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Water dissipation mechanism of residential and office buildings in urban areas

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Indoor humidity directly impacts the health of indoor populations. In arid and semi-arid cities, the buildings indoor humidity is typically higher than outdoors, and the presence of water vapor results from water dissipation inside the buildings. Few studies have explored indoor humidity features and vapor distribution or evaluated water dissipation inside buildings. This study examined temperature and relative humidity (RH) changes in typical residential and office buildings. The results indicate a relatively stable temperature with vary range of ±1°C and a fluctuation RH trend which is similarly to that of water use. We proposed the concept of building water dissipation to describe the transformation of liquid water into gaseous water during water consumption and to develop a building water dissipation model that involves two main parameters: indoor population and total floor area. The simulated values were verified by measuring water consumption and water drainage, and the resulting simulation errors were lower for residential than for office buildings. The results indicate that bathroom vapor accounts for 70% of water dissipation in residential buildings. We conclude that indoor humidity was largely a result of water dissipation indoors, and building water dissipation should be considered in urban hydrological cycles.

urban hydrology, building water dissipation (BWD), water consumption, indoor humidity

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1 Introduction

The building indoor environment, not only determines the comfort but also affects the health of the inhabitants. Temperature and humidity are the two most important environmental elements directly affecting comfort and health [1,2]. As humans maintain a constant body temperature, indoor temperature requirements are relatively high and are always maintained at a suitable level by heating or air conditioning, usually in the range of 20–26°C [3]. In contrast, humidity is more difficult to control, even indoors. Indoor humidity was influenced by several factors, such as air flow, the indoor building materials [4], and moisture sources [5]. Some studies showed that the humidity in the room is also related to the occupancy of the building [6] and the outdoor humidity [7], which in the case of open windows. Measured indoor humidity value in winter showed that the radiator heating system was non-significantly associated with higher humidity, and humidifiers were needed to increase the indoor humidity [8]. Further literature have shown that most studies were about the indoor humidity prediction [9], humidity distribution [10] and laws inside the building, and some

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calculations based on computational fluid dynamics (CFD) models [1,11].

Indoor humidity is mainly caused by human water consumption inside the building when the windows and doors are closed and without the influence of ventilation equipment and humidifier. This study gave rise to a new concept: building water dissipation (BWD), which describes the transformation of liquid water into gaseous water in buildings. In general, the word "dissipation" is widely used to describe the dissipation of heat and energy [12]. Water dissipation has been used to describe vapor dissipation on vegetation canopies [13] and on the surface of the human skin [14]. Yamaguchi et al. [14] pointed out that cutaneous insensible water loss should be considered as human body water dissipation, and Kang [15] added human exhaled water should also be included. Human body water dissipation mainly includes cutaneous insensible water loss, inhalation water loss, skin sweating water, and water consume in the body's metabolic processes. Zhou et al. [16] proposed the concept of urban water dissipation, expressing water dissipation that occurs both inside and outside buildings in urban areas. BWD occurs during building water consumption, and it is therefore necessary to study this process to understand BWD mechanisms. According to previous studies and surveys, building water consumption depends on many parameters, such as building function [17], water facilities, indoor population, weather conditions [18], preferences and habits of inhabitants [19], floor number, and the total indoor area [20]. Water consumption has recently been used as an indicator of building occupancy [21], because actual occupancy determines the actual water consumption [22], and this should be considered in BWD calculation models [23]. For high-rise buildings, water consumption also depends on the height of the building [24]. Li et al. [25] showed that toilet flushing water accounts for 40% of total residential building water consumption. Hot water constitutes the largest water consumption in some building types, such as residential, office, and hotel buildings, and heat tank losses, flow rate, and distribution temperature are the most influential parameters [26]. Classification methods are typically used to calculate hot water use [27]; for example, hot water usage can be divided into shower, bath, sink, clothes washing, and dishwashing in multifamily buildings without detailed monitoring [28].

Knowledge of BWD is important for understanding indoor water vapor. However, little research has been done on the BWD mechanism and explore the relationship with the indoor humidity. This research therefore aimed to explore these problems using residential and office buildings as case studies. First, monitored the temperature, relative humidity (RH), and water consumption, and analyzed their changing relationships. Then studied the relationships between the RH and both water consumption and water user number in office buildings, and explored the different room (such as bedroom, bathroom, kitchen) water vapor contribution rate in residential buildings. Subsequently, we proposed a monitoring program to experimentally determine the water dissipation mechanisms inside buildings and establish a BWD calculation model and combined water use and drainage monitoring data to verify the calculation model using the water balance method.

