On the Design to Improve the Bathroom Exhaust Performance in Multi-Unit Residential Buildings

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Abstract
The purpose of this experimental study was to improve the performance of bathroom exhaust systems. In this study, the performance of fans used in bathrooms was measured by a field test and laboratory test. Because there are no specific codes for bathroom ventilation in Korea, different construction companies implement their own regulations when installing fans in the bathrooms of multi-unit buildings. To determine if their exhaust performance meets the 8 ACH standard, field measurements were conducted and the construction methods and design methods were proposed to improve their exhaust performance. In addition, to provide the standard method for installing fans, laboratory tests were conducted to offer a design standard of the fan's components.

Keywords: residential building; bathroom; exhaust performance; design guide; field test; lab. test

1. Introduction
Natural ventilation design or mechanical ventilation design is a legal requirement in multi-unit buildings to ensure a ventilation cycle of 0.5¹ times per hour for a comfortable environment. On the other hand, there is no standard rule for bathrooms inside the units, which produce pollutants. Although ventilation fans are generally installed to eliminate odors and humidity, there are no installation standards, which cause difficulty in operating the system.

Currently, the ASHRAE and CIBSE propose bathroom thermal environment and ventilation standards and some Korean construction companies apply their own performance standards when installing bathroom fans in multi-unit buildings.

As the living standard of residents in multi-unit buildings improves, the need for a better environmental function of bathrooms, a separate space from rooms, living rooms, and dining rooms is also increasing. The major environmental improvements of bathrooms required are exhaust performance, odor removal and thermal comfort². This is because the residents' level of satisfaction with their bathrooms is generally low³. Therefore, it is important to understand this bathroom issue and come up with a solution. In previous studies, researchers conducted a test on how much water vapor, which is one of the pollutants created from bathrooms, is formed from a shower to determine the time required to remove the vapor⁴. They also selected the desired location of outlets in a bathroom⁵ to prevent bathroom odors from spreading out to other spaces and outer zones, and provided fresh out-air from the occupied zones to remove pollutants quickly for comfort ventilation⁶. Previous studies also proposed the desired amount of exhaust air on each floor considering that the airflow out through a common exhaust shaft and vertical shafts caused a decrease in the exhaust performance due to the stack effect in winter⁷.

In general, major construction companies have established standard designs⁸ of bathrooms in multi-unit buildings in Korea according to the areas of each unit. According to the standard specifications, considering that the area of middle and small size multi-unit apartments is 60 - 120 m², the area of the bathrooms is 3.2 - 3.4 m², and large size apartments of 150 - 180 m² have bathrooms, 4.0 - 5.7 m² in area. The most common area of a unit in a Korean residential building under construction is 120 m² (80% or above according to Korean 'A' construction company). Researchers have examined the complaint reports mainly about the bathrooms in common sized units. Most of the complaints were filed due to odors from the bathrooms and mold created by water vapor that could not be sufficiently removed.

To increase the efficiency of the water vapor removal process in bathrooms with shower stalls, architectural strategies and equipment strategies were used to measure the removal efficiency. To improve the exhaust performance in bathrooms, this paper proposes...
design guidelines according to each coefficient of variation. Fig.1. describes the method and scope of the experiment.

| Goal | Coefficient of Variation | Analysis Method | Result |
|------|--------------------------|-----------------|--------|
| Exhaust Performance Improvement Method of Bathroom in Residential Building | Architectural Strategy | Field Test | Design Guide Line for Bathroom |
| Facility Strategy | Fan Shape | Field Test | |
| Fan Attachment | Laboratory Test | | |

Fig.1. Process of Research

2. Bathroom Exhaust Standard

Foreign institutions have the following bathroom environment standards: ASHRAE, CIBSE and Japan Public Construction Institute (JPCI). No laws or regulations regarding the bathroom environment exist, only the ventilation design of residential areas in multi-unit buildings have been established in Korea.

