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Predicting single-sided airflow rates based on primary school experimental study

Yuqiao Tang [a, *], Xiaofeng Li [a], Wumengjian Zhu [b], Pok Lun Cheng [a]

[a] Department of Building Science, Tsinghua University, Beijing 100084, China
[b] School of Architecture, Tsinghua University, Beijing 100084, China

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ABSTRACT

Primary schools in Chinese cities are predominantly located in high-density urban environments with the majority of these schools lacking air conditioning systems. They are extremely dependent on buoyancy-driven natural ventilation because of their location in dense neighborhoods, where local wind velocity is low. This dependency is especially relevant in summer and season transitions, when the temperature difference is small and the relative wind velocity is close to zero. The current authors conducted 168 h of experiments that measured airflow rates in a primary school located in a high-density neighborhood in Beijing. Results from the experiments were used to verify existing correlations that predict airflow rates using meteorological parameters. Three out of the four existing correlations presented a satisfactory prediction when $\Delta T \geq 1$ °C. However, when $\Delta T < 1$ °C, no correlation presented a usable prediction. Therefore, this paper proposes a new hypothetical correlation to predict airflow rates that can accommodate ranges for all temperature differences.

1. Introduction

Indoor air quality in primary schools is an ongoing concern for students and their families. Numerous studies have shown that building occupants in poor indoor air quality are more vulnerable to Sick Building Syndrome (SBS) [1]. Numerous researchers have demonstrated that natural ventilation is an effective way to achieve high indoor air quality and thermal comfort [2–4] which makes the study of natural ventilation in primary schools a popular topic [5,6].

Turanjanin et al. (2014) measured CO_2 concentrations in five schools using the decay method during a hot season in Serbia. The results showed that classrooms in Serbian schools had inadequate ventilation, with CO_2 concentration often exceeding 1000 ppm. These levels can cause health problems for students, thereby increasing their absence from school [7]. In 2004, a team led by D. G. Shendell discovered that a 1000 ppm increase in dCO_2 (indoor minus outdoor carbon dioxide concentration) was associated ($P < 0.05$) with a 0.5–0.9% decrease in annual average daily attendance, corresponding to a relative 10–20% increase in student absences [8].

Compared with office buildings, primary school classrooms are designed with a minimum area of 1.10 m^2 per capita. This area is only one third that of an office building (3 m^2), which subjects primary school students to higher risks [9,10]. As such, a major question to be answered is whether natural ventilation alone can meet the fresh air needs of primary school classrooms. Previous research conducted in the United States of America (US) and Denmark suggests that ventilation rates in primary schools are likely to be below the ASHRAE advised 8 L/s-person. Also, approximately half of the schools in the US, Canada, and Europe were reported to have an average CO_2 concentration measuring above 1000 ppm [6,7].

In China, You et al. (2007) conducted a series of experiments at Nankai University, Tianjin. The team measured ventilation conditions and low air quality related symptoms in 50 rooms, including classrooms, conference rooms, and dormitories. More complaints and symptoms were found in rooms where air exchange rates (AER) were lowest [11]. However, at present, specific data for Chinese primary schools are not readily available, which leaves further research to be done in this area.

Although natural ventilation has limitations that include ventilation heat loss and selective application in specific climates (such as cold winters) [12], government funded primary schools in China are generally not equipped with air conditioning systems

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* Corresponding author.
E-mail address: tang_yq@qq.com (Y. Tang).

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[10]. Relevant considerations here include the ongoing financial burden of air conditioner installation and maintenance, as well as the risk that these systems pose to spreading air-related epidemics. As a result, for summer and season transitions, natural ventilation plays a key role in maintaining the indoor air quality of primary school classrooms in China.

Based on meteorological records measured at Tsinghua University (Beijing) in summer and season transitions (Mar. to Nov.) from 2010 to 2014, static wind comprised approximately 50% of the wind patterns with a wind speed of less than 0.5 m/s at 10 m above ground level. According to Chinese building codes, the height of a primary school building is limited to four stories (approximately 15 m). Also, for health and safety reasons, all classrooms are required to have doors and windows that have direct access to the outdoor environment [10].

In general, tier one cities in China, such as Beijing, contain urban environments filled with high-rise towers and other multi-story buildings. Typically, this produces low wind speeds in the vicinity of low-rise building windows. Therefore, research on building ventilation with low wind speed and pressure is crucial. Furthermore, the importance of this research also extends to circumstances where thermal pressure is low (such as Beijing) and where temperature differences between the indoor and outdoor environment (in summer and season transitions) result in low thermal pressure.