2 Study objects

An office building and residential building were chosen as experimental case studies, both of which have relatively stable water consumption features and locate in Haidian district in Beijing city. Table 1 shows some basic information of the two buildings. Residential buildings essentially include all types of water consumption within a building (except for industrial water consumption). The building area and the number of rooms were from the architectural design information, and the number of people was obtained through investigation. There is no any mechanical ventilation or air renewal device in the two experiment buildings.

3 Methods

3.1 Experimental monitoring

The building drainage monitoring experiment aimed to prove the existence of water dissipation and verify the calculation results of buildings. The experimental monitoring equipment was an intermittent water volume measuring instrument, which is a patented product of the China Institute of Water Resources and Hydropower Research. The equipment was installed in the building drain-pipe outlet, usually in the sewage inspection wells. The equipment quantitatively and automatically determined the drainage water volume by counting the number of times the bucket filled and tipped. The experiment lasted for more than two weeks with mea-

Table 1 Basic information of case study buildings

Building type	Total floor area (m^2)	Room/apartment number	Population	Water dissipation categories
Office	6080	108	478	Toilet flushing, floor washing, drinking
Residential	3600	30	185	Toilet flushing, cooking, showering, washing clothes, personal washing, drinking, cleaning, floor washing

surements at one-hour intervals. Figure 1 shows the intermittent water volume equipment and installation.

Water consumption was measured by the water meter installed on the water supply pipe with a scale range of 10^{-4}–10^{5} m^3. The pipe leakage loss was ignored, because the building pipe drainage path is short. Intermittent water loss at the equipment tips was considered in the calculated drainage flow rate and the drainage flow monitoring experiment results were amended using a correction coefficient. The correction coefficient is measured by measuring the amount of water flowing at the end of the pipe with the meter, which is equal to the ratio of the metering water volume to the metered water quantity of the intermittent equipment.

To verify that water dissipation occurred in the building during water consumption and led to increased air humidity, temperature and humidity loggers (WSZY-1) were used to monitor the indoor temperature and relative humidity (RH) changes. Just like the HOBO Data Logger [29], the WSZY-1 is an automatic recording instrument for temperature and RH, produced by the Tianjianhuayi Technology Development Company. According to product manual, the temperature measurement range is from −40 to 100°C with a uncertainty below ±0.5°C and resolution of 0.1°C, while the RH measurement range is 0–100% with a uncertainty less than ±3% and resolution of 0.1% RH. All WSZY-1s were put together and the monitor data were compared with small difference (the variance of temperature and RH is 0.063 and 0.86 respectively), meanwhile, these instruments were calibrated by Thermostat (XMT-152) with ±0.2°C for temperature and by humidity sounder with range of ±2% for RH. The recorded time step was set to 10 min, and the instrument was installed in the center of the monitored room [30]. It should be noted that the drainage monitoring time interval was one hour; thence we chose the maximum RH value of each hour and the corresponding temperature as the values for subsequent analysis. In order to avoid the impact of outdoor ventilation on indoor humidity [31], the window is closed during the experiment. The actual water users number were measured by person flow counter, which was installed at the entrance of a building or a toilet room. When the human body through the instrument to interrupt the infrared light, the counter counts once, so the number of people in the lavatory door is equal to the counter value divided by 2, and the maximum counter number is 999999. The number of water user in lavatories was recorded in hours, which was same with water supply monitor time step.

Building indoor temperature and RH monitoring experiments were held in December 2016–February 2017 in object buildings in Haidian district of Beijing. This time is winter in Beijing, and most buildings were warmed by water heating, which means the indoor temperature is relatively stable during this time. The windows were closed in order to exclude the influence of outdoor temperature and humidity on indoor temperature and humidity. Some concepts have been introduced in the result analysis, for example, drainage coefficient refers to quantity of drainage water divided by quantity of water supply for a building in a specific period. The drainage coefficient is used to verify the calculation model of building water dissipation. *D*-values was proposed to describe the difference between the maximum and minimum RH and temperature values for each hour, which was used to show the RH increment and corresponding temperature changes in the unit time.

