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Evaluation on Retrofit of One Existing Residential Building in North China: Energy Saving, Environmental and Economic Benefits

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Abstract

Energy efficiency retrofit of residential buildings, widely carried out in north China, has been aroused a great concern during recent years. In this case, one typical residential building with energy efficiency retrofit was selected in Tangshan as a case study. Indoor thermal environment and space heating use of the building were measured before and after the retrofit. A methodology is developed to evaluate the energy-saving, environmental and economic benefits for the retrofit. Results show the full-scale retrofit in this building can meet the 50% energy saving target set by the government. Indoor thermal environment achieved a good improvement after the full-scale retrofit as well. The results could be a reference of evaluation and optimization of energy efficiency retrofit schemes of residential buildings in north China.

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Keywords: Benefit evaluation; Energy efficiency; Retrofit; Residential building; North China

1. Introduction

Due to the large scale retrofit work of existing residential buildings in north China, the retrofit quality becomes a key element to affect the realization of the national energy conservation target set by Chinese government. Hence,

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the evaluation for the actual effect of retrofit work, including energy saving, economic and environmental benefits, is of great importance. In fact, it has been aroused a great concern about evaluation and optimization of retrofit scheme during recent years in many countries[1-4]. In China, Zhi[5] and Lan et al.[6] measured the space heating use of one building after the retrofit, and compared the energy use with that of a similar building without retrofit. Peng et al. measured the indoor temperature, hydraulic performance of the space heating system and thermal property of the retaining envelope before the retrofit[7]. By view of previous literature, however, there is insufficient knowledge of the benefits brought by the large-scale energy efficiency retrofit together with the heat metering reform[8]. A systematic and scientific evaluation method is also essential to be developed and used to evaluate the actual benefits by case studies. In this study, we intend to find out a scientific way to evaluate the actual retrofit effect by a case study in North China. The space heating use and indoor and outdoor thermal environment before and after retrofit in the target residential building were analyzed, and the precise benefits of energy conservation, environment and economy were also evaluated, which could be a reference for policy support of future retrofit work.

2. Methods

One target residential building built in 1990s in Tangshan, was selected as a case study. It was one brick-concrete structure with 6 floors and 72 families. Figure 1 shows the layout of the standard floor. This building has 6 units which are identified by Unit.1 to Unit. 6 from west to east; in each floor of one single unit, there are 2 families which the west one is identified with No.1 while the east one is No.2. The tenement in the east side of the first floor of Unit 1 can be identified by 1-102. The heating system was designed as a vertical single-pipe heating system consists of 4 subsystems, where Unit 1 and Unit 4 are heated by one subsystem each, and Unit 2 together with Unit 3, Unit 5 together with Unit 6 are heated by one subsystem, respectively.

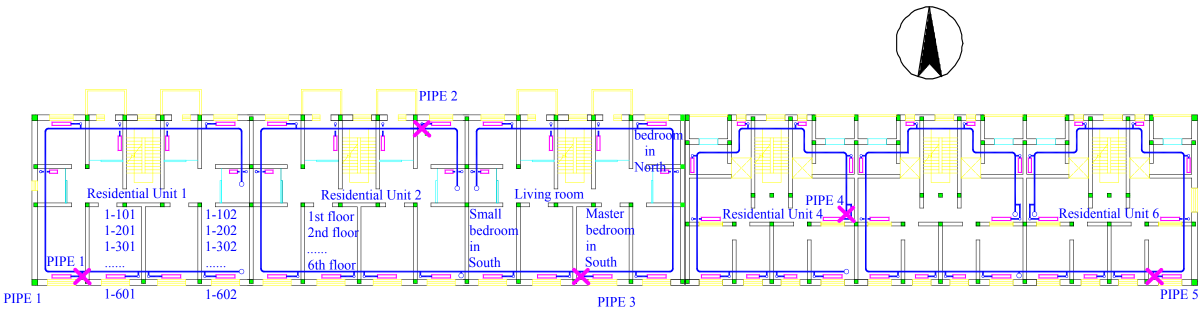


Fig. 1. Layout of the building with space heating system

Table 1 shows the retrofit measures and the performance of both envelopes and space heating systems before and after the retrofit. According to the retrofit package, both the envelope and the space heating system were totally retrofitted, including the external wall, exterior window, floor slab of the first floor, and household heat meter and individual temperature control of the heating system.

