Ventilation Performance by the Concentration Change of HCHO and TVOC with Three Models of Two Ventilation Systems and One Natural Condition

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Abstract
This study has prepared three models with two different types of ventilation systems including a natural ventilation system with a solar chimney installed, a mechanical ventilation system equipped with a fan which has a volume flow rate of 0.736 m³/min, and one type of natural condition that depends only on infiltration. The ventilation performance of each model was then measured and evaluated by analyzing the amount of concentration change of HCHO and TVOC. The results of this analysis showed that the concentration reduction rate of HCHO and TVOC were 38.9% and 68.4%, respectively, in the natural ventilation system that had a solar chimney, while concentrations were 31.5% and 64.9%, respectively, in the mechanical ventilation system that was equipped with a fan.

Keywords: solar chimney; mechanical ventilation system; infiltration; formaldehyde; volatile organic compounds

1. Introduction
As the overall financial situation of most people in Korea has improved, a more pleasant living space has become more desirable. Consequently, within the construction industry, there has been an increasing interest in improving indoor air quality as well as in creating comfortable temperatures for living spaces.

In Korea, the Indoor Air Quality Guideline for Newly Constructed Apartment Houses has been effective since 2006, and the results of its measurements need to be made accessible to the public for 60 days, starting 3 days prior to the move-in date of residents. During this time, pollutants such as HCHO and TVOC, are rapidly emitted from many types of construction materials. In order to reduce the concentration level of these contaminants, the ventilation system that can replace indoor air with fresh outdoor air is generally used as the method for improving indoor air quality in living spaces. Natural ventilation system can be classified into two types, one is the buoyancy driven force using stack pressure and the other is wind pressure driven force. In contrast, the mechanical ventilation system controls its performance using electrical power. In England, it has been reported that energy consumption of mechanical ventilation systems, such as pumps, fans etc in office building, constitutes about 20 % of the total energy consumption¹.

In related research conducted by J. Hummelaarda et al.², results have been documented of studies that compare temperature and CO₂ concentrations in office buildings that are equipped with five different types of mechanical ventilation systems and four natural ventilation systems. Through examination
and simulation, Clito Afroso et al.⁵), have verified the ventilation performances of the solar chimney, as adopted by this study. In addition, Jyotirmay Marthura et al.⁴), have examined an experimental model of the solar chimney and reported the results for the appropriate size of the solar chimney in accordance with the ratio between the height of the heat absorbers and the gap between the glass and the absorber. While there are individual research results of ventilation performances for natural and mechanical ventilation systems, it is difficult to find results of studies that have compared ventilation performances between natural ventilation systems and mechanical ventilation systems on the same model and same situations. Furthermore, there has only been a few studies conducted on ventilation performance evaluation that take into account HCHO and TVOC contaminants, both of which have recently become major issues in this field.

The purpose of this study is to investigate the ventilation performances of each ventilation system by measuring the concentration of HCHO and TVOC in different types of ventilation system models and to obtain data that will assist the development of the Hybrid type ventilation system, which could appropriately integrate the best qualities of the mechanical ventilation system and the natural ventilation system.

2. Standard Concentration of HCHO and VOCs in Korea

In 1996, the Ministry of Environment endorsed the 'Air Quality Control in Underground Locations Act', which outlined the recommendation standards for maximum emissions of TSP, CO, CO₂, SO₂, NO₂, HCHO, and Pb⁴). The legal title of the Act was then modified in 2003 to, 'The Act of Indoor Air Qualities for Multiple Use Facilities'. Table 1. shows the 6 items that are used to measure indoor air quality in apartment buildings and their recommended values, which have been effective since January 2006.

| Components          | Standards value |
|---------------------|-----------------|
| Formaldehyde        | 210 μg/m³ or less |
| Benzene             | 30 μg/m³ or less |
| Toluene             | 1,000 μg/m³ or less |
| Ethylbenzene        | 360 μg/m³ or less |
| Xylene              | 700 μg/m³ or less |
| Styrene             | 300 μg/m³ or less |

3. Principle of Natural Ventilation and Ventilation Rate Calculation

Natural ventilation relies on a combination of ventilation from the stack effect and from wind pressure. Therefore, the amount of ventilation produced by natural ventilation can be calculated by obtaining the temperature differences within the chimney and by the wind velocity and direction.

