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A case study of air pressure fluctuations in drainage stacks of high-rise residential buildings

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Abstract

Pressure variation in drainage stack is one of the key design parameters for a healthy drainage system in high-rise residential buildings as it might deplete the water seals of any connected appliances that prevent the ingress of foul gases into a habitable space. In this study, diurnal pressure variations in a drainage stack of a typical in-use high-rise residential building in Hong Kong were investigated. With the survey data of occupant load variations and diurnal WC flushing patterns collected from a number of similar local buildings, a significant association between the expected hourly WC flushes in the building and the air pressure variations in the stack was reported. Mathematical expressions were proposed to correlate the occurrence of maximum air pressure at certain locations in a stack with the expected hourly WC flushes in high-rise residential buildings. The results would be a useful source of reference to the development of control strategies against probable appliance seal loss in high-rise residential buildings.

Keywords

Drainage stack, high-rise, residential buildings, air pressure variations

1 Introduction

Hong Kong is a developed city having a population of 6.7 million and limited area of 1,067 km^2. The tiny portion (20%) of flat land for construction has led to a densely populated high-rise environment. The tallest residential buildings in Hong Kong are Sorrento (tower 1: 75 floors, 256 m high; tower 2: 66 floors, 236 m high; both were completed in 2003), The Harbourside (75 floors, 255 m high, completed in 2003), The Harbourfront Landmark (70 floors, 233 m high, completed in 2001) and The Belcher's towers 1-6 (61-63 floors, 221-227 m high, completed in 2001) [1]. In addition to the private residential buildings, there are many other government funded ones with heights over 140 m.

Following the massive outbreak of Severe Acute Respiratory Syndrome (SARS) in early 2003, the drainage system in high-rise residential buildings has become a major concern [2-4]. The contaminated single stack system was the suspect of transporting the virus into the living units connecting to it.

Air pressure fluctuation control in vertical drainage stacks, to which building height is a challenge, has been identified as an important factor in ensuring the performance of a building drainage system [2,5]. The transient air pressure generated in a poorly designed drainage stack by the system operations would contribute to the probable trap seal depletion of any connected appliances that prevent the ingress of foul gases into a habitable space [6]. For designing a healthy building drainage system, such pressure with unsteady partially filled pipe flow has been investigated intensively through simulations and laboratory tests [5,7-11]. Simulations based on a four-stack network that illustrated the flow mechanisms within the pipework following both appliance discharges and sewer-generated transients were performed to enable the development of measures like air admittance valve design against excessive air pressure variations in stacks [7]. The influence of design parameters including stack diameter, roughness, height, and applied water flow rate was also examined to determine the air pressure regime within the drainage vent system [8]. By laser measurement of annular flow velocities under representative unsteady flow conditions, the model predictions were validated [11].

Apart from the ventilation pipe designs, the air pressure variations are closely related to the discharge flow rates and patterns of appliances. Indeed, water discharge patterns are transient and dependent on occupant load variations, occupant usage patterns and the types of appliances installed. How the usage varied significantly throughout a day and between appliances was demonstrated [1, 12-14]. Studies showed that the diurnal patterns of total WC flushes could be presented in two distinct profiles, i.e. on an average weekday and an average weekend [12-14]. Nevertheless, stack air pressure variations in high-rise residential buildings due to the occupant usages were not investigated in details.

There are external factors such as wind pressure across openings and operations of mechanical fans or washroom windows/doors which might affect the transient air pressure in a drainage stack, but it is believed that WC flushing operations dominate the stack pressure variations. Based on experimental tests, mathematical expressions were proposed for air pressure transients in drainage stacks due to WC flushing operations [5,8].

This study investigated the diurnal air pressure variations in a drainage stack of a typical in-use high-rise residential building in Hong Kong and correlated the measured pressure variations with the expected hourly WC flushes. The results would be a useful source of reference to the development of control strategies against probable appliance seal loss in high-rise residential buildings.

2 Field studies

The field studies were composed of 2 parts: (1) a survey study of diurnal drainage discharge patterns on typical weekdays and holidays, and (2) measurements of air pressure variations in an in-use drainage stack of a high-rise residential building.

