Analysis of Wind-Induced Inflow and Outflow through a Single Opening using Large-Eddy Simulations

Shinsuke Kato\textsuperscript{a}, Takamasa Hasama\textsuperscript{b}, Ryozo Ooka\textsuperscript{a}

\textsuperscript{a} Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
\textsuperscript{b} Department of Architecture, The University of Tokyo, Tokyo, Japan

ABSTRACT: In order to investigate induced flow properties through a single opening, large-eddy simulations (LES) are performed on ventilated air through the single opening of a room. In this flowfield, the outdoor air flows parallel to the wall and to the opening, and the room airflow is induced by the outdoor flow through the opening. Both the outdoor and indoor airflows are simultaneously simulated. Firstly, the dependency of the induced room airflow to the shape of the opening is investigated (by changing the shape of the opening). Secondly, the distributions of mean and turbulent variables at the boundary plane of the opening are investigated. It is clarified that the shape of the opening and the resultant mixing layer thickness developed along the opening boundary plane affect the characteristics of the air exchange rate and the feature of the room’s airflow. In the case of a longer opening, the change in air exchange characteristics is apparent.

KEYWORDS: single-opening ventilation, induced flow properties, large-eddy simulations

1 INTRODUCTION

In fluid engineering applications, a wide range of fluid mixing phenomena through a single opening (such as a cavity flow) have been analyzed\textsuperscript{1,2,4}. There are however not many analyses where two flows are parallel to the separating panel and one of the flows is driven by the other through a single hole. In such a flowfield, the mixing layer characteristics at the opening play a crucial role for the exchange properties of the two flows since most of the fluid exchange is driven by turbulent motion through the mixing layer developed at the opening boundary plane\textsuperscript{3}. The shape of the opening and the boundary layer that develops along the upstream separated panel will affect the characteristics of the mixing layer at the opening and flow exchange characteristics.

In this study, to clarify the induced flow properties through the single opening, we deal with the room ventilation via a single opening to the outdoor flow. In this flowfield, the outdoor air flows along the building wall and the room air is only connected to the outdoor air through a small lateral opening. The room airflow is driven by the lateral outdoor airflow. Large-eddy simulations (LES) were performed on the flowfield. We examined the dependency of the properties of the flowfield in a room with the shapes of the openings, and investigated the mixing characteristics of air from the distributions of mean and turbulent variables at the boundary plane of the opening.

2 CALCULATION CONDITIONS

2.1 Flow model and calculation conditions

The dimensions of the flow model are shown in Fig. 1(a). In this calculation, the standard Smagorinsky model (Cs=0.12) was applied. As the inflow boundary, a $U_{in}=3.0$ [m/s] fluctuating...
wind generated in the driver region was applied in conjunction with a convective outflow condition. The Reynolds number standardized by $U_{in}$ and opening width $D$ (=50 mm) is 9750. No slip wall boundary condition was applied. In each case, we computed 500 non-dimensional times as integral time steps after pre-computation of 500 non-dimensional times. Additionally, all variables used in this study were standardized by the inflow velocity $U_{in}$ and the opening length $D$. A central differential scheme was applied to all spatial discretization. As a time marching scheme, Adams-Bashforth and Crank-Nicolson schemes were applied to advection and diffusion terms respectively.

2.2 Calculation cases

Three types of opening shape were used to examine the dependency of the induced room airflow with the opening shapes; CASE-S (standard case), CASE-T (5 times thicker wall dividing the inner and outer regions compared with the standard case), CASE-A (2 times longer opening compared with the standard case), shown in Fig. 1(b). The grid numbers for each case are as follow; CASE-S: 106 × 47 × 64, CASE-T: 107 × 47 × 75, CASE-A: 137 × 47 × 76.

3 RESULTS AND DISCUSSION

3.1 Inner side flow features

The patterns of the streamlines of the time-averaged flowfields are shown in Fig. 2. The streamline source points were located at the leeside edge of the opening. A recirculation induced by the outer flow was formed in the room in all cases, but the patterns of the streamlines greatly differed from one another. The inflow angle to the opening plane changed with the opening shape as shown in Fig. 3. The inflow angle seems to depend on the wall thickness and the momentum transport in the streamwise direction.
3.2 Inflow air characteristics

The distributions of the time-averaged velocity vector are shown in Fig. 3. The properties of the inflow jet changed significantly in each case. The mixing layer in each case was generated along the opening boundary plane. One side of the layer was in the room while the other was in the outer region. The ratio of the mixing layer thickness in the room to the wall thickness will explain these changes in the inflow jet. Schematic views of the mixing layer around the opening are shown in Fig. 4. In CASE-T, the mixing layer in the room hit the thick wall and was deflected sideways. In CASE-A, significant momentum was transported into the room with the growth of the mixing layer. Accordingly, the longer opening promoted greater air exchange.

![Figure 3. Velocity vector distributions (time-averaged, x-z plane along y-axis center line)](image)

![Figure 4. Mixing layer characteristics formed around the opening](image)

3.3 Air exchange mechanism

The distributions of the time-averaged velocity components, pressure and Reynolds stress at the boundary plane of the opening are shown in Fig. 5. All the variables shown are of the grid scale. With the mixing layer growth at the opening, the streamwise velocity of CASE-A was larger than the other cases. It is noted that the vertical component of velocity is not uniform and is distributed in CASE-A. The positive value of the vertical velocity leads to distribution around the side edge of the leeward opening. Due to the pressure distribution, suction occurred in such area. This phenomenon was not readily apparent in CASE-S and CASE-T.

![Figure 5. Distributions of each variable on the opening surface (time-averaged)](image)
As shown in the Reynolds stress distribution, the suction seems to be driven by the turbulent momentum transport since the pattern of the mean pressure and the Reynolds stress corresponded well. There is the possibility that these phenomena are related to the interaction between the recirculating flow in the room and the outflow. The recirculating flow corresponded to the increase in momentum shown in Fig. 3.

3.4 Turbulence energy balance

The distributions of turbulence energy, turbulence energy production and turbulence energy dissipation for CASE-A are shown in Fig. 6. These results are grid-scale values. In accordance with the Reynolds stress distribution, the turbulence energy was distributed, and was produced in the suction area. The energy dissipation was active around the leeside edge of the opening, in which the momentum transportation by the GS fluctuation components was active. The order of dissipation value was however very low compared with the other results.

![Figure 6. Distribution of turbulence energy, turbulence energy production and turbulence energy dissipation for CASE_A on the opening surface](image)

4 CONCLUSIONS

- Three LES calculations (corresponding to three types of opening shapes) were carried out to investigate the wind-induced inflow and outflow through a single opening.
- The inner flowfield was affected by the shape of the opening. The ratio of the thickness of the mixing layer to that of the wall explains the change to the inner flowfield.
- In the longer opening case, the air exchange characteristics were significantly different to the other cases. There is the possibility that these phenomena are activated by the interaction of the recirculating flow in the room and the outer flow.
- Further investigation is required to clarify the air exchange mechanism for these types of flows.

5 REFERENCES