Characteristics of Rain Penetration Through a Gravity Ventilator Used for Natural Ventilation

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Gravity ventilators rely simply on air buoyancy to extract air and are widely used to exhaust air contaminants and heat from workplaces using minimal energy. They are designed to maximize the exhaust flow rate, but the rain penetration sometimes causes malfunctioning. In this study, the characteristics of rain penetration through a ventilator were examined as a preliminary study to develop a ventilator with the maximum exhaust capacity while minimizing rain penetration. A model ventilator was built and exposed to artificial rain and wind. The pathways, intensities and amounts of penetration through the ventilator were observed and measured in qualitative and quantitative fashions. In the first phase, the pathways and intensities of rain penetration were visually observed. In the second phase, the amounts of rain penetration were quantitatively measured under the different configurations of ventilator components that were installed based on the information obtained in the first-phase experiment. The effects of wind speed, grill direction, rain drainage width, outer wall height, neck height and leaning angle of the outer wall from the vertical position were analyzed. Wind speed significantly affected rain penetration. Under the low crosswind conditions, the rain penetration intensities were under the limit of detection. Under the high crosswind conditions, grill direction and neck height were the most significant factors in reducing rain penetration. The installation of rain drainage was also important in reducing rain penetration. The experimental results suggest that, with proper configurations of its components, a gravity ventilator can be used for natural ventilation without significant rain penetration problems.

Keywords: gravity ventilator; natural ventilation; rain penetration

INTRODUCTION

A good industrial ventilation system is crucial to protecting industrial workers from airborne contaminants and heat stress. Industrial ventilation is categorized as either general or local exhaust ventilation. General ventilation can be achieved by mechanical or natural force, and it can function as dilution ventilation and/or heat control ventilation (ACGIH, 2004).

Compared to mechanical ventilation, natural ventilation has the advantage of lower installation and operating costs and can be a practical choice in regions with warm climate because the openings of a natural ventilation system do not have to be shut off during any season, including winter. Because it saves energy, it will get more and more attention in view of the reduction of greenhouse gases in the near future (Hunt and Kaye, 2006). Also, it does not cause the noise problem that operating mechanical ventilation systems may create.

Natural ventilation has been studied in the fields of greenhouse ventilation, livestock building ventilation...
and building ventilation along with indoor air pollution control (Boulard et al., 1997; Bjerg et al., 1999; Hunt and Linden, 1999; Yu et al., 2002; Katsoulas et al., 2006; Ji et al., 2007). Smoke ventilators have been another research item for fire safety control (Ghosh, 1993; Kramer and Gerhardt, 1993; Sanquer, 2002). On the other hand, there are not many studies in the field of industrial hygiene, even though natural ventilation is widely used in industrial buildings.

The driving forces of natural ventilation depend on wind effects, thermal buoyancy and their combination (Li and Delsante, 2001). The size and position of the ventilation openings are some of the major factors that affect the efficiency of natural ventilation. The openings include doors, windows, louvers on the sidewalls, gravity ventilators on the roofs of industrial buildings, etc.

Gravity ventilators rely on the air buoyancy, with the hot air rising through them and out of the roof. They are sometimes referred to as monitors, streamline monitors, or guided flow or saw tooth roof monitors (Goodfellow, 1985). They are available in many different styles and materials of construction and are used for natural ventilation and/or a means of fire safety in many industrial halls in Korea. They are often used as an additional contaminant control measure to supplement local exhaust ventilation. Gravity ventilators can be used very effectively in the industrial companies with hot processes such as foundries and tire-manufacturing companies because hot plumes from the hot processes can easily rise toward the building roofs and then escape through the gravity ventilators by buoyant force. Also, gravity ventilators are cost-effective measures to alleviate heat stress of workers working in hot industrial halls, especially in the summer time.

Only a few studies have reported the ventilation characteristics of various gravity ventilators (Kramer and Gerhardt, 1988; Ha and Kim, 2002; Ha et al., 2002; Kim et al., 2006). These studies were mainly focused on how to measure and improve aerodynamic efficiency of the ventilator, but there is still much room to improve efficiency and control.

One of the most critical problems of using gravity ventilators is rain penetration. In many Korean industrial companies, we observed that the openings of the ventilators were blocked due to the rain penetration problem. Instead of fixing the problem, the companies reinstalled mechanical ventilators and their natural ventilators became unused. There must be some trade-off between maximization of ventilation flow rate and minimization of rain penetration, but there is a knowledge gap on this matter.