According to the U.S. ANSI/ASHRAE Standard 62.1\(^9\), a ventilation standard of bathrooms is categorized by public and private use. The private bathrooms standard is 42 - 85 CMH (Cubic Meters per Hour/unit) and the public bathroom standard is 85-119 CMH/unit. The standard value may vary according to the frequency of use and the operation time of the exhaust.

The U.K. CIBSE\(^{10}\) stipulates that the size of a vent (minimum height of 1.75m) must account for 1/20\(^{th}\) of the floor area of bathrooms or 6 L/s. The unit of mechanical ventilation must be incorporated in the design. Even for the design of bathrooms in non-residential areas, the size of a vent must be 1/20\(^{th}\) of the floor area or 6 L/s or 3 ACH (Air Change Rate per Hour) of mechanical ventilation must be ensured. The JPCI\(^{11}\) proposed to determine the number and method of ventilation based on the mechanical exhaust ventilation and natural supply to ensure the exhaust air is 5 - 15 CMH.

In Korea, there are no regulations or recommendations regarding bathroom ventilation. Some companies merely apply their internal ventilation regulation (8 ACH)\(^{12}\) to install exhaust fans. The Society of Air-Conditioning and Refrigerating Engineers Korea (SAREK) is currently creating a design standard of ventilation systems for multi-unit buildings (as of March 2015), and is planning to propose 10 ACH\(^{13}\) for the number of ventilations.

3. Bathroom Exhaust Performance Test

In general, there are standard design specifications according to the residential unit size for Korean residential building bathrooms\(^4\). In the case of small and medium-sized residential units of 60 - 120m\(^2\), the standardized bathroom area is 3.2 - 3.7m\(^2\). In regards to large-sized residential units of 160 - 200m\(^2\), the standardized bathroom area is 4.0 - 5.7m\(^2\). To determine the exhaust performance of bathrooms in multi-unit buildings, a multi-unit building with an area of 120m\(^2\) was selected as the test subject.

This multi-unit building is a 31-floor building with a 2.7m ceiling height that was constructed by "A" construction company in 2011. The bathroom exhaust test was conducted before the residents moved in. As shown in Fig.2., the bathroom area is 3.78 m\(^2\) and the floor height is 2.1 m. A shower stall made of glass is installed. These bathrooms are classified into a bathtub type and a shower booth type. In this particular study, shower booth-type bathrooms, which may affect the airflow, were selected to measure their exhaust performance.

Architectural elements and equipment elements were considered in the test to measure the exhaust performance in the bathrooms. The architectural elements were the floor height of each unit, a glass partition for a shower stall, and the open and closed door. A type of a diffuser in the fans was a design element.

3.1 Overview of the Bathroom Exhaust Performance Test

The amount of airflow was set to be the first variable in the test to confirm the impact of the architectural elements on the bathroom exhaust performance. As it was not possible to measure the performance on all 31 floors, the tests were conducted on every 5\(^{th}\) floor up from the 2\(^{nd}\) floor (2nd, 12\(^{th}\), 16\(^{th}\), 20\(^{th}\), 26\(^{th}\), and 31\(^{st}\)). The amount of airflow was measured when the door was open and closed, and the water vapor removal time was measured in the bathroom with a shower stall.

A multi-functional measuring instrument was used to measure the amount of airflow from the fans for 10 seconds and the mean value was calculated in accordance with KS F 2807\(^{15}\). The multi-functional measuring instrument was composed of a main body, a vane and a vent. The instrument can measure the temperature, humidity and wind velocity. The temperature measurement range was -20 to +70°C, and its accuracy was ±0.3°C. The range of the wind velocity measurement was from 0 to 20m/s, and its accuracy was ±0.1m/s.
TR-72U (T&D) was used to measure the water vapor removal time by tracking the time in 5-second intervals until the absolute amount of water vapor (relative humidity & absolute humidity) after a shower returns to the same value before a shower.

The amount of time taken to remove the water vapor generated from a shower was measured by some preliminary experiments. As a result, the amount of time required for the amount of water vapor in the air to revert to its initial state was greater than the amount of time required for the evaporation of water remaining on the walls and the floor. Therefore, the amount of time required to remove water vapor was set to be the amount of time required for the amount of water vapor generated from a shower to revert to the initial amount of water vapor.

