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# Assessing of thermal comfort in multi-stories old and new residential buildings in China

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## Abstract
In China, the most common heating system in old residential buildings is district heating systems without private control. However, in 2010, the standard JGJ26-2010 has a mandatory requirement on the heating system namely that it should be installed with household-based heat meters and Thermostatic Radiator Valves (TRVs) for each radiator. Many previous studies have demonstrated that the PMV model performed well for Chinese buildings, however, studies lack of to identify how the upgraded standards will affect thermal comfort in both types of old and new buildings. Hence a thermal comfort survey was carried out in both new and old dwellings according to updated standards.

The survey was carried out in two sets of dwellings in cold zone of North China in winter, that is, 7 new and 7 old apartments, starting from 15th February and ending at 15th March of 2014, the winter season when heating is on. During the survey, occupants' thermal sensation, clothing insulation etc. were collected by subjective questionnaires, and important environmental parameters were measured concurrently by proper sensors, according to the ISO 7730, ISO 7726 and ISO 10551. The results show that the correlations between Predicted Mean Vote (PMV) and people's Actual Mean Vote (AMV) in new and old apartments. In addition, percentage of acceptable of occupants is higher in new apartments when compared with that in the old apartments. Another finding from this study is that females respond worse thermal acceptability to indoor thermal environment, when compared with males in both new and old apartments.

Keywords: Thermal comfort, PMV, Residential building, China

## 1 Introduction
Thermal comfort has a significant impact on occupants' productivity and health, and it plays an important role when evaluating the performance of buildings. In the past 40 years, the Predicted Mean Vote (PMV) model developed by Fanger has been considered as the most important landmark, and it has been adopted by many building design standards, such as ASHRAE 55 and ISO 7730, to evaluate thermal comfort conditions in buildings. People spend majority of the time occupancy in their domestic dwellings (ASHRAE55, 2010; ISO7730, 2005). Therefore it is essential to evaluate the thermal sensation of occupants in residential buildings and understanding how people have feeling to their thermal environment and useful to ensure the thermal comfort responses to efficient energy use in future work. Numerous studies in both thermal environment and thermal responses have been investigated in residential buildings (Han, et al., 2009; Wang, 2006; Cao, et al., 2014; Luo, et al., 2014; Anon., 2009; Oseland, 1994). Moreover, previous researchers report about thermal comfort on winter conditions related to energy consumption in residential buildings. Hong et al. focused on thermal comfort of occupants on domestic conditions in England in winter, results showed that better insulation and energy efficient heating system lead to

better thermal comfort and related to energy demand (Hong, et al., 2009). Field study of Cao et al in Chinese residential buildings showed that the mean indoor temperature in dwellings installed with individual boiler heating system compared to that in district heating system exceeded 1.6°C (Cao, et al., 2014). Becker and Paciuk used the Fanger's model as standard and conducted field study in 189 dwellings in winter, the results from survey showed the actual mean votes(AMV) were significantly higher than predicted mean votes(PMV), in addition gender, age of occupants have no obviously effect on thermal responses (Becker & Paciuk, 2009). Field study of the thermal comfort conditions in residential buildings were conducted in two zone of China, Yang et al found that 68% of occupants feel slightly cool in winter and neutral temperature were much higher than indoor air temperature (Yang, et al., 2013).

Generally, China can be separated into five climatic zones namely severe cold, cold, hot summer and cold winter, hot summer and warm winter and moderate as shown in Figure 1 (GB50178-93, 1993). In 1996, the Chinese government firstly announced an energy conservation design standard JGJ26-95 for new heating residential buildings. This standard focuses on energy efficient measures in order to reduce the energy consumption of residential buildings in Severe Cold and Cold Zones of China. Since 1996 the development of new residential buildings with district heating systems has started to be guided by the new developed standard. However, in 2010, the newer standard revised and has a mandatory requirement on the heating system namely that it should be installed with household-based heat meters and Thermostatic Radiator Valves (TRVs) for each radiator, room temperature can be adjust within a range (JGJ26-2010, 2010). In China, the most common heating system in old residential buildings is district heating systems, which are operated by constant water flow rate and variable water temperature. Whilst there are no heating control systems and occupants can only open their windows or doors to adjust indoor thermal conditions (Xu, et al., 2009).