3.2 Indoor vapor calculation

According to the physical properties of water vapor, the mass of indoor water vapor is equal to the density multiplied by the volume, which is calculated by eq. (1):

$$m_{\mathrm{v}} = \rho_{\mathrm{v}} \times V, \quad (1)$$

where m_{v} is the indoor vapor content (g); V is the interior volume of the building (m^3); and ρ_{v} is the vapor density (g m^{-3}), which is calculated by eq. (2) [32]:

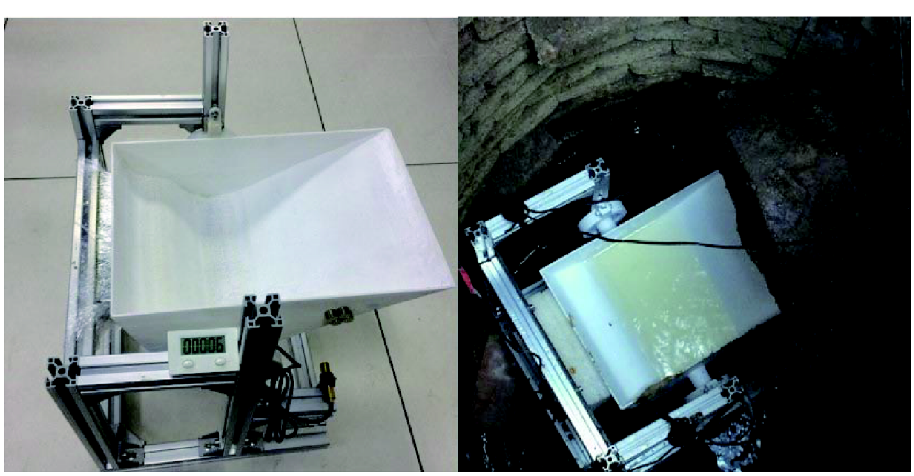

Figure 1 (Color online) Intermittent water equipment and drainage monitoring.

$$\rho_v = \frac{0.622e}{R_d T}, \quad (2)$$

where 0.622 is the ratio of the water vapor molecular weight divided by the dry air molecular weight (18.016/28.966); R_d is the gas constant of the dry air (J (kg °C)$^{-1}$, R_d=287.04); T is the absolute temperature (K), where T=273+t (indoor temperature is in °C); and e is the actual water vapor pressure (Pa).

$$e = RH \times e_s, \quad (3)$$

where e_s is saturated vapor pressure (Pa), calculated by eq. (4):

$$e_s = 6.11 \times 10^{at/(t+b)}, \quad (4)$$

where a and b are constants (a=9.5, b=265.5); and RH is indoor relative humidity (%).

Considering the measurement error of the monitoring instruments, the maximum error in the product manual is used in the study of the contribution rate of residential water vapor, although this error value is higher than the calibration standards.

3.3 BWD model

The study assumed that the human body maintains a stable weight over a short period of time; thus, human body water dissipation was viewed as water released by breath, sweat, and urine which is equal to the water dissipation due to drinking. Cooking water dissipation referred to steam dissipation that occurs during cooking. The shower water dissipation includes wet towels, wet surfaces, and the dissipation occurs during showering. Clothes washing dissipation was equal to the weight difference between wet clothes and dry clothes. Personal washing referred to the loss of water vapor during the process of hand washing, face washing, brushing teeth, etc. Floor washing dissipation corresponded to wiping water on the floor. Toilet flushing referred to the evaporation of surface water from the appliance.

We calculated artificial water dissipation by determining the water dissipation categories and counting the number of water users in the building. Furthermore, floor washing water dissipation was calculated based on the floor area and the quota of floor washing. The calculation model was as follows:

$$W_D = \sum_{i=1}^{k} N_i \times D_i + A_t \times \delta \times D_f, \quad (5)$$

where W_D is the BWD (L); i is the water dissipation category (dependent on building function); N_i is the number of water users corresponding to category i; D_i is the amount of water dissipation for category i (L); A_t is the total floor area of the building (m^2); δ is the washing rate of the building floor; and D_f is the water consumption per unit area of ground (mm).

4 Results and discussion

4.1 Office building water use

The two-week monitoring period with one-hour intervals included 10 working days and 4 weekend days. We used the average values of water use, water drainage, and indoor RH over the entire monitoring period. Figure 2 shows the trends of average water consumption, water drainage, and RH at hourly intervals for both weekdays and weekends. The indoor temperature of the office building was constant, varying by less than 1°C. Therefore, it is assumed that the internal temperature of the office building had no effect on RH during the experiment [33]. Thus, the RH represents the absolute humidity of the room. The humidity inside the experimental office building began to drop at midnight and typically reached a minimum value at 07:00–08:00 on both workdays and weekends. During the day, the indoor RH trend was similarly to that of water consumption during the daytime (08:00–18:00), whereas at night, RH typically increased from 18:00 to 24:00 and decreased from 00:00 to 08:00. The weekend trends of RH and water consumption showed a closer correlation than those during the week. Furthermore,

