Study of airflow in a naturally cross-ventilated house -Evaluation of natural cross ventilation considering flow fluctuation by using large-eddy simulation (LES)

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SUMMARY

Cross ventilation in interior spaces is a commonly used natural ventilation method in Japan during moderate seasons, including summer. Clearly, cross ventilation is a complex phenomenon. In a previous study, a steady airflow distribution was studied over time for a simple house model with two windward and leeward openings on opposite walls, however, the wind direction and velocity outside the house was found to vary. Consequently, the airflow distribution varies depending on the outside wind direction and velocity. Moreover, the outside wind turbulence affects cross ventilation, for example, in the case of two wall openings symmetrical to the wind direction. Recently, unsteady fluid flow phenomena were analyzed using large-eddy simulation (LES). LES can simulate the time variation of a flow. In this study, airflow computation results for a cross-ventilated house are reported. Five cases of a simple house model were considered, and a natural cross-ventilation evaluation method, which considers flow fluctuations, is proposed.

INTRODUCTION

Replication of the actual phenomenon due to unsteady fluid flow is very important in the natural cross-ventilation evaluation. In actual ventilation phenomenon, there are opening conditions that can obtain ventilation in unsteady fluid flow, but no-ventilation occurs on steady RANS simulation. For example, For example, in the case that two openings are positioned symmetrically on leeward wall, on average, these show the same pressure distributions in openings position. Consequently, there is no ventilation in steady fluid flow. However, in actuality, there is ventilation in unsteady flow owing to the ever-changing pressure distribution.
That is, actual phenomenon vary over time, and a steady state is not maintained. Therefore, mere replication of cross ventilation by steady fluid flow is insufficient, and we should also analyse by unsteady state (taking into consideration changing air current). In a previous study on unsteady fluid flow, the visualization and analysis method of the turbulent flow (using Large-Eddy Simulation; LES) are examined as prediction technology of unsteady flow around buildings and city blocks. In this study, we performed analysis by LES (Dynamic Smagorinsky model) on the simple house model with some openings installed. Fluid flow conditions (around openings, or inside buildings) were conducted by analysis of the replication of

unsteady flow. Moreover, we aimed to develop an evaluation method of natural ventilation performance under conditions of unsteady fluid flow.

ANALYZING METHOD

Analysis object

Table 1 shows the analysis cases. Figure 1 shows the analysis domain. Figure 2 shows plans of the simple house model. The analysis object is a simple house model (300-mm cube). In Case Model A, the openings are installed at the center of each opposite wall (windward and leeward sides). In Case Model B, the openings are installed at the center of opposite walls (parallel to the fluid direction). In Case Model C, both openings are installed on the same wall (windward side). In Case Model D, both openings are installed on the same wall (leeward side). In Case Model E, the openings are installed on the same wall (parallel to a fluid direction). Areas of openings are each 1,600 mm^2 (40-mm square). The centers of the openings are at a height of 150 mm from the ground line. The interval of openings (Models C~E) is 130 mm. The analysis domain is set to imitate the wind tunnel (length=7,800 mm, height=1,800 mm, width=1,800 mm).

Table 1. Analysis cases

Case No.	Case 1	Case 2	Case 3	Case 4	Case 5
Simple house model	Model A	Model B	Model C	Model D	Model E