The purposes of this study were (i) to investigate the characteristics of rain penetration through a gravity ventilator under various conditions and (ii) to evaluate the design factors that affect the amount of rain penetration through the ventilator. Our ultimate goal is to develop a gravity ventilator that has a good configuration of its structural components, so that the ventilator would have maximum aerodynamic efficiency and minimum rain penetration. This study serves to fulfill part of our ultimate goal.

**METHODS**

The paths, intensities and amounts of penetration through a natural ventilator were observed and measured in qualitative and quantitative fashions. These experiments were performed in two phases. In the first phase, we visually observed the pathways and intensities of rain penetration. From those observations, the characteristics of rain penetration were qualitatively evaluated. In the second phase, we quantitatively measured the amounts of rain penetration under the different configurations of ventilator components that were installed, based on the information obtained in the first-phase experiment.

**Phase 1: qualitative inspections of rain penetration**

For a preliminary and qualitative study, a model gravity ventilator was built as shown in Fig. 1. The front and side of the ventilator were made of Plexiglas so that we could see the inside of the ventilator and observe the rain penetration paths. The length of the ventilator was 1000 mm and the dimensions of other components are given in Fig. 1. The shape and structure of the model gravity ventilator represents the typical gravity ventilator used in Korea. The model gravity ventilator had the exactly same dimensions (neck width = 700 mm) as those of the smallest gravity ventilators commercially available in Korea. The specific dimensions were obtained from the catalogues of gravity ventilators commercially available in Korea.

In order to investigate the characteristics of rain penetration, rainy and windy conditions were artificially created. The experimental equipment and setup are shown in Fig. 2. Since we intended to test rain penetration under severe weather conditions, we applied relatively heavy rainfall and high wind speed. A rainfall intensity of 30.3 mm min\(^{-1}\), which meets the definition of heavy rain, was used, and a wind speed of 15 m s\(^{-1}\) was chosen as a typical value for high wind speed in Korea.

Artificial raindrops were made by injecting water through 2.5-mm diameter holes on 1200-mm long and 25-mm inner diameter pipes. A total of 11 rows of pipes were used and each pipe had 71 equally distanced holes. As shown in Fig. 2, these pipes hung over the top opening of the ventilator so that the raindrops fell directly into the ventilator. The water injection pipes were positioned 1500 mm above the ventilator’s top opening. The total flow rate of the artificial raindrops was 40 l min\(^{-1}\). This flow rate is equivalent to the rainfall intensity of 30.3 mm min\(^{-1}\),
which was calculated by dividing the total flow rate by the rain area. This high flow rate was used in order to study the characteristics of rain penetration in the worst case, i.e. a very heavy rain.

Artificial crosswind was generated by placing two sets of dual jet fans (4600 CMH Pro Multi Fan PMF-VTS 12; Myung Jin Air Tech Co., Korea) next to the top opening of the ventilator, at a slightly higher elevation (as shown in Fig. 2). The average wind speed at 100 mm above the top opening of the ventilator was 15 m s⁻¹, and its direction was parallel to the top opening.

Colored papers were placed on the bottom floor between the grills of the ventilator. Those colored papers were used to trace the watermarks that were made by the raindrops that penetrated the ventilator. The number and size of the watermarks formed on the colored papers were observed. We also observed

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**Fig. 1.** Model gravity ventilator used in the qualitative experiments (Phase 1) (unit: mm).
the paths of rain penetration through the transparent front and side of the ventilator.

In order to find factors influencing rain penetration, six different configurations of ventilator components (rain drainage width, neck height, grill direction, leaning angle of the outer wall and outer wall height) were used as test conditions. Also, all those conditions were tested with and without crosswind to examine the influence of crosswind on rain penetration. Therefore, Phase 1 included 12 test conditions, shown in Table 1.

**Phase 2: quantitative measurements of rain penetration intensities**

The model gravity ventilator used in Phase 1, which had a neck width of 700 mm, was modified to have a wider neck width of 800 mm, and all other dimensions of the gravity ventilator were proportionally adjusted. This modification was made because the small size original ventilator used in Phase 1 caused some unrealistic penetration of raindrops due to the deflection from too close outer walls, so that the ventilator with neck width of 700 mm was vulnerable to rain penetration problems. The schematic diagram of experimental set-up is shown in Fig. 3.

