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Unsteady indoor airflow analysis of non-isothermal natural ventilation using domain decomposition technique with LES

Tomohiro Kobayashi[1*], *Toshio* Yamanaka[1], *Noriaki* Kobayashi[1], *Narae* Choi[1], *Toru* Matsubara[1], *Shohei* Miyazawa[1], *Zitao* Jiang[1], and *Chisato* Tambara[2]

[1]Osaka University, Department of Architectural Engineering, 2-1, Yamadaoka, Suita, Osaka, Japan
[2]Obayashi Corporation, Technical Research Institute, 4-640, Shimokiyoto, Kiyose, Tokyo, Japan

Abstract. The paper presents a CFD technique named Domain Decomposition Technique which enables analysing indoor airflow for natural ventilation. Since it has been studied for the isothermal condition with RANS model, the present paper aims to propose a method to apply it for the non-isothermal condition using Large Eddy Simulation (LES). The technique is composed of three steps, i.e., 1) outdoor simulation to obtain boundary conditions at possible opening locations, 2) calculating three components of velocity at the openings as boundary conditions, and 3) indoor airflow analysis. Two cases of the wind direction are studied in the paper, i.e., wind is assisting/opposing the buoyancy. By comparing the indoor temperature and velocity distribution between the whole domain analysis and DDT, the applicability of the DDT is studied.

1 Introduction

Natural ventilation is a beneficial way not only to obtain thermal comfort but also to save energy for cooling in a moderate climate. To design a well performing natural ventilation system in a building, it is preferable to predict natural ventilation rate and airflow field in a design phase, for which CFD prediction could be beneficial. In some condition like small wind pressure difference between openings, RANS model cannot predict airflow pattern appropriately, while Large Eddy Simulation (LES) works well. However, due to a high computational load of LES analyzing both indoor and outdoor, it is not easy to conduct a parametric study changing the opening location. Kurabuchi et al. [1] proposed a Domain Decomposition Technique (DDT) with RANS model, which runs a calculation for outdoor area once obtaining the wind pressure and velocity around the wall where the openings could be located to create inlet/outlet boundary conditions for the calculation analyzing the indoor area only. In performing an indoor airflow calculation with other cases of opening location, no additional outdoor calculation is required. However, studies on DDT are limited to isothermal RANS calculation. This paper aims to propose a method to apply it for the calculation with non-isothermal condition using LES and explores its applicability by comparing the results with LES for a whole domain including both indoor and outdoor.

2 Domain Decomposition Technique

This section gives a brief description of DDT using LES for the non-isothermal condition. The DDT is composed of three steps, i.e., 1) outdoor airflow simulation (STEP 1), 2) airflow rate calculation (STEP 2), and 3) indoor airflow simulation (STEP 3). Fig. 1 gives the schematic of STEP 1.

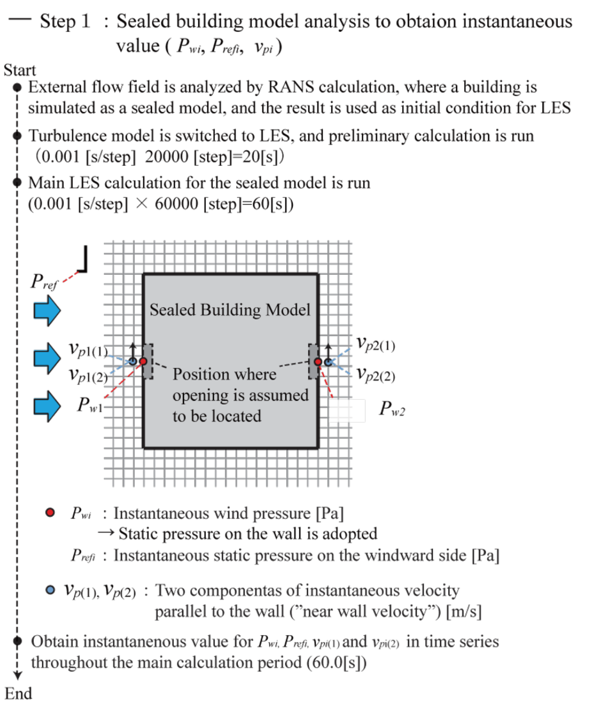

Fig. 1. STEP 1 : Outdoor airflow analysis.