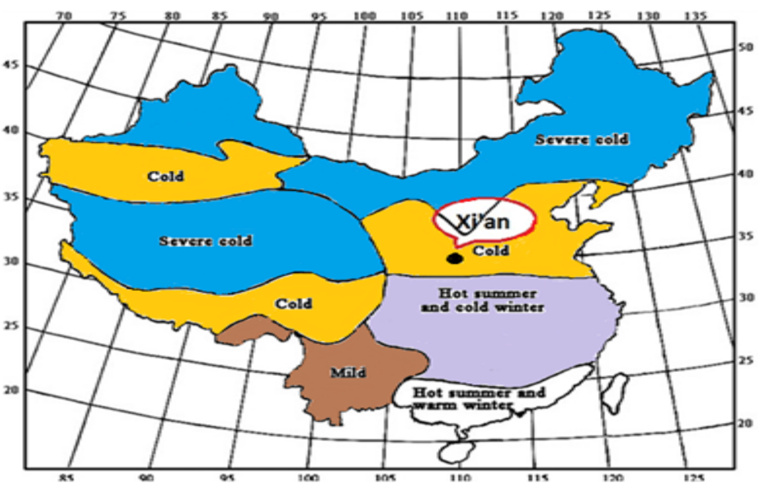



Figure 1. Five climatic zones of China based on GB50178-93

Many previous studies have demonstrated that the PMV model performed well for Chinese buildings (Yang, et al., 2013; Han, et al., 2007; Peng, 2010; Wang, 2006), however, studies lack of to identify how the upgraded standards have effect on thermal comfort in both types of old and new residential buildings. To exam this issue for Chinese residential buildings on winter conditions, a thermal comfort survey was carried out in both new and old buildings according to updated standards, in the winter of 2014 and thermal comfort experiment is produced from 7 old apartments and 7 new apartments in same district. This study is to determine the validity of applying the PMV model in two types of residential buildings: old building comprised uncontrolled heating with payment based on floor area; New residential building install personal control on the heating system(TRVs), together with 'pay for what you use' tariffs. Furthermore, the purpose of study is to identify the difference of occupants' thermal sensation in two type buildings. In addition, the comparative analysis was presented on result from householders in new and old building in this paper.

## 2 Methodology

### 2.1 Building description

The investigations were conducted between 15th February and 15th March 2014. This field study had been carried out in Xi'an of Shaanxi province in north China. Xi'an city is typical city in cold zone in China and has a cold and dry climate in winter in cold zone. Figure 2(a) shows a typical district heating system with TRVs in new building and Figure 2(b) shows a typical district heating system without personal control. The two types of buildings are both multi-story and each apartment contains one living room and two bedrooms. The new residential building was newly built within five years and the old building was built late 1990s.

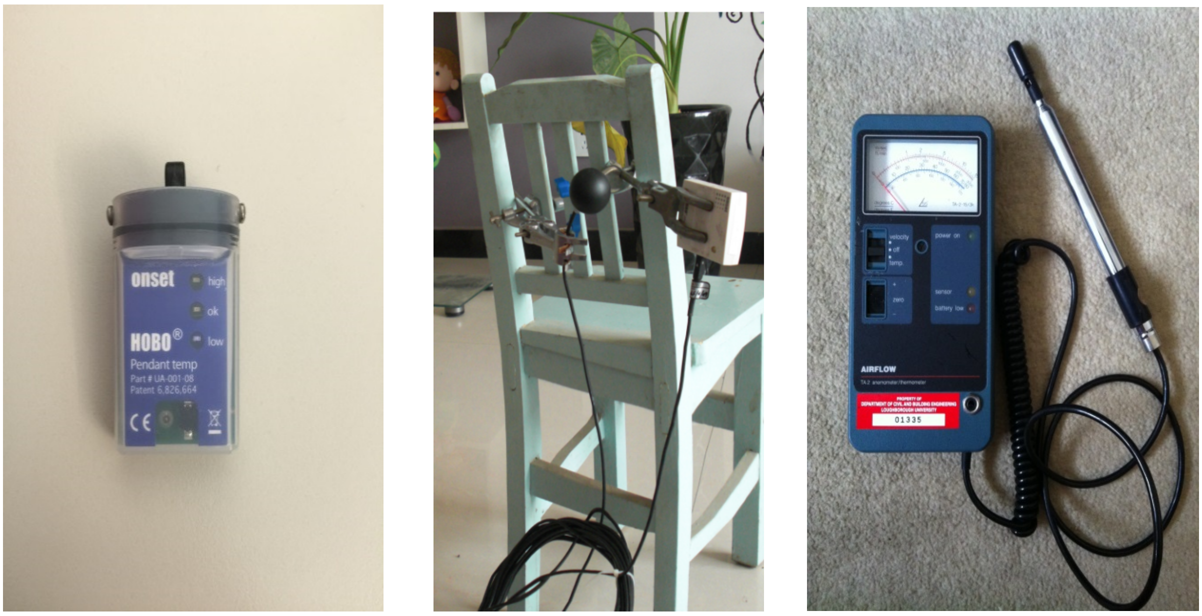
(a) (b)