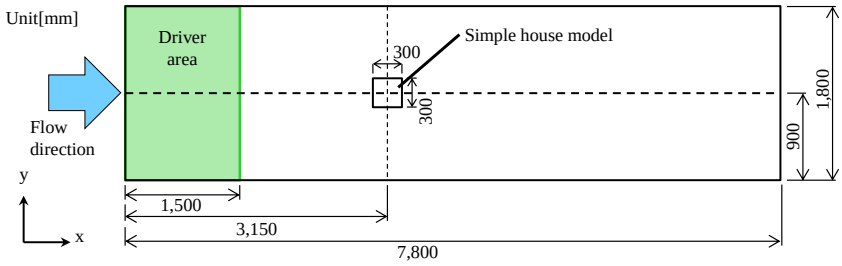


Figure 1. Analysis domain

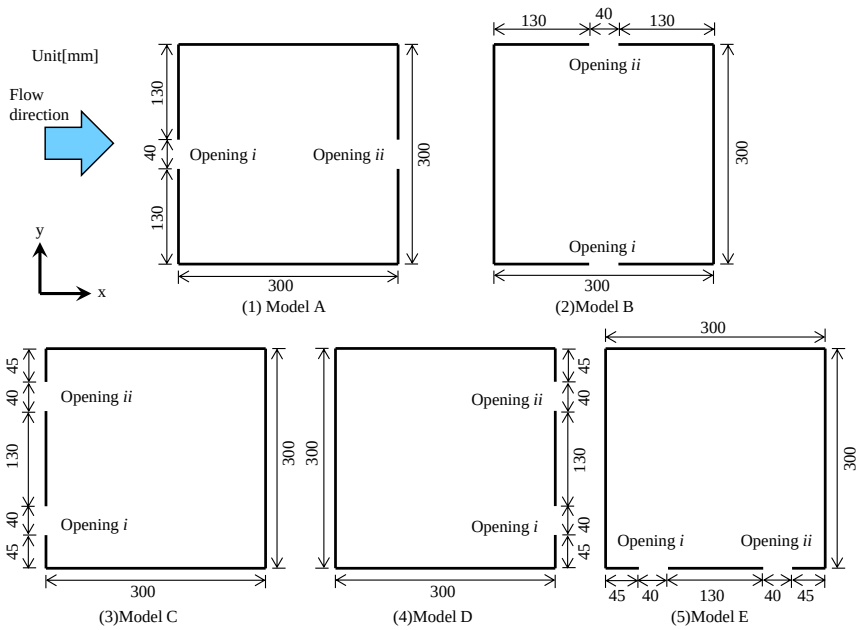


Figure 2. Plans of simple house model

Analysis conditions

Table 2 shows the analysis conditions. In this study, software for computational fluid dynamics; STREAM ver.9 is used for LES. The dynamic Smagorinsky model is used as the subgrid scale model. Temperature is constant. The Werner-Wengle wall model extended for three layers is used for the wall boundary conditions.

In this study, LES analysis was performed in three steps. In the first step, driver area is made by using a simple house model without any openings. In the second step, inflow changing-air current is made by pre-analysing. In the last step, some openings are installed for the simple house model and analysed truly. The first 2.6 seconds is a pre-analysing period. Moreover, the first 2.0 seconds in the true analysis period is cancelled as transient time. On the lowest side of the driver area (x=1,500 mm), average velocity is 5.0 m/sec at standard height (h=1,000 mm). The average velocity at the eaves height (300 mm from ground) is 3.74 m/sec.

Table 2. Analysis conditions

SGS model	Dynamic smagorinsky model		
Analysis region	x=7.8, y=1.8, z=1.8[m]		
Size of house model	x=0.3, y=0.3, z=0.3[m]		
Opening Area	0.04×0.04＝0.0016[m^2]		
Boundary condition	Inflow	Produced by driver region	
	Out flow	Naturaly flow out	
	Wall Boundary	Side, Top	Free slip
		Ground	Three layer model of Werner-Wengle wall functions
		Building wall	
Analysis time	Pre-analysis	2.6[sec]	
	Main analysis	10.0[sec]	
Δt	0.00001[sec]		
Minimum mesh size	0.005[m]		
Number of meshes	210(x)×148(y)×117(Z)＝3,636,360		

RESULTS OF ANALYSIS

Openings are installed on opposite walls, windward and leeward (Case 1)

Figure 3 shows velocity distribution around a simple house model in Case 1. Liner fluid flow is produced from windward opening i to leeward opening ii shown in average velocity distribution (c). Inflow is produced on the windward opening i (v_y=3.0 m/sec), shown in instant velocity distribution (a). While, inflow is produced on the opening i (v_y=-3.0 m/sec), shown in (b). Therefore, instant flow occurs on the amplitude state for the y-direction. Moreover, turbulence occurs in the corner of the interior. Around the house, near the opposite wall parallel to wind direction, separation is generated and adverse flow is produced.