* Corresponding author: kobayashi@arch.eng.osaka-u.ac.jp

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In this step of calculation, only an outdoor area is calculated using a sealed building model. The calculation in this step is run under an isothermal condition. As shown in Fig.1, instantaneous static pressure on the wall surface (wind pressure) is monitored throughout the calculation at all the points where an opening could be installed. In the vicinity of these points on the surface, two components of instantaneous air velocity parallel to the wall are monitored as well, which are hereinafter referred to as "near-wall velocity". These monitored quantities are to be used in the STEP 2 to create unsteady boundary condition for the indoor airflow analysis.

Fig.2 shows the STEP 2, which is an iterative calculation to obtain instantaneous flow rate driven by both wind and buoyancy. The driving force by wind is estimated by the wind pressure obtained in STEP 1. Since the present paper focuses on non-isothermal conditions, there assumed to be a certain temperature difference between indoor and outdoor. Based on a tentative indoor temperature, T_{in}, density difference, $\Delta\rho$, is also estimated, which gives the overall pressure difference through a whole flow path. It must be noted that a uniform indoor temperature was assumed here for simplicity. Then, instantaneous flow rate, Q_{in}, is obtained by the standard orifice equation. Considering this advection, internal heat generation, and heat loss/gain through the wall, the indoor temperature is calculated again and updated, and it is iterated until all the parameters are converged. This is a calculation procedure for one

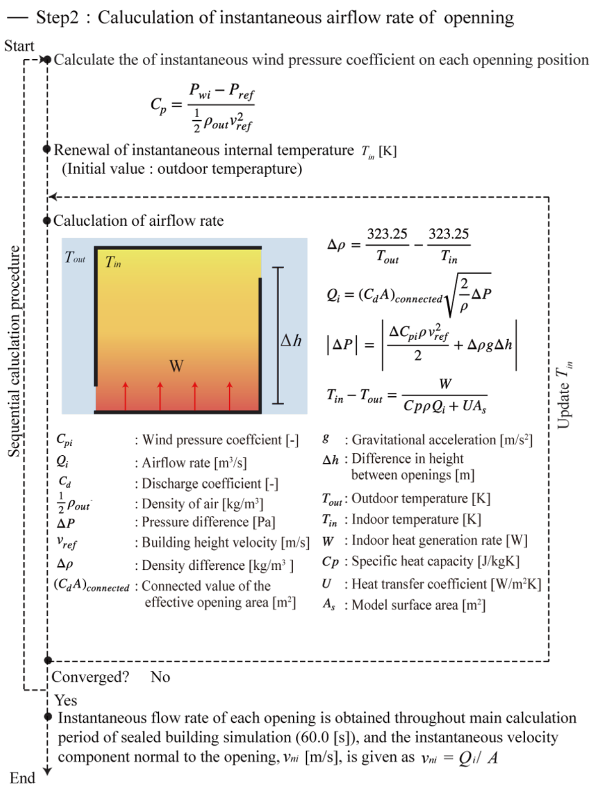

Fig. 2. STEP 2 : Flow rate and indoor temperature calculation.

time step to obtain instantaneous values, and this was repeated throughout a whole calculation period to obtain time series of T_{in} and Q_{in}. Dividing Q_{in} by the opening area, instantaneous velocity component normal to the opening, v_{ni}, is obtained, which is to be used as the boundary condition given uniformly over the inlet/outlet opening. In this step, it must be noted that Kurabuchi et al. [1] tried to modify the discharge coefficient depending on inflow angle. Nevertheless, this work adopted a constant of 0.67 for simplicity.

Fig.3 gives the schematic of STEP 3 analysing indoor airflow only. As mentioned in the previous step, the instantaneous velocity component normal to the opening, v_{ni}, obtained in the previous step is given for each of inlet/outlet opening as a boundary condition. It is also important to give the inflow direction appropriately at the opening to predict indoor airflow. Therefore, in addition to v_{ni}, other two components which are parallel to the wall must also be considered. For these, near-wall velocities monitored in STEP 1 are given as boundary conditions of velocity parallel to the opening.

3 Studied Model and Cases

In order to explore the applicability of DDT with LES for non-isothermal natural ventilation flow field, and also to identify issues to improve its accuracy, a simple cubic model was investigated using LES. Fig.4 depicts the test model studied, which was provided with an opening on each of windward and leeward wall. The model had an external side length of 300 mm and the openings had a dimension of 30 mm × 30 mm. There two openings were located at different height. This assumed a scaled model of 1:10, which simulated the wind tunnel experiment performed beforehand for validation.