Furthermore, the air inside the chimney rises due to the transfer of heat between each surface and the inside air of the chimney, which is warmed by solar heat. The warm air is then exhausted to the outside.

Heat transfer on each inside surface of the solar chimney is caused by heat conduction, heat convection and radiation. Therefore, the surface temperature rises since it has been heated by solar heat during the day. The heat transfer between this heated surface and the inside air of the chimney produces a rising current of air. Fig.1. illustrates this heat transfer process inside the chimney. The temperature of each surface can be calculated using the heat balance equation. Solar radiation that penetrates inside through a glass surface reaches each interior surface, which increases the temperature of each surface.

![a) Heat transfer within solar chimney](image)

Fig.1. Heat Transfer within a Solar Chimney

The heat balance equation for each surface could be written as Eq. (1) - Eq. (4).

1. Heat gain and heat loss on the glass surface:

\[
\alpha_{gl} \, \delta z = \beta \, \delta z \, (T_g - T_{gl}) + \beta \, \sum_{l \neq A, D} F_{gl} \, h_{gl} \, (T_l - T_g) \, \delta z + q_{g} \quad (1)
\]

2. Heat gain and heat loss on each inside wall of the solar chimney:

\[
\tau_{i} \, a_{i} \, \delta z = S \, d z \, (T_{i} - T_{si}) + S \, \sum_{l \neq i, A, D} F_{il} \, h_{il} \, (T_{l} - T_{i}) \, \delta z + q_{si} \quad (2)
\]

\[
\tau_{i} \, a_{i} \, \delta z = S \, d z \, (T_{i} - T_{si}) + S \, \sum_{l \neq i, A, D} F_{il} \, h_{il} \, (T_{l} - T_{i}) \, \delta z + q_{si} \quad (3)
\]

\[
\tau_{i} \, a_{i} \, \delta z = S \, d z \, (T_{i} - T_{si}) + \beta \, \sum_{l \neq i, A, D} F_{il} \, h_{il} \, (T_{l} - T_{i}) \, \delta z + q_{si} \quad (4)
\]

If it is assumed that three walls of solar chimney were insulated completely, \( q_{w2} \), \( q_{w3} \), \( q_{w4} \) by heat conduction could be neglected and \( q_{G} \) by heat conduction could be neglected due to heat conduction heat rate, which is much smaller than convection and radiation heat rate. The convective heat transfer coefficient (\( h \)) can be calculated from the relationship between the Nusselt number and the Rayleigh number. When it is assumed that air is incompressible, in a viscid flow, and in a steady state condition, the amount of natural ventilation caused only by the stack effect can be calculated using the Bernoulli equation and the Continuity equation. The amount of natural ventilation produced only by the stack effect through one solar chimney depends on the air temperature difference.
between the top and the bottom of the chimney and on the difference from the height of the neutral pressure level to the reference height. This can be shown as follows in Eq. (5).

\[ Q_d = C_d A_d \left[ 2g \Delta h_{\text{net}} \left( \frac{T_{\text{in}} - T_{\text{out}}}{T_{\text{in}}} \right) \right] \tag{5} \]

In Eq. (5), \( C_d \) is a discharge coefficient related to the difference of temperatures and the shape of the opening, and can be calculated as shown in Eq. (6). The discharge coefficient depends on the relationship between the quantity of airflow and heat in the actual building.

\[ C_d = 0.0835 \left( \frac{\Delta T}{T} \right)^{-0.3} \tag{6} \]

where, \( T \) : average air temperature (\(^{\circ}\)C)

The amount of ventilation produced by wind pressure is dependent upon the wind velocity and the wind direction. Fig.2. indicates the angle between the wind direction and the building, while Eqs. (7) and (8) are wind pressure coefficients of the angle of direction.