Figure 2(a). Sample of typical district heating with TRVs in new building; (b) Sample of typical district heating without TRVs in new building

### 2.2 On site measurements and instruments

The experiment is divided into both subjective questionnaires survey and objective measurements. The subjective surveys were based on the thermal sensation reported by occupants. In addition, the gender should be considered into the evaluation of thermal comfort in both types of building. Equilibrium between males and females has also been considered during the selection of occupants. In this study, there are two occupants that will participate in each apartment that one male and one female. Moreover the ages of occupants range from 18 to 65. The clothes insulation and thermal sensation were carried out from the interviewed survey and the simultaneous measurement of environmental parameters of air temperature, mean radiant temperature (MRT), air velocity and relative humidity.

A HOBO data logger (Fig.3a) was used to measure the indoor air temperature in living room in each apartment. The air temperature measurements ranged from -20 to 70°C and accuracy of temperature is ± 0.35°C from 0° to 50°C. For measuring the relative humidity, the range is from 5% to 95% RH and the accuracy of RH is ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5%. Furthermore, mean radiant temperature was estimated from globe temperature and also assessed using a 38mm diameter black Ping-Pong ball globe thermometer (Fig.3b) and it had been calibrated in chamber. Indoor air velocities were measured by hot-wire anemometer (Fig.3c) at 0.1m, 0.6m and 1.1m height during interview survey. The range of the hot-wire anemometer for air velocity is from 0 to 15m/s with an accuracy of ±0.05. All the equipment accuracies correspond to ISO 7726 (ISO 7726, 2001).




(a) (b) (c)

Figure 3. Experimental devices

### 2.3 Questionnaire survey

The questionnaire was developed based on the standard of ISO 10551 (ISO 10551, 2001) and used in each apartments. In order to ensure valid and accurate results, all questionnaires had been translated into Chinese based on thermal comfort standard (Liu & Qin, 2006). A consent form was issued and the actual mean votes (AMV) form was explained to them. There are three main questionnaires: first is application form to take part in the thermal experiments that involved the name, age, physical conditions. Second is the main thermal sensation of participants and how they feel about the thermal environments. It includes the 7-point ASHRAE sensation scale, ranging from -3(cold) to +3(hot) and 0(neutral). Additionally, the three thermal performance scales were provided by warmer, no change, cooler. And the personal acceptability of indoor thermal environment is two scales of yes or no, following with question: “would you accept this indoor thermal environment?”. The third one is used to identify the clothing insulation values for females and males and it divided into two parts, one is participants identifying the clothing insulation values and given a total figure for it, another one is observed by observer from distance. The spot measurement of thermal comfort survey was conducted on individual occupants who were seated watching TV in living room in each apartment. All occupants were kept seated for 45mins and they were asked to fill AMV form after 30mins and 45mins. The survey involved 28 subjects in total, 14 females and 14 males. Averagely, there were two times questionnaires survey during interviews, one was conducted at begin day of whole experiment periods, and another one was conducted at the final day of whole experiment periods. Therefore, total valid questionnaires are 112, there were 56 questionnaires from new apartments, and 56 questionnaires from old apartments.

