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Air change rates in urban Chinese bedrooms

Jing Hou[1], Yuexia Sun[1*], Qingyan Chen[1,2], Rongsai Cheng[1], Junjie Liu[1], Xiong Shen[1], Hongwei Tan[3], Haiguo Yin[4], Kailiang Huang[5], Yao Gao[6], Xilei Dai[1], Leiming Zhang[4], Bowen Liu[6], Jan Sundell[1]

[1]Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin, China 300350
[2]School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA
[3]School of Mechanical Engineering, Tongji University, Shanghai, China 200092
[4]School of Building Services Science and Engineering, Xi’an University of Architecture and Technology, Xi’an, Shaanxi, China 710055
[5]Department of Municipal and Environmental Engineering, Shenyang Jianzhu University, Shenyang, China 110168
[6]Shenzhen Institute of Building Research Co., Ltd., Shenzhen, China 518049
[*]*Corresponding email: yuexiasun@tju.edu.cn*

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Practical implications

This study provides a database of air change rates in urban residences in China and concludes that ventilation in Chinese urban residences should be increased. The data are potentially useful for further analyses of indoor air quality, human exposure to indoor air pollutants, and energy consumption in buildings. The database can be useful in formulating Chinese regulations for residential building air change rates.

Abstract

The ventilation modalities in most Chinese residences are infiltration and opening windows. We measured infiltration rates and air change rates at night, with no attempt to change occupants’ behaviors, of urban residences in 5 climate zones of China during 4 seasons. Using the CO_2 decay method, we found the median infiltration rate for 294 residences to be 0.34 h^{-1}. Using occupant generated CO_2 as tracer gas, we determined air change rates over the course of one year in 46 bedrooms at night from mass balance considerations. In 54% of the measurements, windows were closed, so ventilation was only by infiltration. Windows were mainly closed when the outdoor temperature was below 15 °C, and above 26 °C. The median infiltration rates did not differ appreciably among seasons and climate zones, and were always less than 0.45 h^{-1}.

Introduction

Ventilation is the exchange of air between indoors and outdoors. Air change rates are affected by building characteristics, the surrounding environment, climate conditions and occupants’ behavior.[1,2]

People spend most of their time indoors, and especially at night, in residences.[3] Low air change rates result in greater pollution from indoor sources. In the presence of human occupants, low air change rates result in higher indoor air humidity which in turn increases the risk of house dust mite infestation, which adversely affects occupants' health.[4-11] Bornehag et al. found that allergic symptoms in children were related in a dose-response way to lower air change rates in their residences.[8] Sun et al. demonstrated that crowded dormitories with low air change rates were associated with more respiratory infections among college students.[6] Sundell et al. showed that sick building syndrome (SBS) was associated with low air change rates.[12,13] Thus, it is important to study air change rates in residences.

Sweden has measured air change rates since the 1940's, and the resulting historical record shows that air change rates in residences have decreased. In 1947, Rydberg reported a median air change rate of 1.20 h^{-1} in Stockholm residences.[14] In 1968, Carlsson and Sundell reported a median air change rate of 0.80 h^{-1} for Stockholm residences.[15] Later studies in Sweden reported air change rates of 0.33 h^{-1} in residences (1992),[16] and 0.37 h^{-1} (2002).[8] These studies show that the efforts to save energy beginning in the mid-70s have reduced air change rates. At the international Healthy Buildings conference in Stockholm 1978, a main theme was "Build tight - Ventilate right". Since then, the mantra "Build tight" has been the dominant philosophy in most countries.[1] As different countries use different building codes and have different cultures with respect to occupant behaviors, the corresponding air change rates likely differ as well. Table 1 reports air change rates in residences from large scale studies (more than 200 residences). These investigations used passive tracer gas techniques (PFT) and mass balance of occupant generated CO_2 to measure the air change rates. The air change rates were mostly less than 1 h^{-1}.

Table 1 Large scale air change rate measurements (more than 200 residences) in residential buildings

Study	Location	Number of residences	Method and measurement duration	Measured period	(Mean or median) Air change rates (h^{-1})	Comments
Ruotsalainen et al. [17]	Finland	242	PFT [a], 2-week	1988.11-1989.4	0.52	Residences, mean
					0.62	Apartments with natural ventilation, mean
Stymne et al.[16]	Sweden	1143	PFT	1991.11-1992.4	0.33[b]	Single-family houses with natural ventilation, mean
					0.48[b]	Apartments with natural ventilation, mean
Öie et al.[18]	Norway	344	PFT, 14-day	1992.05-1995.05, excluding summer months	0.73[b]	Apartments with natural ventilation, mean
					0.68[b]	Single family houses with natural ventilation, mean
Emenius et al.[19]	Sweden	540	PFT, 4-week	1994-1996, winter	0.68	Residences, mean
Yamamoto et al.[20]	US	509	PFT, 2-day	1999-2001	0.71	Residences, median
					0.87	California, residences, median
					0.88	New Jersey, residences, median
					0.47	Texas, residences, median
Bornehag et al.[8]	Sweden	390	PFT, 1-week	2001.10- 2002.04	0.36	Single-family houses, mean
					0.48	Multi-family houses, mean
					0.37	Single-family houses with natural ventilation, mean
					0.34	Bedroom of single-family houses with natural ventilation, mean
Langer et al.[21]	France	567	CO2 method[c], nighttime	2003.10- 2005.12	0.44	Bedrooms, median
Bekö et al.[22]	Denmark	500	CO_2 method, nighttime	2008.03- 2008.05	0.46	Bedrooms, geometric mean

