Study on natural ventilation control by optimizing fluid diode plates based on Tesla valve for building windows

Hong Hu [1], Ikuryo Son [2], Hideki Kikumoto [3]

[1]*The University of Tokyo, Tokyo, Japan, kokou00@iis.u-tokyo.ac.jp*
[2]*The University of Tokyo, Tokyo, Japan, Son5784@iis.u-tokyo.ac.jp*
[3]*The University of Tokyo, Tokyo, Japan, kkmt@iis.u-tokyo.ac.jp*

SUMMARY:
In this study, a fluid diode plate (FDP) was optimized based on a Tesla valve that can control the airflow direction to achieve highly efficient ventilation. We performed FDP optimization with 2D computational fluid dynamics (CFD) simulations and conducted 3D simulations to evaluate its performance when it was used as a fluid diode window (FDW) within a building model for building ventilation control. The pressure loss and indoor concentration ratios were used to evaluate the performance of the optimized FDP and the corresponding FDW, respectively. Compared with the original FDP proposed in a prior study, the pressure loss ratio of the optimized FDP increased by 2–4 times at different wind speeds. The minor loss coefficients of the forward and reverse configurations obtained from the 2D simulations were used to define the pressure jump of the FDW as an opening in the building model in the 3D simulations. The results showed that FDW could efficiently control the airflow of natural ventilation in buildings, particularly when the airflow velocity was high, and the optimized FDW performed better.

Keywords: fluid diode window, airflow direction control, ventilation

1. INTRODUCTION

For natural ventilation in buildings, a general opening is difficult to control the direction and path of airflow and may even lead to an unexpected deterioration in the indoor air quality. Therefore, an opening must be designed that can control airflow direction to achieve high-efficiency ventilation with a low environmental load using natural ventilation. A fluid diode has been proposed as a structure capable of airflow direction control, a typical example of which is the Tesla valve structure (Tesla, 1920) shown in Fig. 1. It provides a lower (ideally zero) resistance to the flow in the forward direction and a higher (ideally infinite) resistance to the flow in the reverse direction. In the field of building ventilation, Cao et al. (2020) conducted a series of wind tunnel experiments and numerical simulations to determine the effects of a fluid diode plate (FDP) based on the construction principle of the Tesla valve on airflow under different influencing factors and optimized the structure. Our previous study (Hu et al., 2022) conducted numerical simulations in which this structure was installed as an opening

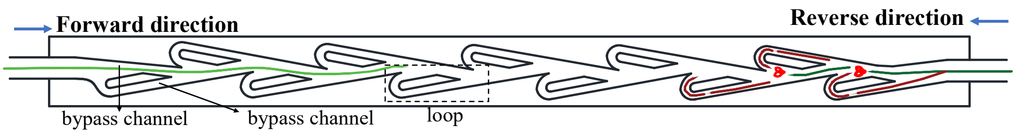

Figure 1. Structure of a fluid diode valve (Tesla, 1920).

in the bathroom of an experimental house, and its performance in airflow direction control was evaluated. The results showed that using FDP as building openings could control the ventilation path because the backflow from the bathroom window to the living room was prevented. However, the internal structure of the FDP still needs to be optimized because this anti-backflow function is limited.

This study aims to optimize the internal structure of an FDP and evaluate its performance through numerical simulations when it is used as a window (termed as fluid diode window, FDW) of a building. The normalized FDP performance was analyzed using the pressure loss ratio and compared with the FDP proposed by Cao et al. (2020). The indoor concentration was used to evaluate the airflow control ability of the FDW in building ventilation.

2. OPTIMIZATION FACTORS OF FLUID DIODE PLATE

The aim of the structural optimization is to reduce the forward flow resistance and increase the reverse flow resistance as much as possible. The geometrical parameters to be optimized include the channel ratio (H_b/H_m), number of loops, and porosity ($\sum H_m/H$), as shown in Fig. 2. These parameters are optimized to maximize pressure loss ratio F_{FDP} (= ζ_R/ζ_F), in which minor loss coefficients ζ_R and ζ_F (= $2\Delta P/\rho v^2$) are defined as the ratios of the head loss through the internal structure of the FDP (ΔP) in the reverse (R) or forward (F) directions, respectively, to the velocity head ($0.5\rho v^2$). In our optimization performed in this study, the number of loops and main channel diameter (H_m) were fixed, and the loop length (L1), bypass diameter (H_b), and slope (Θ) were varied.

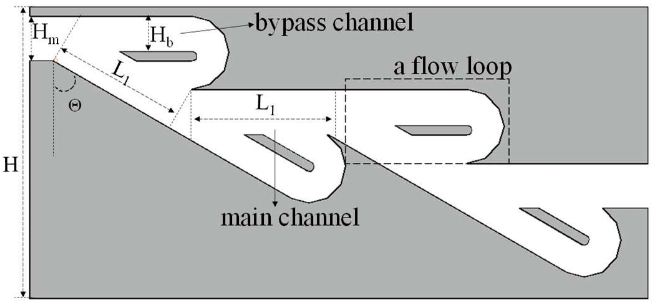

Figure 2. Schematic of parameters affecting the pressure loss of a fluid diode plate (FDP) in forward and reverse directions.