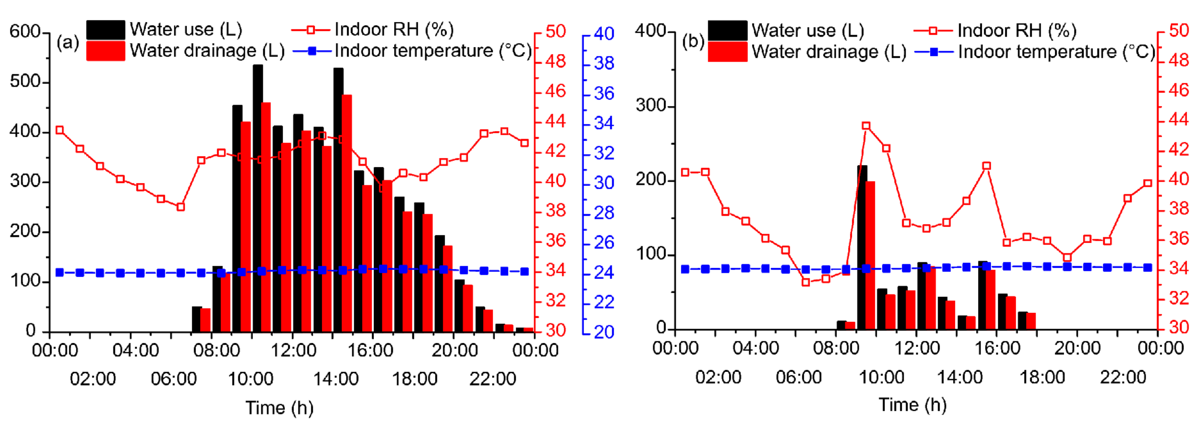

Figure 2 (Color online) Hourly distribution of water use, water drainage, indoor relative humidity (RH), and indoor temperature in the office building on (a) weekdays and (b) weekends.

although the weekday daily water consumption was much higher than that during the weekend, the difference in humidity between the two periods was not substantial.

The red columns (the right side column with the first vertical axis on the right) in Figure 2 indicate water drainage, which had a relatively stable relationship with water use. The drainage coefficient (Figure 3) was zero at night due to no water use from 00:00 to 07:00 on weekdays and from 19:00 to 07:00 on weekends. The drainage coefficient range was small (0.84–0.94), and it varied randomly within this range, indicating that the office building had a relatively stable drainage coefficient. According to the experimental data, the average drainage coefficient for working days and weekends was 0.9. This showed that 90% of the water was transformed into sewage discharge, with the remaining 10% being dissipated. The dominant mechanism of dissipation was the change of liquid water into water vapor.

As the main water consumption parts and major water dissipation sources, lavatories were chosen for further experimental monitoring. Monitoring data included the amount of water used and the number of users in addition to temperature and RH. Figure 4 shows that indoor temperature was essentially stable, with a range of 23.9–24.2°C. Water use has a similar trend to the number of water users, and the per capita water use ranged from 5.9 to 11 L. Linear fitting showed that water use and number of water users had a good linear correlation (R^2=0.89), which explain the occupation density influences the indoor environment [21,34].

4.2 Residential building water use

Figure 5 shows the changes in temperature and RH between an occupied and unoccupied residential room. The room had an area of 9 m^2 with one door and one window. The monitoring period lasted from 00:00 (midnight) on April 28, 2017 to 12:00 (noon) on May 6, 2017. The recording interval was 10 min, and the maximum RH of each hour and the corresponding temperature was used in this study. From 00:00 on April 28 to 06:00 on May 1, there was nobody in the room, and the window and door were closed. During this time, the RH range was 25%–35%, with a temperature range of 25°C–30°C. The average RH was 30.8%, and the average temperature was 27.3°C. From 06:00 on May 1 to 00:00 on May 6, the room was occupied. The curve shows that RH varied significantly during this period, from 25% to 55%, and temperature ranged from 26 to 30°C. The average RH and temperature in occupied condition were 8.2% and 1.2°C higher than the unoccupied status respectively. The timing of peak humidity was typically during cooking. It should be noted that there was no bathroom in the experimental room.

