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Measured air tightness performance of residential buildings in North China and its influence on district space heating energy use

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ABSTRACT

There is little known about air tightness performance of residential buildings in north China and its effect on district heating. Air tightness performance of two buildings in the cold zone of China, namely Hui'an building and Ruiguang building was measured by blower door method. Hui'an building has the average air change rate of 0.24 h^{-1}, and Ruiguang building has the value of 0.98 h^{-1}. The families located at the ends of the building have the worse air tightness performance than the families in the middle, while the performance of the family on the top floor is worse than those on the middle floor. Comparing with the foreign studies, the performance of Hui'an building is comparable with the similar buildings in Lithuania, UK, Russia and USA, but Ruiguang building has the worst performance among all these studies. Foreign standards have higher requirement, where the performance of Hui'an building can only meet the Netherlands' standard, and falls behind the standards of Finland, Belgium, Denmark, Canada, USA and UK, and Ruiguang building cannot meet any of these standards. Simulation shows the total energy use of district heating is reduced by 12.6% when ACH of Ruiguang building is reduced from 0.98 h^{-1} to 0.5 h^{-1}.

1. Introduction

District space heating is widely used in north China, with the total floor area of more than 3.3 billion m^2 in the year of 2008 [1]. The energy use of district space heating of urban residential buildings in north China occupies as large as 25% of national building energy use [2]. It runs full time and full space in the buildings with poor performance, and hence a lot of energy is wasted every year. In this circumstance, energy efficiency retrofit of residential buildings in north China is carried out in large scale, under the management of Chinese central government. The current energy efficiency retrofit focuses on the improvement of thermal performance of envelope, and no measures were taken on air tightness performance in China [3]. However, according to the retrofit experience in foreign countries, air tightness retrofit can achieve considerable energy saving at the low retrofit cost [4,5]. Many foreign countries began the air tightness researches since 1980s, and measurements were taken to figure out the actual air tightness performance of buildings, and more and more strict standards were worked out for the air tightness performance. The equivalent leakage area of detached houses in Japan was measured and calculated in 1980s [6]. In the UK, the air tightness performance of the families in multi-family apartments on the top floor, middle floors and the ground floor is compared, and results show that the air tightness performance of the families on middle floors is the best [7]. In France, measurements show the air tightness performance of apartment buildings is better than that of single houses [8]. The standards for air tightness performance in different countries are introduced in literatures [7,9], and it is found that there is a variety of air-tightness levels among different countries, and the criterion becomes more and more strict over time even in the same country. Compared with foreign countries, there is little research on air tightness performance of residential buildings in north China. The air tightness performance of residential buildings in north China was measured only in one research, but the results were not ideal because the measurement method is not reasonable [10]. Hence it is very important to know how the air tightness performance of residential buildings in north China is, and further analyze its influence on space heating energy use. In this paper, two typical buildings in the cold zone of China were selected, and their air tightness performance was measured by blower door method. Simulation is made to figure out the quantitative effect of air tightness on district space heating energy use.

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Fig. 1. Appearance of Ruiguang in Tangshan.

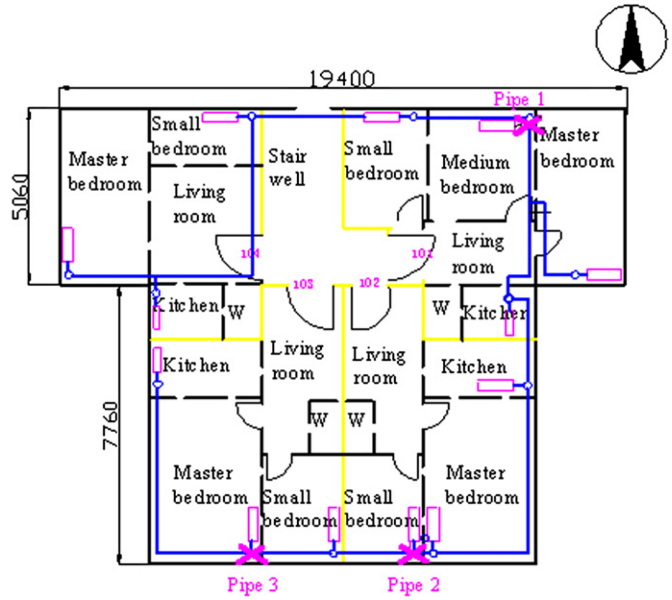

Fig. 3. Ichnography of Ruiguang building in Beijing.

