Natural Ventilation Simulation for Application to Environmental Planning in the Early Design Stage

Nozomu Ota1, Sei Ito1
1Shimizu Corporation, Tokyo, Japan

Abstract
A natural ventilation simulation tool has been developed with three issues set for practical application, with the objective of investigation of natural ventilation in real-time in the early design stage. Also, to evaluate the tool, its ease of use was checked by application to an actual project, and the validity of the calculation results was verified by comparison with environmental measurements.

Key Innovations
- Proposal of natural ventilation potential maps
- Development of Visual NETS in which automatic opening and closing of ventilation apertures is provided as standard
- High-speed thermal and airflow network model calculation
- Evaluation of the tool by design and measurement of actual buildings

Practical Implications
High-speed investigation of natural ventilation in the early design stage

Introduction
Natural ventilation greatly affects architectural schemes, so repeated performance investigation in the early design stage and feedback into the design in real-time is important for increasing energy efficiency.

However, natural ventilation performance (in this paper the effect of ventilation rate and energy efficiency) is affected by the local characteristics, nearby buildings, building shape, layout of ventilation apertures, opening and closing methods, etc., so there are very few tools that can be used with the limited time and resources at the early design stage (for example, arriving at a conclusion after a few days). Yoon and Malkawi (2017), Alejandra Menchaca et al. (2008), Purup and Petersen (2016) proposed natural ventilation tools for the early design stage and performed analysis of the relationship between building shapes and wind pressure coefficients. They have focused on specific aspects, but there are almost no tools that are capable of comprehensively investigating from exterior air flow to energy efficiency effect on the air conditioning load.

Therefore we have developed a natural ventilation simulation tool that is highly practical for the early design stage. First, the authors who are engaged in natural ventilation environmental design projects in Japan identified three issues. Table 1 shows the issues.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Issue A</td>
<td>There are few hints for the layout of ventilation openings</td>
</tr>
<tr>
<td>Issue B</td>
<td>Reproduction of automatic opening and closing control of ventilation apertures for calculating energy efficiency is difficult</td>
</tr>
<tr>
<td>Issue C</td>
<td>Analysis speeds to improve the real-time properties</td>
</tr>
</tbody>
</table>

(Issue A) In real projects restrictions due to design and cost are applied, so it is difficult to set the parameters for optimization of ventilation opening layout. Therefore in almost all cases the designer decides the locations of the ventilation openings. Normally wind pressure coefficients obtained from CFD analysis are used to guide the location of the ventilation openings. Sanquer et al. (2015) and Yoon, N et al. (2019) have proposed the arrangement and optimization of ventilation openings from wind pressure coefficients. However, in these researches the wind was blowing from one direction only. In particular, Japan is surrounded by sea, and it is frequently difficult to determine the predominant wind direction, so it is necessary to perform evaluation over all natural ventilation time periods to obtain hints for the layout of the ventilation openings.

(Issue B) There are four seasons in Japan, and in areas where natural ventilation is effective only in limited time periods, if there is no automatic opening and closing of the ventilation apertures there is a possibility that thermal load will actually be imposed. Therefore reproduction of automatic opening and closing control is necessary in order to calculate the energy efficiency effect (Simonosono and Kohri (2019)). Mohammadzadeh et al. (2019) have reproduced automatic opening and closing control using the EnergyPlus EMS system. It is possible to incorporate automatic opening and closing control with EnergyPlus or TRNFlow, but it would require construction of a complex system, and this is not suitable for the early design stage.
(Issue C) Analysis speed in the early design stage is very important because it affects the number of options that can be investigated.

In this paper, first an overview of the tool is presented, together with an explanation of the means of resolving the above three issues. Next to evaluate the tool, the ease of use is checked from analysis of the exterior air flows to the calculation of the natural ventilation performance, and the results of verification of the calculation results by comparison with environmental measurements are described.