The measurements were done before and after the retrofit during two space heating seasons, namely Nov.1 2009 to Mar. 20 2010 and Nov.7 2010 to Mar.20 2011. Indoor and outdoor temperature and space heating use were measured. Automatic thermometers with data loggers were installed in the rooms on the bottom, middle and top floors of the building, which were heated by five pipes shown in Fig.1, and indoor temperature of these rooms was recorded every 30 minutes. Meanwhile, typical families on the top, middle and bottom floors, namely 1-601, 2-301, 3-102, were also chosen to measure the indoor temperature of each room every 30 minutes. Ultrasonic heat meters were installed on the main supply pipe of the space heating system in the building, to record the space heating uses of two heating seasons. Besides, questionnaire survey was conducted to reflect the residents' subjective evaluation on indoor thermal environment before and after the retrofit.

To evaluate the actual benefits in energy conservation, environment and economics, the retrofit scheme and cost were recorded by field investigations, and building characteristics and prosperities of the heat supply system before and after retrofit were known as well. An evaluation method was developed to calculate the energy saving amount. Environmental benefits were analyzed, including CO_2 emission reduction, and improvement of indoor temperature. Lift cycle cost assessment (LCCA) model was used to assess the economic benefit.

Table 1. The retrofit measures and performances of envelope and heat supply systems

Item	Before retrofit		Retrofit measures	After retrofit	Limit value
	Material	K (W/m^2* °C)		K(W/m^2* °C)	K(W/m^2* °C)
Envelope					
Wall	370mm brick wall with mortar on two sides	1.54	External thermal insulation, and 80mm expandable polystyrene board	0.425	0.6
Roof	RC slab with 80mm polystyrene plates	0.51	/	0.51	0.45
Window	One layer plastic steel window, single panel	4.7	Two-layer hollow plastic steel window	2.7	2-3.1
1st floor	100 mm concrete slab	2.63	60mm extruded polystyrene board	0.45	0.65
Space heating system					
Type of pipe network	Vertical single pipe system	/	Crossover pipe between the inlet and outlet of every radiator	/	/
Individual temp. control	Without thermostatic valves	/	Auto-thermostatic valves	/	Therm-ostatic valves
Household heat metering	No heat meter	/	Ultrasonic heat meter and heat distribution meter	/	Applic-able

3. Results

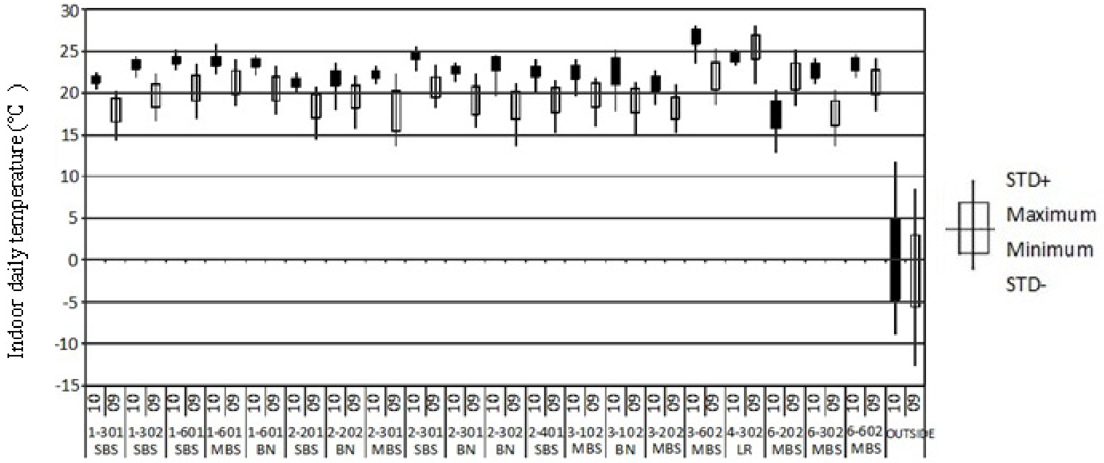
3.1. Space heating use and indoor temperature before and after retrofit

