Wind Engineering Joint Usage/Research Center
FY2015 Research Result Report

Research Field: Indoor Environment
Research Period: FY2015～ FY2016
Research Number: 152008
Research Theme: Researches on ventilation of buildings in urban environment

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Budget [FY2015]: 213,000 Yen

*If the research was not continuous, this will be the Final Result Report, so the contents of the report has to be detailed.
*There is no limitation of the number of pages of this report.
*Figures can be included to the report and they can also be colored.
*Submitted reports will be uploaded to the JURC Homepage.

1. Research Aim

The goal of this study focuses on validation of stack ventilation for natural ventilated single-sided rooms. Two parameters of the equation will be studied experimentally; window opening area under constant indoor and outdoor temperature difference and constant window opening area with variable temperature difference. The ventilation rate from stack ventilation equation will be validated by tracer gas technique.

2. Research Method

Single-sided stack ventilation

For the past several decades, several researchers have studied and developed expressions for calculation of natural ventilation in buildings. In the calculation of airflow in single-sided ventilation, it is not possible to just look at the average pressure difference and wind velocity, which is often done for cross-ventilation. The openings only exist in one side of the building, making the airflow through the opening much harder to predict. The main driving forces consist of indoor and outdoor temperature and wind pressure. When natural ventilation is driven only by thermal buoyancy, the ventilation rate can be calculated with the Bernoulli equation:

$$Q=\frac{1}{3}C_D A\sqrt{gH\frac{T_i-T_o}{T_i}}$$

Where: Q is the ventilation rate, C_D is the discharge coefficient, A is the window opening area, g is the gravitation force, H is the window height and T_x is the temperature. The pressure difference is created by different densities in the warm and cold air, eg. inside and outside a building

Tracer gas technique

To measure ventilation rates of naturally ventilated buildings, tracer gas methods are used and often the only method possible. These include infiltration and air change rate measurements, fume hood efficiencies and spreading of pollutants. Tracer gas techniques also have special importance in estimation of natural ventilation, where no measurements in the duct system can be performed. Nevertheless, tracer gas methods are often used for measurements of ventilation for its accuracy and easy use. For unsteady ventilation rates, only the constant injection method can be used.

Calculation of ACH

The air changes per hour (ACH) calculation process for the constant injection method is based on a parametric iteration technique, where the change in the tracer gas concentration between two measurements (indoor and outdoor concentrations) can be expressed as:

$$\Delta C = \frac{\Delta \tau}{V_{zone}}(F - NV_{zone}(C_1 - C_e)) \tag{1}$$

where ΔC is the change of tracer gas concentration, $\Delta\tau$ is the time interval, V_{zone} is the zone volume, F is the steady-state tracer gas release rate, N is the number of ACH, C_1 is the indoor concentration and C_e is the outdoor concentration. The unknown parameter is N, with all the rest as input values.

The calculation was repeated for each consequent time interval to get a theoretical curve. The C_1 is the first concentration measured of the time interval, followed by a theoretical concentration $C_{2,t}$ at the end of the time interval calculated as a sum of the initial concentration (C_1) and the individual step increase ΔC. The calculation process is repeated for every single following time interval, giving a theoretical exponential curve of $C_{2,t}$.

At last, Eq. 1-2 was applied to calculate the difference between the measured and theoretical values. The Solver tool Add-in in Microsoft Excel was then used for the curve fit to minimize the sum of the errors between the measured and theoretical values (curve fit).

$$\mathrm{Error}\left(\mathrm{C}_{i,t}\right) = \left(\mathrm{C}_1 - \mathrm{C}_{i,t}\right)^2 \tag{2}$$

Index i=0…k, where k is the number of measured concentrations

In order to minimize the calculation error, the measured indoor tracer gas concentration was divided up between step-up, constant and decay concentration in order to calculate the ACH. The calculated sums of the errors were small due to this method, and varied between 1-5%, so the curve fit had an error of 1-5%. This calculation method is applicable with a variable indoor concentration when the air exchange rate is not stable.