The first study was conducted in 14 high-rise residential buildings of 5 Hong Kong estates [1,4,13-14]. The estates were selected based on their geographical locations, building ages and architectural designs. They provided 26,500 apartments for a population of 113,000. Invitation letters introducing the study objectives, the survey period and details were sent to 1,300 selected households. Representatives of the 597 responded households participated in a face-to-face interview in their respective apartments. The daily occupant load variations throughout a week were surveyed. Most of the interviewees were those occupants staying at home the longest time. During the interview, they were asked to provide information of the appliance usage patterns on the day prior to the interview, and the hourly usage patterns on weekdays, Sundays and holidays. The average time between appliance demands was surveyed. For each installed appliance, its type, physical size, brand name, fill level and usage frequency were recorded. Average flow rates of water taps installed at the sink, washbasin, shower and bath were measured with simple operations by the occupants; the discharge and refilling times of each WC cistern were measured as well. Floor area of each apartment was obtained from the facilities management, direct measurement, or record drawings of piping arrangements.

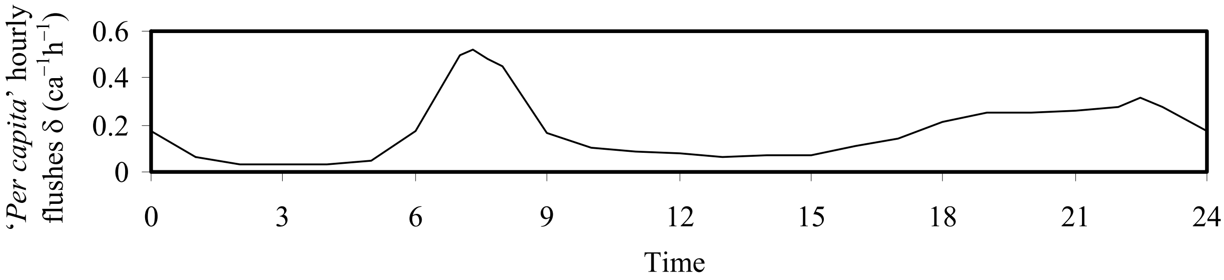

Figure 1: Example diurnal patterns of total flushes [4,12]

Air pressure variations in a PVC drainage stack of a 38-storey in-use residential building in Hong Kong were investigated in the second study. The stack pipe was 150 mm in diameter and fully vented by a 100-mm ventilation pipe with cross vents installed on alternate floors. Both the stack and ventilation pipe extended throughout the building (of height 110 m) and terminated at 1 m above the building roof. The stack collected effluents from the en suite washrooms on every floor. Each of these washrooms was equipped with a WC, a washbasin, a bath tub and a floor drain. This field study employed a data acquisition system which included a pressure sensor (measurement range ±837 Pa; probable error ≤ 2 Pa) and a data logger with a minimum sampling frequency of 1 s. The pressure sensor was installed at 'level 6' of the stack (i.e. 16 m above the bottom bend of the stack). Taking account of the atmospheric pressure in the washroom, it measured the transient pressure variations in the stack from Monday to Wednesday in a week.

3 Result and discussion

Figure 1 shows the example diurnal patterns of '*per capita*' total flushes δ for an average weekday. A sharp peak occurred during the morning period of 5 a.m. − 9 a.m., with a maximum rate of 0.52 $ca^{-1}h^{-1}$ at around 7:30 am. A period of lower flush rate followed from 11 a.m. till 3 p.m. The second peak occurred in the evening and it lasted for about 5 hours (6 p.m. – 11 p.m.). The late night minimum also lasted around 4 hours (2 a.m. – 5 a.m.) at a rate of approximately 0.032 flushes per capita per hour.

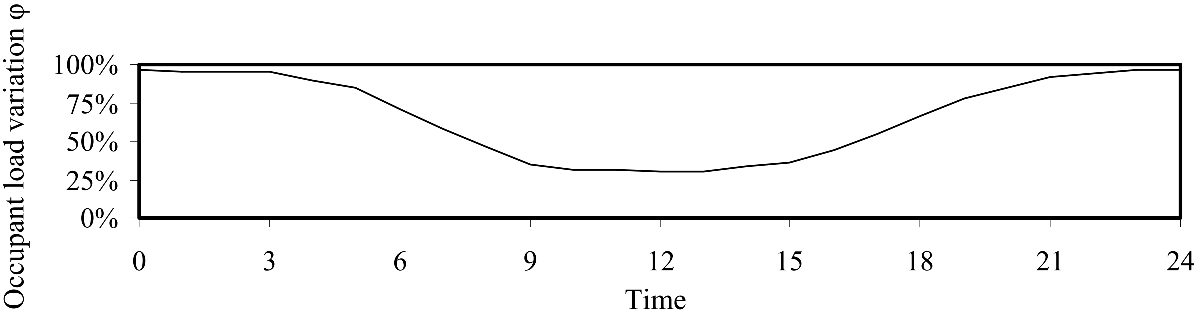

Figure 2: Weekday occupant load variations φ of high-rise residential buildings in Hong Kong

It was reported that the average maximum occupant load factor of the 600 apartments surveyed was very close to some design criteria, e.g. 4.5-9 m^2 per capita as in the local codes of practice [1,4]. Figure 2 shows the occupant load variations as a percentage of the reported 'full' occupant load. Loads nearly full were found at midnight and lasted for about 5 hours, they then dropped to the minimum (i.e. 25%) at 9 a.m. for 6 hours as shown.