A rain detection device was developed in order to measure the amount of raindrops that penetrated the ventilator. This device was made by coiling a pair of 1-mm diameter insulated copper wires around an acrylic plate (760 × 170 × 20 mm) and scratching the upper surface of the coil to remove the insulation coating of the copper wire. As shown in Fig. 4, two wires were used. The wires were unconnected at one end, and at the other were connected through an ammeter and a battery (2 V DC) in series. Raindrops bridging the wires complete a circuit and cause a current proportional to the length bridged.

A calibration curve for the device was obtained by comparing the amounts of water that were impulsively injected on the coiled plate and the measured electric currents. A microsyringe was used for the injection of water drops. The relationship between the quantity of raindrops (µl) and the electric current (µA) was linear with an $R^2$ value of 0.9977. The limit of detection (LOD) of this device was calculated...
using equation (1), in accordance with the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use (ICH, 1996) guidelines.

\[
\text{LOD} = 3.3(\sigma/S),
\]

where \(\sigma\) is the residual standard deviation of the regression line and \(S\) is the slope of the calibration curve. The LOD was 1.3 \(\mu\text{A}\), which is equivalent to 1.8 \(\mu\text{l}\), the total amount of rain that accumulated on the plate during the test.

The water spray system used in Phase 1 was used in Phase 2 too. The rain detection device was placed on the floor of the ventilator. The water spray system was turned on for 60 s and then turned off. Electric currents were immediately measured after the spray using the rain detection device. All those experiments were repeated three times and an average value of electric currents was calculated. The average values for each test condition that is described below were reported.

In order to find factors influencing rain penetration, two different settings in the crosswind speed and five ventilator components (grill direction, rain drainage width, outer wall height, neck height and leaning angle of the outer wall from the vertical position) were used as test conditions, giving a total of 64 conditions. Table 2 shows the different settings for each influencing factor. The lower wind speed of 5 m s\(^{-1}\) in Phase 2 replaced the no-crosswind conditions in Phase 1 because that condition gave almost no raindrop penetration in Phase 1.

Statistical significance of results was tested at the 95% confidence level using the multivariate analysis of variance (MANOVA) method in the generalized linear model (SPSS 12.0).

**RESULTS AND DISCUSSION**

**Phase 1: qualitative inspections of rain penetration**

Rain penetration paths under the no-crosswind condition. Major paths of rain penetration under no-crosswind conditions are illustrated in Fig. 5. In
In this case, raindrops fell directly into the ventilator openings by gravity, hit the roof of the ventilator and dropped to the bottom floor. Because rain drainage was not fitted in Test 1, some rain slipping off the roof fell directly inside the grills before it reached the bottom floor (Fig. 5a). Some of the raindrops that hit the bottom floor were deflected into the grills. This was different from the other tests, Tests 2–6, in which a rain drainage was fitted which removed most of the rain reaching the roof of the ventilator. In Tests 2, 4, 5 and 6, the majority of rain penetration to the grills was the raindrops deflected after hitting the bottom floor (Fig. 5b,c). The major paths of rain penetration were very similar to each other in those tests, so grill direction (Test 2 versus Test 4), leaning angle of the outer wall (Test 2 versus Test 5) and outer wall height (Test 2 versus Test 6) were not significant factors in determining rain penetration under the no-crosswind conditions. However, by increasing the neck height by 100 mm (Test 3), many of the water drops deflected from the floor were intercepted by the neck as illustrated in Fig. 5d. There was no sign of raindrops on the colored paper in Test 3. Therefore, neck height and rain drainage of the ventilator were the major influencing components for reducing rain penetration, under the no-crosswind conditions.

**Rain penetration paths under the 15 m s\(^{-1}\) crosswind condition.** Under the 15 m s\(^{-1}\) crosswind conditions, the patterns of rain penetration were different in each test case and their pathways are depicted in Fig. 6. In Test 7, in which there was no rain drainage fitted, the paths or rain penetration consisted of direct inflow, deflection from the bottom, direct deflection from the outer wall and deflection from the bottom after hitting the outer wall (Fig. 6a). In contrast, no direct inflow was observed in Tests
8–12 where a rain drainage was installed. Examination of watermarks on the colored papers in Test 8, in which a rain drainage was installed, revealed that the quantity of rain penetration and the size of the water drops were reduced in Test 8 compared to those in Test 7. The fact that the size of the penetrating water drops in Test 8 was smaller than those in Test 7 implies that the water drops hit the surfaces of the ventilator components at least once before they entered through the grills.

