Air pressure variations at drainage stacks of high-rise residential buildings

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Abstract

Purpose – The purpose of this paper is to examine the air pressure variations in an in-use drainage stack of high-rise residential buildings with the probable influence of occupant loads.

Design/methodology/approach – The air pressure variations in a drainage stack of a typical in-use high-rise residential building in Hong Kong were correlated to the number of water closet (WC) flushes of the building. In particular, measured diurnal WC flushing patterns of the residential buildings were used to correlate the diurnal pressure variations measured at 16 m above the stack base in a 115 m high, 150 mm diameter fully vented drainage stack of a typical high-rise residential building of Hong Kong.

Findings – The occurrence of the maximum air pressure in the stack could be correlated with the expected hourly WC flushes of the high-rise residential buildings with mathematical demonstrations.

Research limitations/implications – There may be high speed transients in the stack (>1 hertz) which was not measured.

Originality/value – The result would be a useful source of reference for the development of control strategies against probable appliance seal loss in high-rise residential buildings.

Keywords Residential property, Building services, Water supply, Hong Kong, Pressure

Paper type Research paper

Introduction

Transient air pressure control in drainage stacks of high-rise buildings has been identified as an important factor in ensuring the performance of a building drainage system (Cheng *et al.*, 2004; Swaffield, 2006; Jack *et al.*, 2006; Wong and Mui, 2006a). Following the massive outbreak of severe acute respiratory syndrome (SARS) in early 2003, the design of the drainage system in high-rise residential buildings has become a major concern in Hong Kong nowadays (World Health Organization, 2003; Fernandes and Goncalves, 2006).

The transient air pressure generated in a poorly-designed drainage stack would contribute to the probable trap seal depletion of any connected appliances that prevent the ingress of foul gases into a habitable space. In order to design a healthy building drainage system, such pressure with unsteadily filled pipe flow has been investigated intensively through simulations and laboratory tests (Cheng *et al.*, 2004; Swaffield *et al.*, 2004; Swaffield, 2006). Simulations based on a four-stack network illustrated the flow

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mechanisms within the pipework following both appliance discharges and sewer-generated transients were used to identify the role of the active air pressure control devices in maintaining system pressures below certain target limits (Swaffield, 2006). A study showed that airflows induced warm detergent-based water would be significantly higher than those measured in drainage experiments with clean water systems (Campbell and Macleod, 2001). Recent experiments showed that solids had an effect on the pressure regime in a vertical stack (Gormley, 2006). The influence of design parameters including stack diameter, roughness, height, and applied water flow rate would be examined to determine the air pressure regime within the drainage vent system (Swaffield, 1995). By laser measurement of annular flow velocities under representative unsteady flow conditions, the model predictions were validated (Swaffield *et al.*, 2004; Swaffield, 2006).

Apart from the drainage vent system design, the air pressure variations are also closely related to the discharge flow rates and discharge patterns of domestic appliances. Indeed, water discharge patterns are transient and dependent on occupant load variations, occupant usage patterns and the types of appliances installed. The characteristics and variations were reported in some studies (Friedler *et al.*, 1996; Wong and Mui, 2004, 2006b). Studies showed that the diurnal patterns of total WC flushes could be presented in two distinct profiles, i.e. on an average weekday and on an average weekend. Nevertheless, stack air pressure variations in high-rise residential buildings caused by the occupant usages were not investigated in detail. Besides, 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 were not studied too. However, 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 (Cheng *et al.*, 2004; Swaffield, 2006; Jack *et al.*, 2006; Wong and Mui, 2006c).

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 result would be a useful source of reference to the development of control strategies against probable appliance seal loss in high-rise residential buildings.

Survey

A survey study was conducted in 14 high-rise residential buildings of five Hong Kong estates (Wong and Mui, 2004, 2006b). The estates were selected based on their geographical locations, building ages and architectural designs. They provide 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 and a total of 597 responses received. A representative from each of the responded households participated in a face-to-face interview at his/her apartment. Most of the interviewees were those occupants who stay at home the longest time. The daily occupant load variations throughout a week were surveyed. 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-up 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. The information about the total floor area of each apartment was obtained from the facilities management, direct measurement, or record drawings of piping arrangements.

On-site measurement

Transient air pressures in a 150 mm diameter PVC drainage stack of a 38-storey in-use high-rise residential building in Hong Kong were measured in three weekdays (Wong and Mui, 2006a). The stack collected effluents from two washrooms on every floor, where a total of four stacks for a floor of eight washrooms. Each of these washrooms was equipped with a WC, a washbasin, a bath tub and a floor drain. Separate stack for kitchen and washing machine was installed but it was not included in this study. The stack pipe was fully vented by a 100 mm ventilation pipe with cross vents installed on alternate floors. Both the stack and ventilation pipe of a height of 115 m extended throughout the building and terminated at 1 m above the building roof.