2. Experiment method

2.1. Descriptions of measured residential buildings

Two typical buildings were selected in Beijing and Tangshan of the cold zone where district space heating is popularized. The building in Beijing, named Ruiguang building, is a typical 1980s-built building, while the one in Tangshan, named Huian building, is a typical building built in 1990s. Figs. 1 and 2 show the appearance of the two buildings. The buildings built in 2000s in China are mandatory to meet the energy conversation standards which have high requirement of air tightness performance, but the buildings constructed in 1980s and 1990s, which occupy a large percentage in current building stock in north China, are not required to meet such high air tightness performance, and hence become the meaningful objects for air tightness study. The type of space heating system used is a one-pipe vertical system using hot water in the two buildings, and no thermostats were installed in the dwellings.

Ruiguang building is a six-story, one-section building. There are four families on each floor and totally 24 families. Fig. 3 shows its ichnography. The families on the first floor, counted clockwise from the northeast, south to northwest, are numbered 101, 102, 103, 104. Hui'an building is six-story, six-section building with totally 72 families. The sections from west to east are numbered from section 1 to section 6, with two families in each section on one floor. The floor plan of Hui'an building is shown in Fig. 4.

Fig. 2. Appearance of Hui'an building in Beijing.

Table 1 shows the building characteristics of the two buildings. Both of the two buildings are brick and concrete structure with no heat conversation materials on the wall. The shape coefficient of Ruiguang building, which is the ratio of surface area to building volume, is larger than that of Huian building. Most of the families in Ruiguang building have used single pane steel windows for more than 20 years, shown in Fig. 5, and many of these steel windows cannot be closed firmly right now. Some families changed steel windows to plastic steel windows or aluminum windows. Some window glasses in the staircase are broken and no repairs are made during the winter in Ruiguang building. As for Huian building, it is also easy to find the cracks between ceilings and walls, as shown in Fig. 6. There is a big single pane window with the size of 2.4 m × 1.5 m in the balcony in each family from session 1 to session 3. Each family has the smoke exhaust ventilator in the kitchen, which is connected to the vertical smoke chimney by a big hole on that. There is exterior door in each session on the first floor in Hui'an building, but it is not always closed in winter.

2.2. Measurement method of blower door

Three families were selected in each building for the air tightness experiment. To ensure the representativeness, these studied families are located on the 1st, middle and top floors respectively, and some are at the two sides of buildings and some are in the middle sessions. Two families on the south of the 4th floor, named family 402, 403, and one family on the top floor, named family 604, were selected in Ruiguang building. As for Hui'an building, family 1-601 located on the top floor in Session 1, family 6-302 located on the middle floor in session 6, and family 3-102 located on the 1st floor in session 3 were selected. Blower door method was used to measure the air tightness performance of these selected families in accordance with ASTM E779-10 [11]. Before the measurement, the space of the apartment is separated from the outside environment by closing the windows and outdoors, while interconnecting doors in the selected family are opened. All exhaust

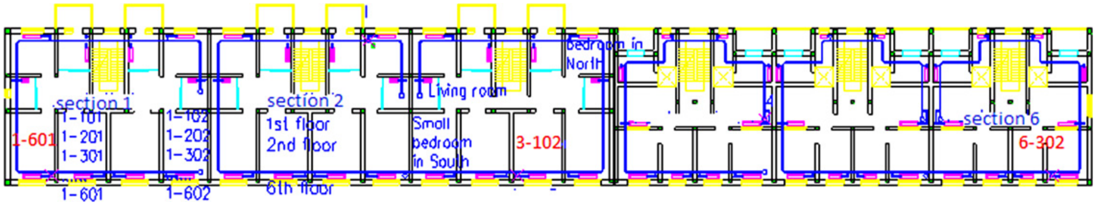

Fig. 4. Ichnography of Huian building in Tangshan.