Tracer gas source

To get a steady-state release rate of tracer gas, dry ice in an insulated box was used. The sublimation rate of CO_2 from dry ice is affected by the insulation of the box and indoor temperature. If the dry ice is placed in an insulated box, the heat transfer will eventually reach steady state. The internal box temperature will remain constant, close to the dry ice sublimation temperature and the sublimation rate of the dry ice should remain constant as long as there is sufficient dry ice in the box. Since dry ice has a temperature of -78.5°C and indoor temperatures varies between 20-25°C, it can be assumed that small indoor temperature changes wouldn't affect the emission rate that much.

The weight loss of the dry ice box was used to calculate the emission rate of CO_2 with the following formula:

$$F_{CO_2} = \dot{m}\frac{V_m}{M_m} \tag{3}$$

where F_{CO2} is the steady-state release rate of CO_2, V_m is the molar volume of CO_2 and M_m is the molar mass of CO_2. The dry ice requires to be weighted 2-3 times per day to get the sublimation rate, due to the unstable indoor temperature (weight will be provided by us). The usual release rate is between 150-200g/h, when using an insulated foam box.

CO_2 measurement

The tracer gas method requires the CO_2 in the room to be fully mixed (uniform), in order to calculate the ACH with minimum errors. To do that, each room will require a mixing fan and several CO_2-sensors. The position of the fan will be as far away from the window as possible, blowing towards the opposite direction. The CO_2-sensors will determine if the room is uniform, so a total of 6 sensors will be scattered around the room.

Temperature

Indoor and outdoor temperature will be measured as well, to get an equation based on ventilation rate and indoor and outdoor temperature difference (thermal buoyancy). The ventilation rate measurements have to be done on days without wind for this to happen. A total of 4 temperature sensors (scattered around the room) will be positioned indoor and 1 outdoor.

3. Research Result

Calculation of ACH

The experiments were continuous over a couple of days, due to the constant release rate of CO2 from dry ice. As shown in Fig. 1, dry ice was refilled once every day, with CO2 and temperature logged throughout the experiment. This procedure was done for each experiment conducted.

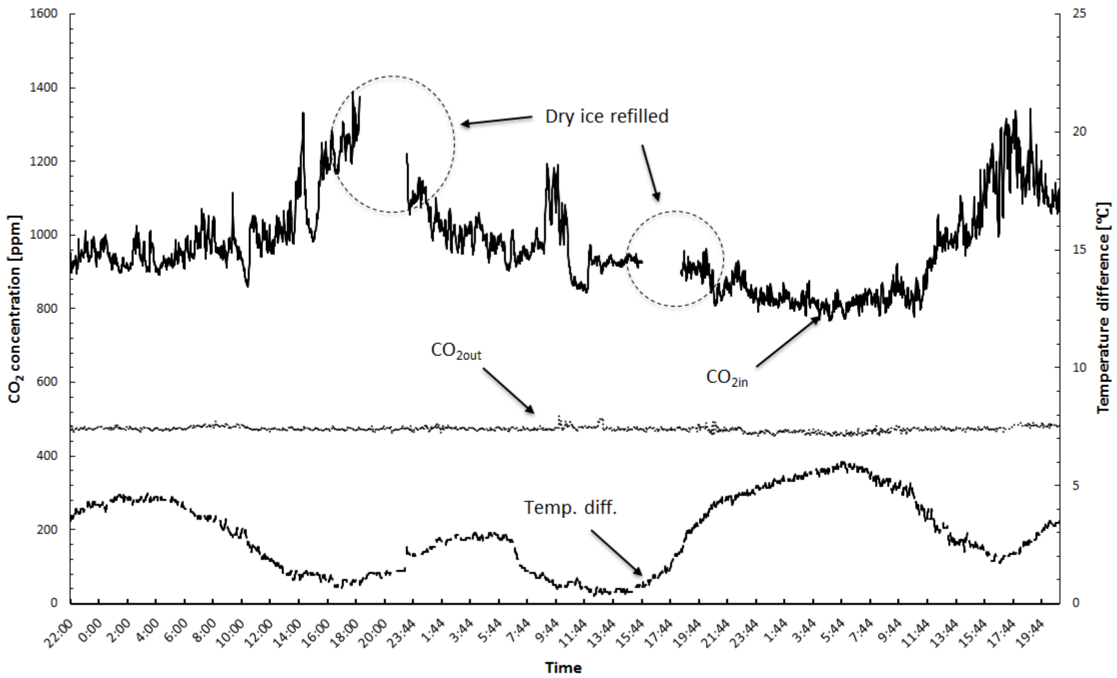

Fig. 1. Measurement data from a typical experiment.