Interestingly, by plotting against the occupant load variations φ on weekdays, the average '*per capita*' hourly flushes δ could be grouped into 4 categories. As shown in Figure 3, these categories are: (1) morning peak period with high usage 0700-1000; (2) low occupancy period with general usage 1100-2300; (3) high occupancy period with low usage 0100-0500; and (4) transitional usage stages from low to high at 0600 and from high to low at 0000. The 'slope' in the figure indicates the demands of WC flushes in various periods throughout a day. With an average slope of nearly 1, a significant correlation was found for the morning peak average ($p \leq 0.05$). The 'steep' slope indicated a congested demand in that period due to the assumption of a number of occupants flushing the WCs almost simultaneously. In the low occupancy period, there was also a significant correlation between δ and φ ($p = 0.0000$) with an average slope of

0.3. In the period of high occupancy with low usage, where the average '*per capita*' hourly flushes was 0.04 $ca^{-1}h^{-1}$ with a standard deviation of 0.01 $ca^{-1}h^{-1}$, no significant correlation was found between δ and φ ($p > 0.95$).

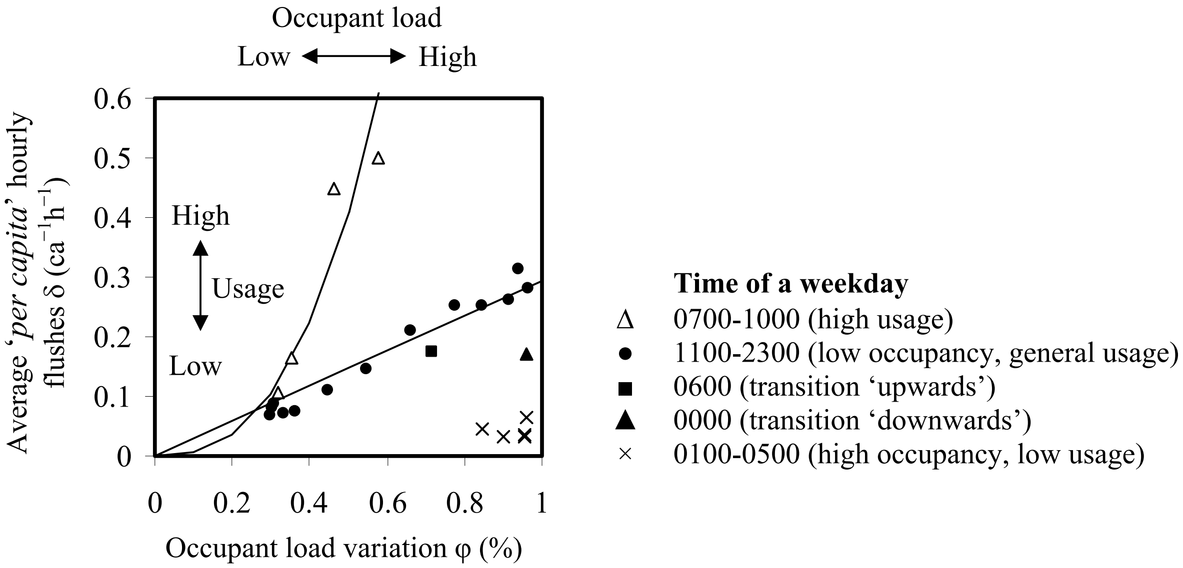

Figure 3: Number of flushes against occupant load variations

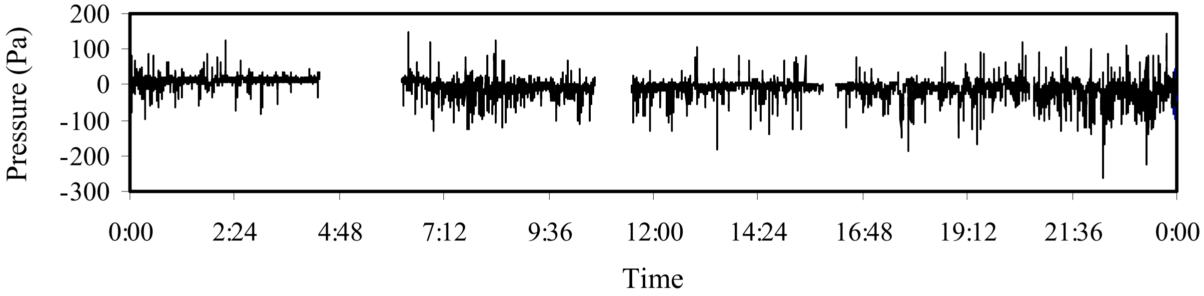

Figure 4: Example diurnal patterns of air pressure in a drainage stack

Figure 4 shows the diurnal air pressure variations measured in the drainage stack. Considerably 'large' fluctuations were reported in both the morning and evening peaks as shown. The probability P of air pressure ξ in the stack exceeding certain pressure limits $\pm\xi^*$ is expressed below, where ϕ is the probability density function of ξ in the stack,

$$P = 1 - \int_{-\xi^*}^{\xi^*} \phi(\xi)d\xi \qquad \ldots (1)$$

In this study, P was also approximated by the proportion of the number of measurements with air pressure fluctuations exceeding the set pressure limits as follows, where N is the number of measurements in the stack with an air pressure ξ,

$$P = 1 - \frac{N_{-\xi^* \le \xi \le \xi^*}}{N_\xi} \qquad \ldots (2)$$