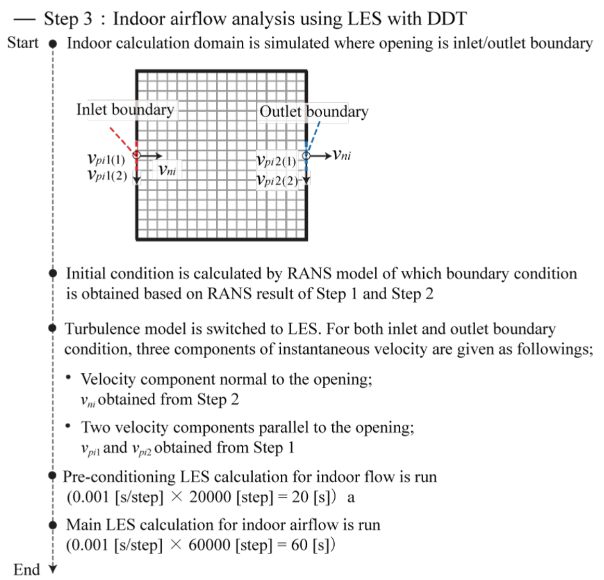

Fig. 3. STEP 3 : Indoor airflow analysis.

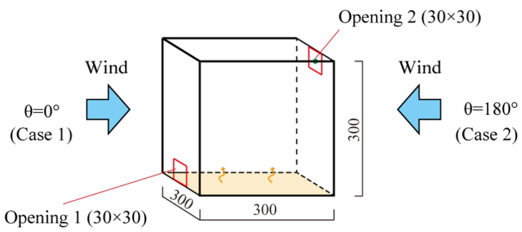

Fig.4. Studied model and wind direction.

To generate buoyancy due to the temperature difference, the model was assumed to have heat generation from the floor. More details are provided in the following section explaining the CFD set-up including boundary condition. Two cases of wind direction were studied as shown in Fig.4. In Case 1 (θ=0°), the wind and buoyancy were acting as driving forces in the same direction. In other words, the wind is assisting buoyancy. In Case 2 (θ=180°), on the other hand, the wind is opposing the buoyancy.

In the present paper, these two cases are analysed by two methods with LES. One is a conventional approach which calculate both indoor and outdoor simultaneously, while the other is DDT analysing outdoor and indoor separately.

4 CFD Setup

4.1 Whole Domain Analysis (WD) with LES

To study applicability of DDT and identify the issues to improve its accuracy, LES calculations analysing both indoor and outdoor simultaneously (whole domain analysis) were performed, results of which are to be compared with DDT. The LES simulation was simulating the above-mentioned preliminary wind tunnel experiment whose approaching flow was given as the boundary condition for inlet velocity and turbulent intensity at the inlet of the domain. Fig.5 shows the inlet boundary conditions and computational domain with mesh layout. The profile of the approaching flow was based on the measurement using I-Type hotwire anemometer with 1.0 kHz, and the fluctuation of the instantaneous velocity was here produced based on Smirnov et al. [2]. The average velocity of the approaching flow was set at 1.0 m/s at the height of the model roof top. The internal heat generation was given as the heat flux from the floor and set as 1077.5 W/m² uniformly. The radiative heat transfer was also considered by using surface-to-surface model. Table 1 gives the summary of CFD including DDT calculation described in the following section.

Table 1. Summary of CFD setting.

CFD Code		Ansys Fluent 2022 R2
Turbulence Model		Large Eddy Simulation (Smagorinsky-Lilly Model : Cs=0.12)
Algorithm		PISO
Descretization scheme for advection term		Central Differencing
Time Step		0.001 sec (10 kHz)
Pre-conditioning period		20,000 time steps (20 sec)
Main calculation period		20,000 time steps (60 sec)
Boundary Condition (Velocity)	Inlet	Smirnov's method based on experimental value
	Outlet	Gauge Pressure : 0 Pa
	Walls	Werner and Wengle two-layer model
Boundary condition (Thermal)	Inlet	17.4 °C
	Floor	Heat flux : 1077.5 W/m²
	Interior Wall	Given considering the followings 1) Interior surface : Temperature wall function 2) Conduction : Thermal conductivity: 0.19 W/(m·K) Wall thickness : 5.0 mm 3) Exterior surcace : Convective heat transfer coefficient Leeward wall : 6.0 W/(m²·K) Other walls : 10 W/(m²·K)
Total number of cells	Whole domain	1,133,140
	Outdoor simulation	1,052,170
	Indoor simulation	107,000

4.2 DDT analysis with LES

As described in Section 2, LES calculation for outdoor airflow field was first conducted using a sealed building model. The setting of CFD was the same as that shown in Table 1, but energy equation was not solved because it was the isothermal calculation. The static pressure on the wall (wind pressure) was monitored at the central position of the