## 3 Results and discuss

### 3.1 Indoor climates in new and old apartments

Statistical summaries of the variations of indoor air temperature for 7 new apartments and 7 old apartments during investigation period are given in table 1. The mean outdoor air temperature is 8.9°C, the maximum and minimum temperatures are 27.7°C and -1.9°C respectively during the investigation. According to the results of questionnaires, in old apartments, the majority of occupants respond that the windows were opened because it was hot inside apartments and they prefer to have cooler indoor environments. It also can be seen from table 1, results show that the mean indoor temperature in all old apartments is 22.5°C and the indoor air temperature in new one is 20.7°C which is respectively 1.8°C lower than the value measured in old apartments. The mean radiant temperature (MRT) ranged from 22.5°C to 23.3°C in old apartments, whilst in new apartments, the mean value of MRT with a ranged of 19.8°C–21.9°C. The mean Relative humidity obtained in the old apartments was 48.3%, which is slightly higher than 43.5% in the new apartments. The indoor air velocity in old apartments ranged from 0.03m/s–0.05m/s respectively in new apartments has value range from 0.01m/s–0.06m/s. Meanwhile, shows that the majority of air velocity in both new and old apartments was low, with a mean value of 0.056 m/s, which was not more than 0.15 m/s, which meets the winter thermal comfort standard (Wang, et al., 2011). The metabolic rate were observed and ensured same activities of estimated values of 1.1 met in each apartment during interview.

Table 1. Summary of the indoor climate measurement data

| Residential Building Types | Home No. | Indoor Air Temperature | | |
|---|---|---|---|---|
| | | Mean | Max. | Min. |
| Old apartments | 1 | 22.2 | 23.6 | 16.7 |
| | 2 | 22.6 | 24.7 | 18.1 |
| | 3 | 22.4 | 23.5 | 18.2 |
| | 4 | 22.5 | 25.2 | 16.1 |
| | 5 | 22.9 | 24.8 | 17.3 |
| | 6 | 22.2 | 25.7 | 15.7 |
| | 7 | 22.7 | 25.1 | 17.2 |
| New apartments | 1 | 21.0 | 23.4 | 17.4 |
| | 2 | 20.9 | 22.4 | 17.5 |
| | 3 | 20.8 | 22.2 | 15.8 |
| | 4 | 21.1 | 22.2 | 17.3 |
| | 5 | 21.6 | 22.6 | 16.1 |
| | 6 | 19.7 | 23.2 | 15.8 |
| | 7 | 19.6 | 23.4 | 15.9 |

### 3.2 Clothing insulation

The statistical summaries of clothing insulation values were taken from what occupants themselves as estimated from clothing insulation lists. The values are given in Table 3.2. Based on the chair insulation effect on occupants, in this study the insulation of the chair is assumed to be 0.35clo as all participants were sitting on a fabric sofa during the survey (de Dear & Brager, 1997). Clothing insulation value ranged from 0.78clo to 1.197clo with a mean value of 0.9clo in new apartments. In old apartments, the clothing insulation values varied from 0.608clo to 1.28clo with a mean value of 0.79clo. Clothing is a behavioural adjustment that directly affects heat balance(RP-884) and responds one of key thermal adaptive responses (de Dear & Brager, 1997). Figure 4 show that the relations between clothing insulation level and indoor temperature. From liner correlation the coefficient of determination $R^2$ can be observed as 0.12 for old apartments and 0.08 for new apartments.