Under the experimental conditions of Test 9, with a rain drainage and a 100-mm higher neck than those in the other tests, the raised neck of the ventilator intercepted some of the rain penetration deflected from the bottom floor. The raised neck helped to shield the water drop penetration due to bottom floor deflection, as shown in Fig. 6b.

In Test 10, with the downward grills, most of the raindrops that were deflected from the outer wall hit the upper side of the grill plate and then were deflected away from the grill surface. Only a portion of the raindrops that hit the grill surface reached inside the grills (Fig. 6c) Therefore, we can expect a good shielding effect by just adopting a downward grill, but a downward grill would cause more resistance to the airflow than an upward grill, giving less total exhaust flow rate in a natural ventilation system.

In Test 11, where the leaning outer wall was installed, the angle of deflection was increased and the amount of rain penetration due to the outer wall deflection was reduced. Finally, in Test 12, where the outer wall was 100 mm lower than it was for other tests, the impact area of raindrops was decreased, which resulted in the decrease of rain penetration. However, if the outer wall is lowered too much, the exhaust flow might be disturbed by crosswind.

Summary of Phase 1: qualitative inspections of rain penetration. There were four different paths of rain penetration. Those were (i) direct inflow of water when the rain fell from the roof of the ventilator to the bottom; (ii) the raindrops were deflected from the bottom floor between the grill and the outer wall; (iii) the water droplets were reflected from the outer wall and (iv) the water droplets hit the outer wall, fell to the bottom and were consequently deflected.

Fig. 6. Rain penetration paths: 15 m s\(^{-1}\) crosswind conditions: (a) Test 7, (b) Test 9 and (c) Test 10.
toward the grills. Paths (iii) and (iv) were especially apparent in windy conditions. The installation of a rain drainage and raised neck helped to reduce rain penetration under both the no-crosswind condition and the 15 m s\(^{-1}\) crosswind condition. Under the 15 m s\(^{-1}\) cross condition, a downward grill, leaning outer wall and lower outer wall also further reduced rain penetration.

**Phase 2: quantitative measurements of rain penetration intensities**

In Phase 2, 64 different tests were performed and Table 3 shows the amounts of rain penetration under those test conditions. As shown in the last column of the table, the overall average amount of rain penetration was below the LOD (1.8 \(\mu l\)) for 5 m s\(^{-1}\) crosswind conditions and 11.9 \(\mu l\) for 15 m s\(^{-1}\) crosswind conditions, respectively. In other words, rain penetration was significantly affected by the crosswind speed.

**Rain penetration intensities under the 5 m s\(^{-1}\) crosswind condition.** As shown in Table 3, in 5 m s\(^{-1}\) crosswind, no significant raindrops penetrated the ventilator in most of those cases. Exceptions were the test conditions with downward grill, lower neck height and narrow rain drainage width. In these cases, the rain penetration was caused by the raindrops deflected from the bottom floor because the lowest part of the grills guided the deflected raindrops into the ventilator. This could not be stopped due to the lower neck and narrower drainage configurations. When the ventilator was equipped with a higher neck and wider drainage, no detectable rain penetration was measured under the 5 m s\(^{-1}\) crosswind conditions.

**Rain penetration intensities under the 15 m s\(^{-1}\) crosswind condition.** The bottom part of Table 3 shows the measured rain penetration under the 15 m s\(^{-1}\) crosswind condition. The measured values were in the range of 2.7–36.9 \(\mu l\). Under the tested conditions, the minimum rain penetration occurred when a downward grill, a higher neck height (300 mm) and a wider drainage width (150 mm) were used.

Table 4 shows the group average values of each configuration of the ventilator components under the 15 m s\(^{-1}\) crosswind condition and their \(P\)-values from the MANOVA results. At the 95% confidence level, only the changes in the grill direction and the neck height significantly affected rain penetration. A downward grill works better than an upward grill in reducing rain penetration, but a downward grill would reduce airflow rate as discussed above. Similarly, although a higher neck substantially reduced rain penetration, a higher neck would be in the way of exhaust air, which would result in reducing the exhaust flow rate. There might be an optimum height that achieves both rain protection and aerodynamic efficiency.