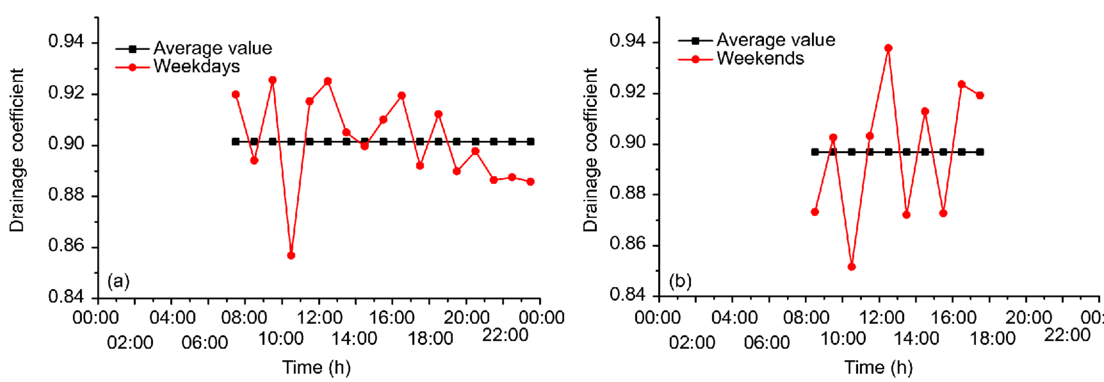

Figure 3 (Color online) Hourly distribution of the water drainage coefficient in the office building on (a) weekdays and (b) weekends.

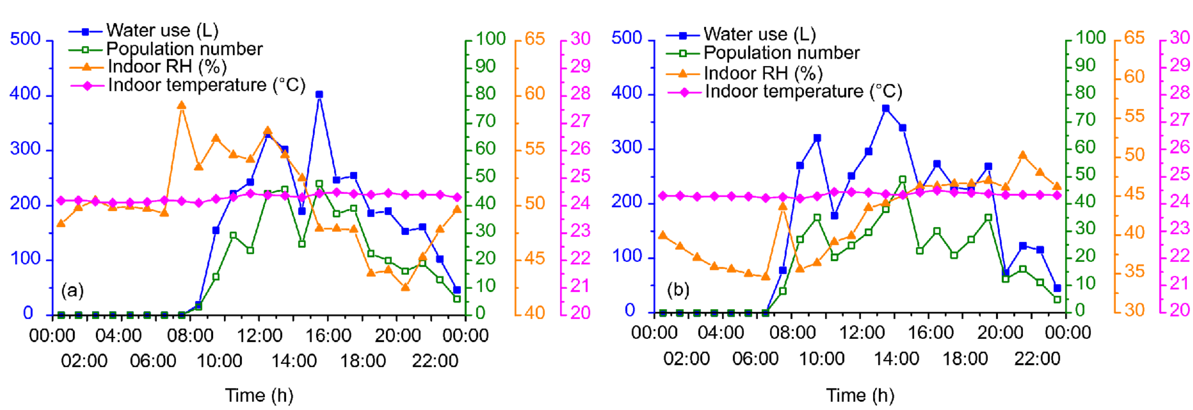

Figure 4 (Color online) Hourly distribution of water use, indoor relative humidity (RH), water users, and indoor temperature in office building lavatories: (a) male toilet and (b) female toilet.

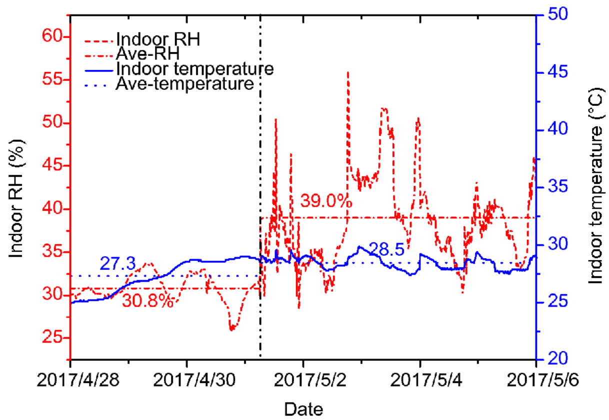

Figure 5 (Color online) Change in relative humidity (RH) and temperature between an unoccupied (00:00 April 28–06:00 May 1) and occupied (06:00 May 1–00:00 May 6) residential room.

To further explore the residential water vapor dissipation and analyze the source of humidity in the residential room, we selected a residential house with a bathroom, kitchen, and bedroom as the case study. Figure 6 shows the maximum RH and corresponding temperature curve over 24 h in one day, which were the average values of the two-week monitoring period. The indoor temperature change was very small (<1°C) throughout the day. The RH values represent the humidity inside the building during the experimental period. Figure 6(a) shows that RH had two peaks in the bathroom during the day, at 09:00 and 17:00. The bedroom and kitchen showed two small peaks during the day, close to the bathroom peak times. This was due to regular human activity in the house, whereby inhabitants arise to wash, eat breakfast, and leave for work prior to 09:00, and returned home at 17:00, when they begin to cook dinner and consume water in other ways.