The exhaust performance based on the fan system was tested with and without fan diffusers to determine if the existence of fan diffusers can be a variable when the laboratory test of accessory equipment in the fans begins. Fig.2. presents the measurement points of the architectural and equipment variables that affect the exhaust performance.

At this point, the rated airflow rate of the bathroom fan is 90 CMH (11.2 times/h), and the electrical power consumption was 12W. As shown in Fig.3., the fan uses a circular casing for aesthetics. According to the P-Q performance curve of the fan in Fig.3., the amount of airflow is 92 CMH at 0 Pa and the amount of airflow that meets the exhaust standard of 8 ACH is 63 CMH; the pressure at this point is 49 Pa.

(1) Bathroom Exhaust Performance Test by Floors

In general, the air from exhaust fans is routed through a single shaft to the outside of the building. On the other hand, in this single shaft, backflow to diffusers of the fans, from lower floors to higher floors can occur due to the stack effect in winter. Considering this pattern, the test was performed on 5 different floors to study the bathroom exhaust performance on each floor. The indoor temperature was 5 ºC while the outdoor temperature was 22 ºC with a pressure difference of 17 ºC, the stack effect based on the height was computed as follows:

\[ \Delta P_s = (\rho_o - \rho_i)g(H_{NPL} - H) \]

\[ \rho_o = \rho_i \left( \frac{T_o - T_i}{T_i} \right) g(H_{NPL} - H) \]  \( \text{(2)} \)

\( T_o \): Outdoor Temperature, K
\( T_i \): Indoor Temperature, K
\( \rho_o \): Outdoor Air Density, kg/m³
\( \rho_i \): Indoor Air Density, kg/m³
\( H_{NPL} \): Height of the Neutral Plane from Base Level, m

As described in Table 1., when the height of the neutral plan is 41.9m, the stack effect on the 2nd and 31st floor was -24.7 Pa and 28.4 Pa, respectively. To meet the standard of the bathroom exhaust fan in a building where the test was conducted, the pressure difference must be 49 Pa or below. The computation indicated that this building met the standard because the maximum pressure difference was 28.4 Pa. On the other hand, considering that the indoor temperature remains at 22 ºC, the stack effect is believed to affect the exhaust performance if the outdoor temperature is below -7 ºC. Based on this analysis, the results of exhaust performance are depicted on Fig.4. When the exhaust flow was measured, the doors of bathrooms and shower stalls were closed to set the condition of a shower. Regarding the top and ground floors, the air volume of a bathroom fan must be 82 - 87 CMH on account of the difference in pressure depending on the overall height of the building (see Fig.3.).

The exhaust performance of all units of the building was lower than 8 ACH, the standard value. When the stack effect decreases the exhaust performance, anabatic flow occurs in the single shaft causing an increase exhaust performance in low floors but a decrease in the exhaust performance in higher floors. Despite this, the test result indicated no sign of such a correlation. Factors other than the stack effect based on the elevation...
of the floors are believed to cause a decrease in the bathroom exhaust performance in the building.

In general, the residential building bathroom fans are designed to allow a margin of approximately 10 CMH for the exhaust air volume for each fan, taking into consideration the resistance of the accessories that are fastened to the fan. Bathroom fans were designed to allow a margin of approximately 20 CMH in the measured residential building; however according to their experimental results, they failed to satisfy the standards for the bathroom exhaust performance.

In the case of bathrooms, whose exhaust performance was relatively low, it was confirmed that the duct length was relatively long (2m or longer) compared to the other floors, or that the fastening portions of the ducts had not been fitted to be airtight. Differences in exhaust performance among the existing measured residential building bathrooms were observed, depending on the technical proficiency of the people who installed the bathroom fans. In addition, the testing, adjusting and balancing (TAB)\(^\text{18}\) of the facilities, which is usually performed before people start living in a residential building, are limited to a ventilation system in each household. On the other hand, the bathroom exhaust fans are excluded from the TAB process. Therefore, the workmen pay less attention to the TAB process when installing the bathroom fans.