Table 2 shows the space heating use of the two heating periods before and after retrofit. In 2009, the outdoor average temperature in Tangshan was -1 ºC, and the heating use of this building was 35.27 W/m^2 and indoor average temperature is 20.09 ºC. After a full scale retrofit of both envelope and space heating system, the indoor average temperature raised to 22.91 ºC and the space heating use was reduced to 19.27 W/m^2, with 0.22 ºC of the outdoor average temperature. Figure 2 compares the indoor daily average temperature between the heating period in 2009 and in 2010. It can be found that all these families enjoyed a higher daily average temperature in 2010 than that in 2009 with a few exception. In 2010, all these rooms had a daily average temperature of more than 20 ºC except the master bedroom of 6-202 with the indoor average temperature of only 17.4 ºC. In contrast, in 2009, 62% of measured rooms have the daily average temperature below 20 ºC. The standard deviation of daily average temperature shows a slight fluctuation with ranges from 1.2 ºC to 2.4 ºC in 2009, and 0.4 ºC to 1.6 ºC in 2010.

Figure 3 shows the variation of indoor daily temperature of a typical family (Family 3-102), during the two space heating periods. Before the retrofit, the indoor daily temperature of 3-102 ranges from 15 ºC to 21 ºC in 2009, while in 2010, the daily temperature rise to 18 ºC to 25 ºC. Before the retrofit, furthermore, the indoor temperature keeps similar variation trend with outdoor temperature. However, after the retrofit the indoor temperature keeps a limited fluctuation, although the outdoor temperature still varied in a large range.

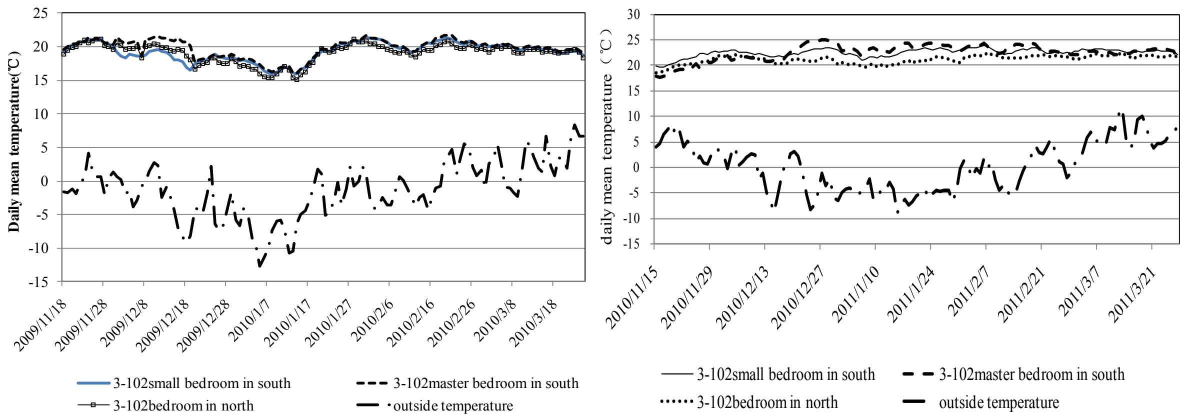
Table 2. Space heating use of the two heating periods before and after the retrofit

Year	Total heat (GJ)	Heating area (m^2)	The number of heating days (d)	Average indoor temp. (ºC)	Average outdoor temp. (ºC)	Space heating use (W/m^2)
2009	2053.1	4646.16	145	20.09	-1	35.27
2010	1036.05	4646.16	134	22.91	0.22	19.27



SBS: small bedroom in the south, MBS: master bedroom in the south, BN: bedroom in the north, LR: living room

Fig. 2. Indoor daily temperature in the two heating periods of 2009 and 2010



(a) Before the retrofit 2009 (b) after the retrofit

Fig. 3. Variation of indoor daily average temperature of a typical family

3.2. Analysis of energy saving benefit

To estimate the reduction of heating use and the improvement of indoor thermal environment, the space heating use under the condition of different indoor and outdoor temperature should be converted to a uniform condition of the same indoor and outdoor temperature, and then the difference of space heating use before and after the retrofit can be compared. In this study, the space heating use is converted to the standardized condition prescript in the national standard JGJ 26-2010[9], as shown in Equation (1),

$$q_b' = q_s \times \left(t_{ib} - t_{ob}\right) / \left(t_{is} - t_{os}\right) \tag{1}$$

Where q_s is the actual space heating use (W/m^2) during the heating periods of 2010 and 2011, t_{is} is actual indoor temperature, t_{os} is actual outdoor temperature, q_b' is the corrected space heating use, which is converted to the standardized condition in the national standard JGJ 26-2010, t_{ib} is indoor average temperature under standardized conditions (18 ºC), t_{ob} is mean air temperature of the target city in winter under the standardized condition, namely -0.6 ºC in Tangshan.