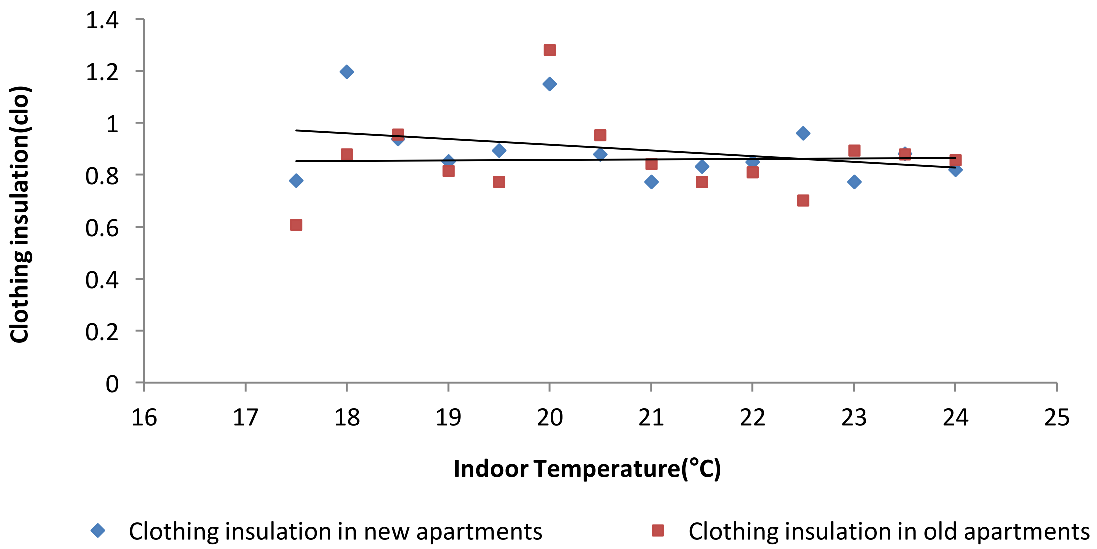



Figure 4. Comparison of clothing insulation between old apartments and new apartments

### 3.3 Thermal comfort responses

#### 3.3.1 Comparison of thermal sensation vote in new and old apartments

Figure 5 shows that the occupants' overall the thermal sensation voted for the surveyed new and old apartments. For the new apartments, majority of subjects voted the range from slightly cool (-1) to slight warm (+1). It can be seen that 29% of occupants feel neutral (0). However, the greater number of occupants in old apartments voted the range from slightly warm (+1) to warm (+2) and also have 16 percentage of occupants voted hot (+3) that much more than none of subjects vote hot (+3) in new apartments. From figure 5 indicated that in old and new apartments, majority of occupants voted within the central three categories against that the ASHRAE Standard 55-2004 specified that an acceptable thermal environment should have 80% of occupants vote for the central categories (-1,0,+1).

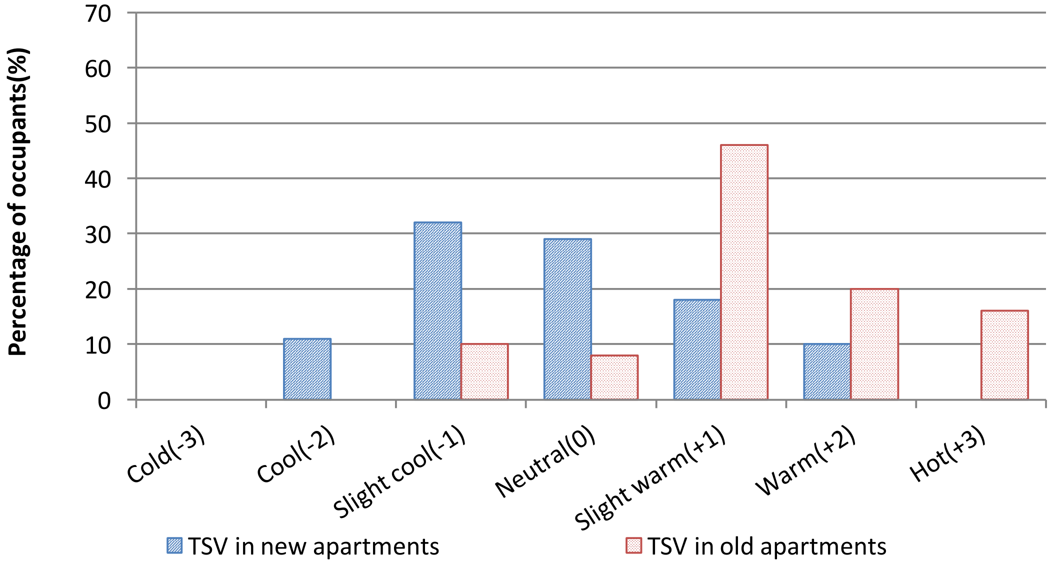



Figure 5. Comparison of thermal sensation vote of occupants in new and old apartments