Apart from the air pressure transients due to human activities and wind pressure across the stack openings (e.g. operation of mechanical ventilation fans), the probability P is correlated with the expected WC flushes. For the air pressure measured at certain stack level, this study proposes the following mathematical expression (R = 0.6, standard error = 0.04), where N_f is the expected hourly flushes,

$$P(\xi > \xi^*) = 305\xi^{*-3.08} e^{(14.55 - 0.053\xi^*)N_f} \; ; \; N_f = \delta\varphi \qquad \ldots (3)$$

Figure 5 shows this P, with the pressure limits ξ^* of 50 Pa, 75 Pa and 100 Pa arbitrarily selected in the study, against N_f. A significant association was found between P and N_f ($p<0.0001$). As expected, the probability of the stack air pressure going beyond certain limits was proportional to the expected WC flushes. The measurement results showed that the WC flushes would dominate the air pressure variations in a stack and uncertainty of these variations due to other factors was about 8% with 95% confidence intervals.

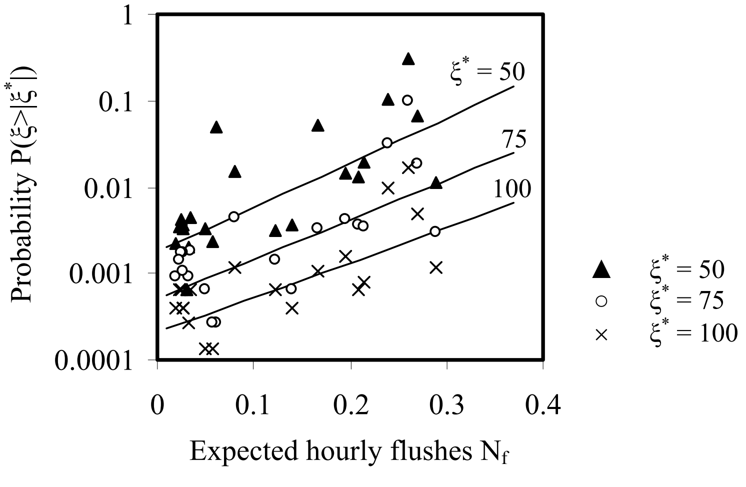

Figure 5: Correlations between stack air pressure and expected hourly WC flushes

4 Conclusion

In this study, diurnal pressure variations in a drainage stack of a typical in-use high-rise residential building in Hong Kong were investigated. With the survey data of occupant load variations and diurnal WC flushing patterns collected from a number of similar local buildings, a mathematical expression was proposed to correlate the occurrences of maximum pressure measured at certain locations in a stack with the expected hourly WC flushes in certain high-rise residential buildings. For the studied building, the probability of transient stack air pressure exceeding certain pressure limits was correlated with the expected hourly WC flushes. The measurement results showed that WC flushes would dominate air pressure variations in a stack and uncertainty of these variations due to other factors was estimated to be 8% with 95% confidence intervals.

5 Acknowledgment

The work described in this paper was substantially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 5129/04E; A/C code: BQ801).

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