Table 3 shows the the temperature-corrected energy use amounts in the two space heating periods before and after the retrofit under the standardized condition. The values in 2009 and 2010 were31.11W/m^2 and 15.8 W/m^2 respectively, which reflects an energy saving rate of 49.2%. According to the limit value in the standard JGJ 26-2010, the space heating use amount after the retrofit should meet the limit value of the standard, which is 15.3W/m^2 for Tangshan. And thus, it can be found that this building nearly met the 65% energy saving target after the comprehensive retrofit of its envelope and household heating metering and temperature control of indoor space heating system [10].

Table 3. Temperature-corrected space heating use and energy saving rate

Year	Indoor average temp. (ºC)	Outdoor average temp. (ºC)	Actual heating use (W/m^2)	Corrected heating use (W/m^2)	Energy saving rate
2009	20.09	-1	35.27	31.11	49.2%
2010	22.91	0.22	19.27	15.8	
Standard value	18	-0.6	15.3		

3.3. Analysis of environment benefit

After the retrofit, the average indoor temperature of this building raised from 20.09 ºC to 22.91 ºC. It indicates that no matter before or after the retrofit, the indoor temperature has always reached the indoor design temperature (18 ºC) of the standard JGJ26-2010. The questionnaire survey was also conducted during the two heating periods before and after the reforming to get knowledge of residents' subjective evaluation on the indoor thermal environment. The survey in 2009 reveals that about about 61% of the families feel unsatisfied with the indoor temperature before the retrofit, and none of them thought it was overheated inside; however, the situation is totally changed after the retrofit, where 66.7% of the families express their satisfaction with the indoor temperature, and 16.6% feel too hot and 16.6% feel too cold instead. Thus it seems that residents' higher expectation might bring higher temperature inside. Overall, the retrofit of the retaining envelope and indoor space heating system has brought great improvement to the indoor thermal environment.

In north China, the hot water in the space heating system is commonly supplied by the coal-fired boilers in regional heating plants or boiler rooms. Considering the operating efficiency of the boilers and the distribution efficiency of the outdoor pipe network, the coal quantity saved by the retrofit can be calculated by Equation (2):

$$Q = \frac{\left(q_b - q_a\right) \times t \times s}{\eta_b \eta_p} \tag{2}$$

Where Q is the amount of saved coal (kgce), q_b is space heating use amount per unit floor area before retrofit

(W/m^2,31.11 W/m^2 in this case), q_a is space heating use amount per unit floor area after retrofit (W/m^2, 15.8W/m^2 in this case), t is time of space heating in the heating period (s), S is floor area of space heating (m^2), $\eta_b$is operation efficiency of boiler (0.68 in this case), $\eta_p$is distribution efficiency of outdoor pipe network (0.9 in this case). In this calculation, the greenhouse gas discharge of unit mass standard coal was given by the standard[11]. According to Table 3, during the heating period of 120 days in Tangshan, 41.2 tons of standard coal can be saved every year. The greenhouse gas emission of saved standard coal can be calculated to be 102711.6 kg/year for CO_2, 453.2 kg/year for particle matter, 824 kg/year for SO_2, 370.8 kg/year for NO.