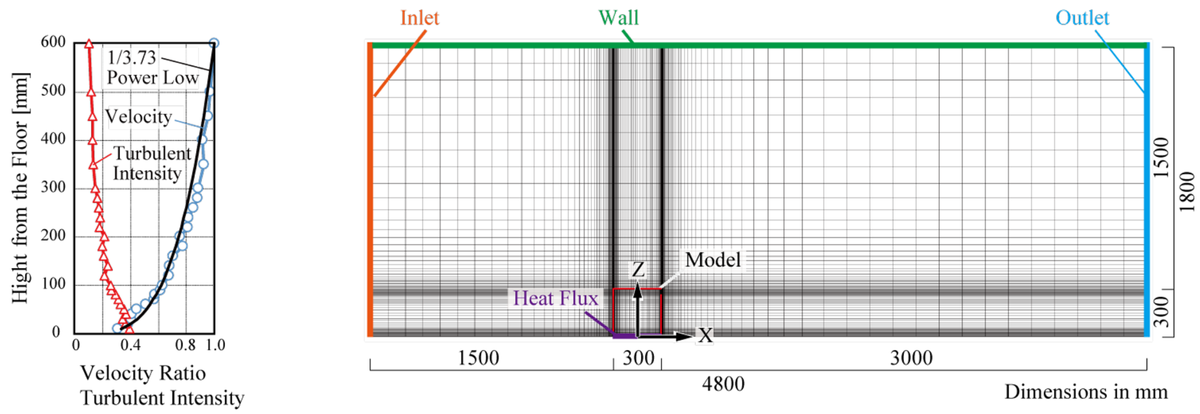

Fig. 5. Computational domain and boundary layer flow given as a boundary condition.

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openings for cases of wind direction. Given a symmetric model shape, the outdoor analysis was performed once, and the pressure was monitored at four points. In addition, the near-wall velocities were also monitored at 7.5 mm away from the monitoring point of the wind pressure, which corresponds to 1/4 of the side length of the opening [1]. According to the STEP 2 shown in Fig.2, time series of the instantaneous velocity at inlet/outlet opening was generated for each of three components and given as the inlet/outlet boundary condition for the indoor airflow analysis of STEP 3, which are shown in Fig.6. Fig.7 shows the computational domain for the indoor airflow analysis whose grid layout is the same as that in the whole domain analysis. The inlet boundary condition of temperature is fixed at 17.4 °C as well as the whole domain analysis, and wall boundary was also given in the same way as the whole domain analysis, which are summarised in Table 1.

5 Results and Discussion

5.1 Airflow Rate

As a basic investigation, the airflow rates obtained from the whole domain analysis and indoor airflow analysis using DDT are first compared as shown in Fig.8. The flow rate from the whole domain analysis was obtained by integrating the instantaneous inflow and out velocity component normal to the opening