The amount of ventilation by wind is calculated using Eq. (9).

\[ Q_{\rho} = C_{\rho} AV \tag{9} \]

The total amount of natural ventilation from a solar chimney can be shown as the sum of the amount of ventilation produced by the stack effect and by wind pressure. The computation of the total ventilation rate is based on the proportional rate to the square root of pressure difference, and is given by Eq. (10).

\[ Q_t = \sqrt{(Q_s)^2 + (Q_d)^2} \tag{10} \]

4. Outline of the Experimental Set-ups and Measurement

4.1 Outline of the experimental set-ups

The concentration change of HCHO and TVOC was measured by using experimental set-ups that adopted two types of ventilation systems and one type of natural condition. The two types of ventilation systems and one type of natural condition are outlined as follows:

1) Natural ventilation system with a solar chimney installed

2) Mechanical ventilation system equipped with a fan, which has a flow velocity of 0.736m\(^3\)/min

3) Natural condition that depends only on infiltration.

This experiment was conducted in the laboratory which is located near Pusan, Korea. Each model was made of plywood with the exception of the front-side, which was made from acrylic board for the purpose of taking a picture of the interior. The size of the model was 1.2m (width) × 1.2m (length) × 1.2m (height). A pane heater was attached to the exterior of the three plywood sides of the solar chimney in order to maintain the surface temperature of the inner part of the chimney, based on the amount of solar radiation at the summer solstice. It would be beneficial to measure the change of the surface temperature every on the hour of the summer solstice. However, since the control of the pane heater could be accompanied by the difficulties in maintaining the surface temperature, a specific time was set for when it is assumed that the chimney effect is most effective.

The size of the solar chimney was set at 0.25m (width) × 0.25m (length) × 0.6m (height) and five points were measured along its height. In order to calculate the ventilation rate through the solar chimney, thermocouples were set at five points, at 150 mm apart, as shown in Table 2. The air temperature inside the solar chimney was then measured from 10 am to 5 pm every 20 minutes every day.

The fan equipped on the mechanical ventilation system was also operated from 10 am to 5 pm. An experimental model with a mechanical ventilation system was equipped with a fan on the roof, the size of which was 0.08m(width) × 0.08m(length) × 0.025m (height) and the quantity of air flow was 0.736m\(^3\)/min.

The experimental model of natural condition was not equipped with any ventilation system, and the concentration change of the indoor air was measured. The same wallpaper and glue were used to give the same experimental condition in each model of the laboratory. The glue used for woodworking was PVAc (Poly vinyl acetate). There is no Korean standard for the amount of PVAc to use.

4.2 Survey of measurement

In order to observe the concentration changes of HCHO and TVOC, these have been measured from 12 Oct. 2006 to 2 Nov. 2006. The construction
process of the experimental model and the date of its measurement are shown in Table 3.

In order to measure the indoor concentration at each stage of the construction process, the concentration was measured on 12 Oct., and then measured again 7 days after the ceiling paper was applied. The final concentration was then measured on 2 Nov.

But there was an error in the HCHO concentration measured on 2 Nov, HCHO concentration was measured again on 9 Nov. for the natural ventilation system equipped with a solar chimney. The indoor concentration levels of HCHO and TVOC in the laboratory were also simultaneously measured on each measuring date.

5. IAQ and Ventilation Performance of the Experimental Set-ups

5.1 Temperature distribution within the solar chimney

In order to examine ventilation performances with two types of ventilation systems and one type of natural condition, the surface temperature on the inside wall of the experimental model was calculated at due south using Eq. (1) to Eq. (4), based on the data obtained from the Pusan local meteorological administration for the amount of solar radiation during the summer solstice, as shown in Fig.3 and Fig.4.