3.4. Analysis of economic benefits

To evaluate the economic benefit of retrofit projects, the investment cost of this retrofit package can be calculated, including the cost of energy efficient materials and the construction cost by LCCA model. The analysis compares the investment costs of the retrofit package with the resulting energy cost savings over the lifetime of the investment, to decide whether this retrofit package is economical or not[12]. A dynamic investment analysis by means of the discounted cash flow (DCF) method is conducted for the energy-efficient retrofit package that is applied to a specific model building. In this method, future cash flows (e.g. energy cost savings that occur during the lifetime of the investment) are discounted to present time values and thus made comparable to today's investment expenditures. Both the net present value (NPV) and payback period (PBP) as two indicators of the DCF method, were used to evaluate the economic efficiency of the retrofit project. They are derived from the following equations [13-14]:

$$NPV = \sum_{t=0}^{T} cf_t \left(1+i\right)^{-t} \quad (3)$$

$$PBP = P/A \quad (4)$$

Where cf_t is the cash flow at time t (positive for earnings, negative for expenditures), T is the lifetime of the investment, i is the discount rate, NPV is net present value (an investment is considered as profitable when the value is positive), PBP is payback period (years), P is total cost of investment (RMB), A is annual net income (RMB). Based on above equations, the retrofit investment of the building can be calculated as shown in Table 4. The cost of each retrofit item included that of both materials and construction. Moreover, the lifespan of residential buildings in China is around 50 to 70 years. Considering that this building was built more than 20 years ago, the remaining time of 20 and 40 years after the retrofit can be asumed respectively to know the life span's impacts on the economy. According to the impacts of current investment return rate, capital opportunity cost, and social discount rate on the long- and short-term projects, the National Development and Reforming Committee issued the economical evaluation method on the construction projects (third version), which assumes the social discount rate as 8%. While in Switzerland, for building investments by private investors, a real discount rate of 3%–3.5% is recommended[15]. Combined the current situation of both home and abroad, we assumed the social discount rate as 3% and 8% for sensitivity analysis. In the calculation, this building saves 41.2 tons of standard coal after the retrofit. The price of the coal with the heating value of 5500 calorie/ton is 891Yuan/ton, which means that the price of the standard coal is 1134.49 Yuan/ton[15]. Thus it can be seen that after the retrofit this building can save 46741 Yuan every year.

Table 5 shows the payback periods and NPV of the retrofit packages of the building calculated by the LCCA model above. It can be found that the payback period of this building is 17.4 years. Considering the remaining lifetime of this residential building is still 20-40 years after the retrofit, 17.4 years is acceptable to get the investment back. The net present value also indicates that the application of this retrofit measure package in this building is promising under the situation of i=3%, n=40 yrs.

Table 4. Retrofit investment of the building

Wall exterior insulation	Roof insulation	Doors and windows	Basement roof heat preservation	Indoor pipe network	Auto-thermostatic valves	Heat distribution meter	Total

23.08	2.38	41.39	3.84	0.94	4.96	4.75	81.34

Table 5. PBP and NPV of the retrofit packages of the building in the basic scenario

PBP	NPV (Yuan)			
(year)	Case 1: i=3%, n=20 yrs.	Case 2: i=3%, n=40 yrs.	Case 3: i=8%,n=20yrs.	Case 4: i=8%, n=40 yrs.
17.4	-118011	266971.5	-354492	-256060

4. Discussion

A full scale evaluation has been done for a retrofit project of a residential building in Tangshan city. This selected building represents a very typical category of existing residential buildings in this city, and the retrofit scheme is widely taken by the local government, which is expected to achieve the target of 50% reduction of space heating intensity. However, the results show that even 65% reduction can be nearly achieved by this retrofit scheme. From the perspective of economic benefit, the result shows that this retrofit scheme is only promising under the situation of i=3%, n=40 yrs. However, the social discount rate of 8% is ususally recommended by the Chinese government. In this case, the subsidy from the Chinese government is necessary in order to make this retrofit more attactive for the related stakeholders, especially for the business investors in Chinese market.

5. Conclusions

To evaluate the actual effect of energy efficiency retrofit of residential buildings in north China, one typical residential building was selected as a case study. Some conclusions can be made as follows:

1) The full-scale retrofit of both envelope and household heat metering and temperature control of the space heating system which are commonly adopted in Tangshan can be beyond the 50% energy saving target and even nearly reach the 65% reduction of space heating intensity set by the government for building retrofit in north China, and the energy saving rate before and after retrofit can reach 49.2%.

2) The full-scale retrofit of both envelope and the space heating system inside this building can also achieve a good improvement of indoor thermal environment in general, and the fluctuation of indoor temperature also becomes smaller.

3) The economic benefit analysis indicates that the application of the full-scale retrofit package of this building is profitable under the situation of i=3%, n=40 yrs, and the payback period of this building is acceptable.

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