Fig. 5. Window in Ruiguang building in Beijing.

ventilators and fans, vented dryers, and air conditioners were all closed. Table 2 shows the experiment condition, including the volume and surface area of the selected families, outdoor and indoor temperature during the experiment. It is found from Table 2 that the difference of outdoor and indoor temperature is very small, which can meet the requirement in the standard of ASTM E779 that the product of absolute value of indoor/outdoor temperature difference multiplied by the building height is less than 200 mK. During the measurements a fan was used to supply or exhaust air from dwellings at rates required to maintain a specified pressure difference across the building envelope, as shown in Fig. 7. The air flow and the pressure difference were measured. After the test conditions were stabilized, the air flow and the pressure difference were recorded. The air flow was recorded every 5 Pascals from ±20 Pa to ±60 Pa in both pressurization course and depressurization course. The calculated air flows were corrected for the difference between indoor and outdoor temperatures with reference to the calibration temperature [11,12].

Fig. 6. Cracks between wall and ceiling in Hui'an building in Tangshan.

2.3. Different indices to evaluate air tightness performance

Several different indices are commonly used to evaluate air tightness performance. Different units are used to describe air tightness performance of studied families in many other researches. In order to make the results in this experiment comparable with other researches, the air tightness performance of the measured families in this experiment is expressed in the following units respectively.

(1) ACH50: ACH50 tells us how many times per hour the entire volume of air in the building is replaced when the building envelope is subjected to a 50 Pa pressure.
(2) Average natural infiltration rate shows the air tightness at the natural condition. It can be calculated based on ACH50, as shown in Eq. (1).

$$\text{Average natural infiltration rate} = \frac{\text{ACH50}}{n} \tag{1}$$

n: correlation factor, related with climate, stack effect, windiness and wind shielding, and type of leaks. $n = 17$ for Chinese buildings [13].
(3) Equivalent Leakage Area (EqLA): EqLA is defined by Canadian researchers at the Canadian National Research Council as the area of a sharp edged orifice (a sharp round hole cut in a thin plate) that would leak the same amount of air as the building does at a pressure of 10 Pa [14].

Fig. 7. Blower door method to measure air tightness performance.

Table 1
Building characteristics.

Building	Construction structure	Shape coefficient of building	Exterior wall		Window		Roof	
			Material	u value (W/m^2 × °C)	Material	u value (W/m^2 × °C)	Material	u value (W/m^2 × °C)
Ruiguang building in Beijing	Brick and concrete structure	0.36	360 mm brick wall	1.67	Single pane steel window. Some plastic steel windows or aluminum windows	6.4	130 mm concrete with 100 mm cement expanded perlite	1.3657
Huian building in Tangshan	Brick and concrete structure	0.275	360 mm brick wall with mortar	1.538	Plastic steel window	4.7	RC cast-in situ slab or precast slab with 80 mm polystyrene plates	0.466

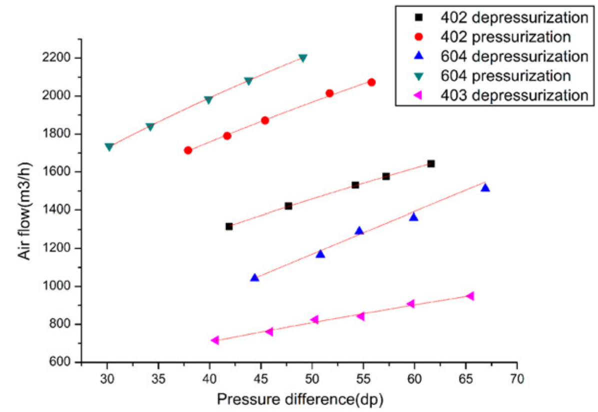

Fig. 8. Air flow in pressurization/depressurization courses of tested families in Ruiguang building.