(2) Exhaust Performance with Open and Closed Doors

Normally in Korea, the bathroom door is built air-tight to reduce the noise and odors in residential areas when the occupants use their bathrooms. Therefore, to examine the impact of air-tightness on the bathroom exhaust performance, the test was conducted on each floor with the doors open and closed.

As shown on Fig.5., regardless of whether the doors were open and closed, the performance of the exhaust fan did not satisfy the standard (8 ACH). A 0.5 ACH increase was observed, which is not significant to affect the exhaust performance.

(3) Exhaust Performance Based on the Shape of Shower Stalls

The water vapor created from a shower was considered to be a pollutant and the water vapor removal time was measured based on different durations of a shower to determine if the shape of shower stalls affects the exhaust performance. Supposing that the average shower lasts for 10 minutes\(^\text{19}\), even though people spend different amounts of time in a shower, the duration of a shower from 5 minutes up to 20 minutes was considered when the measurement was conducted.

To determine if the sequence of the fan operation affects the water removal time, time measurements were conducted when the fan was operated during a shower and when the fan was operated after a shower. At this point, because the amount of the water vapor varies depending on the water temperature, the water temperature was set to 42 °C\(^\text{20}\).

Because the exhaust performance may vary depending on the indoor and outdoor air conditions, the relative humidity was used to measure the vapor removal time during or after a shower. Therefore, in this experiment, the time required for the absolute humidity after and during a shower to return to that before a shower was set to be in that range. Fig.6. shows the absolute humidity at different times of measurements.

The gap between the two absolute humidity values upon the fan operations increased with increasing shower time. The difference was up to 5.5g/kg (D) of water vapor in 20 minutes of a shower. Table 2. lists the required water vapor removal time.
When the fan is operated during a shower, the water vapor removal time can be reduced by up to 16 - 44% compared to the fan operation after a shower. When a shower takes 10 minutes, the required fan operation time to remove the water vapor was approximately 70 minutes. The fan must be operated for more than 1 hour. Because only a few occupants operate the fan for more than 1 hour because of the electricity cost, a measure to increase the efficiency of the water vapor removal process is necessary. This experiment suggested the design of a partition in Fig.7. to prevent the spread of the water vapor and remove it from a closed space with higher efficiency.

When the water vapor removal time was measured after the upper portion of the glass partition was blocked, it took 31 minutes. As this implies a 50% decrease, the shape change of a partition is believed to help improve the bathroom exhaust performance.

3.2 Impact of the Equipment Elements on the Exhaust Performance

In general, the diffuser portion of the fans is covered by a casing for aesthetic purposes so that the inside of the fan will not be visible to the occupants. As depicted in Fig.8., the diameter of a casing is 16 cm, which is 1 cm longer than that of the vent (15 cm) causing a large amount of static pressure that was expected to hinder the exhaust performance.

The exhaust performance with and without a diffuser casing was measured on each floor because the shape of the diffusers is one of the elements that affect the static pressure. As shown in Fig.9., when a casing is removed from a fan, it provides improved exhaust performance that enables some of the units to meet the ventilation standard, 8 ACH.

4. Performance Measurement of Bathroom Ventilation System

The components required when installing a fan are diffusers, ducts and iron connectors. To conduct a laboratory test, the variables that affect the exhaust performance are the type and length of diffusers and compression rate. A fan tester was used in the laboratory test according to KS B 6311:2011[15]. The airflow measurement range of the fan test was -50 to +50 mmAq and the measurement accuracy rate was ±3% of the standard device and the reproducibility was ±2%.