**Tool**

**Overview of the tool**

Figure 1 shows an overview of the tool developed. It is divided into two phases in accordance with the normal progress of design: a site environment analysis phase using CFD analysis, and a natural ventilation performance calculation phase using Visual NETS (developed in-house) incorporating a thermal and airflow network model simulation program.

In the site environmental analysis phase, the wind environment of the site is analyzed in order to obtain the design conditions in the early design stage, the effectiveness of natural ventilation is evaluated at the planned site, and the strategy of the environmental planning is decided. First, CFD analysis of the exterior is performed using a Rhinoceros 3D model. Grasshopper is used for data coupling, and by incorporating an algorithm for automating analysis mesh division and analysis of 16 wind directions, the work is speeded up. Next, the CFD analysis results are incorporated into Grasshopper, and natural ventilation potential maps described later are visualized on Rhinoceros. Using the natural ventilation potential maps, the designer can obtain hints regarding the effective layout of ventilation apertures.

In the natural ventilation performance calculation phase, the natural ventilation rates and energy efficiency of many proposals are evaluated, and the natural ventilation planning is brushed up to a better one. The Rhinoceros 3D shapes and the wind pressure coefficients are linked to Visual NETS using Grasshopper. Visual NETS is a simulation tool having the functions of 3D modeler that produces models for natural ventilation, provision of libraries and default values for each building use, generation of thermal and airflow network models, post-processing, and linking data to BIM and Rhinoceros. The calculation engine incorporates the thermal and airflow network model simulation program xNETS.

This is a tool that enables comprehensive investigation from analysis of the external air flow to the energy efficiency effect on air conditioning in the early design stage, by fully automating data linking between each process and speeding up the investigation.

**Natural Ventilation Potential Maps**

The natural ventilation potential maps are proposed as a measure to solve Issue A. Natural ventilation potential maps visualize the locations where there tends to be strong positive pressure or negative pressure during times of natural ventilation on 3D models, with the purpose of providing hints on the layout of ventilation apertures. If ventilation apertures are provided at locations of positive or negative pressure, efficient ventilation can be expected.

The calculation equations for the positive pressure potential $\text{PPP}_j$ and the negative pressure potential $\text{NPP}_j$ are as follows.

$$\text{PPP}_j = \sum_{WD} (\Delta C \times \text{FREQ}_{WD}) \quad (1)$$

Where,

$$\text{PPP}_j : \Delta C = \begin{cases} C_{PW,j} - C_{PW,AVG} & (C_{PW,j} - C_{PW,AVG} \geq 0) \\ 0 & (C_{PW,j} - C_{PW,AVG} < 0) \end{cases}$$

$$\text{NPP}_j : \Delta C = \begin{cases} 0 & (C_{PW,j} - C_{PW,AVG} \geq 0) \\ C_{PW,j} - C_{PW,AVG} & (C_{PW,j} - C_{PW,AVG} < 0) \end{cases}$$
Using the average wind pressure coefficient for each wind direction as reference, values greater than the average are on the positive pressure side, and less than the average on the negative pressure side. By evaluating the difference from the average value, the wind pressure coefficient for each wind direction is standardized. The value weighted by the wind direction frequency aggregated during periods of natural ventilation is the natural ventilation potential, and by dividing them into positive pressure side and negative pressure side, they are prevented from canceling each other out.

Figure 2 shows an example calculated for an office test model (about 4,000 m²) located in Tokyo. Due to the effect of the surrounding buildings, significant positive pressure in the main wind directions (NNW, S) was found only on the upper part of the south external wall. On the east face there were no high surrounding buildings and there were East winds with a certain frequency, so as a result the potential was higher. It would have been difficult to discover this by investigating the main wind directions only. Similarly, it is difficult to find places where negative pressure increases. In this case, the negative pressure potential was highest in the southwest corner except for the top of the building.

Figure 3 shows the mean air change per hour (mean ACH) in the test model due to differences in the layout of ventilation apertures. It was confirmed that the arrangement of ventilation apertures taking into consideration the wind pressures based on the natural ventilation potential map increased the mean ACH on each story by a factor of 1.2 to 1.5 compared with an orthodox ventilation aperture arrangement.