					0.62	Bedrooms, arithmetic mean
Langer and Bekö[23]	Sweden	305	PFT, 2-week	2007.10-2008.05	0.38	Residences, median
Hou et al.[24]	China	399	CO_2 method, nighttime	2013.09- 2016.06	0.27	Spring, residences, median
					1.11	Summer, residences, median
					0.29	Autumn, residences, median
					0.30	Winter, residences, median
					0.57	Spring, bedrooms, median
					1.81	Summer, bedrooms, median
					0.45	Autumn, bedrooms, median
					0.45	Winter, bedrooms, median

[a] Passive tracer gas techniques (perfluorocarbon tracer).[25]

[b] Units were converted to ‘h^{-1}’ from ‘$l/(s \bullet m^2)$’ corresponding to a room with a height of 2.5m.

[c] Mass balance for occupant generated CO_2.

In China, few residential buildings use mechanical ventilation. Outdoor air is brought in primarily through infiltration and window opening. Information on air change rates in Chinese residences is scarce.[24] It is not known whether the natural ventilation (infiltration and window opening) widely used in China provides residences with sufficient airflow from outdoors. To evaluate the importance of air change rate on indoor air quality and occupants' health, we launched a national investigation of ventilation in residences in 2016. The present study aims to provide a database on infiltration rates (i.e., with window closed) and air change rates at night in four seasons in Chinese residences in five climate zones.

Methods

In order to have a more complete view of residential ventilation status in China, we conducted this study in all five climate zones: severe cold zone (SC), cold zone (C), mild zone (M), hot summer and cold winter zone (HSCW), and hot summer and warm winter zone (HSWW), as shown in Fig. 1. Since more than half of the Chinese population lives in cities, this study focused on cities of 11 representative provinces/municipalities in the five climate zones with high population density: Xinjiang, Liaoning, Tianjin, Shaanxi, Shanghai, Hubei, Hunan, Chongqing, Yunnan, Guangdong and Guangxi. Table S1 in the supplementary information shows the climatic characteristics of these five climate zones.[26]

We first performed a background survey to investigate building characteristics of residences in each area. The survey asked occupants to report construction year, heating system, cooling system, ventilation system, floor level and window type of the residences. The questionnaire was answered by approximately 300 randomly selected residents in each region. Then, 30-60 residences were randomly recruited in each region for measurements and inspection. We made both on-site short-term measurements and on-line long-term measurements, as shown in Fig. 2. The short-term measurements were for infiltration rate in each season and air change rate with windows fully open in winter. The long-term measurements were for air change rate at night (with no attempt to change occupants' behaviors) and the opening status of windows/doors, and were conducted continuously from January 1, 2017 to December 31, 2017. Seasons are defined by heating and cooling periods: spring is defined as 16 March to 31 May, summer as 1 June to 31 August, autumn as 1 September to 14 November, and winter as 15 November to 15 March.

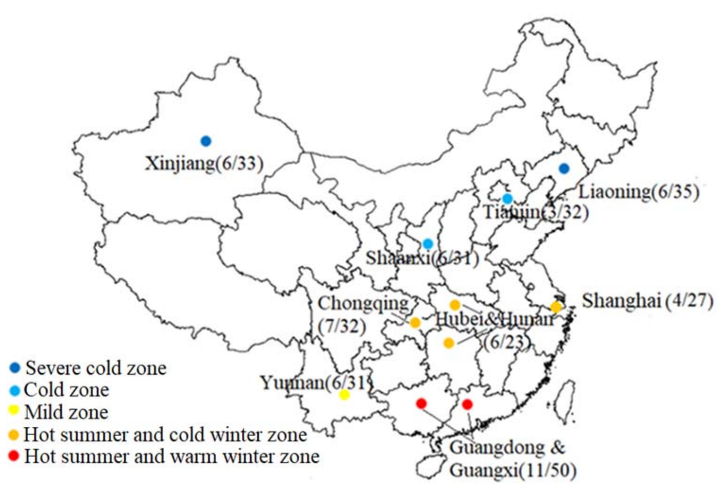

Fig.1 Residence locations and climate zones (Number of residences for long-term measurement / short-term measurement)