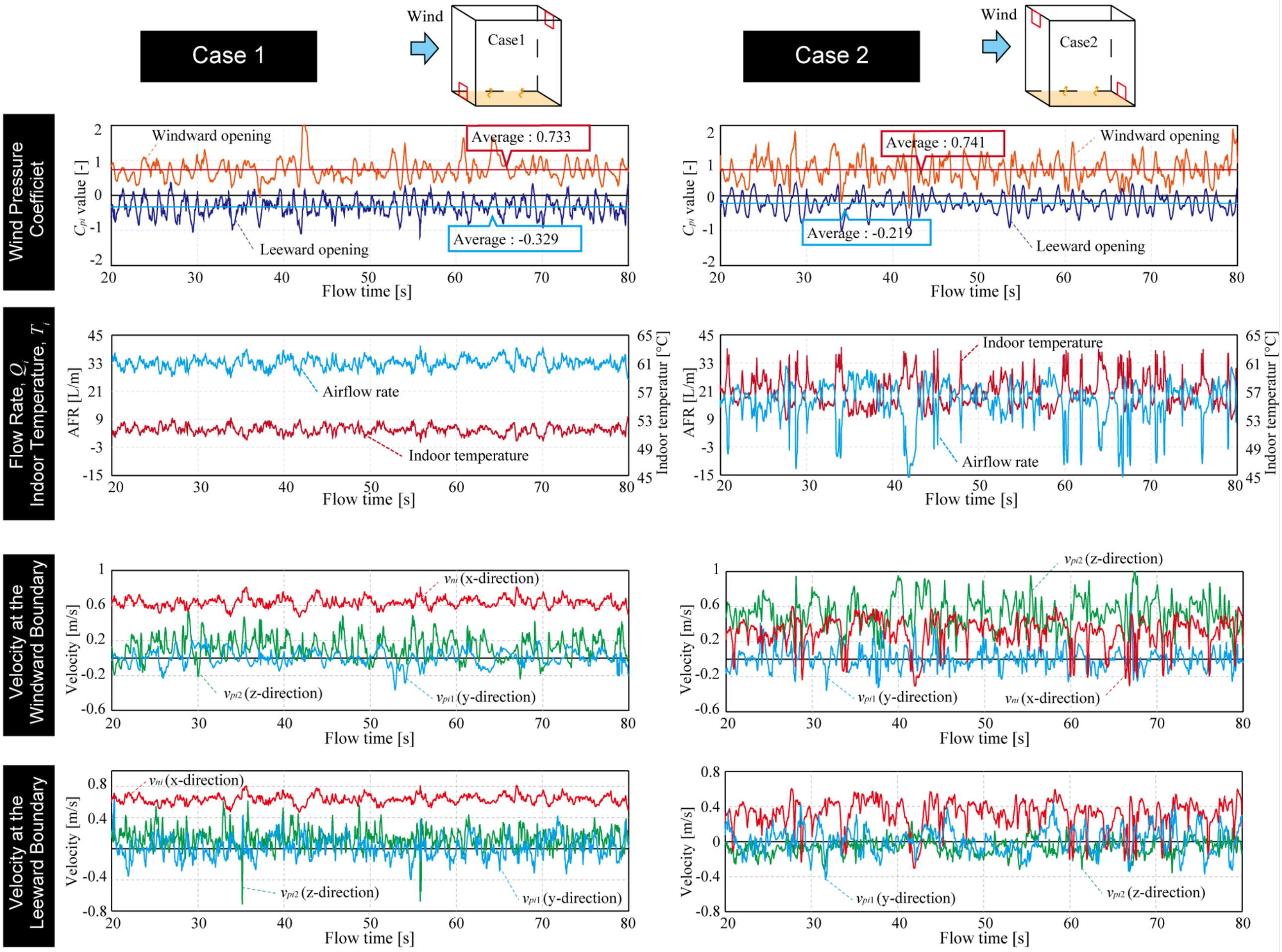

Fig.6. Fluctuation of flow quantities obtained in STEP 2 and given as boundary conditions in STEP 3

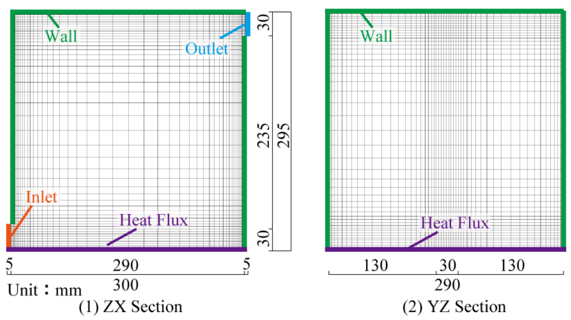

Fig.7. Mesh layout for indoor analysis in DDT

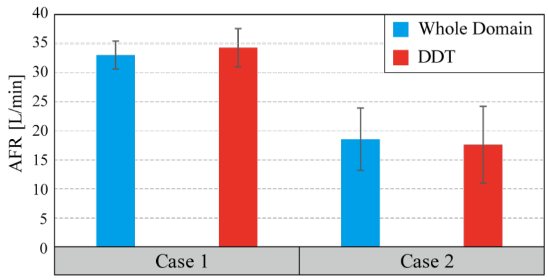

Fig.8. Mean airflow rate and its standard deviation.

separately, and its time average value and standard deviation were calculated. This comparison means an accuracy verification of the flow rate calculation based on the orifice equation assuming a uniform indoor temperature distribution. In both Case 1 and Case 2, the mean airflow rate well agrees between the whole domain and DDT analyses. Although the flow rate calculation in DDT ignored temperature distribution, it was shown that its influence was not significant. In addition, no significant difference in fluctuation of the flow rate was also seen. This seems to be due to that the wind pressure coefficient and its fluctuation was well predicted by outdoor analysis in the STEP 1 of DDT analysis.