(4) Effective Leakage Area (ELA): ELA was developed by Lawrence Berkeley Laboratory (LBL) and is used in their infiltration model. The Effective Leakage Area is defined as the area of a special nozzle shaped hole (similar to the inlet of the blower door fan) that would leak the same amount of air as the building does at a pressure of 4 Pa [11,15].

3. Analyses of air tightness performance of two residential buildings in Tangshan and Beijing

3.1. Experiment results

Volume flow rate and pressure difference can be related by the following equation

$$Q = C(dp)^n \tag{2}$$

where Q: flow rate; dp: pressure difference; C: air leakage coefficient; n: pressure exponent

Take the log–logarithm for Eq. (2), which means

$$lgQ = n(lgdp) + lgc \tag{3}$$

In this way, Eq. (2) is transformed to a liner regression between lgQ and lg(dp), as shown in Eq. (3), and it yields lg$c$ as its intercept and n as its gradient, which makes easier to calculate the values of C and n. The tests give several points on each family's flow versus pressure difference. Take the log–logarithm of flow and pressure difference of each family, and get the values of C and n for each family based on Eq. (3), shown in Table 3.

The pressure exponent of n has a theoretical range from 0.5, for fully turbulent flow, to 1.0, for purely laminar flow, and the value of n between 0.5 and 1 usually indicates the experiment is successful. Table 3 shows the air tightness performance of the tested families in the two buildings. The value of n in Table 3 is from 0.5 to 0.96. The infiltration rate in natural condition is from 0.09 h^{-1} to 0.38 h^{-1} in Hui'an building with the mean value of 0.24 h^{-1}, and from 0.46 h^{-1} to 1.6 h^{-1} in Ruiguang building with the average of 0.98 h^{-1}, and this shows that the air tightness performance of Hui'an building is much better than that of Ruiguang building. There is a large difference in air change rates among the tested families in Ruiguang building, while the variance in Hui'an building is much smaller. Further analysis shows that in Hui'an building, the two tested families located at the two ends of the building have worse air tightness performance than the family located in the middle of the building, while the family on the top floor has larger average infiltration rate than the families on the middle floor in Ruiguang building.

Figs. 8 and 9 further illustrate air flows versus the series of pressure differences in the pressurization course and the

Table 2
Building characteristics, ambient conditions and indoor temperature.

Buildings	Family	Floor area (m^2)	House volume (m^3)	Surface area (m^2)	Experiment condition		
						Indoor Temp.	Outdoor Temp.
Hui'an building	1-601	53	139	112.04	Pressurization	26	24
					Depressurization	25.7	23.9
	6-302	41	103	47.25	Pressurization	27	30
					Depressurization	27.1	30.2
	3-102	53	132	34	Pressurization	25	25
					Depressurization	25.2	25.3
Ruiguang building	402	41	100	41	Pressurization	32.6	34.5
					Depressurization	32.6	34.5
	604	38	81	65	Pressurization	32.3	33.4
					Depressurization	32.3	33.4
	403	41	104	41	Depressurization	37	31

Table 3
Air tightness performance of the selected families in the two buildings.

Buildings	Family	Pressurization	Experiment results					
		Depressurization	C	N	ACH50 (l/h)	Average infiltration rate (l/h)	ELA (cm^2)	EqLA (cm^2)
Hui'an building	1-601	Pressurization	88.2	0.50	4.43	0.26	189	308.6
		Depressurization	59.3	0.58	4.2	0.25	143.3	253.6
	6-302	Pressurization	100.4	0.51	6.47	0.38	211.4	341.5
		Depressurization	39.6	0.65	4.84	0.29	104.6	196.4
	3-102	Pressurization	33	0.63	2.94	0.17	84.9	156.7
		Depressurization	42.4	0.51	1.59	0.09	80.4	121.2
Ruiguang building	402	Pressurization	289.8	0.51	19.90	1.17	617.5	1005.3
		Depressurization	145	0.59	14.36	0.84	351.8	624.1
	604	Pressurization	310.1	0.50	27.16	1.60	669	1098.1
		Depressurization	27.4	0.96	14.19	0.83	111	276.3
	403	Depressurization	77.4	0.69	7.77	0.46	191.4	343.6