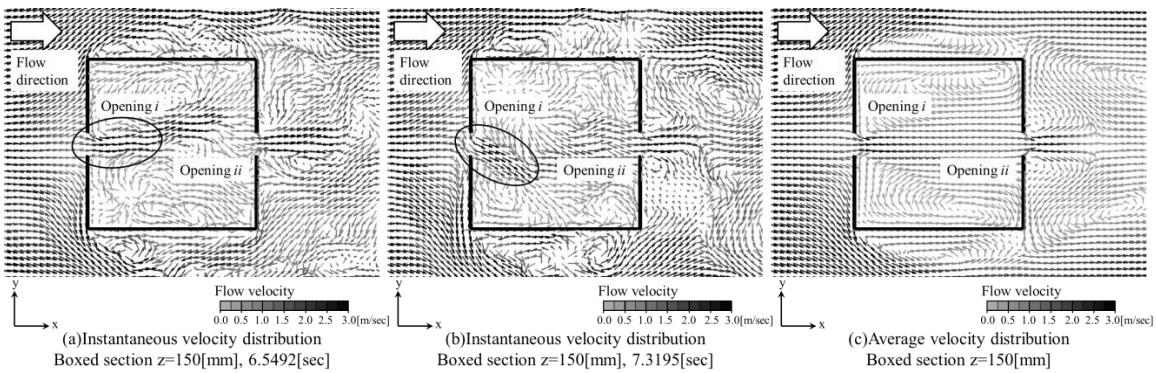


Figure 3. Velocity distribution around the simple house model in Case 1

The analysis time (10s) is determined by symmetricalness of time-averaged air-flow velocity distribution in a simple house model (Case1). Figure 4 shows that the field (z=150mm, center of openings) for inspection is divided in two areas parallel to wind flow. Furthermore, each area are divided into 50 square meshes. Time-averaged air-flow velocity are calculated and compared with corresponding values in each mesh. Figure 5 shows that Coefficient determinations in each analysis time until ten seconds, the value is surpass 0.85 exceeds 5s. Based on this, analysis time of 10s is enough for the time-averaged air-flow field.

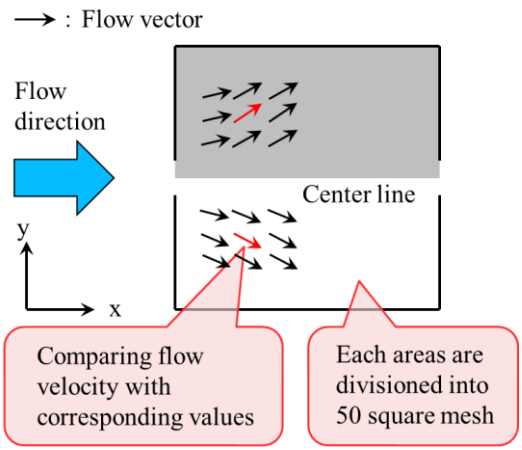


Figure 4. The field (z=150mm, center of openings) for inspection is divided in two areas parallel to wind flow. Furthermore, each area are divided into 50 square meshes.

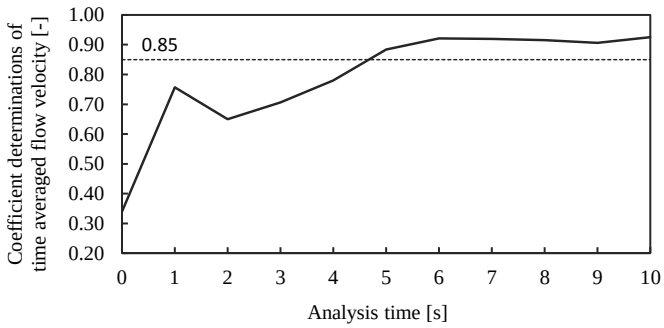


Figure 5. Coefficient determinations in each analysis time until ten seconds.

Openings are installed on opposite walls, parallel to the fluid direction (Case 2)

Figure 6 shows the velocity distribution around the model in Case 2. Inflow is not observed in average velocity distribution (c). However, inflow is produced on opening i (v_y=2.0m/sec), shown in instant velocity distribution (a). While, inflow is produced on the opening ii (v_y=-2.0m/sec), shown in (b). Therefore, inflow is generated by turns i and ii. Turbulence occurs in the corner of the house. Around the house, near the opposite wall parallel to wind direction, separation is generated and adverse flow is produced.