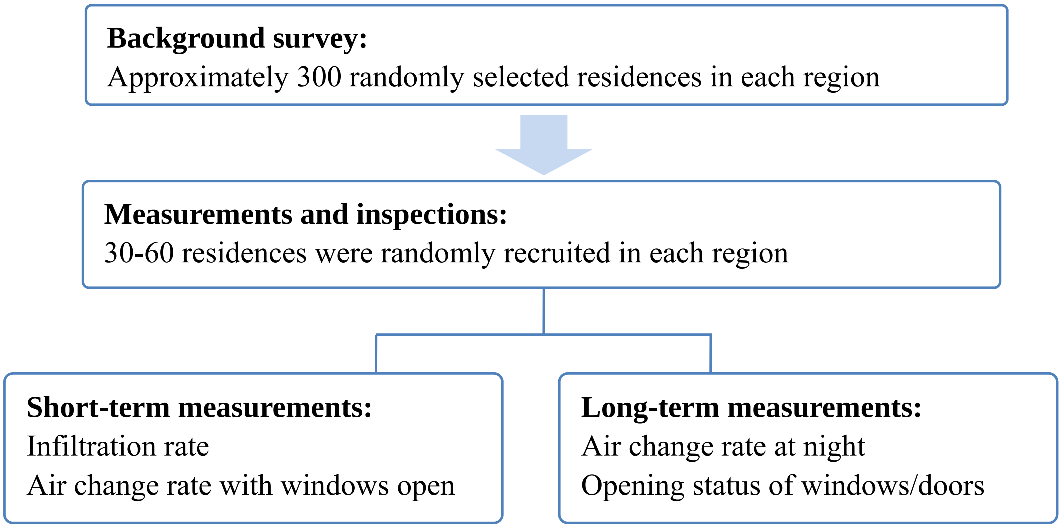

Fig.2 Flow chart for sample selection

Air change rate measurements and calculations

We used the decay method to measure infiltration rate and air change rate with windows open for short-term repeated measurements with no people in the room. For long-term measurements we used the constant injection method (mass balance of occupant generated CO_2) for air change rates at night when people are sleeping, and thus have approximately constant CO_2 emission rates.

1)Short-term repeated measurements of infiltration and air change rates with windows open

Air change rates in bedrooms with windows and doors closed (i.e., infiltration rate), as well as with windows fully open, were measured using the CO_2 decay method.[27] CO_2 from a portable gas tank was released as the tracer gas, and mixed by fans in the bedrooms. CO_2 monitors (AZ 7798, AZ Instrument Corp., Taiwan, China; or Telaire T7001, Telaire Ltd., Santa Barbara, CA, USA) sampled and recorded the concentration at intervals of one minute for 30 to 60 minutes, during which there was no tracer gas source in the bedroom. The CO_2 monitors have an accuracy of 50 ppm, or ±5% of reading. CO_2 monitors were calibrated before the measurements. We assumed an outdoor CO_2 concentration of 400 ppm. The infiltration rate measurements were repeated in each season, but the air change rates with windows open were only measured in winter.

2)Long-term measurements of air change rate at night (with no attempt to change occupants' window opening behavior)

The air change rates in bedrooms at night were measured with occupants maintaining their regular routine regarding opening doors and windows. The CO_2 produced by occupants was used as the tracer gas. Miniature infrared sensors (SenseAir S8) were used to measure CO_2 concentrations at one-minute intervals. Before the measurements, the sensors were calibrated.

These sensors have an accuracy of 70 ppm, or ±3% of reading. They were installed in bedrooms and living rooms and connected to a central server through Wi-Fi. The monitored CO_2 concentrations were uploaded through the server. Magnetic sensors were used to record the window and door opening status. Two-hour average outdoor meteorological parameters, including outdoor air temperature, were obtained from the nearest weather stations for the whole year.

Hou et al.[24] details the method for calculating air change rate by the "CO_2 method". Here we briefly describe the method. First, CO_2 emission rates were calculated from each occupant's weight and height,[28] and volumes of the bedrooms were measured. The air change rate was determined by fitting a non-linear curve based on the mass balance equation to the measured pattern of CO_2 concentration at a given CO_2 emission rate (calculated from weight and height data), room volume and outdoor CO_2 concentration (as shown in Supplementary Document, "Air change rate calculation by using 'CO_2 method'"). Outdoor CO_2 concentration was assumed to be 400 ppm. We measured CO_2 concentration for three hours between 0:00 and 7:00. The air change rate with the minimum sum of the squares for nonlinear fitting was used to represent the air change rate for that night. The whole residence was considered as a single zone when the difference between CO_2 concentrations in living room and bedroom was less than 10%;[29] that is, the bedroom had the same air change rate as the whole residence. Otherwise, the investigated bedroom was considered as a separate zone, which may bring uncertainty due to ignoring internal zone air flow. However, a previous study demonstrated that this uncertainty was less than 30%.[22] The residences in Shanghai, Hubei and Hunan had no CO_2 sensor in the living room, so if the occupant reported that the bedroom door was open during night, we treated the whole residence as a single zone.

Results

We obtained 2223 responses from the background survey, a response rate of 79.1%. Supplementary Table S2 compares building characteristics between the surveyed and inspected residences. More than 90% of both surveyed and inspected residences were built after 1990. Older residences (built before 1980) were very few (3.1% of surveyed residences and 1.4% of inspected residences). Most residences had metal frame windows (90% of survey and 96% of inspected) and double glass panes (64% of survey and 77% of inspected). Thus, the inspected residences represent Chinese urban housing stock well.

We selected 294 residences for inspection, and monitored 55 of these for a full year. Fig. 1 and Table 2 summarize the distribution of these residences in different climate zones and their building characteristics.

Short-term on-site measurements of infiltration rates were repeated in each season. Air change rates with windows open were measured in winter only. We missed doing measurements in some bedrooms in some seasons. Table 3 shows the final sample size for data analysis of the short-term on-site measurements (i.e., infiltration rate and air change rate with window open). Among the 55 residences that participated in the long-term measurements, eight families moved and the internet connection failed for one home. Thus, we have long-term on-line measurements for 46 residences.