Figure 7 shows the *D*-values of RH and corresponding temperature in each monitoring time step. The data were the averages of two weeks of monitoring data from 10 apartments of the experimental residential building. Because the temperature *D*-value range was less than ±1°C during the day, the *D*-value of RH reflected the changes in humidity per unit time (1 h) in the building. The *D*-values of the bathroom (Figure 7(a)) were substantially higher than those of the bedroom and kitchen. The maximum *D*-value was over 30% (bathroom), while the minimum was less than 1% (bedroom).

Using the RH and indoor temperature data for the bathroom, bedroom, and kitchen, the indoor vapor was calculated by eq. (1), and the contribution rate of each room is shown in Figure 8. The contribution rate was calculated by area weighting, which was determined by the water vapor density and room size. The average water vapor contribution rate of the bathroom was significantly higher than that of the kitchen and bedroom, and higher than the sum of the latter two. There was no substantial difference between the contribution rates of the kitchen and those of the bedroom. The average results of the two weeks' monitoring data showed that the water vapor contribution rate of the bathroom in the re-

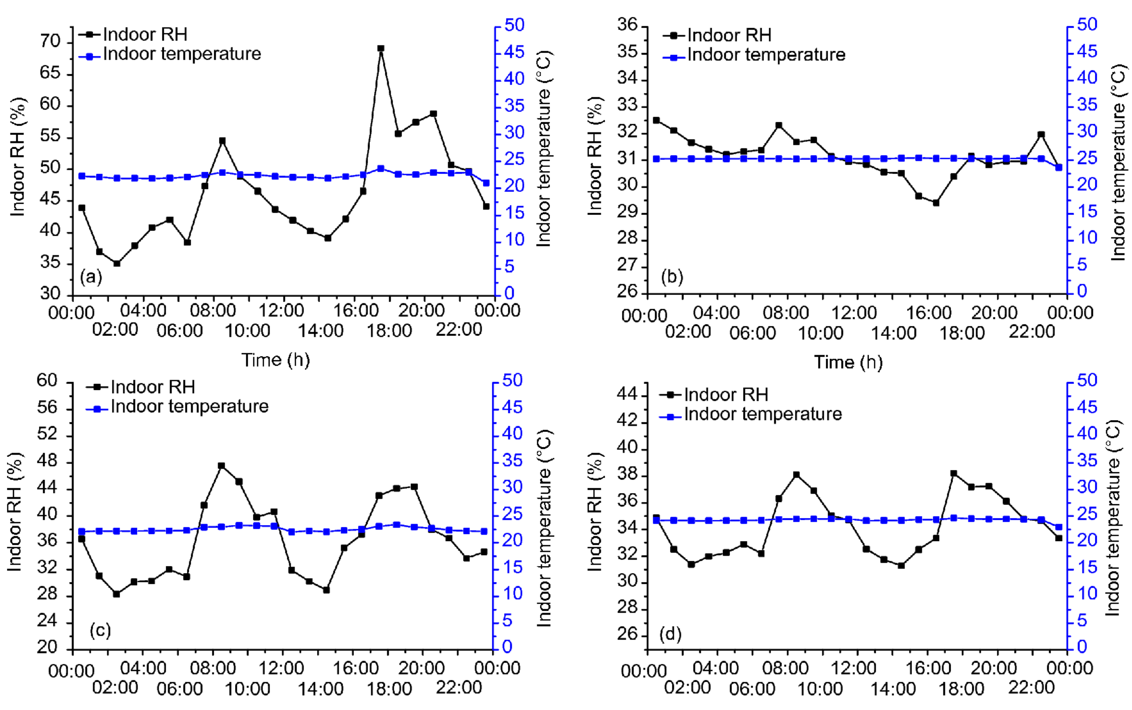

Figure 6 (Color online) Average relative humidity (RH) and temperature changes during a 24-hour period in a residential house in (a) the bathroom, (b) the bedroom, and (c) the kitchen, with (d) the weighted average.