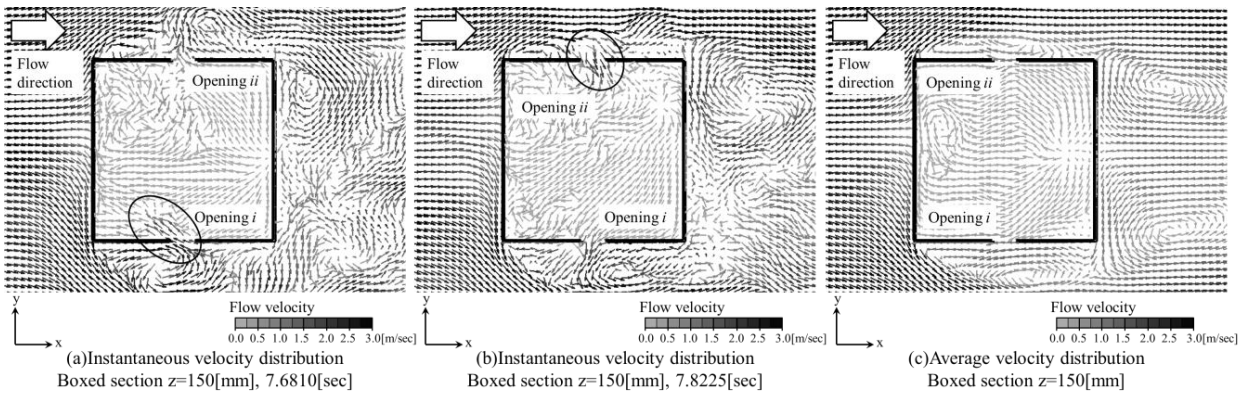


Figure 6. Velocity distribution around the simple house model in Case 2

Openings are installed on opposite walls, parallel to the fluid direction (Case 5)

Figure 7 shows velocity distribution around the model in Case 5. Two openings are installed on the same wall, parallel to the wind direction. In average velocity distribution (b), inflow occurs on leeward opening ii (v_y=1.3m/sec) and a flow circulation field inside the house model occurs by the inflow. The instant inflow velocity is about 2.5 m/sec. Fluid flows in over the surface of the inner wall. The flow field in the house model is observed in detail.

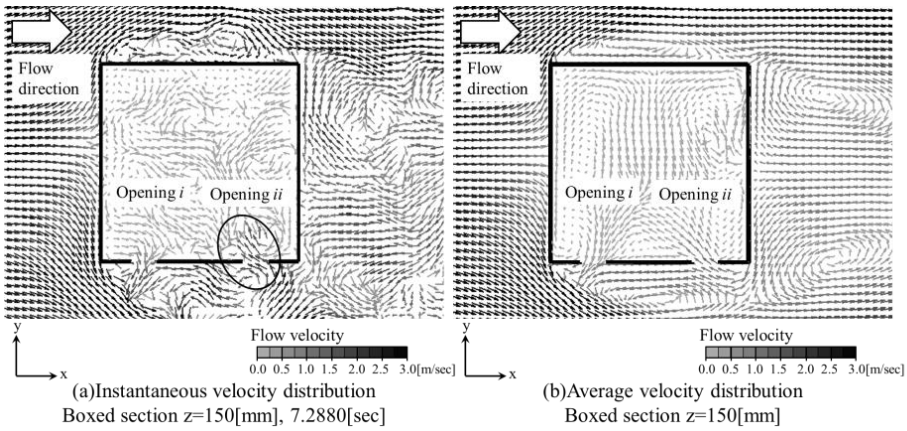
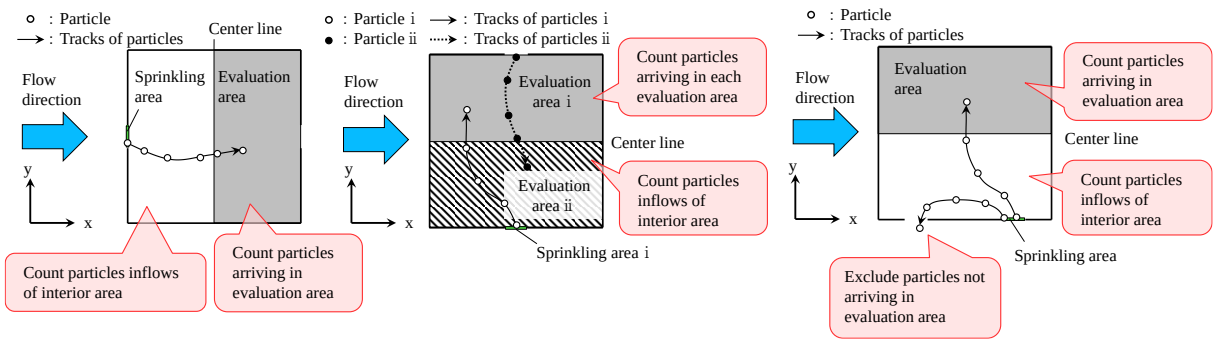