Automatic Ventilation Aperture Opening and Closing Control

An automatic ventilation aperture opening and closing control function was provided as standard in Visual NETS, as a measure to resolve Issue B. The natural ventilation
apertures open and close automatically depending on the outside air condition and the indoor air condition. Figure 4 shows the user interface. The five most popular conditions for opening and closing control of natural ventilation apertures can be set. If the selected conditions are all satisfied the ventilation apertures open. Control is by feedback using the values of the external air state in the present cycle and the values of the interior air states in the immediately previous cycle. Also, there is a function for reading the exterior air as another room, so an extension is provided in which not only is it possible to open and close by comparison with the exterior air, but also opening and closing can be performed by comparison with the temperature and enthalpy of another room. Conditions other than these default five conditions can be set with versatility, by directly editing input files.

**High-speed Calculation**

The previous calculation engine NETS was improved for higher speed to resolve Issue C. NETS, which was developed by Okuyama (2007), is a thermal and airflow network model simulation program that can quantify solid and air heat transfer, and air and gas mass transfer. Networks of three point mass systems for heat, ventilation, and gas are constructed without separation between transfer within walls and transfer between walls and air, and equations are established for the balance at each node. Also, by solving a system of three simultaneous equations by the implicit method, the amount of heat, air flow, and the gas transfer between nodes are calculated. Ito (2017) performed the basic tests of ASHRAE Standard 140, and confirmed that the thermal load calculation results were within the range of other program results.

The problem with NETS was that the calculation speed was slow which restricted its use in actual practice. Therefore, the block skyline method (Uchiyama (1994)) for solving simultaneous equations at high speed was adopted, and calculation in the program overall was made more efficient, so major reduction in calculation time was achieved, and the amended program was named xNETS. As a result of this improvement the speed was increased by a factor of several tens of thousand compared with NETS (test calculation: 1993 nodes, 52 zones, 4320 cycles), so its utilization in actual practice became feasible.

The analysis speed of xNETS and EnergyPlus 9.3 were compared using the test model described previously (Visual NETS model: 1060 thermal nodes, 36 ventilation networks, 28 gas nodes). xNETS simultaneously solves for the temperature within walls, so in addition to CTF, EnergyPlus was compared with conduction finite difference. Table 2 shows the calculation method and output format, and Figure 5 shows the speed verification results. The speed relative to CTF was a factor of 6.6 higher, and relative to conduction finite difference was a factor of 5.7 higher, so it was confirmed that the tool is sufficiently practical for use in the early design stage. However, the calculation logics are greatly different, so it is not possible to the definitive regarding the speed comparison.

**Evaluation of the Tool**

By using the developed tool on the design of an actual project, it was confirmed that the natural ventilation potential maps and speeding up of calculation contributed to speeding up investigation in the early design stage. Also, the validity of the calculation results of the

<table>
<thead>
<tr>
<th>Location</th>
<th>Nerima-ku, Tokyo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>9,100 m², B1F-4F-PH0F</td>
</tr>
<tr>
<td>Structure</td>
<td>Structural steel</td>
</tr>
<tr>
<td>Use</td>
<td>Offices (2-3F)</td>
</tr>
<tr>
<td>Completion</td>
<td>2017</td>
</tr>
</tbody>
</table>
A simulation that reproduces the automatic opening and closing control of the ventilation apertures was verified by comparison with environmental measurements after completion of construction.

Ease-of-use during Design

Table 3 shows Building Overview, and Figure 6 shows the exterior View and Section through double-skin façade (DSF) on which the tool was used. The design was undertaken with the objectives of achieving a comfortable interior environment and an environmentally friendly building. In particular, DSF was adopted on the south side and north side since the beginning of the design, because it was necessary to block noise and the line of sight from the front road because of a special office requirement.