This field study employed a data acquisition system which included a pressure sensor (measurement range ± 837 Pa; probable error $\leq$ 2 Pa) and a data logger with a minimum sampling frequency of 1 s. It is noted that the sampling frequency of 1 hertz might be inadequate for detecting high speed transients present in the system and excessive average results would be recorded. The pressure sensor was installed at "level 6" of the stack (i.e. 16 m above the bottom bend of the stack) and taking account of the atmospheric pressure in the washroom.

Result and discussion

Figure 1 shows the diurnal patterns example of "per capita" hourly demands δ with a standard error from all survey data. For WC cistern, a high demand occurred during the morning period from 7 a.m. to 9 a.m., with the rate of average demand of 0.39 hd^{-1} h^{-1} (SD = 0.19 hd^{-1} h^{-1}) at around 7:30 a.m., the recorded maximum usage rate was 1 hd^{-1} h^{-1}. A period of relatively lower flushing rate followed from 11 a.m. to 3 p.m. The other peak occurred in the evening around 6:00 p.m. to 9:00 p.m., with an average of 0.59 hd^{-1} h^{-1} (SD = 0.20 hd^{-1} h^{-1}), the recorded maximum was 1.25 hd^{-1} h^{-1}, respectively. The late night minimum also lasted around three hours (2 a.m. to 5 a.m.) with a minimum rate of approximately 0.007 hd^{-1} h^{-1}. It was reported that the peak would occur at different period, however, no significant difference in the average demand rate (0.587 hd^{-1} h^{-1}, $p \geq 0.27$, t-test) at peak hour was reported for this survey compared with the other surveyed result of 0.524 hd^{-1} h^{-1} in another city recorded by Friedler *et al.* (1996).

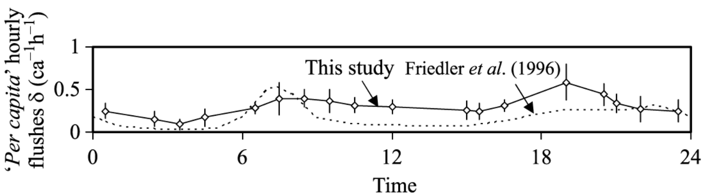

Figure 1.
Diurnal patterns of WC total flushes

It was reported that the average maximum occupant load factor of the surveyed apartments was very close to some design criteria, e.g. 4.5-9 m^2 per capita as in the local Codes of Practice (Wong and Mui, 2006c, 2007). Figure 2 shows the occupant load variations φ as a percentage of the reported "full" occupant load. Nearly full loads were found at midnight and lasted for about five hours, they then dropped to the minimum (i.e. 25 per cent) at 9 a.m. for six hours as shown.

Interestingly, by plotting against the occupant load variations φ on weekdays, the demands expressed by the average "per capita" hourly flushes δ could be grouped into four categories as shown in Figure 3, with the demands shown in equation (1) below.

$$\delta = \begin{cases} \sim N(0.32, 0.05) & t \in \tau_A = 088 - 1700 \\ 0.77\varphi^{1.17} & t \in \tau_B = 1600 - 1900 \\ 2.25 - 2.12\varphi & t \in \tau_C = 1900 - 0300 \\ 0.66 - 0.57\varphi & t \in \tau_D = 0400 - 0800 \end{cases} \qquad (1)$$

Group (A) demand characteristics were observed in the period of lower occupant load about 25 per cent to 50 per cent of the reported maximum occupant loads, around time t of school hours/working hours from 08:00 to 17:00. The demands were reported relatively steady irrespective to the occupant loads ($p \geq 0.6$, t-test for correlation coefficient $R = 0.176$). The survey samples showed that the demands would be described by a normal distribution ($p \geq 0.5$, Chi-square test) with a mean of 0.32 $ca^{-1}h^{-1}$ and a standard deviation of 0.05 $ca^{-1}h^{-1}$.