3. NUMERICAL SIMULATION CONDITIONS

First, 2D computational fluid dynamics (CFD) simulations with a standard k-ω SST model were conducted to evaluate the values of ζ_R and ζ_F of the FDP. Fig. 3 (a) shows the computational domain for a conduit of the FDP. The total number of cells was approximately 54,200.

Subsequently, a 3D CFD simulation was performed to evaluate the

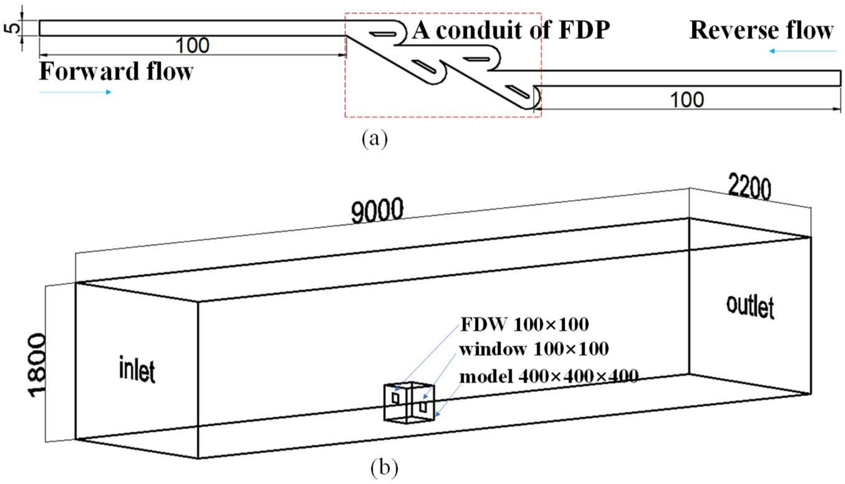

Figure 3. Sketch of 2D simulation domain for a conduit of FDP (a) and 3D simulation domain for a model with FDW (b) (mm).

cross-ventilation for a building model with two openings, as shown in Fig. 3 (b). A pressure jump, corresponding to minor loss coefficient ζ_F or ζ_R, was created on the front opening to make the flow easy or difficult to pass through the room. Such an opening is referred to as a FDW in the remainder of this paper. A steady Reynolds-averaged Navier–Stokes model with a realizable k–ε two-layer model was applied in this simulation. The inflow boundary condition followed the 1/7 power law of the wind profile. For either the forward or reverse configuration, four values of the reference velocity (defined as the inlet wind speed at the model height) were tested: 2.97, 4.70, 6.23, and 7.79 m/s. Tracer gas was emitted uniformly in the room at an emission rate of 1 ppm/s to evaluate the ventilation performance.

4. OPTIMIZATION AND COMPARISON RESULTS

4.1. Improvement of FDP via 2D simulations

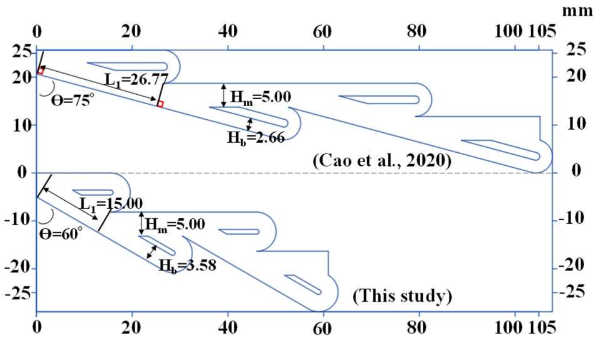

Figure 4. FDP structure.

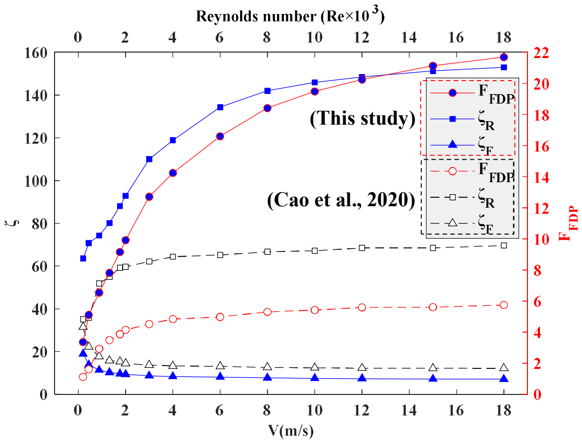

Figure 5. Pressure loss ratio and minor loss coefficient.