Natural ventilation potential maps were produced in order to confirm the possibility of natural ventilation at the early design stage. Figure 7 shows the results of analysis of weather data (measurement height 7.9 m) near the site, and Figure 8 shows the results of the natural ventilation potential maps. A DSF was provided on the north and south sides, so potential locations for the natural ventilation apertures were on the east and west side. However the positive pressure potential on the east and west sides was low, and the mean wind speed was low at 0.3 to 1.1 m/s. Therefore, it was anticipated that the wind pressure ventilation effect could not be obtained, so the idea was changed to natural ventilation utilizing the DSF. This is an example in which the natural ventilation potential maps have contributed to a major strategy decision in the early design stage.

As shown in the spring and autumn season mode in Figure 9, the natural ventilation scheme was to intake external air...
from the north side DSF where the temperature rise was small, and to discharge heat from the south side DSF using the solar chimney effect. Also, as shown in the summer and winter season modes in Figure 9, the DSF system was effective throughout the year using the dampers on the top and bottom of the DSF.

Table 4 shows the analysis conditions for evaluation of natural ventilation performance, and Figure 10 shows the calculation results for the ACH and the reduction in cooling load effect using Visual NETS. Wind forced cross natural ventilation with the same natural ventilation calculation results for the ACH and the reduction in natural ventilation performance, and Figure 10 shows the scheme (natural ventilation using DSF). The mean ACH of this scheme was 3.6 times higher than wind forced cross natural ventilation. Also, the cooling load reduction effect of wind forced cross natural ventilation is about 1%, and in contrast the energy reduction effect in this scheme was 10%.

Note that about 30 cases were studied before the ventilation aperture sizes and opening and closing conditions were decided upon, but the analysis time per case was about 16 seconds, so it was possible to perform investigations interactively tracking the changes in design.

**Validity of the Calculation Results**

Environmental measurements were taken after completion of construction of this project, and the validity of the simulation calculation results was confirmed. The building was in use during the measurement period. The measurement period was during the intermediate season mode from October 6 until October 26 (measurement was stopped from October 11 to 15 due to a typhoon). The solar radiation and the external air temperature and humidity were measured on the rooftop; the air temperature and humidity were measured within the DSF; the air temperature and humidity were measured within the offices; and the velocity, temperature, and humidity were measured within the natural ventilation pass ducts.

Figure 11 shows the plan and the measurement points. Pass duct for natural ventilation connecting the DSF and the office rooms were provided at 6 locations on one side, of which measurement was carried out in 1 location. Figure 12 shows the Measurement points around the pass duct. The air velocity and air temperature (a) were measured near the apertures on the interior side of the pass ducts connecting the interior and the DSF, and the air direction was determined as outflow when the air

![Figure 10: Mean ACH and Cooling Load](image)

**Table 4: Analysis conditions and Analysis cases**

<table>
<thead>
<tr>
<th>Analysis period</th>
<th>April 1 to November 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate data</td>
<td>Expanded AMEDAS weather data</td>
</tr>
<tr>
<td>Air conditioning</td>
<td>8:00 to 18:00 hours</td>
</tr>
<tr>
<td>Internal heat gain</td>
<td>2F 30 W/m², 3F 15 W/m²</td>
</tr>
<tr>
<td>Apertures opening conditions</td>
<td>Aperture A: DSF temperature &gt; 20°C</td>
</tr>
<tr>
<td></td>
<td>Aperture B: Always open</td>
</tr>
<tr>
<td></td>
<td>Aperture C: DSF temperature &gt; 35°C</td>
</tr>
<tr>
<td></td>
<td>Aperture D1-D4: No rain, 15°C &lt; Outdoor temperature &lt; Indoor, 5.5 g/kg &lt; Outdoor humidity &lt; 11.4 g/kg</td>
</tr>
</tbody>
</table>