5.2 Velocity distribution

Fig.9 shows the distribution of mean velocity magnitude and Fig.10 shows vertical profile of the mean velocity and its standard deviation inside the model, which were obtained from the whole domain analysis and DDT. As for Case 1, the inflow from the windward opening crawls along the floor. This is due to the vertically downward velocity component because the opening is located lower than the stagnation point. On the other hand, more horizontal inflow direction is seen in the result of DDT. Correspondingly, the difference in vertical velocity profile was also seen. This is because the boundary condition of the vertical component of velocity was different from that in the whole domain analysis,

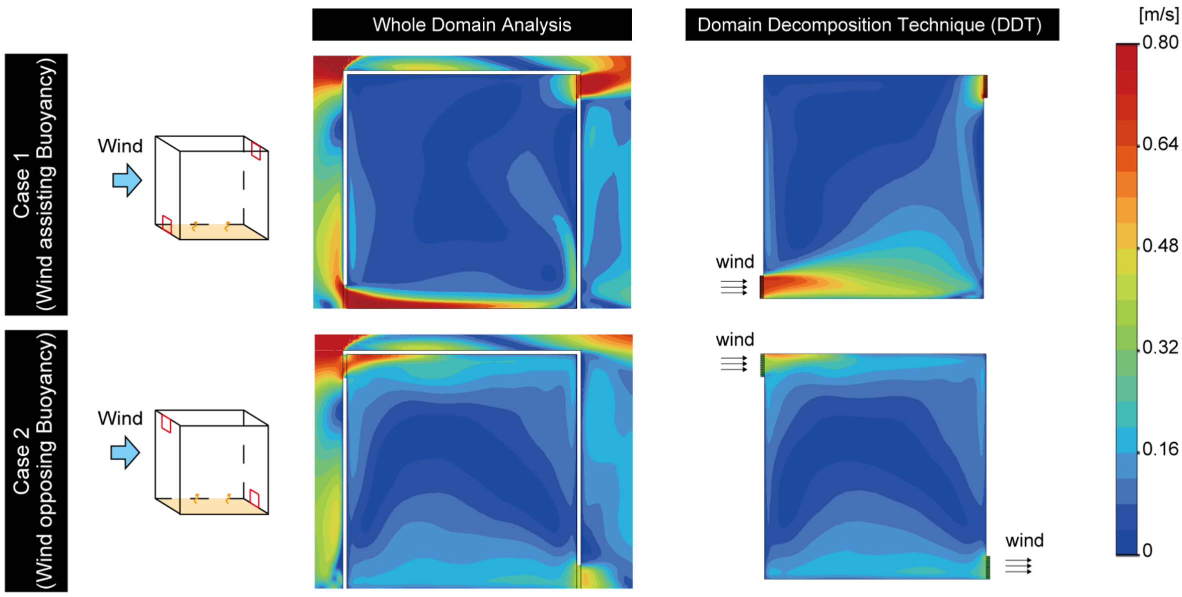

Fig. 9. Mean velocity magnitude obtained from the whole domain analysis and domain composition technique.