depressurization course for each tested family in Ruiguang building and Hui'an building. The plots of each family are shown in log–log coordinates, which are perfectly fit as the line function of Eq. (3). In Fig. 8, the air flow varies a lot at the same pressure difference among different families in Ruiguang building where the smallest air flow is 830 m^3/h at the pressure difference of 50 Pa in Family 403, while the largest air flow can reach 2168 m^3/h at 50 Pa in Family 604. This indicates there is a big difference in air tightness performance among different families in Ruiguang building. Compared with Ruiguang building, the difference of air flow among different families is smaller in Hui'an building, as shown in Fig. 9, which indicates the difference of air tightness performance is smaller among the families in Hui'an building.

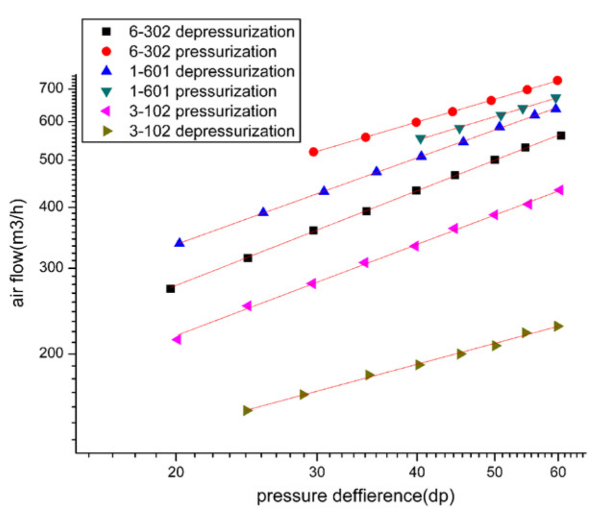

Fig. 9. Air flow in pressurization/depressurization courses of tested families in Hui'an building.

3.2. Questionnaires

Questionnaire surveys were also taken for all the families in the two buildings, to figure out the subjective evaluation of the residents on the air leakage. Fig. 10 shows the subjective feeling on the frequency of air infiltration of windows in the two buildings. The residents in Ruiguang bldg. founds more frequent air leakage from windows, where 36% of the families felt air leakage frequently, and 27% felt air leakage sometimes, and 18% occasionally felt air infiltration, and only 18% had no perception. In Hui'an building, more than 60% of the families had no perception of air leakage from the windows, and only 4% and 21% felt the window leak air frequently and sometimes. As for the strength of air infiltration from the windows, most of the families in both buildings feel weak or very weak air infiltration, shown in Fig. 11.

3.3. Comparisons with other studies in different countries and related foreign standards

In order to know how the measured air tightness performance of the two buildings is in deed, their results should be compared with

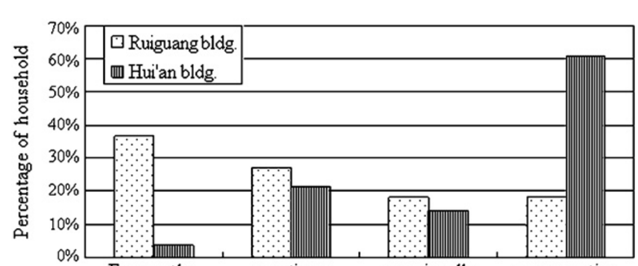

Fig. 10. Subjective feeling on the frequency of air infiltration of windows in the two buildings.

Table 4
Comparison with other studies in foreign countries.

Country	ACH50 (l/h)	Average infiltration rate (l/h)	Notes
China (current study)	4.08	0.24	Hui'an bldg., a multi-family building built in 1990s
	16.7	0.98	Ruiguang bldg., a multi-family building built in 1980s
Sweden [16]	1.4	/	Flats in the buildings constructed between 1976 and 1988
Lithuania [12]	6.7	/	33 multi-family buildings constructed from 1960–1990
UK [7]	5.25	/	177 flats
Russia [17]	7.9	/	47 apartments with pre-cast concrete panel structure
USA [18]	/	0.27	New apartments with exhausted fans under natural driving forces