The purpose for the installation of the glass pane on the south side was mainly for the penetration of solar radiation. The amount of ventilation produced by the stack effect depends on the heat transfer between the inner surface of the wall and the air inside the solar chimney. Therefore, due to the large amount of solar radiation available at 3 pm, this was set as the standard time for this experimental model research in order to clearly examine the performance of natural ventilation. According to the calculated results, the surface temperature within the solar chimney was 37.3°C at east, 29.5°C at west and 28.1°C at south. In order for the inner surface temperature of the model to be based on these calculations, a pane heater was installed on the exterior of the model to control the temperature. The distribution of air temperature according to the height inside the solar chimney was measured on 19 Oct., 26 Oct. and 2 Nov. in 2006. These results are shown in Table 4.

On 19 Oct. the inner temperature was measured at 24.4°C in the experimental set-ups, 25.2°C at 150mm height, 27.0°C at 300mm height, 27.7°C at 450mm height and 27.3°C at 600mm height within the solar chimney.

These results showed that the air temperature increased according to the height, but that the temperature decreased when the height approached.

Table 2. Outline of the Three Experimental Set-ups by Ventilation System Type

| Type                              | Natural ventilation system using solar chimney | Mechanical ventilation system using fan | Natural Condition |
|-----------------------------------|----------------------------------------------|----------------------------------------|-------------------|
| Configuration                     | ![Solar Chimney](image1.png)                  | ![Fan](image2.png)                     |                   |
| Photo                             | ![Photo of Solar Chimney](image3.png)         | ![Photo of Fan](image4.png)            |                   |

Table 3. Construction Process and Measuring Date

| Construction Process | Constructed ceiling paper | Constructed wall paper | Constructed floor |
|----------------------|---------------------------|------------------------|-------------------|
| Constructed photo    | ![Photo of Constructed Ceiling Paper](image5.png) | ![Photo of Constructed Wall Paper](image6.png) | ![Photo of Constructed Floor](image7.png) |
| Constructed date     | 12 Oct. 2006              | 19 Oct. 2006           | 26 Oct. 2006      |
| Measuring date (7 days after each constructed date) | 19 Oct. 2006 | 26 Oct. 2006 | 2 Nov. 2006 |
The air temperature outside the model was about 2.9°C lower than the temperature measured inside the experimental model. This implies the formation of an ascending air current. On 26 Oct., the temperature was measured at 22.8°C on the inside of the experimental model, and 23.1°C at the height of 150 mm, 24.4°C at 300 mm, 26.0°C at 450 mm and 25.6°C at 600 mm. The temperature difference between the top and the bottom of the solar chimney was 2.8°C, and the temperature distribution was similar to that obtained 7 days prior to this measurement.

On 2 Nov., the temperature was recorded as 22.1°C on the inside of the experimental model, and 24.6°C at the height of 150 mm, 25.7°C at 300 mm, 26.2°C at 450 mm and 25.6°C at 600 mm. The temperature difference between the top and the bottom of the solar chimney was 3.5°C, which differed considerably from the results obtained in the previous two experiments.

The average temperature difference between the top and the bottom of the solar chimney ranged from 2.8 ~ 3.5°C during the experiment periods. It could therefore be assumed that an ascending air current was formed inside the solar chimney and that indoor air was exhausted to the outside.

These results also showed that the air temperature at the top point (600mm) of the solar chimney decreased, because the laboratory air temperature near the top point affected the air temperature. However, if the temperature at the height of 450mm under the top point is compared with these values, the air temperature difference at the height of 450mm was slightly higher, ranging from 3.2~4.1°C. In order to examine the amount of natural ventilation produced, the air temperature difference was used for the area of chimney between 450mm high (which was unaffected by the outdoor air temperature), and the bottom of the solar chimney.

5.2 Calculation of the ventilation rate of mechanical ventilation system and the solar chimney

Since indoor flow velocity in the Korean standards is set at 0.5m/s, and this experiment was conducted indoors, the amount of ventilation produced by wind pressure was calculated with the assumption that the indoor air velocity of laboratory was 0.5m/s and the inclination angle was 45°. The average amount of ventilation in the experimental model of the natural ventilation system equipped with a solar chimney was 33.5m³/h, the average ventilation rate was 19.4 ACH, and the average ventilation rate in the mechanical ventilation system was 25.6 ACH. Fig.5. shows the amount of ventilation produced by the solar chimney and by the mechanical ventilation system.