Table 2 Building characteristics of 294 inspected and measured residences

Characteristic		n	%
Type of building			
	Villa	10	3.4
	Apartment	284	96.6
Area of residence (m^2)			
	<80	53	18.5
	80-120	122	42.7
	>120	111	38.8
	No information	8	
Floors			
	1 -3	67	23.8
	4 -6	74	26.3
	7 -10	43	15.0
	11 -19	49	17.1
	⩾20	48	16.8
	No information	3	
Construction year			
	⩾2011	141	50.9
	2001-2010	99	35.7
	1991-2000	27	9.7
	1981-2000	6	2.2
	≤1980	4	1.4
	No information	17	
Retrofit year			
	≥2011	216	76.1
	2001-2010	61	21.5
	1991-2000	7	2.5
	No information	10	
Type of window frame			
	Wood	4	1.4
	Aluminum	120	42.4
	Plastic-steel	153	54.1
	Others	6	2.1
	No information	11	
Type of glass pane			
	Single pane	62	22.0
	Double pane	216	76.6
	Others	4	1.4
	No information	12	
Type of window			
	Sliding window	101	36.9
	Casement window	170	62.0
	Pivoted window	3	1.1
	No information	20	

Table 3 Sample size for air change rate analyses

Season	Short-term measurement		Long-term measurement
	Infiltration rate	Air change rates with windows open	
Spring	208		
Summer	227		46 residences for one year
Autumn	196		
Winter	216	165	

Short-term measurement of infiltration rates and air change rates with windows open

Table 4 shows the total of 847 measurements of infiltration rates in bedrooms, and Table 5 shows their association with building characteristics and climate zones. Infiltration rates in summer and winter were higher than those in spring and autumn, but the seasonal differences were not significant (p=0.15). The bedrooms in northern China (SC and C zones) had lower infiltration rates compared to those in southern China. However, throughout China, and in all seasons, the infiltration rates were consistently low, with a median value of 0.34 h^{-1}. Residences with different building characteristic had different infiltration rates. Residences with casement windows had significantly lower infiltration rates than those with sliding windows (p=0.00). In northern China (SC and C zones), rooms with casement windows (74.8%) and double glass pane windows (96.7%) were more common than in southern China (M, HSCW and HSWW zones) (casement window: 52.7%, double glass pane window: 62.8%).

Table 4 Annual and seasonal infiltration rates in the bedrooms of 294 residences

Season	Number of measure-ments	Infiltration rate, h^{-1}						
		Min	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile	Max
Annual	847	0.01	0.08	0.22	0.34	0.56	1.12	3.57
Spring	208	0.01	0.07	0.18	0.32	0.59	1.21	3.57
Summer	227	0.01	0.09	0.24	0.38	0.60	1.16	3.10
Autumn	196	0.01	0.06	0.20	0.32	0.49	0.95	1.70
Winter	216	0.02	0.12	0.24	0.36	0.54	1.30	2.41

Table 5 Infiltration rates in bedrooms stratified by building characteristics and climate zones in 294 residences

Parameter		Number of measurements (%)	Median, h^{-1}	p-value[a]
Floors				
	1 -3	190 (23.1)	0.32	0.82
	4 -6	218 (26.7)	0.33	
	7 -10	125 (15.3)	0.35	
	11 -19	151 (18.5)	0.34	
	⩾20	134 (16.4)	0.33	

Construction year				
	⩾2011	419 (51.5)	0.36	0.35
	2001-2010	283 (34.7)	0.33	
	⩽2000	112 (13.8)	0.32	
Retrofit year				
	≥2011	634 (76.8)	0.34	0.74
	2001-2010	171 (20.7)	0.34	
	≤2000	20 (2.4)	0.48	
Type of window frame				
	Aluminum	346(43.4)	0.31	0.05
	Plastic-steel	451 (56.6)	0.36	
Type of glasses pane				
	Single pane	174 (21.2)	0.37	0.33
	Double pane	648 (78.8)	0.33	
Type of window				
	Sliding window	275 (34.8)	0.37	0.00
	Casement window	516 (65.2)	0.32	
Climate zone				
	Severe cold zone	190 (22.4)	0.30	0.00
	Cold zone	227 (26.8)	0.31	
	Mild zone	118 (13.9)	0.38	
	Hot summer and cold winter zone	185 (21.8)	0.41	
	Hot summer and warm winter zone	127 (15.0)	0.34	

[a] *p*-value in Kruskal-Wallis H test.

We measured the air change rates of 165 bedrooms with windows fully open in winter. The distribution of these air change rates compared to winter infiltration rates is shown in Table S3. The median air change rate with windows fully open was 17 times higher than the median infiltration rate. The results indicate sufficient ventilation in those residences with windows open. However, people tend to close windows in favor of thermal comfort, as shown in Figs. 3 and 4.

Long-term measurements of air change rates at night and window status

Fig. 3 depicts the window status in bedrooms at night. In northern China with severe cold and cold climate, bedrooms had windows closed for more than 81% of winter nights, while in southern China with hot summer climate, bedrooms had closed windows for 46%-61% of summer nights. Fig.4 further illustrates the association between outdoor air temperature and opening windows at night. When the outdoor air temperature was either low (below 15 ℃) or high (above 26 ℃), people tended to close windows. In addition to outdoor temperatures, other factors such as bedroom size, occupancy level, proximity to a main road and cooling/heating style may also influence window opening/closing behavior. The effects of these factors on window opening behaviors at night were analyzed in logistic regression models, as shown in Supplementary Table S4. Statistical analyses show that people who had their bedroom near to a main road and used air conditioning tended to close windows, and the associations were significant (p<0.05).