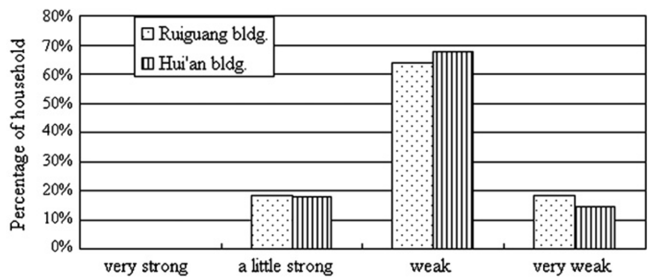

Fig. 11. Subjective feeling on the strength of air infiltration of windows in the two buildings.

related standards or the performance of other residential buildings. As there is no research currently in China to measure the actual air tightness performance of residential buildings in north China, the results have to be compared with the measured air tightness performance of similar multi-family buildings in foreign countries or related foreign standards. Table 4 lists the tested air change rate of multi-family buildings in several other countries, which have the similar construction years or the same construction structures as that of the measured buildings in this paper. It is found that Hui'an building has better air tightness performance than the studied buildings in Lithuania, UK, and Russia, and even the new apartments in USA has the air tightness performance nearly the same as Hui'an building, while only Swedish flats in the higher latitude have better air tightness performance than Hui'an building. The air infiltration level of Ruiguang building is the most worst among all the measurements in all these countries.

As for the related standard, only one Chinese standard JGJ26-95 has a very simple item that the air change rate of energy efficiency buildings should be no large than 0.5 h^{-1}, and this air changed rate is mainly resulted from air infiltration of windows and doors, and it also includes the natural ventilation by window opening if the air tightness of the building is good. This limit value of 0.5 h^{-1} is worked out from the perspective of occupants' health. Compared the tested results of the two buildings with this limit value, the air tightness performance of Hui'an building is better than the requirement in the standard, but Ruiguang building cannot meet the standard. Further comparing the Chinese standard with foreign standards, it is found that the Chinese standard is much less stringent. Table 5 lists the limit values of air tightness performance for residential buildings in different foreign standards. Compare the test results in this paper with the standards in different countries, although the air infiltration performance of Hui'an building is better than the threshold in Chinese standard, it cannot meet most of the foreign standards, where it is a little worse than the requirement in Switzerland, Germany and Denmark, and far from the limit value in Finland, Belgium, Denmark, Canada, USA and UK. The only the standard which Hui'an building can meet is the Netherlands' standard. As for Ruiguang building, its air infiltration performance is much worse than the requirement in any of the standards listed in Table 5.

3.4. Discussion

Further analyses show there are several reasons leading to the difference in air tightness performance between the two buildings: (1) Ruiguang building was built earlier, and the conditions of envelope is much worse than that of Hui'an buildings. The exterior wall is only made of brick, even without any mortar. Steel windows are widely used in Ruiguang building, and many of them cannot be closed firmly, while plastic steel windows used in Hui'an building have better air tightness performance. The shape coefficient of building is larger in Ruiguang building, and this indicates the air infiltration amount per building volume is possibly larger in Ruiguang building because of the larger surface area per cubic meter. (2) Occupants' consciousness to prevent air leakage from windows is also greatly helpful to improve the air tightness performance. On-site investigations in these tested families reveal that some families, such as 1-601 in Hui'an building and 403 in Ruiguang building, use weather strips to seal the gas between window frame and the walls on one's own initiative, and they felt the air leakage from window has been distinctly improved, but some other families, such as family 403 in Ruiguang building, just use some newspapers to bung up the big inlet in the smoke chimney. This is one of the reasons that some families, even on the same floor