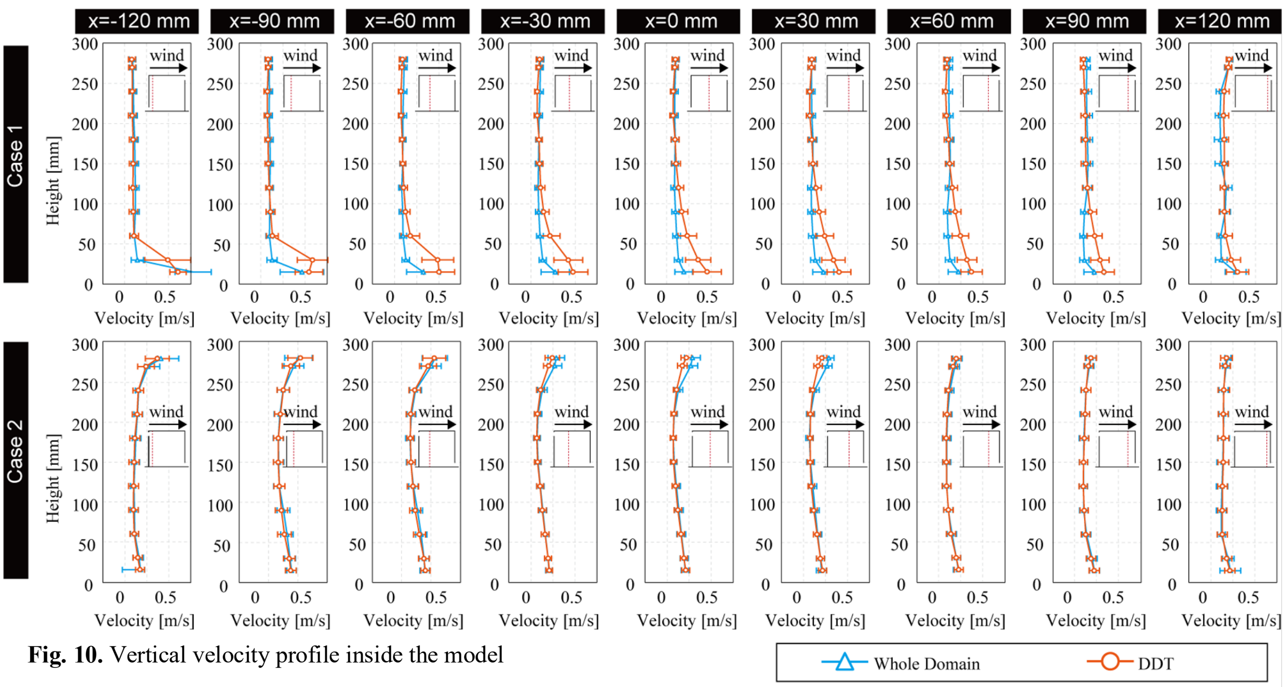

Fig. 10. Vertical velocity profile inside the model

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which indicates that the monitored near-wall velocity in the STEP 1 was not appropriate. Since the location of this monitoring point was close to the floor, there seemed to be a vortex generated by the windward wall and floor. Although this could be improved by changing the location of the monitoring point for near-wall velocity in STEP 1, it was shown that inflow direction could not easily reproduced when the opening is located close to the floor.

Moving to Case 2, general velocity distribution from DDT agrees relatively well with that from the whole domain analysis. The tendency of the inflow from the windward opening that is going upward is also seen in the results of DDT. Although the velocity magnitude of the inflow in DDT is underestimated a little, this is due to the uniform boundary condition over the inlet opening. The vertical profiles of the velocity in Fig.10 showed small differences between x=-30 and 30 mm, the indoor airflow characteristics could be well reproduced.

5.3 Temperature distribution

Fig.11 shows the mean temperature distribution inside the model. Fig.12 gives the vertical temperature profile at x=-133, 0, 133 mm along the central cross-section and horizontal-averaged indoor temperature. In Case 1, the indoor temperature resulted in approximately 45 °C except the area closed to the inlet opening in both whole domain and DDT results. This is because the airflow rates were well predicted by DDT and temperature in the well mixed area showed similar results. However, related to the results of velocity distribution, the temperature around the inlet opening showed the difference between the whole domain analysis and DDT in Case 1. Although vertical profile of the horizontal-averaged indoor temperature in Fig.12 showed similar results, some improvement of prediction accuracy of inflow direction is required because the purpose and strength of LES is to predict a detailed distribution of indoor velocity and temperature distributions.