The experiments for the current research were conducted in a newly built primary school in downtown Beijing. The school is a typical Chinese primary school with no air conditioning, but with doors and windows opened to a semi-outdoor atrium. These conditions ensured that the sample building was in an ideal location for a single-sided ventilation study. The location of the school (highly-dense urban neighborhood) and the time period (March and April) both represented a typical ‘worst-case scenario’ for Chinese primary schools with regards to air quality control.

Many previous studies focused on certain features of single-sided ventilation, such as driving force [13,14], flow characteristics [15], or single-story building applications [16]. Also, previous simulations focused on predicting airflow rate [17,18], airflow modeling [19,20], and design analysis [21–24]. However, due to limitations of the traditional tracer gas method [25,26], previous theories were seldom tested using large sums of data samples. Therefore, the purpose of this paper is to verify existing correlations for single-sided ventilation with results obtained from full-scale experiments using the tracer gas dry ice method [26]. Then, to use the verifications to determine a suitable correlation that can predict airflow rates in circumstances where thermal pressure and wind velocity are low. This may assist the design of future schools with regards to general and ventilation-specific opening dimensions.

2. Review of existing correlations

Numerous measurements and simulations have previously been undertaken for single-sided natural ventilation that are driven by thermal buoyancy or wind pressure (or both). Several equations have been proposed to solve airflow rates based on temperature and wind velocity parameters.

2.1. The Bernoulli equation

This equation considers the bi-directional airflow occurring through a large, vertical opening between two zones of different temperature. The equation assumes there is a neutral pressure level in the middle of the opening height, $\Delta p(y = H/2) = 0$, a constant temperature in both rooms, and linear pressure profiles (it also applies the ideal gas law); as such, an integration in the vertical direction can be derived to calculate the airflow rate, Q:

$$Q = W \int_{y=0}^{y=H/2} \sqrt{\frac{2\Delta p(y)}{\rho}} \mathrm{d}y \tag{1}$$

where Δp is the pressure difference across the opening (Pa); ρ is the fluid density (kg/m^3); H is the opening height (m); and W is the opening width (m).

This leads to the airflow rate into the room:

$$Q = \frac{1}{3} C_D A \sqrt{gH \frac{T_i - T_o}{T_i}} \tag{2}$$

where Q is the airflow rate (m^3/s); C_D is the discharge coefficient; A is the area of the opening (m^2); T_i is the internal temperature (K); T_o is the external temperature (K); and g is the gravitational acceleration (m/s^2)

Eq. (2) is often referred to as the Bernoulli equation [17,27].

An empirical constant, C_D, is introduced in Eq. (2) in order to allow for effects such as viscosity, streamline contraction, swirling flow and turbulence. The value of C_D is determined by the characteristics of both the opening shape and the flow field. Usually, C_D is set at 0.6 [20,27,28]. Based on a series of CFD simulations conducted by Favarolo and Manz in 2005, the value of C_D can vary from 0.4 to 0.7 due to wall thickness, number of openings, width of opening, and dimensionless height, (H′) of the opening. H′ is defined as:

$$H' = \frac{d_f}{H_{room} - H} \tag{3}$$

where d_f is the height of the window sill; H_{room} is the height of the room; and H is the height of the opening.

According to CFD simulation results, C_D can be set at 0.6 when H′ is close to 0 and set at 0.7 when H′ is close to 1 [17].

2.2. Correction of Bernoulli equation

In 1995, Dascalaki et al. used a correction factor (CF) to replace the discharge coefficient (C_D):

$$Q = CF \cdot \frac{1}{3} A \sqrt{gH \frac{T_i - T_o}{T_i}} \tag{4}$$

By measuring 52 single-sided natural ventilation configurations using the N_2O tracer gas decay method, they found that CF could be calculated by:

$$CF = 0.08 \left(Gr/Re_D^2 \right)^{-0.38} \tag{5}$$

Here, $Gr = \frac{g\Delta T H^3}{T\upsilon^2}$ is the Grashof number;

$Re_D = \frac{UD}{\upsilon}$ is the redefined Reynolds number;

where υ is air viscosity (m^2 s^{-1}) and H and D are the characteristic lengths of the flow (m).

2.3. Combined effect of wind and thermal buoyancy

In most cases, the airflow rate of a building is simultaneously determined by thermal buoyancy, wind pressure and other factors such as air fluctuation. Previous research focused on proposing a correlation that could predict the airflow rate of single-sided ventilation driven by the combination of wind pressure and thermal buoyancy.