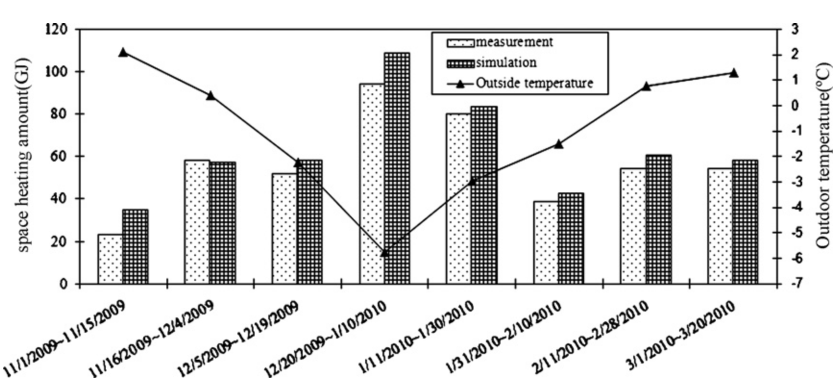

Fig. 12. The comparison between simulation result and actual measured data in different time of space heating period in 2009.

Table 5
Comparison with related foreign standards.

Countries	Air-tightness standards	Limit value in standards		
		ACH50	ELA	EqLA
UK	AECB (Association for Environment Conscious Building) Carbon Lite Middle Standard [19]	0.6	/	/
UK	Passivhaus Standard [19]	0.6	/	/
Netherlands [20]		6		/
Switzerland [20]		3.6		/
Germany [20]		1.8–3.6		/
Denmark [21]		2.8		/
Belgium	NBN D50-001 [22]	1 or 3	/	/
Finland	National Building Code of Finland, Part C3 [23]	1	/	/
USA [9]	LEED	/	0.87 cm^2/m^2 envelop	/
Canada [9]	Canadian R-2000	/	/	0.69 cm^2/m^2 envelop
Chinese standard	JGJ26-95	8.5		
China (current study)	Hui'an bldg.	4.08	2.42 cm^2/m^2 envelop	4.1 cm^2/m^2 envelop
	Ruiguang bldg.	16.7	8.1 cm^2/m^2 envelop	13.9 cm^2/m^2 envelop

Table 6
The ways to get the actual data of all the input parameters in the model.

Input parameters	The way to get the actual data
Climate data in the space heating period of 2009, namely from November 1st 2009 to March 20th, 2010	Gotten from the local meteorological station
Thermal performance of envelope	By architectural construction drawing, and on-site investigations
Appliance powers and operation schedules	By on-site questionnaire investigations of all the families in this building.
Air infiltration rate	By blower door method, described above
The setting of indoor temperature in winter	Real time recorded every half an hour in the space heating period of 2009, by automatic temperature record loggers
Space heating energy use	The space heating energy use in the space heating period of 2009, namely from November 1st 2009 to March 20th, 2010, was recorded by a heat meter installed in the water supply main pipe

Table 7
Average household appliance powers.

Items	Lighting	Cooking	Refrig	Miscellaneous
Power (electricity)	0.3 w/ft^2	1.04 w/ft^2	0.39 w/ft^2	2.42 w/ft^2
Power (gas)		25 ($Btuh/ft^2$)		

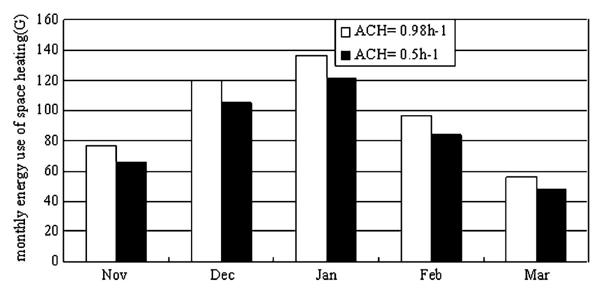

Fig. 13. Monthly reduction of space heating energy use, when ACH is reduced from 0.98 h^{-1} to 0.5 h^{-1}.

with the same physical conditions, or even having better physical condition, have large air change rate.

