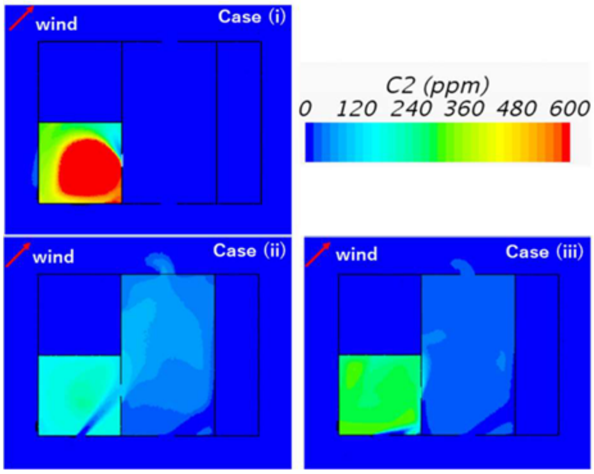

Fig. 5. Concentration (C_2) distribution inside and outside the experimental house at the height of 1.39 m for the NW wind direction

Table 4. Volumetric flow rate, concentration flux, and ventilation rate results for NW wind direction

NW	Volumetric flow rate (m^3/s)			
	Fan	Door	Window	FDW
(i)	0.078	-0.078		
(ii)	0.078	0.102	-0.178	
(iii)	0.078	0.043		-0.124

NW	Concentration flux of C_2 (ppm・m^3/s)			
	Fan	Door	Window	FDW
(i)	34.2	-3.4		
(ii)	13.5	17.5	-0.4	
(iii)	23.7	6.6		-0.9

NW	Ventilation rate (1/h)	
	Multipurpose room	Bathroom
(i)	5.1	6.2
(ii)	6.5	21.2
(iii)	5.1	13.1

reduced by installing an opening window or FDW. The bathroom ventilation rates also more than tripled in case (ii), and doubled in case (iii). The ventilation rate of the multipurpose room is almost the same as in cases (i) and (iii). However, it increased from 5.1 times to 6.5 times per hour in case (ii). This shows that in case (ii), a large amount of air (tracer gas) flowed into the multipurpose room, which increased the ventilation rate. In addition, the volumetric flow rate from the bathroom door to the multipurpose room decreased by 50% when case (iii) was compared with case (ii). As the result, the concentration flux flowing into the multipurpose room through the door decreased by two-thirds. The FDW effectively prevented the tracer gas in the bathroom from flowing into the multipurpose room. However, the strategy of applying the FDW could be further optimised because a certain amount of tracer gas still flowed into adjacent rooms in case (iii).

5 Conclusion

In this study, CFD simulations were performed using the RANS model to evaluate the performance of an FDW installed in the bathroom of an experimental house. For comparison, the activation of the fan in the bathroom was considered under three different conditions set for bathroom window: (i) closed window, (ii) open window, and (iii) FDW.

The results show that an open window or FDW in the bathroom reduced the concentration and increased the ventilation rate. For the wind directions at which the airflow exits through the window or FDW, it flows out at almost the same volumetric flow rate. In the cases where the airflow enters the bathroom through the window or FDW, the effect of preventing backflow from the bathroom window to the multipurpose room can be observed when the FDW is utilised, resulting in a reduction or even prevention of the tracer gas from entering the multipurpose room.

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