Figure 7. Velocity distribution around the simple house model in Case 5

EVALUATION METHOD OF NATURAL VENTILATION PERFORMANCE AT UNSTEADY FLUID FLOW

Figure 8 shows evaluation methods of natural ventilation performance in different cases. In this study, particles are sprinkled and the results are analyzed by the LES method and the arriving rate of the inner part of the house model is used in the evaluation method of unsteady fluid flow. The evaluation area is the inner part over the center line in order to exclude short circuit phenomenon. 100 particles are sprinkled from the opening per second. The results of analysis for 10 seconds are used periodically until steady state (arriving rate results in a stationary state). In Case 1, the results of analysis show that inflow only occurs on the windward opening. We sprinkled particles from the windward opening. In Case 2, inflows occur at each opening in turn. We sprinkled 100 particles from each opening. In Case 5, most inflows occur on the leeward opening. Therefore, we sprinkled particles from only the leeward opening. Next, only particles that reached the evaluation area are counted as contributing to natural cross-ventilation. The arriving rate is computed from Equation (1) and effective ventilation is computed from Equation (2) by the amounts of inflow on the opening and arriving rate. Equation (5) shows the ratio of effective ventilation by the results of Case 1 and other cases.



(a) Model A (b) Model B (c) Model E

Figure 8. Evaluation method of natural ventilation performance by the cases

$$r = n_r/n_{in} \quad [\%] \tag{1}$$

$$Q_e = Q \times r \quad [m^3/h] \tag{2}$$

$$Q_s = Q/(v \times A) \quad [-] \tag{3}$$

$$Q_{se} = Q_s \times r \quad [-] \tag{4}$$

$$r_e = Q_e/Q_{e1} \quad [-] \tag{5}$$

r : Arraival rate [%], n_r : Number of arrived particles [number], n_{in} : Number of inflow particles [number],

Q_e : Effective ventilation [m^3/h], Q : Inflow volume [m^3/h], Q_s : Standard inflow volume [-],

v : base velocity (5.0) [m/sec], A : Area of opening (0.0016) [m^2], Q_{se} : Standard effective ventilation [-],

r_e : Ratio of effective ventilation [-], Q_{el} : Effective ventilation in case 1[m^3/h]

EVALUATION RESULTS OF VENTILATION PERFORMANCE

Inflow rate in each case

Figure 9 shows the inflow rate in each case. In Case 1, all particles are inflow. In Cases 2, 3, and 4, about half of the particles are inflow. In Case 5, about 90% of sprinkled particles are inflow.

Arriving rate in each case

Figure 10 shows the arriving rate in each case. In Case 1, the arriving rate is over 85% and 97% on average. In Case 2, the arriving rate is over 25% and 42% on average. In Case 5, the arriving rate is over 3%, 49% on average, and under dispersion.

Effective ventilation in each case

Figure 11 shows effective ventilation in each case. In Case 1, effective ventilation is 10.43 m^3/h. The ratio of effective ventilation is shown by Equation (5) based on effective ventilation 10.43 m^3/h in Case 1. In Case 2, effective ventilation is 0.98 m^3/h. In Case 5, effective ventilation is 1.70 m^3/h.

Comparison of each case

Figure 12 shows the ratio of effective ventilation in each case. In Case 2, the ratio is 0.0937 on average. In Case 3, the ratio is 0.1685 on average. In Case 4, the ratio is 0.1154 on average. In Case 5, the ratio is 0.1626 on average. Consequently, in Cases 2~4, ventilated in unsteady fluid flow, but there is no ventilation in steady flow.