4. The effect of air tightness performance on district space heating by simulation

District space heating is running full time and full space in the residential buildings in North China. If there is serious air leakage, a lot of energy will be wasted in such circumstance, to maintain a stable indoor temperature. In order to know the quantitative effect of air tightness performance on energy use of district space heating, energy saving amount is evaluated by simulation in the case of air change rate is reduced. The software of eQUEST (the Quick Energy Simulation Tool) is used to make the simulation. eQUEST is widely used building energy analysis tool which allows to perform detailed analysis of building design technologies using building energy use simulation techniques. Ruiguang building is used to establish the building model. Its ichnography shown in Fig. 3 is input into EQUEST. The values of all the input parameters in the simulation model are from the actual investigations and measurement in Ruiguang building. On-site investigations and measurement were taken from November 1st, 2009 to March 20th, 2010, in order to get the input information related to building characteristics, appliance operation, indoor temperature and actual energy use of space heating. Table 6 explains the ways to get the actual data of all the input parameters in the model. Questionnaire surveys were taken for each family in Ruiguang building to get the appliance powers and operation schedules, family information, etc. Building information was gotten from the architectural construction drawing and on-site investigations. As for the indoor temperature in the winter, 11 typical families on the 1st floor, middle floor and top floor were selected, and automatic temperature record loggers were installed in each family to record the real time temperature every half hour. The average indoor temperature in the space heating period of 2009 is 19 °C by measurement. A heat meter was installed in the water supply main pipe and the space heating energy use of the whole building was recorded around every half month during the space heating period from November 1st, 2009 to March 20th, 2010. The air infiltration rate of the building was input as 0.98 ACH based on the actual test. The thermal performance of the envelope is shown in Table 1. Table 7 shows the average household appliances powers in the model.

Firstly, the actual data of parameters were all input the model and district space heating energy use is simulated. Actual energy use value of space heating is used to validate the model. Fig. 12 illustrates the simulated energy use of space heating and actual measured energy use, and it is found that the two kinds of data can match with each other very well, where the total measured amount of space heating for this building is 453.55 GJ, and the simulation result is 484.9 GJ, with the difference of 6.9%.

After the model is validated by actual space heating energy use, the air infiltration rate is reduced from 0.98 h^{-1} to 0.5 h^{-1}, which is prescript in the standard JGJ26-95 [24], and the space heating energy use is simulated again. The simulation result shows that the total energy use of district space heating was reduced by 12.6%. Fig. 13 further shows the monthly reduction of space heating energy use, when ACH is reduced from 0.98 h^{-1} to 0.5 h^{-1}.

5. Conclusions

Air tightness performance has an important effect on district space heating of old residential buildings, especially in North China where district space heating runs full time and full apace, but there is no any research on actual air tightness performance of current residential buildings in north China and its quantitative effect on space heating. Aiming at this, two typical buildings were selected, and their air tightness performance was measured by blower door method. Results show that Hui'an building has the average air change rate of 0.24 h^{-1}, and Ruiguang building has the mean value of 0.98 h^{-1}. The families located at the two ends of the building have worse air tightness performance than the family located in the middle of the building, while the family on the top floor has larger average infiltration rate than the families on the middle floor. By analyzing the factors affecting air tightness performance, it is found that the poor condition of the envelope, such as the steel windows which cannot close firmly, the large shape coefficient of buildings, are the possible reasons leading to the terrible air tightness performance, and occupants' consciousness to prevent air leakage from windows is also an important factor to improve air tightness performance, and that is why the families with similar physical condition have different air infiltration performance.

Comparing the air tightness performance of the two buildings with the researches in foreign countries, Hui'an building has better air tightness performance than the studied buildings in Lithuania, UK, and Russia, and even the new apartments in USA, while only Swedish flats have better air tightness performance than Hui'an building. The air infiltration level of Ruiguang building is the most worst among all the measurements in all these countries. But the foreign standards have much higher requirement of air tightness performance. The air tightness performance of Hui'an building can only meet the Netherlands' standard, and falls behind the requirement in the standards of Finland, Belgium, Denmark, Canada, USA and UK. Ruiguang building cannot meet any of the foreign standards.

In order to quantitatively analyze the effect of air tightness performance on district energy use, Ruigang building is taken to establish building model, and simulations were made to calculate energy use of district space heating when air change rate is 0.98 h^{-1} and 0.5 h^{-1}, respectively. The simulation result shows that the total energy use of district space heating was reduced by 12.6% when ACH is reduced from 0.98 h^{-1} to 0.5 h^{-1}.

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