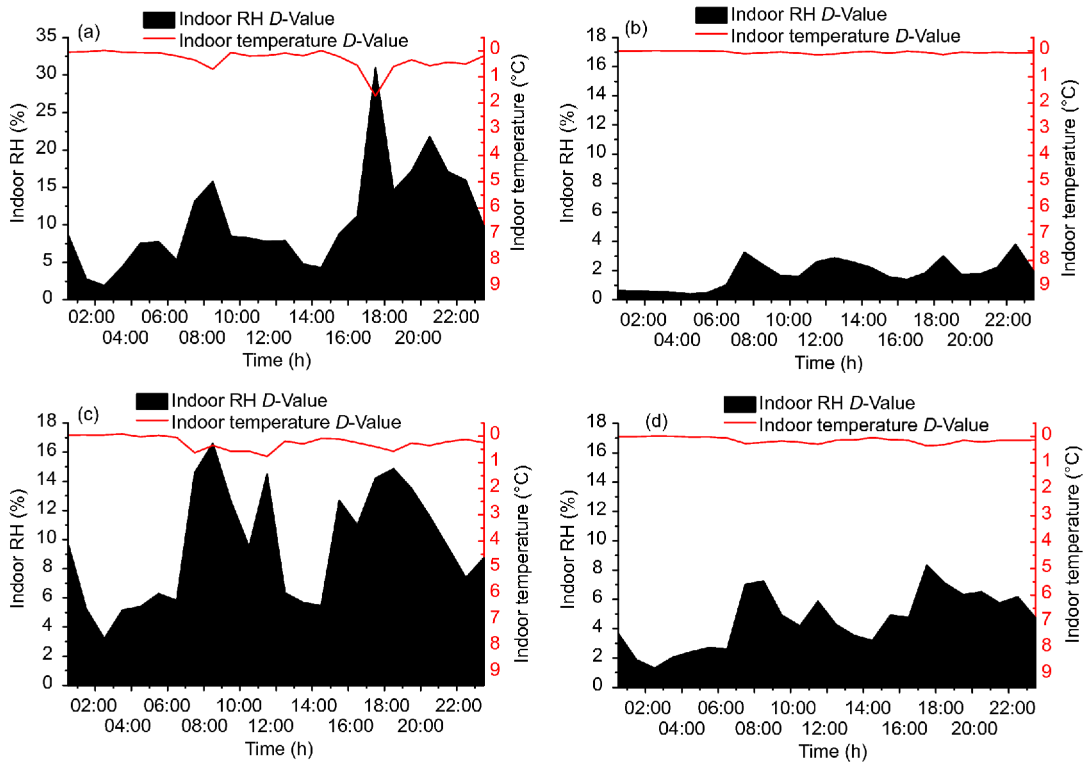

Figure 7 (Color online) Difference value (*D*-value) of the relative humidity (RH) and temperature for each hour of the day in a residential house: (a) bathroom, (b) bedroom, (c) kitchen, and (d) weighted average. Note the different vertical scale in (a).

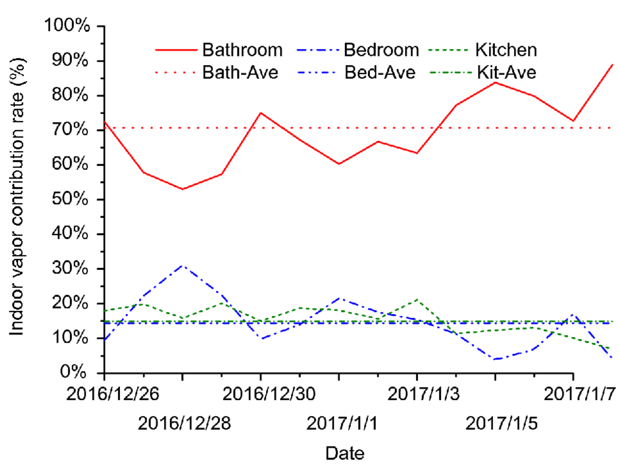

Figure 8 (Color online) Water vapor contribution rate of each room in a residential house.

sidential building was 73.4%, and the bedroom and kitchen was 12.4% and 14.2% respectively. Taking into account the monitoring equipment error (humidity is −3%, temperature is −0.5°C), the contribution rate of bathroom, bedroom, and kitchen is 75.3%, 10.1%, and 14.6% respectively. On the contrary, when the monitor error is 3% for RH and 0.5°C for temperature, the contribution rate of bathroom, bedroom, and kitchen is 65.1%, 19.1%, and 15.8% respectively.

Previous studies have shown that the bathroom had the largest water use of any room in residential buildings and accounted for 60%–70% of total residential water consumption [35]. Toilet flushing and showering represented the largest proportion of water use, and their sum was nearly 80%–90% of bathroom water consumption [36]. However, the main source of bathroom water vapor was showering and personal washing. In the kitchen, cooking was the main source of vapor, and the frequency of cooking determined how much liquid water was transformed into water vapor. Humidifiers were the main source of bedroom vapor; otherwise, breathing and floor moisture were the main sources.