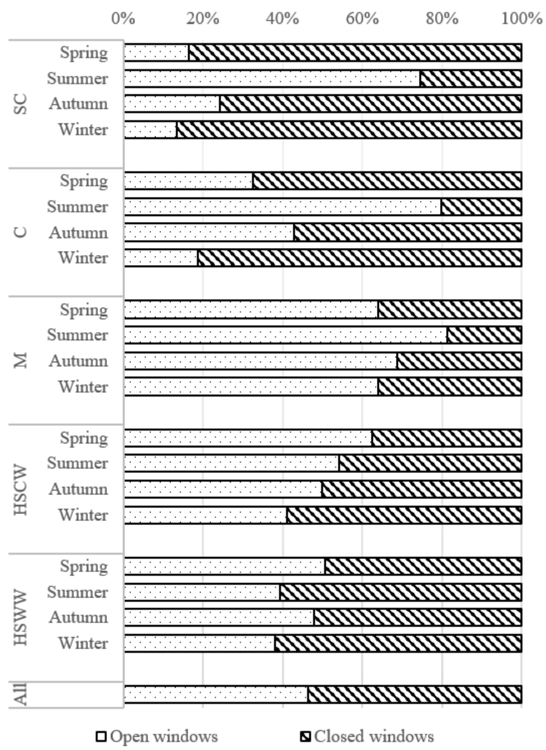

Fig. 3 Window opening status in bedrooms at night in 46 residences. (SC: severe cold zone, C: cold zone, M: mild zone, HSCW: hot summer and cold winter zone, HSWW: hot summer and warm winter zone)

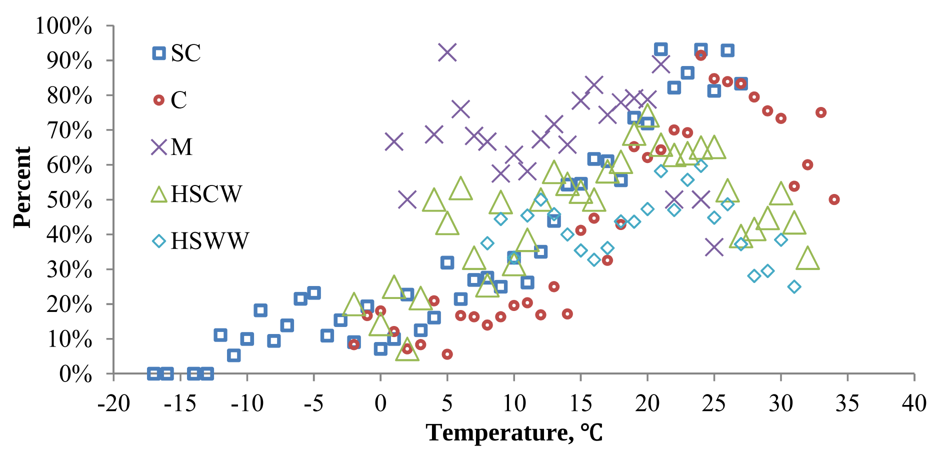

Fig. 4 Percentage of open windows at night in 46 residences in different outdoors air temperatures (SC: severe cold zone, C: cold zone, M: mild zone, HSCW: hot summer and cold winter zone, HSWW: hot summer and warm winter zone)

Table 6 shows air change rates in different climate zones and their associations with window status. In the severe cold zone, windows were closed 82% of the time in spring, autumn and winter, resulting in a median air change rate for these three seasons of 0.34±0.01 h^{-1}. In the cold zone, windows were closed 69% of the time in spring, autumn and winter, resulting in a median air change rate of 0.46±0.05 h^{-1}. Summer had relatively higher air change rates in these two climate zones. On the other hand, the warmest climate zone, with hot summer and warm winter, had windows closed 61% of the time in summer, and were totally closed 56% of the time. Opening windows yields different air change rates in different seasons. In cold seasons, opening windows means a relatively small increase in air change rate, while in warmer season opening windows means more ventilation. Table 7 shows the distribution of CO_2 concentrations in bedrooms at night. The highest median CO_2 concentration during the year was found in the HSWW zone. In winter and autumn in the SC zone and the summer and winter in the HSWW zone, days when the CO_2 concentration was higher than 1000 ppm were more common (more than 60%).