4.1 Overview of the Exhaust Fan Performance Test

A static pressure test was conducted with the P-Q, performance of the fan, types of diffusers, types and lengths of ducts, and compression rate as factors to affect the performance of exhaust fans. Table 3. describes the variable of fan performance test.

| Test List | Parameters | Note |
|-----------|------------|------|
| Fan Performance | Fan P-Q Curve | Rated Airflow Rate |
| Static Pressure Test | Diffuser Type | Cone Type | Nozzle Type |
| Duct Length | 500 mm | 1000 mm | Absorption Duct/Tapolin Duct |
| Duct Compression Rate | Max. | 50% | Max. Tensile |
| | Compression | Compression Length: 1500 mm |

Table 2. Water Removal Time during and after a Shower (min)

| Duration of a Shower | Fan Operation during a Shower | Fan Operation after a Shower |
|----------------------|-----------------------------|----------------------------|
| 5 min                | 39                          | 49                          |
| 10 min               | 69                          | 79                          |
| 15 min               | 87                          | 101                         |
| 20 min               | 108                         | 126                         |
4.2 Performance Test of Bathroom Ventilation Systems

(1) P-Q Performance Curve Test of Fans

By utilizing a fan tester to apply static pressure gradually until the fan stops, the P-Q Curve of a fan was drawn. After the duct was connected in the same way it is installed in the bathroom where the test was conducted, the P-Q performance of the fan was measured. Fig.10. describes how the P-Q performance was tested.

Although the basic specification performance of the fan introduced by the manufacturer was 90 CMH, as depicted in Fig.11., the test result showed that the actual performance was 73 CMH, which is 17 CMH lower than the specification provided by the manufacturer. To meet the standard of the bathroom exhaust performance, 64 CMH (8 ACH), the static pressure must be 20.4 Pa or lower.

When the duct was connected to a fan in the same way it is installed in the bathroom where the test was conducted, the result indicated that the rated airflow rate was 60 CMH, which does not meet the pressure standard, and the basic performance of the fan needs to be improved.

(2) Static Pressure Test of the Fan Components

a. Static Pressure Test by Diffuser Types

To determine how the shape of a diffuser affects the performance of a fan, a cone type diffuser, which is generally used in bathrooms, and a nozzle type diffuser that has lower static pressure were subjected to a static pressure test (refer to Fig.12.). As listed in Table 4., the cone type diffuser had a 7 Pa larger pressure drop than the nozzle type. Considering the characteristics of P-Q performance of the fan, the nozzle type fan with a lower static pressure is believed to be more favorable to improving the bathroom ventilation performance.

b. Static Pressure Test Based on the Type and Length of Duct

To determine if the ducts affect the bathroom fan performance, pressure drops according to duct types and lengths were measured. As shown in Fig.13., the static pressure drops were measured at Tapolin ducts and sound absorption ducts with their length up to 2000 mm by every 500 mm.

Table 5. lists the static pressure according to the different types and lengths of ducts. Each value is the mean of 3 tests. According to the result, the amount of static pressure reduction of the sound absorptions ducts was less than that of the Tapolin ducts up to a length of 1500 mm. On the other hand, the amount of the static pressure spiked up when the length started to exceed 1500 mm, which ultimately gave a larger static pressure than the Tapolin ducts. Tapolin ducts generated a large static pressure but the length no longer affected the static pressure once the length became 1500 mm.
In general, when installing a sound absorption duct to reduce noise, a length of less than 1500m will give the more efficient exhaust performance. If noise does not need to be considered and a fan is installed far from a single shaft, the use of a Tapolin duct will be more effective.

5. Conclusion
The main purpose of this paper was to present design guidelines for apartment bathroom ventilation fans. Therefore, the exhaust performance of fans installed in Korean residential buildings was measured, considering all the relevant problems. Based on the data, with respect to building construction and the facilities for enhancing the exhaust performance of bathrooms, the following solution methods were proposed:

(1) Problems with the Air Exhaust from Residential Building Bathrooms
In the case of fans installed in residential bathrooms built by "A" Construction firm, fans with no less than 8ACH, which is one of the company's own exhaust performance standards, were installed, but they failed to satisfy the exhaust performance standards.

a) The exhaust air volume of the bathroom fan of each household was measured to evaluate the exhaust performance of the bathroom of each household according to its floor level. As a result, the exhaust performance of the entire bathroom fans failed to satisfy the relevant standards. Therefore, the exhaust performance enhancement of the fans due to the stack effect could not be determined.

b) The technical proficiency of the people who installed the fans had a significant influence on the exhaust performance of the bathroom. When installing the exhaust fans, they did not take the duct length into consideration, nor did they ensure that the portions for fastening them to the ducts were airtight, resulting in pressure drops.

c) The testing, adjusting and balancing (TAB) of the facilities, which is normally performed before people start living in a residential building, are limited to the ventilation system in each household. Therefore, it is necessary to evaluate the relevant legal standards for enhancing the exhaust performance of bathrooms.