Regression of binned actual mean votes of occupants as a function of air temperature is presented as two linear regression equations (de Dear & Brager, 1997) as following:

$AMV=0.1550T_a-3.2461$ (1)

$AMV=0.1681T_a-3.1986$ (2)

Where Ta is air temperature, AMV is actual mean votes. The equation (1) and (2) were used to carry out the neutrality. The neutral temperature for AMV in old apartments and new apartments were determined 20.9°C and 19.0°C, respectively (when the mean thermal sensation vote = 0).

### 3.3.2 Investigating validity of PMV model

The correlation between the calculated PMV and the reported AMV are presented in Figure 6. The correlation coefficients in new and old apartments are 0.70 and 0.73 respectively. It indicate that the PMV model performed well on predicting occupants' thermal comfort in both new and old apartments and provide an indication of the contribution of Fanger model. According to de Dear and Brager pointed that thermal adaptation can be achieved from three categories: behavioural adjustment, physiological acclimatization and psychological habituation (Brager & de Dear, 1998). Evidence reviewed in this paper indicated that thermal sensations of occupants have strong correlation to psychological and behavioural adjustment. Discrepancies observed could mean that there are psychobiological adaptations factors involved in thermal comfort of occupants in new apartments may have higher acceptable, result from controllability of heating system. Furthermore, In this study, occupants in new apartments are able to achieve their psychological expected or satisfied indoor environment via adjust TRVs set point, thus they respond more acceptable of indoor environment than those in old ones. Oppositely, occupants in old apartments have no opportunity to control environmental set point by control systems. Therefore, they respond discomfort with their indoor environments, in particular, they only can open window when room were overheated. It also can be consider that difference of the heating bill payment between new and old apartments. This is can be due to the occupants in new apartments can potential reduce indoor set point by using TRVs to save energy use related to less heating bill payment. Thus they provide better thermal responses. Evidence concluded in this study show that new building standard lead to better thermal comfort of occupants compared with old one.