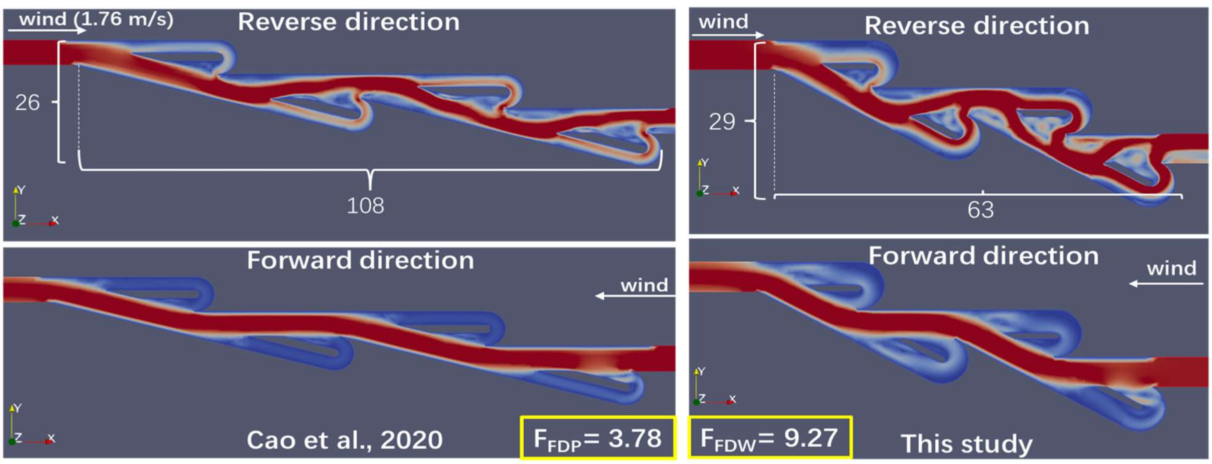

Figure 6. Velocity magnitude distribution in the inlet velocity of 1.76 m/s.

Fig. 4 shows the structures of the FDP optimized in this study and that by Cao et al. (2020). Fig. 5 shows the results for the FFDP, ζ_R, and ζ_F. For a better comparison with the study by Cao et al. (2020), the Reynolds number, computed based on the inlet velocity and main channel diameter, is used as the horizontal axis in Fig. 5. The F_{FDP} of the optimized FDP was 2–4 times higher than that reported by Cao et al. (2020). The velocity magnitude distribution when the inflow velocity was 1.76 m/s is shown in Fig. 6. The results showed that in the optimized FDP, two airflows passing through the bypass channel and main channel collided strongly at the intersection, resulting in flow blockage and increased pressure loss. In particular, pressure loss was more significant in the third and fourth loops. The results of ζ_R and ζ_F were fitted into a function of velocity, as shown in Fig. 5, and were inputted as the interface conditions of the FDW in the 3D building simulations.

4.2. Indoor concentration results using an FDW by 3D building simulations

The indoor concentration ratio of the reverse and forward directions was used to evaluate and compare the ability of the two FDWs for a building model in airflow direction control. Table 1 presents the results of the indoor concentrations and ratios between the concentrations in the forward and reverse cases. The indoor concentrations were lower in the forward direction than in the reverse direction when the FDW was used, demonstrating its role in airflow control for building ventilation. However, the concentration ratios between the forward and reverse directions were larger when using the optimized FDW, proving that the rectification ability of the optimized FDW was better than that of the improved FDW, particularly when the outdoor wind speed was high.

Table 1. Results of mean indoor concentration in a building model with an FDW.

Reference velocity (m/s)	FDW (Cao et al., 2020)			FDW (Optimized in this study)		
	Indoor concentration (Forward・ppm)	Indoor concentration (Reverse・ppm)	Indoor concentration ratio (Reversr/Forward)	Indoor concentration (Forward・ppm)	Indoor concentration (Reverse・ppm)	Indoor concentration ratio (Reversr/Forward)
2.97	16.04	17.72	**1.10**	17.27	20.72	**1.20**
4.60	10.19	11.95	**1.17**	10.55	14.16	**1.34**
6.23	7.33	8.84	**1.21**	7.11	9.85	**1.39**
7.79	5.67	7.43	**1.31**	5.17	8.71	**1.68**

5. CONCLUSION

We performed FDP optimization based on a Tesla valve with 2D simulations and conducted 3D simulations to evaluate its performance in building ventilation control. The pressure loss and indoor concentration ratios were used to evaluate the performance of the FDP and its efficiency as an FDW in natural ventilation control. Compared with the proposed FDP, F_{FDP} of the optimized FDP increased by 2–4 times at different wind speeds. In addition, the FDW was verified to control the airflow of natural ventilation in buildings, particularly when the airflow velocity was high, and the optimized FDW performed better.

ACKNOWLEDGEMENTS

This study was financially sponsored by the Window Research Institute (WRI 2021 Grant Program).

REFERENCES

Tesla, N., 1920. Valvular conduit. US Patent 1,329,559.

Cao, Z., Zhao, T., Wang, Y., Wang, H., Zhai, C., and Lv, W., 2020. Novel fluid diode plate for use within ventilation system based on tesla structure. Building and Environment 185.

Hu, H., Kikumoto, H., and Zhang, B., 2022. A numerical study on natural ventilation promotion and control in experimental house with fluid diode window. The 16th ROOMVENT Conference, E3S Web Conf. Volume 356.