Group (B) demand characteristics were reported in time t between 16:00 to 19:00, i.e. around after school session to the evening peak, with the occupant load variations φ

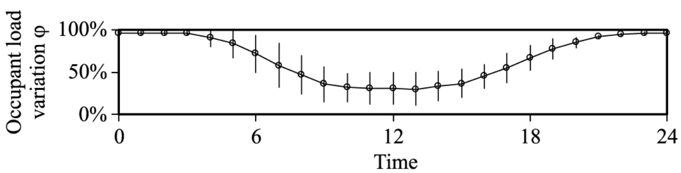

Figure 2.
Weekday occupant load variations φ of high-rise residential buildings in Hong Kong

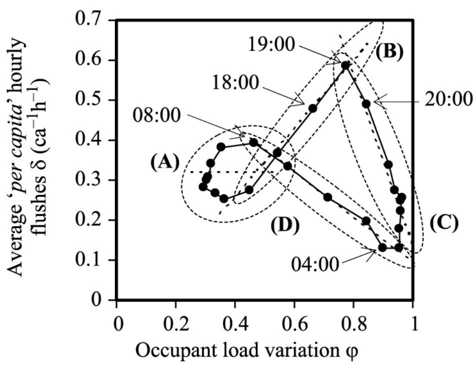

Figure 3.
Time dependent occupant demand locus of WC flushing

from 50 per cent to 80 per cent. The hourly per capita demands were proportionally increased to the occupant loads.

Group (C) demands showed an inversely proportional correlation to the occupant load variations. These demand characteristics would be explained as from a period of congested WC flushes by occupant to a period of very low flushing activity (e.g. after mid-night).

Group (D) demands also showed a negative correlation to the occupant load variations, but the demands were from a very low value increased to those for congressed flushes at the morning peak. Group (C) demands found from the evening peak to the off-peak, i.e. from 19:00 to 03:00, with the occupant load variations from 80 per cent to 95 per cent; and (D) from the off-peak to the morning peak, from 04:00 to 08:00, with the occupant load variations dropped from 95 per cent to 50 per cent.

It was reported that the measured diurnal air pressure variations in the drainage stack showed considerably "large" fluctuations in both the morning and evening peaks. The pressure fluctuations (relative to the washroom) in certain time periods would be expressed as the probability P of the air pressure ξ in the stack exceeding certain pressure limits $\pm\xi^*$ as expressed below, where ϕ is the probability density function of ξ in the stack:

$$P = 1 - \int_{-\xi^*}^{\xi^*} \phi(\xi) d\xi \tag{2}$$

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 in the period (Wong and Mui, 2006a):

$$P = 1 - \frac{N_{-\xi^* \leq \xi \leq \xi^*}}{N_\xi} \tag{3}$$

Apart from the air pressure variations 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, correlation was found in this study ($R = 0.6$, standard error $= 0.04$), where N_f is the expected hourly flushes:

$$P\left(\xi > \xi^*\right) = 57.9\xi^{*-2.64} e^{\left(85.9-0.61\xi^*\right)N_f}; \quad N_f = \delta\varphi$$

Figure 4 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. The expected WC flushes would be used as a dominant parameter in determining the air pressure fluctuation in a drainage stack at certain height of high-rise residential buildings.

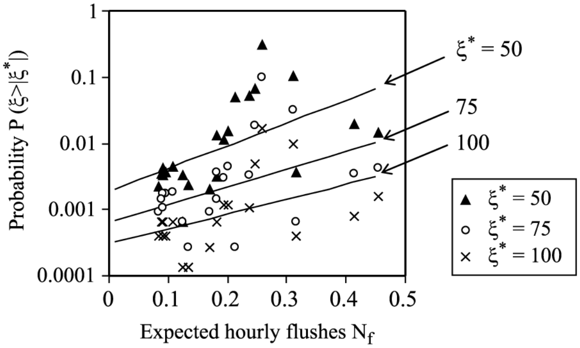

Figure 4.
Correlations between stack air pressure and expected hourly WC flushes

Conclusion

Flushing a WC was believed as one of the dominating activities causing the air pressure variations in the connected drainage stack, which are important for a healthy drainage system in high-rise residential buildings. In this study, the air pressure variations in a drainage stack at certain height of a typical in-use high-rise residential building in Hong Kong were correlated to the number of water closet (WC) flushes of the building. With the diurnal WC flushing patterns of the residential buildings surveyed in 597 residential apartments and the diurnal pressure variations measured in a 116 m high, 150 mm diameter fully vented drainage stack were measured at 16 m above the stack base. Mathematical expressions were proposed to correlate the occurrence of the maximum air pressure in the stack at certain height with the expected hourly WC flushes of the high-rise residential buildings. The results showed that WC flushes would dominate air pressure variations in a stack, and the expected WC flushes would be a leading factor in determining air pressure fluctuation in a drainage stack at certain height of high-rise residential buildings. This study would be a useful source of reference for the development of works related to control strategies against air pressure variations in drainage stack of high-rise residential buildings.

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