Table 6 Air change rates at night in bedrooms of 46 residences

	All		Open window		Closed window	
	N[a]	Median air change rate (h^{-1})	N (%)	Median air change rate (h^{-1})	N (%)	Median air change rate (h^{-1})
Severe cold zone, 10 residences						
Spring	564	0.34	93 (16.5)	1.58	471 (83.5)	0.26
Summer	710	1.92	530 (74.6)	2.95	180 (25.4)	0.33
Autumn	559	0.33	135 (24.2)	1.45	424 (75.8)	0.24
Winter	534	0.34	71 (13.4)	1.32	458 (86.6)	0.30
Cold zone, 8 residences						
Spring	452	0.46	147 (32.5)	1.32	305 (67.5)	0.31
Summer	493	1.44	394 (79.9)	1.74	99 (20.1)	0.40
Autumn	379	0.52	162 (42.7)	1.37	217 (57.3)	0.35
Winter	556	0.41	94 (18.8)	0.87	405 (81.2)	0.37
Mild zone, 5 residences						
Spring	245	1.38	157 (64.1)	2.21	88 (35.9)	0.27
Summer	247	2.32	201 (81.4)	3.16	46 (18.6)	0.17
Autumn	179	1.87	123 (68.7)	2.33	56 (31.3)	0.14
Winter	247	1.61	158 (64.0)	2.08	89 (36.0)	0.33
Hot summer and cold winter zone, 14 residences						
Spring	822	0.96	361 (62.6)	1.74	216 (37.4)	0.42
Summer	1014	0.91	467 (54.3)	1.51	393 (45.7)	0.44
Autumn	588	1.16	238 (49.9)	1.81	239 (50.1)	0.45
Winter	843	0.55	198 (41.2)	1.86	283 (58.8)	0.38
Hot summer and warm winter zone, 9 residences						
Spring	451	0.84	229 (50.8)	2.28	222 (49.2)	0.24
Summer	603	0.57	237 (39.3)	2.38	366 (60.7)	0.36
Autumn	403	0.78	193 (47.9)	2.59	210 (52.1)	0.39
Winter	325	0.43	118 (38.2)	2.07	191 (61.8)	0.26

[a]Sum of measured nights of each residence.

Table 7 CO_2 concentrations at night (0:00-7:00) in bedrooms

		Average CO_2 concentration			Peak CO_2 concentration	Days of CO_2 concentration >1000 ppm
		All	Open window	Closed window		
	N[a]	Median, ppm	Median, ppm	Median, ppm	Median, ppm	N (%)
Severe cold zone, 10 residences						
Spring	564	1076	785	1138	1289	408 (72.3)
Summer	710	558	529	840	692	135 (19.0)
Autumn	559	1056	786	1211	1278	382 (68.3)
Winter	534	1017	878	1037	1165	345 (64.6)
Cold zone, 8 residences						
Spring	452	866	550	1010	1006	229 (50.7)
Summer	493	658	605	936	775	150(30.4)
Autumn	379	833	642	1052	974	173 (45.6)
Winter	556	894	673	976	1012	282 (50.7)
Mild zone, 5 residences						
Spring	245	661	582	950	793	63 (25.7)
Summer	247	570	545	1359	670	32 (13.0)
Autumn	179	613	580	682	715	22 (12.3)
Winter	247	640	588	890	759	57 (23.1)
Hot summer and cold winter zone, 14 residences						
Spring	822	646	514	877	778	278 (33.8)
Summer	1014	653	561	873	799	349 (34.4)
Autumn	588	549	487	952	638	185 (31.5)
Winter	843	855	494	1113	996	424 (50.3)
Hot summer and warm winter zone, 9 residences						
Spring	451	817	549	1402	982	222 (49.2)
Summer	603	1156	492	1525	1375	382 (63.3)
Autumn	403	872	508	1490	1073	212 (52.6)
Winter	325	1296	555	1612	1621	207 (63.7)

[a]Sum of measured nights of each residence.

Fig.5 illustrates window opening behavior in different zones and seasons resulting in strong seasonal variation of air change rates in Chinese residences. From cold climate zones to warm climate zones, seasonal variation of air change rate became smaller and smaller. In winter, air change rates were the lowest in all zones except the mild zone. In northern China with severe cold and cold climate, air change rates were less than 0.5 h^{-1}, the minimum requirement specified in many building codes,[30] on 61% and 62% of winter nights. In southern China with hot summer climate, air change rates were less than 0.5 h^{-1} in 47% (HSCW zone) and 54%

(HSWW zone) on winter nights. In summer, air change rates were the highest except in the climate zones with hot summers. In northern China for severe cold and cold climates, air change rates were less than 0.5 h^{-1} for 17% and 14% of summer nights. In southern China for hot summer climates, air change rates were less than 0.5 h^{-1} for 24% (HSCW zone) and 44% (HSWW zone) of summer nights. In the mild zone, air change rates were lower than 0.5 h^{-1} for 15%-27% of all of the seasons.