The amount of ventilation produced by the fan attached to the model of the mechanical ventilation system was 0.736m³/min (44.2m³/h). The amount of ventilation was significantly high on 2 Nov., when the temperature difference was considerable between the top point (600mm) and the bottom of the solar chimney and the area within the 600mm height.

5.3 Distribution concentration of HCHO and TVOC in experimental set-ups

The results of concentration of HCHO and TVOC using GC/MS analyzer are shown in Table 5. With the exception of HCHO and TVOC, the materials of Benzene, Toluene, Ethyl benzene, Xylene, and Styrene

| Table 4. Temperature Distribution between the Top and Bottom of the Solar Chimney |
|---------------------------------|---------------------------------|---------------------------------|
| a) 19 Oct.                      | b) 26 Oct.                      | c) 2 Nov.                       |
| ![Graph](image1)               | ![Graph](image2)               | ![Graph](image3)               |

Fig.3. Solar Radiation at Summer Solstice (Pusan, Korea)

Fig.4. The Result of Surface Temperature within Solar Chimney

600mm. On the day of measurement, the air temperature outside the model was about 2.9°C lower than the temperature measured inside the experimental model. This implies the formation of an ascending air current.
were excluded in this study because they are within the Korean recommendation for the standard.

To obtain a concentration measurement for HCHO and TVOC, the initial concentration was measured immediately subsequent to the completion of the experimental model. On 12 Oct., before the ceiling paper was installed, each item was examined in the experiment model that was equipped with each ventilation system.

In the experimental model that adopted a natural ventilation system equipped with a solar chimney, HCHO was measured at $934.4 \mu g/m^3$, while TVOC was measured at $1,981.4 \mu g/m^3$. For the experimental model equipped with a mechanical ventilation system, HCHO was measured at $970.2 \mu g/m^3$, and TVOC was measured at $1,469.0 \mu g/m^3$. For the experimental model that uses infiltration, HCHO was measured at $941.2 \mu g/m^3$, and TVOC was measured at $1,164.1 \mu g/m^3$.

Results of the measurements of concentrations of HCHO and TVOC in the laboratory showed that HCHO was $500.5 \mu g/m^3$ and TVOC was $2,545.3 \mu g/m^3$. These results appear to be related to the increasing use of pollutants produced during the construction of the experimental set-ups.

(1) The concentration change of HCHO depending on its time series

The concentration change of HCHO in the experimental model with each ventilation system is shown in Fig.6.

In the case of the model that adopted a solar chimney, the concentration on 19 Oct., seven days after the ceiling had been papered, was $966.9 \mu g/m^3$.

Seven days after the wall paper had been applied, the concentration was $863.3 \mu g/m^3$ on 26 Oct.

In the case of the model that was equipped with a fan, the concentration on 19 Oct. was $972.5 \mu g/m^3$, and after seven days of ventilation, the concentration on 26 Oct. was $784.4 \mu g/m^3$, showing a significant decrease in concentration. On 2 Nov., when the model had been ventilated for seven days subsequent to completion of the floor construction, the concentration was $666.4 \mu g/m^3$, again showing a slight decrease in concentration. Due to the error in the experiment data measured on 2 Nov. for the natural ventilation system, it was considered to be impossible to analyze the ventilation efficiency by using values from the same date (2 Nov.). Therefore, the analysis of the decreased efficiency according to each time series was based on the 9 Nov. for the natural ventilation system equipped with a solar chimney, and on the 2 Nov. for the mechanical ventilation and natural condition. The concentrations of HCHO are shown in Table 6.

By comparing the natural ventilation systems and mechanical ventilation systems on 26 Oct., it can be seen that the decrement-phenomenon was processed somewhat more rapidly in the experimental model equipped with a mechanical ventilation system.

However, if the trend of concentration decrement curve except error data (natural ventilation system) of Fig.6. during 3 weeks is considered, it could not be said that the mechanical ventilation system was significantly more effective in ventilation performance than the natural ventilation system equipped with a solar chimney.