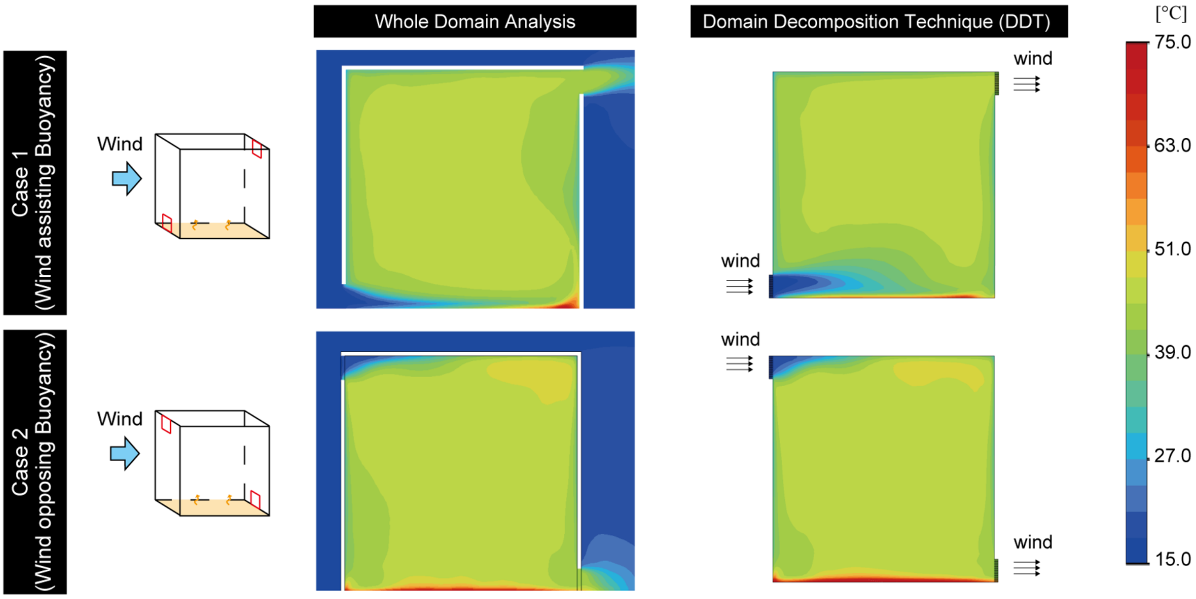

Fig. 11. Mean temperature distribution obtained from the whole domain analysis and domain composition technique.

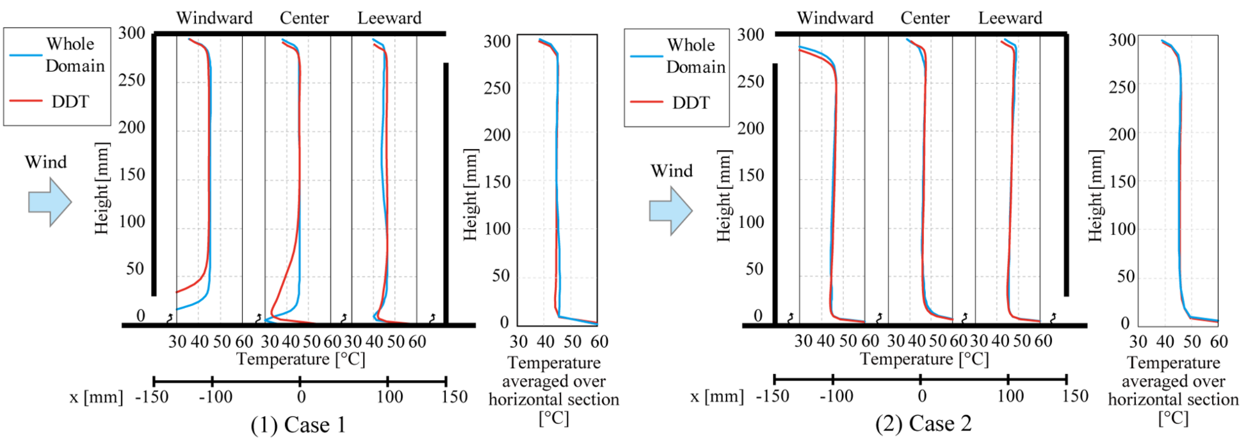

Fig. 12. Vertical profile of mean indoor temperature obtained from the whole domain analysis and DDT.

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As for the results of Case 2, both temperature distribution in Fig.11 and vertical temperature profile in Fig.12 showed good agreement between the whole domain analysis and DDT. Although velocity magnitude was underestimated around the inlet opening, this did not lead to a significant difference in temperature distribution.

6 Conclusions

In this paper, a CFD technique named domain decomposition technique (DDT) to predict the airflow only indoors was applied to non-isothermal flow field using LES. A simple cubic model with natural ventilation airflow driven by both wind and buoyancy was studied, and the results obtained from the whole domain calculation and DDT were compared regarding the indoor velocity magnitude and indoor temperature distribution. Two cases of wind direction were studied, i.e., the wind is assisting (Case 1) and opposing (Case 2) the buoyancy.

The results showed that both the velocity and temperature predicted by DDT in Case 1 showed a difference from the whole domain analysis due to the difference in inflow direction. The main reason of this discrepancy seemed to be caused by the inadequate near-wall velocity obtained at the monitoring point closed to both the windward wall and floor. This also led to the difference in the indoor temperature around the inlet opening. Given the purpose of LES applied for indoor airflow analysis, further improvement of the prediction accuracy for inflow direction is required. Therefore, it is needed to investigate the effect of the location to monitor near-wall velocity in the STEP 1 of DDT. As for Case 2, the indoor velocity distribution could be simulated relatively well, though a small underestimation of the velocity could be seen around the inlet opening due to the uniform boundary condition in DDT. However, this did not cause a significant difference in indoor temperature distribution.

As a future prospect, further studies with different opening location seem to be required clarifying the influence of the position of the monitoring point for near-wall velocities. In addition, since it is well known that the flow rate predicted by the orifice equation could overestimate when the incident wind angle is large, studies on DDT considering the modification of the discharge coefficient are also needed.

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