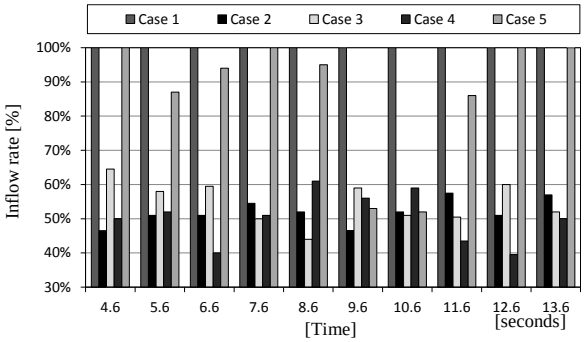


Figure 9. Inflow rate (Number of inflow particles divided by Number of sprinkled particles) in each case

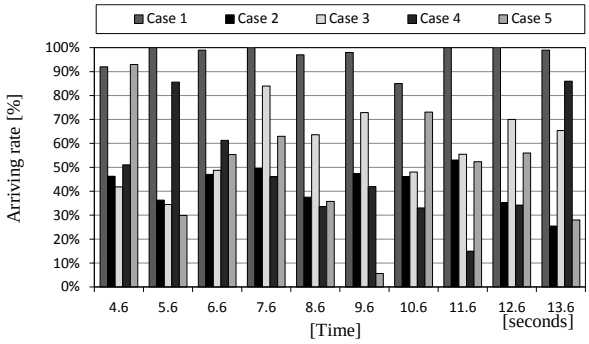


Figure 10. Arriving rate (Number of particles arrived at evaluation area divided by Number of inflow particles) in each case

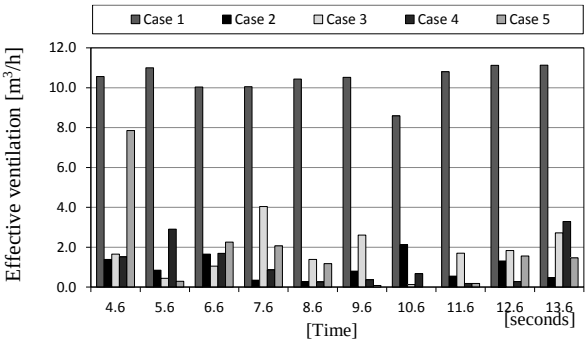


Figure 11. Effective ventilation in each case

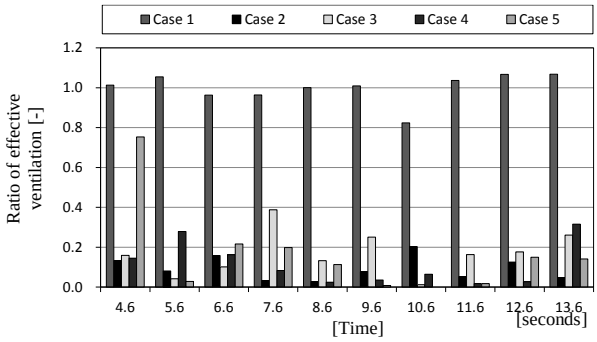


Figure 12. Ratio of effective ventilation in each case

CONCLUSIONS

(1) In Case 1, a liner fluid flow field is produced from the windward opening to the leeward opening shown in average velocity distribution. Instantaneous inflow occurs on the amplitude state for the y-direction. Moreover, turbulence occurs in the corner of the interior.
(2) In Case 2, inflow is not observed in average velocity distribution. On the other hand, inflow is generated by turns at each opening.
(3) In Case 5, in average velocity distribution, inflow occurs on the leeward opening and the flow circulation field inside the house model occurs by inflow. The flow field in the house model is observed in detail.
(4) In Case 1, all sprinkled particles flow in the house model and the arriving rate is over 85%. On average, the arriving rate is 97%. The average effective ventilation is 10.43 m^3/h at a base velocity of 5.0 m/sec and the area of openings is 0.0016 m^2.
(5) In Case 2, about half of the sprinkled particles flow in the house model and the arriving rate is 42% on average. The average effective ventilation is 0.98 m^3/h at a base velocity of 5.0 m/sec and the area of openings is 0.0016 m^2. The ratio of effective ventilation is 0.0937.
(6) In Case 5, about 80 % of particles flow in the house model and the arriving rate is 49% on average. The average effective ventilation is 1.70 m^3/h at a base velocity of 5.0 m/sec and the area of openings is 0.0016 m^2. The ratio of effective ventilation is 0.1626.

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