The different drainage widths did not make much difference in the amount of rain penetration, although Phase 1 had shown that the simple existence of drainage was important. Again, using the wider drainage could block the exhaust airflow.

| Crosswind speed (m s\(^{-1}\)) | Grill direction | Neck height (mm) | Rain drainage width (mm) | Outer wall height | Leaning angle of the outer wall from a vertical position Mean | 0° | 10° | 10° | 0° | 10° | 0° | 10° | 0° | 10° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Upward 25° | 200 | 100 | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 5 | Upward 25° | 150 | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 5 | Downward 45° | 200 | 100 | 2.6 | 2.3 | 2.1 | ND | ND | ND | ND | ND | ND | ND | ND |
| 5 | Downward 45° | 150 | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 15 | Upward 25° | 200 | 100 | 29.2 | 27.5 | 28.0 | 26.2 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 |
| 15 | Downward 45° | 200 | 100 | 17.7 | 9.3 | 13.2 | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 |
| 15 | Downward 45° | 150 | 17.2 | 11.3 | 7.7 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 |

ND, not determined.

\(^{a}\)Below LOD.
Lowering the height of outer wall could help reduce rain penetration, but if the outer wall is too low, there could be a direct inflow of crosswind into the ventilator grills. This horizontal cross-flow could collide with upward exhaust flow, resulting in the reduction of aerodynamic efficiency.

Finally, leaning the outer wall could help reduce rain penetration, but not as effectively as the other factors. This factor should be investigated more thoroughly because we only evaluated conditions with the wall tilted 10°. In addition, the distance between the grills and outer wall should be studied because a fair amount of raindrops penetrated into the grills after colliding with the outer wall.

Summary of Phase 2: quantitative measurements of rain penetration intensities. The crosswind speed was found to be the most influential factor for the rain penetration among the six factors (crosswind speed, grill direction, neck height, rain drainage width, outer wall height and leaning angle of the outer wall). The measurements showed that the penetration intensities of water droplets at 15 m s⁻¹ crosswind were much higher than those of 5 m s⁻¹ crosswind. The second most influential factors were grill direction and neck height. The downward grill is much better than the upward grill, and the higher neck is better than the lower neck for preventing rain penetration through the ventilator.

Implications and limitations of study

The model ventilator used in this experimental study was built as a prototype gravity ventilator generally used in Korea and it represents only one of the many types of ventilators used in the real world. Thus, the experimental results from this study should be used with caution. However, we think that the general mechanisms of rain penetration of a gravity ventilator found in this study can also be applied to other cases.

We tested only under simplistic conditions which did not represent all the real weather conditions, including various raindrop sizes, wind speeds and wind directions. For example, our test set-up did not take into account the effect of the roof. The test wind was generated by fans aligned to the top of ventilator, which generated a horizontal wind direction. In the real world, a gravity ventilator is usually located on the top of factory building and the direction of wind will be changed by the shape of the roof. In addition, the length of a real ventilator should be much longer than the one tested in this study. This structural limitation could affect rain penetration of the side panels.

Finally, the airflow through the ventilator could affect the level of rain penetration. If a factory has a very hot process, i.e. melting furnaces, the hot process will generate the very strong buoyant plume, resulting in outward flow through the ventilator. The outward flow can reduce rain penetration. On the other hand, the factory building could have a very high negative pressure compared to the ambient air, which usually happens due to imbalance between supply and exhaust airflow rate. This can generate strong inward flows through openings, such as doors, windows and ventilators. In this case, the strong inward airflow will increase raindrop penetration of the building.

CONCLUSIONS

This study estimated the influencing power of six experimental factors (one environmental condition and five structural factors for the ventilator) on a real-sized model of the ventilator by the method of experimental analysis. By doing some qualitative and quantitative experiments, the pathways and intensities of rain penetration into the gravity ventilator model were observed. The speed of crosswind, the direction of grills, the height of ventilator neck and the installation of rain drainage were the critical parameters for penetration of raindrops. The experimental results suggest that, with proper configurations of its components, a gravity ventilator can be used for natural ventilation without rain penetration problems. Even though only a specific type of ventilator was tested in this study, the test results could benefit other types of gravity ventilators, too.

This study has several limitations that should be applied for the real world. The model ventilator used in this study did not have exhaust airflow through the ventilator. The crosswind was applied only in a horizontal direction across the top opening of the ventilator, not to the whole ventilator. Also, the test conditions did not represent all the real weather
conditions including various raindrop sizes, wind speeds and wind directions. More experimental studies to investigate the characteristics of rain penetration through a gravity ventilator are warranted in order to promote using the ventilator for natural ventilation without rain penetration problems.

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**REFERENCES**