With a continuous CO2 concentration as shown in Fig. 2, it is possible to calculate the ACH by breaking up the concentration into brackets, divided between step-up, steady-state and decay. This method makes it possible to reduce the calculation error of ACH. The calculated ventilation rates are shown in Fig. 2, along with the outdoor and average indoor CO_2 concentrations. The ventilation rates were calculated with Eqs. 1-2, depending on the pattern of the CO_2 concentrations. Three different patterns were essential for the ACH calculations: Build-up, steady-state and decay of concentration. This is important in order to reduce the calculation errors of ACH, when analyzing the data. By using the dry ice method, it enables us to calculate ventilation rate over a long period of time. This has never been done before, due to the limitation of tracer gas. The dry ice method is therefore perfectly suitable for long-term measurements, with varying ACH.

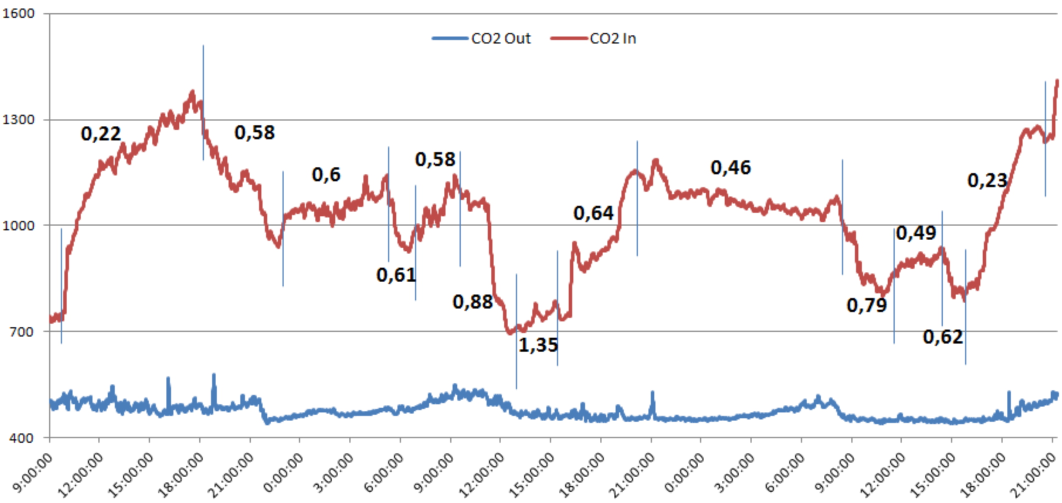

Fig 2. Dividing indoor CO2 concentration for calculation of ACH.

Constant window opening area

In this experiment, the influence of indoor and outdoor temperature difference was studied. Thus, it only required to refill the dry ice at appropriate times. By keeping the window opening area constant, the only difficult part would be to calculate the ACH for different temperature gradients, as shown in Fig 3. The temperature variations were achieved based on outdoor changing temperatures, mostly between day and night.

Each data point represents 20 min of averaged ventilation rate and temperature gradient. The relevance between ventilation rate and temperature gradient shows a fine linear connection, which proves that the stack ventilation is accurate at different temperature range for single-sided ventilation.