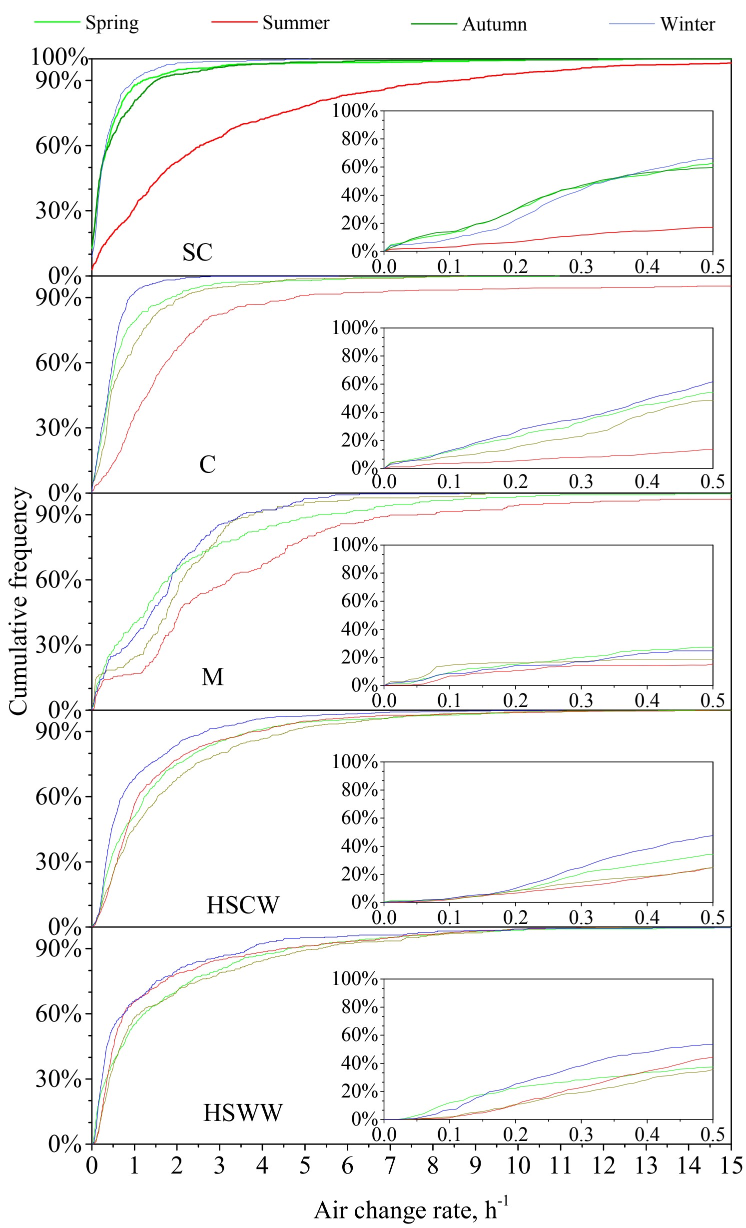

Fig. 5 Cumulative frequency of air change rate (with no attempt to change occupants' behaviors) at night in 46 residences in different seasons (SC: severe cold zone, C: cold zone, M: mild zone, HSCW: hot summer and cold winter zone, HSWW: hot summer and warm winter zone) (The little graphs inside are enlarged for air change rates of 0.0 to 0.5 h^{-1})

Error analysis

In this study, the accuracy of CO_2 monitors and the assumption of outdoor CO_2 concentration (as 400 ppm) may cause errors in air change rate. The accuracy of CO_2 monitors and variation of outdoor CO_2 concentration are shown in Supplementary Table S5. The process of error analysis is shown in Supplementary Document: “Error analysis of air change rate”. In short-term measurement, infiltration rates had errors of -5% to +5%, while air change rates with windows open had errors with a range of -13% to +14% (Supplementary Fig. S1). Air change rates at night in long-term measurement had errors of -22% to +37% (Supplementary Fig. S2).

CO_2 monitors were only calibrated at the beginning of the one-year measurements. Readings of these monitors may drift during the one year of measurement. In order to characterize the CO_2 monitors’ drifting and estimate the resulting error in air change rate, we recalibrated twelve randomly selected CO_2 monitors in 2019, among which six monitors (AZ 7798) were used for short-term measurements and six sensors (SenseAir S8) for long-term measurements. The calibration results are described in detail in Supplement Document: “Error analysis of air change rate”. Readings of CO_2 monitors for short-term measurement did not drift. However, the lower limit of CO_2 sensor for long-term measurement drifted from original -3% to -10%, which caused an 3% extra error of air change rate at night. Therefore, the error of air change rate at night in long-term measurement can be a much as +40%.

Discussion

In this study, we compiled a database of infiltration rates for different building characteristics, seasons and climate zones, and air change rates at night for different window opening behaviors, seasons and climate zones in Chinese urban bedrooms.

In China, few studies have been carried out on infiltration rates in homes.[33-35] Shi et al. measured 34 residences in northern China, and found that infiltration rates ranged from 0.05 h^{-1} to 0.59 h^{-1} with a median value of 0.17 h^{-1}.[33] Cheng and Li measured the infiltration rates in 202 residences in southern China, and found they ranged from 0.05 to 1.32 h^{-1}, with a median value of 0.38 h^{-1}.[35] These rates are consistent with our short-term measurements in which we found that infiltration rates were lower in northern China (SC and C zones) bedrooms than in southern China (M, HSCW and HSWW zones). This may be due to tighter building construction in the cold zones. For example, rooms with casement windows and double glass pane windows were more common in northern China (SC and C zones) than in southern China (M, HSCW and HSWW zones). Additionally, the greater temperature difference between indoors and outdoors in northern China may also contribute to the different infiltration rates. However, our results showed little difference in infiltration rates for four seasons (p=0.15). The infiltration rates obtained from long-term measurements (i.e. air change rate with closed window) were different from those for short-term measurements, which may be due to the different sample sizes and different climates. However, the difference was not significant.