(2) Concentration change of TVOC depending on its time series

The concentration change of TVOC in the experimental model according to each ventilation system is shown in Fig.7.

In the experimental model that adopted the natural ventilation system equipped with a solar chimney, the concentration on 19 Oct., after the ceiling had been papered, was $4,407.6 \mu g/m^3$.

Seven days later, on 26 Oct the concentration showed a dramatic decrease to $1,339.7 \mu g/m^3$. The concentration measured on 2 Nov. was $1,392.3 \mu g/m^3$, which was slightly higher than the previous concentration.

In the experimental model that adopted the natural ventilation system equipped with a solar chimney, the concentration on 19 Oct., after the ceiling had been papered, was $4,407.6 \mu g/m^3$.

Seven days later, on 26 Oct. the concentration showed a dramatic decrease to $1,339.7 \mu g/m^3$. The concentration measured on 2 Nov. was $1,392.3 \mu g/m^3$, which was slightly higher than the previous concentration.

According to the concentration change during 3 weeks, there was a 68.4% decrement effect compared to the concentration on 19 Oct.

In the experimental model that adopted a mechanical ventilation system equipped with a fan, the concentration on 19 Oct., was $3,578.7 \mu g/m^3$.

After seven days, on 26 Oct the concentration was $1,222.2 \mu g/m^3$, showing a 65.8% concentration decrement effect. When the model had been ventilated for 7 days after the completion of the wall paper
The concentration was 1,257.6 μg/m³ on 2 Nov., which was slightly high due to the influence of the completion of the wall paper installation. If the relationship of the final concentration is examined, about 64.9% of the concentration decrement effect could be induced when compared to the concentration on 19 Oct. Table 7 shows the results of analyzing the decrement effectiveness according to a time series. If the natural ventilation system equipped with a solar chimney is compared with the mechanical ventilation system, then it can be seen that there was not a great deal of difference in ventilation performances until the date of 2 Nov.

Finally, when the average rate of the sum of HCHO and TVOC reduction rates on 26 Oct. is considered, there were an average of 40.2% decrease in the natural ventilation system equipped with a solar chimney and 42.6% decrease in the mechanical ventilation system equipped with a fan. Therefore, it is considered
that a significant difference does not exist between the mechanical ventilation system, which is usually considered to have a superior ventilation performance and the natural ventilation system equipped with a solar chimney.

6. Conclusion

The ventilation performance of natural ventilation system with solar chimney and mechanical ventilation system with fan and natural condition is investigated using experimental models. The major results of experimental model are obtained as follows.

1) While most research in this field examines carbon dioxide emissions in ventilation efficiency, this study examines the concentrations of HCHO and TVOC in ventilation systems. In order to evaluate the natural ventilation and mechanical ventilation performances, experiments and analyses were carried out on the concentration change rates of the experimental set-ups equipped with two types of ventilation systems and one type of natural condition.

2) By comparing the results of the reduction rate of HCHO and TVOC, the concentration reduction rate of HCHO and TVOC were 38.9% and 68.4%, respectively, in the natural ventilation system that had a solar chimney, while concentrations were 31.5% and 64.9%, respectively, in the mechanical ventilation system that was equipped with a fan. It could be therefore assumed that the difference between the ventilation performance of the natural ventilation system equipped with a solar chimney and the mechanical ventilation system with a fan is slight.

3) When it can be proven that the driving force of the natural ventilation system equipped with a solar chimney is successful, then this system should be recommended. However, if the driving force is weak, the mechanical ventilation system could be used as a supplementary system. This method could not only improve indoor air quality, but could also reduce the dependence on mechanical ventilation systems. This would eventually lead to the conservation of energy and improvement in ventilation performance.

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Footnote

1 In Korea, the TVOC standard value is 400 μg/m³, which is the standard value endorsed by the Act of Indoor Air Qualities for Multiple Use Facilities for medical institutions and nurture facilities.