(2) Architectural Design Guide
The exhaust performance of bathrooms according to the bathroom space partitioning method was examined through numerous experiments. The results are as follows:

a) Korean residential building bathrooms are built in such a way as to ensure the bathroom door is kept airtight when closed in each residential unit; this is to block the bathroom odors, fan noises, etc. from penetrating into the living space. When opening and closing the bathroom door, the effects on the exhaust performance of each bathroom were measured. Although opening and closing the bathroom door increased the ventilation frequency value by up to 0.5 ACH in some units, no significant difference was found in other units. Therefore, even if the bathroom doors are kept airtight, the required ventilation rate for the air exhaust from each bathroom could be secured by air infiltration.

b) Shower booths in Korean residential buildings are designed in such a way as to ensure the top part of the partition remains open (height: approximately 20cm) (refer to Fig.7.a). The floor of the shower booth is designed by making its inside or outside approximately 3-5cm lower and then an open slit of approximately 1cm is placed on it.

In this study, the top part of the shower booth was blocked off to prevent the water vapor generated in the shower booth from spreading across the entire bathroom, making the exhaust air evaporate in one direction. The air in the bathroom was extracted by making the air flow into the shower booth through an open slit at the bottom part of the partition. As a result, the exhaust performance of the bathroom had increased two fold compared to when the shape of the partition remained unchanged. Therefore, to increase the exhaust efficiency, the vent of the partition should be installed at the bottom part of the partition, so that the water vapor generated from a shower will be removed immediately.

(3) Facilities Design Guide
The exhaust performance of bathrooms in accordance to the bathroom fan accessories was examined by experiments. The results are as follows:

a) A fan performance test was performed on a 90CMH fan in accordance with the provisions of KS B 6311:2011 (refer to Fig.11.). As a result, a difference of approximately 17CMH was observed between the existing measured value and the value specified in the manufacturing company's specifications under the condition of non-static pressure. In addition, when a duct (length: 2m) was installed onto the fan, it could not satisfy the 8ACH, which is one of the exhaust performance standards. Therefore, it is essential to carefully examine the P-Q performance curve provided by the manufacturing company when selecting an exhaust fan.

b) The respective pressure drop values of the cone-type and nozzle-type diffusers were measured. As a result, it was discovered that the pressure drop of the nozzle type was approximately 7Pa lower compared to the cone type. The nozzle-type diffuser is believed to be more advantageous for enhancing the exhaust performance of bathrooms. On the other hand, the cone type is the preferred nozzle type in Korea due to aesthetic reasons regarding the exhaust air opening of the bathroom. Therefore, it is essential to take the pressure drop of the cone type into account when designing a fan.

c) If the duct length is 1500mm or below, the sound absorption ducts perform much better than the Tapolin
ducts because the pressure drop of a sound absorption duct increases dramatically when its length is over 1500mm. Sound absorption ducts are used mainly to block out bathroom fan noises from being transmitted to any other living space through the duct in Korea. A rapid pressure drop occurs when the length of the sound absorption duct is greater than 1500mm. Therefore, the length of the sound absorption ducts needs to be 1500mm or below.

d) The pressure loss generated from the bathroom fan accessories is approximately 71.6 Pa (cone type diffuser + 1.5m absorption duct). Therefore, it is essential to take this pressure loss into consideration when selecting a fan. Because the airtight performance of a bathroom fan and its accessories were secured in this study, there may be a huge difference between the pressure loss mentioned above and the pressure loss that may occur in an actual residential building according to the technical proficiency of the workman installing the bathroom fan and its accessories.

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