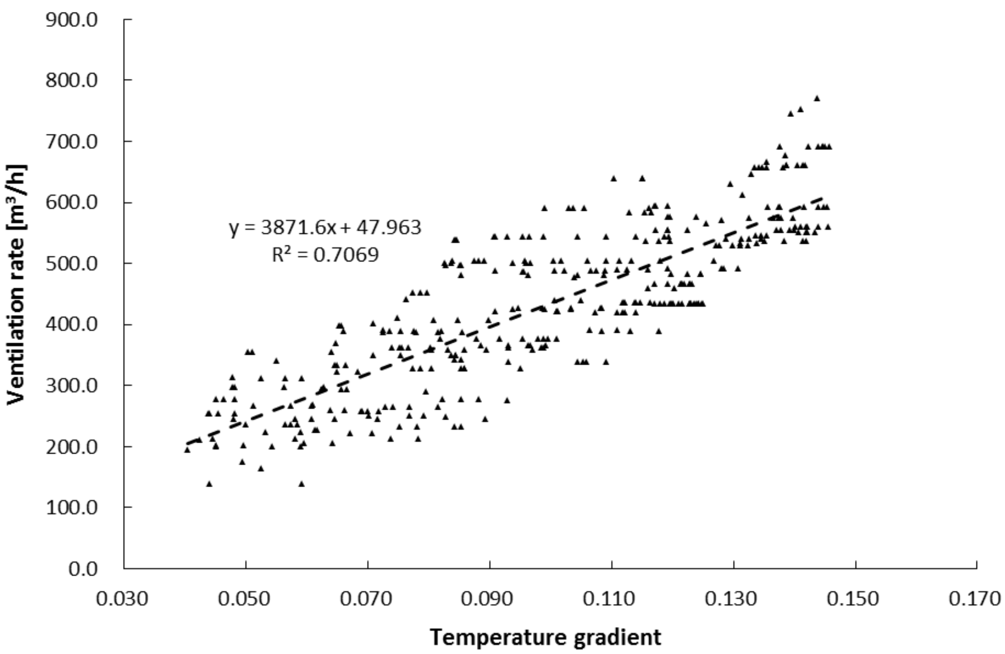

Fig 3. Influence of temperature gradient in stack ventilation.

Constant indoor and outdoor temperature difference

In this section, influence of different window opening areas is shown. The temperature difference was controlled by finding a suitable location with steady-state outdoor temperature. This was found in Japan, Tokyo, during spring, where the outdoor temperature during day-time was kept constant within 1°C. This kind of environment even exceeds climate chambers, where the temperature is usually controlled with an error of ±1°C. In order to test if the temperature difference was kept constant, 4 experiments with constant window opening area were conducted. As shown in Fig. 4, the calculated ACH are within acceptable range. Thus, further experiments on variable window opening areas could be conducted.

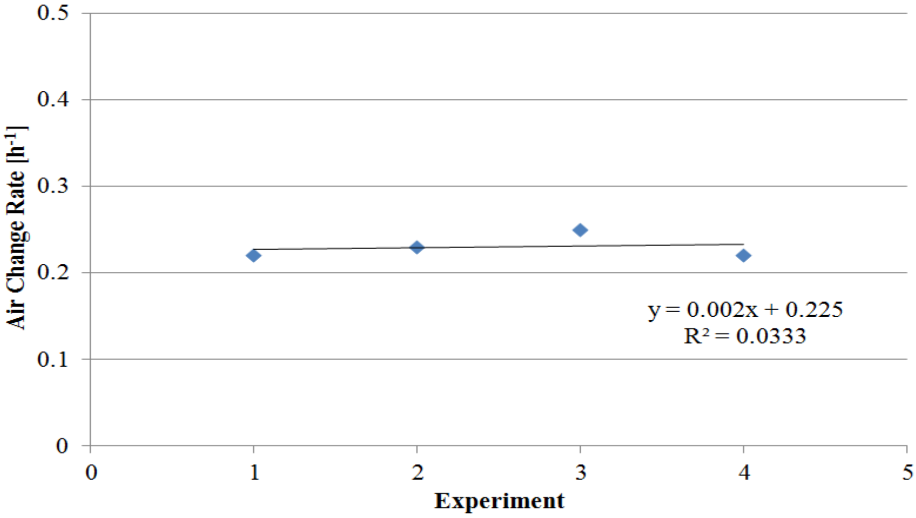

Fig 4. Determining constant ACH with constant temperature difference.

The experiment for constant temperature difference was conducted at two different places. Both experiments were conducted in classrooms, where the windows could be fully opened. Fig. 5 shows the experiment results for case 1. Each data point was averaged for about 1 hour, where each window opening area was repeated 1-2 times. The data shows a linear trend between the window amount and ACH.