4.3 BWD calculation for case study buildings

Using the experimental data, the amount of water dissipation was obtained for each water use category. The main measurement methods are shown in Table 2, and the number of effective experiments for each water dissipation category was ten, where the term “effective experiment” refers to one with a relative deviation of less than 15% [37]. The per capita frequency represents the water use per water user in the experimental building. Both residential and office building values are displayed in Table 2. The per capita daily water dissipation was 9.8 L in the residential building and 1.2 L in the office building. The amount of floor washing was 0.02 L $(m^2\ d)^{-1}$. This study only calculated the daily value of each case study building; thus, we ignored the water dis-

Table 2 Per capita frequency and amount of water consumption in the residential and office buildings

	Residential building		Office building	
	Frequency	Amount (L)	Frequency	Amount (L)
Personal washing	5	0.1	5	0.025
Cooking	1	2.2	0	2.2
Showering	1	4	0	4
Toilet flushing	3	0.025	3	0.025
Drinking	1	1	1	1
Clothes washing	2	1	0	1

sipation from wet floors.

Water dissipation for the studied residential and office buildings was calculated using the calculation model of eq. (5) and based on the parameters in Tables 1 and 2. We used the measured water consumption volume and the water dissipation calculated by the model to obtain the simulation value of drainage water. Subsequently, we compared this with the experimentally determined water drainage to verify the reliability of the model. Figure 9 shows the model and experimental drainage coefficients for each day over one week. The calculation error of drainage coefficient was from −0.09 to 0.12 which based on the product manual maximum error range. The simulated drainage coefficient results were similarly to measured values for both the office and residential buildings. However, the simulation results of the residential building were better than those the office building, because the number and habits of water users in the former were more stable. Quantitatively, the office building drainage coefficient was higher than that of the residential building; reasons included that the residence building had many higher water dissipation categories, including showering, cooking, and washing clothes. The differences can be

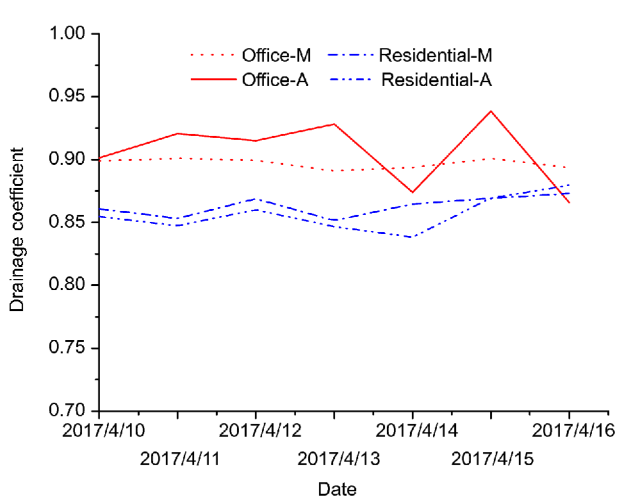

Figure 9 (Color online) Modeled (Office-M, Residential-M) and actual measured (Office-A, Residential-A) drainage coefficients for the office and residential buildings.

seen from Figure 2 (office building) and 6 (residential building), and the temperature values are similar but the RH in Figure 6(a) is higher than those in Figure 2.

5 Conclusions

This study evaluated the indoor humidity changes in an office building and residential building based on monitored RH and temperature data and explored the indoor water vapor sources in these buildings. The measured RH and temperature data in the studied buildings showed a relatively stable RH fluctuation trend throughout the day, which was similar with the water consumption. It is worth noting that the indoor temperature range was very small (<1°C). This means that RH represented the indoor humidity in this study. Compared with the office building, the indoor humidity characteristics of the residential building was more stable. Humidity *D*-values in the bathroom, kitchen, and bedroom of the residential building indicated that the bathroom was the main contributor to residential indoor vapor. The contribution rate was approximately 70%, which was higher than the sum of the kitchen and bedroom humidity values.

BWD was proposed as a concept to describe the transformation of water from a liquid to a gas during the water consumption process. Furthermore, we developed a calculation model that accounted for the number of water users and the total indoor floor area and used the building function to determine water dissipation categories. The model was employed to simulate water dissipation in the studied buildings, and the results were verified using measured water consumption data and drainage coefficients. Both office and residential building simulation results proved the rationality of the model, with a lower simulation error for residential buildings, which was due to internal staff activities and more stable water consumption. As a typical artificial water system, city buildings consume a large proportion of urban water [38]. In China in 2015, buildings made up 37% of the total annual urban water consumption. In Hong Kong, 40% of the total water consumption was domestic water [39]. In developed countries, the building sector is responsible for a much more significant share of total water consumption than in developing countries [40]. Therefore, building water use plays an important role in the urban water cycle flux, and BWD may contribute to the local atmosphere in dry season with good air flow with outdoors. Further research should focus on the conversion mechanism between the indoor and outdoor humidity of buildings and explore the hydrological effect of BWD on the urban water cycle and regional climate change.

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