* Refer to Figure 9 for A to D

**Table 5: Analysis conditions**

<table>
<thead>
<tr>
<th>Climate data</th>
<th>Temperature and humidity: measured value</th>
<th>Wind direction and speed: Japan Meteorological Agency data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis period</td>
<td>October 6 to October 26, 2019</td>
<td></td>
</tr>
<tr>
<td>Air conditioning</td>
<td>4:00 to 22:00 hours</td>
<td></td>
</tr>
<tr>
<td>Internal heat gain</td>
<td>2F 28 W/m², 3F 15 W/m²</td>
<td></td>
</tr>
<tr>
<td>Apertures opening conditions</td>
<td>Aperture A: DSF temperature &gt; 20°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aperture B: Always open</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aperture C: Always open</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aperture D1-D4: No rain, 15°C &lt; Outdoor temperature &lt; Indoor, 5.5 g/kg &lt; Outdoor humidity &lt; 11.4 g/kg</td>
<td></td>
</tr>
</tbody>
</table>

* Refer to Figure 9 for A to D
temperature (a) approached the room temperature (b), and as inflow when it approached the DSF temperature (c). The air flow rate was calculated by multiplying the measured air velocity by the area of the aperture.

Table 5 shows the analysis conditions for the simulation to reproduce the measurement period. The conditions were set based on the central monitoring data and the setting values for the automatic control equipment. The wind pressure coefficients reflected the CFD results.

Figure 13 shows a comparison of the opening and closing states of the natural ventilation apertures (excluding nighttime and lost time). There is general agreement, but there are several times when the central monitoring data is closed slightly more than the simulation. This occurs close to the external air temperature lower limit value or the external air humidity upper limit value, so there is a possibility that the external air sensors for opening and closing the natural ventilation apertures are provided separately from the overall external air sensors, but the cause has not been determined yet.

Figure 14 shows a comparison of temperatures inside DSF at 4F level. There are time periods when the measured values are slightly higher than the simulation results, but high reproducibility was confirmed.

Figure 15 shows a comparison of the natural ventilation rates on a representative fine day. In the morning when the temperature of the south side DSF was high, the measurement results showed that there was inflow of external air from the north side and outflow from the south side, so the behavior anticipated during design was confirmed. The simulation results also generally reproduced this trend. On the other hand, in the afternoon...
when the temperature of the south side DSF reduced, there were ventilation apertures where inflow and outflow were reversed between simulation and measurement. It is considered that the difference between simulation and measurement occurred due to the position of the neutral pressure level being lowered, causing instability in the ventilation flow direction. The reason that the inflow and outflow in the ventilation flow rates do not match is because there was also a ventilation path in the stairwell at the elevator.

Figure 16 shows a comparison of the daily integrated ventilation amount. A high correlation was found for both inflow and outflow. It can be seen that the simulation tended to produce slightly larger values. It is considered that the causes include the assumed discharge coefficient being different from the actual, and that the measurement was performed while the building was in use so the number of measurement points was small and as a result the measurement accuracy was not high. However, it was demonstrated that the tool has high reliability for the purpose of determining the natural ventilation performance in the early design stage.

**Conclusion**

A tool has been developed that incorporates measures to resolve the three issues for practical application of natural ventilation simulation in the early design stage. The three measures were natural ventilation potential maps, provision of a function for automatic opening and closing control of ventilation apertures as standard, and improving calculation speed.

The ease-of-use for application to design was confirmed and the validity of the calculation results were verified by comparison with environmental measurements, and it was confirmed that the effect in design of the measures taken with respect to the three issues were as expected.

This tool automates the links between the analysis phases, and the operations from CFD analysis of the exterior to investigation of multiple patterns of natural ventilation can be performed in 2-3 days. It is considered that its interactive properties make it practical to be used in the early design stage.

**Nomenclature**

\[ j : jth division of the grid on the outer skin \]
\[ WD : the wind direction (N, NNE, \ldots, NNW) \]
\[ Cp_{WD,j} : the wind pressure coefficient at the jth grid in the WD direction \]
\[ Cp_{WD,AVG} : the average wind pressure coefficient on the outer skin in the WD direction \]
\[ FREQ_{WD} : the frequency of occurrence of WD(0-1) \]

**References**