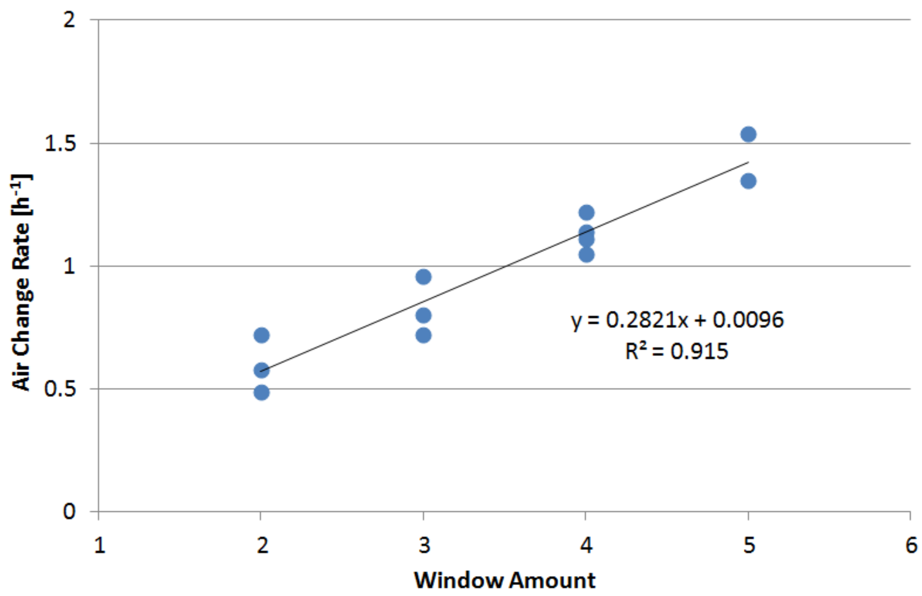

Fig 5. Influence of window opening area case 1.

In case 2, shown in Fig. 6, the windows are half of the size as case 1. This was in order to see the influence of the windows at low ACH. Similar to case 1, it shows a linear trend as well. This means that the window opening area parameter is proven to be accurate for single-sided stack ventilation.

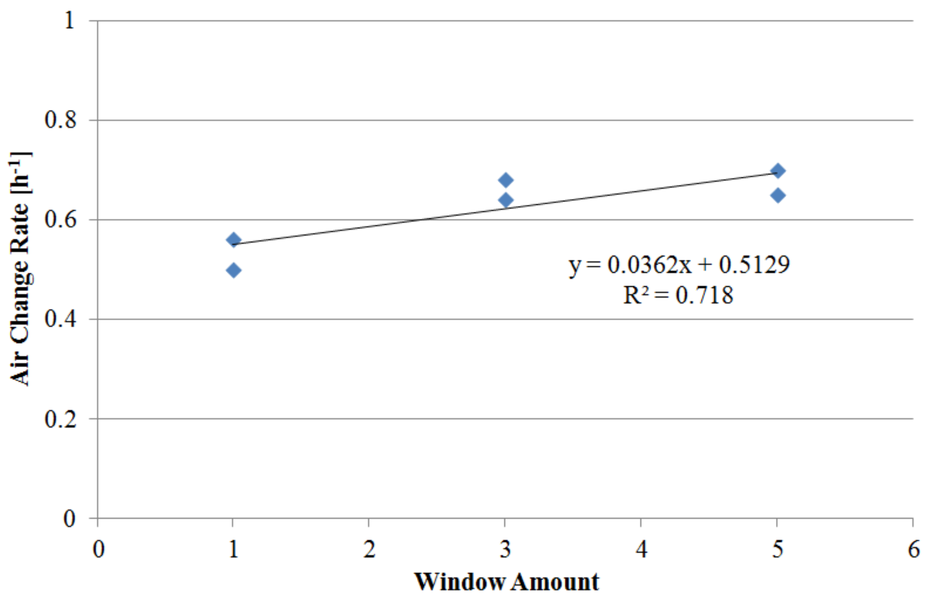

Fig 6. Influence of window opening area case 2.

Conclusions

1. Dry ice method has proven to be highly accurate, suitable for long continuous measurements
2. The new method is more practical for getting more data points when measuring unstable temperatures
3. The dry ice method also proved that the buoyancy equation is accurate at a different temperature, ventilation and window opening range

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

[Presentations at academic societies]

[Published books]

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5. Research Organization

1. Representative Researcher

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2. Collaborate Researchers

Weirong Zhang, Tokyo Polytechnic University, Japan, Associate Professor