Air change rate is strongly influenced by occupants’ window opening behavior. Thus, the residents play an important role in the ventilation level in their own homes. In a Japanese study, 87% of the total air change rate was accounted for by the behavior of the occupants.[36] Howard-Reed et al. found that window opening increased the air change rate by 0.10-2.8 h^{-1}.[37] A study in Denmark found that the air change rates in bedrooms with windows half-open or ajar were approximately twice as high as those in rooms with closed windows.[22] In our study, the air change rate in bedrooms with fully open windows was 17 times higher than in bedrooms with closed windows. The air change rates with open windows in long-term measurements were lower than in short-term measurements. One explanation is that occupants did not fully open windows in everyday life, and additionally that opening windows in cold season means a small opening, while in warmer season, windows are more widely open. Generally, people do not often open windows in Chinese residences in winter or in summer. The different proportion of closed windows in different climate zones and seasons could be due to the different outdoor temperatures. Occupants do not open windows in winter as it will be cold indoors, and in summer they do not open windows as they are likely using air conditioning.

Most of the large scale studies of residential air change rates in other countries (see Table 1) have been conducted in Nordic countries during cold seasons, where the climate is similar to that in northern China. These studies show that a large percentage of the residences did not fulfil the minimum requirement of 0.5 h^{-1}.[30] A Danish study measured air change rates in 500 children's bedrooms in March to May 2008 and reported that approximately 57% of bedrooms had air change rates lower than 0.5 h^{-1}.[22] The DBH-study of Sweden found that 80% of the single-family houses and 60% of the multi-family houses had air change rates lower than 0.5 h^{-1} in October 2001 and April 2002.[8] Another Swedish study found that 74% of apartments measured during October 2007 and May 2008 had air change rates lower than 0.5 h^{-1}.[23] In a study in mainland France, 51% of apartments had air change rates at night lower than 0.5 h^{-1}.[21] The only previous study of air change rates in Chinese residences (China, Children, Homes, Health study in Tianjin) was conducted in the cold zone and reported that at night, approximately 71% of residences had an air change rate lower than 0.5 h^{-1} for the whole year,[24] which is consistent with our study, that air change rates at night in northern China (SC and C zones) in spring, autumn and winter were generally lower than 0.5 h^{-1}. In southern China (HSCW and HSWW zones), especially in the HSWW zone, air change rates at night in both summer and winter were low. Air change rates at night in the mild zone were the highest, consistent with the high percentage of open windows. There have been no data on air change rates in residences in southern China in previous studies. A Shanghai (HSCW zone) study, reported significantly higher CO_2 concentrations in winter than summer or autumn, and that average CO_2 concentrations in 45.6% of residences were higher than 1000 ppm at night regardless of the season,[38] which is slightly greater than in our study.

Residences in general are not single zone and air change rates differ between zones, in which case a multizone mass balance equation should be used to account for the effects of interzone airflows.[39] The CO_2 method in our study, however, has its limitations regardless of possible interflow from adjacent rooms. When we treated the bedroom as a separate zone, we may have overestimated air change rates in bedrooms because of possible interflow from adjacent rooms. Bekö et al.'s analysis concluded that the average error is less than 30%.[22] This means that actual air change rates in urban Chinese bedrooms are likely even lower than what we have reported here. When the whole dwelling is considered as a single zone, errors arise from the assumption that the CO_2 concentrations in other bedrooms are consistent with those of the measured space. A study found that the error from the single and well-mixed air zone assumption could be 16%.[40]

Strengths and Limitations

The novelty and strength of this study are that we report data for all climate zones in China, and for all seasons. We measured ventilation as it was during normal occupancy and window opening behavior. The measurement period in this study was one year, which is longer than in all previous large scale studies (Table 1).

One limitation of our study is that only residences in urban areas (i.e., apartments and villas) were selected while typical rural residences, i.e. Pingfang, were not studied. However, our previous study of air change rate at night in the same climate zone showed no significant differences between urban residences (0.32 h^{-1}) and rural residences (0.30 h^{-1}).[24]

A second limitation of this study is that the sample sizes were small for long-term measured air change rates. There may be limited variability in underlying factors, for example, the occupants' behaviors and building characteristics. Although these residences might be typical in China, the limited number make it difficult to generalize results. However, the air change rates and CO_2 concentrations are distributed similarly to those reported in previous Chinese studies for the same seasons and the same climate zones.[24,32,38] Our measured air change rates may thus validly characterize air change rates for Chinese residences.

A third limitation is that the majority of inspected residences were new compared to the surveyed residences according to Supplementary Table S2. However, we did not find significant differences from the median air infiltration rate of 0.34 h^{-1} for different years of construction. This may be because (1) residential construction technology has not changed appreciably in the past 30 years; (2) most Chinese urban residences were built after the 1990s;[31] and (3) many older buildings have had windows replaced (Table 2).

Conclusions

In northern China, people prefer to close windows during spring, autumn and winter. In summer, people throughout China do not open windows when the outdoor temperature is high, probably because they are using air conditioning. The result is that in approximately 54% of Chinese bedrooms, regardless of climate region or season, the only outdoor air entering bedrooms is by infiltration, and infiltration rates are low (median: 0.34 h^{-1}). Natural ventilation (with no attempt to change occupants' behaviors), that is open windows, cannot be relied on for achieving an adequate actual air change rate in residences. In Chinese residential building, ventilation systems, that is, mechanical or natural, are needed.

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