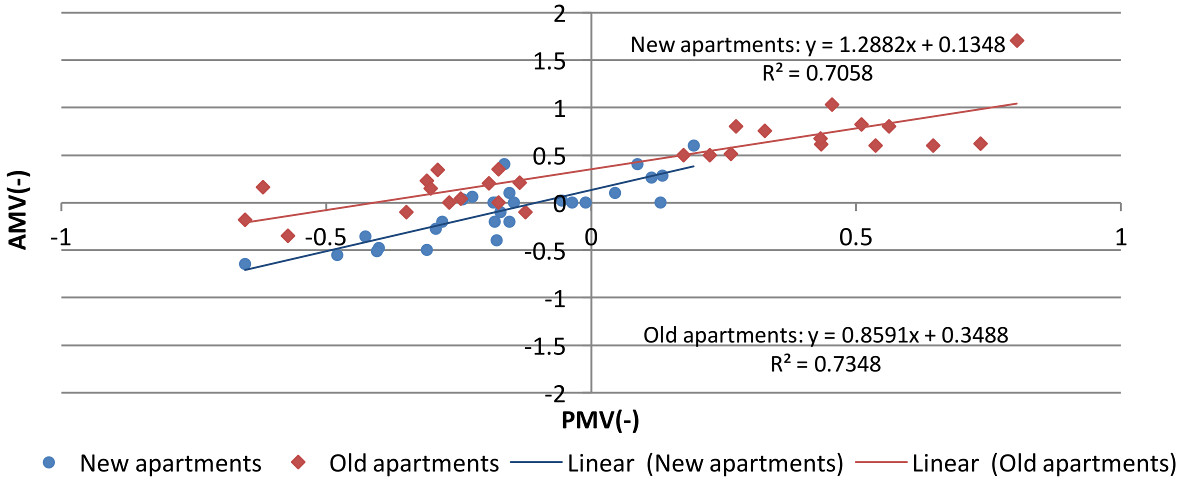



Figure 6. Regression lines of AMV versus PMV in new and old apartments

### 3.3.3 Thermal preference

Figure 6 shows the thermal preference scale from occupants' survey, 57% occupants in old apartments want to change their indoor environment to be cooler, while 28% occupants do not want to change their environments. However, in new apartments, occupants provide higher acceptable of indoor environment, 42% occupants do not want to change their environments. One possible explanation being put forward was that there are control systems in new apartments, and occupants can control TRVs to change heating set point in order to get their actual satisfied environments. However, occupants in old apartments only can open window when they not satisfied with their indoor climates. It is interesting to note that the similar findings were investigated from field study by Cao et al in Chinese residential buildings during winter period. It was found that the occupants in apartments with individual boiler heating respond higher acceptable evaluation than district heating without private control. This can be due to indoor environments were controlled by the users according to their actual demand in individual boiler heating apartments (Cao, et al., 2014).

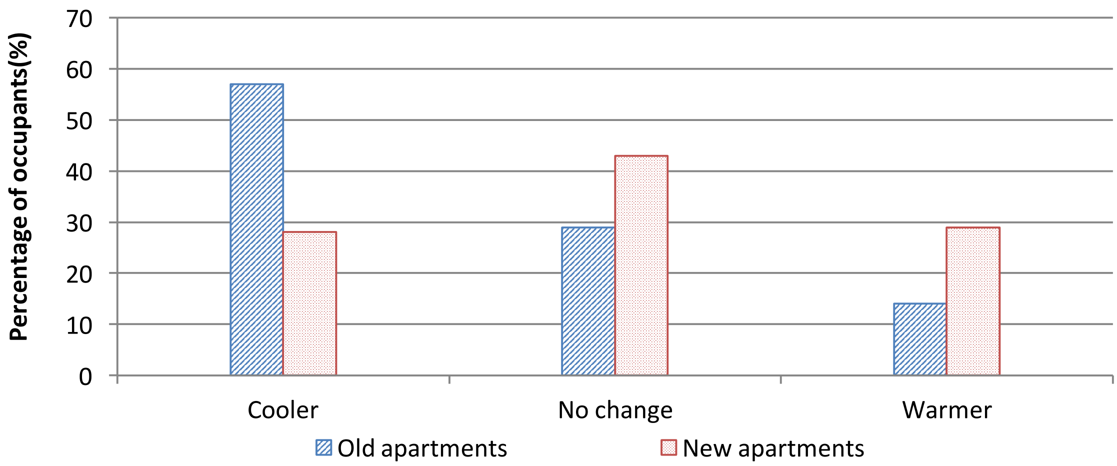



Figure 6. Distribution of thermal preference in new and old apartments

### 3.3.4 Indoor environment acceptability

Indoor environment acceptability votes reflect occupants' acceptability to the total environment (Wang, et al., 2011). Overall there are over 57% of satisfactions for thermal environment in the new apartments higher than that of 29% in old apartments (Fig.7). One possible explanation being put forward was that the indoor air temperature in old apartments higher than that in new ones, and occupants in old apartments prefer to have cooler indoor environment as well. Furthermore, it needs to take into account that the adaptive factors in new apartments should be considered into this field study.

In addition, gender influence thermal performance of AMV and reflect that the personal factors are important to be considered. Gender differences on thermal comfort were investigated based on objective and subjective surveys in Chinese building during winter period, Lan et al. of laboratory experiments showed not only the male skin temperature is constantly higher than that of female but also the female is more sensitive to air temperature. Furthermore, females prefer warmer conditions than males (Lan, et al., 2008). According to interview survey, overall female occupants were more dissatisfied with indoor thermal environment than male occupants in either new or old apartments. In the phases of occupants were not satisfied with indoor environment, difference between females and males were more prominent than that in phase of satisfactions votes (Fig.7). From the results, overall, the 71% female and male occupants are satisfied to the thermal environment in old apartments. Generally, a comparative analysis of data collected from males and females in old apartments show a slightly disparity of thermal sensation between them. However, generally females have much higher complaint than males in both types of building. Comparing the female comfortable sensation, the higher numbers of females in old apartments feel uncomfortable than males in new ones.

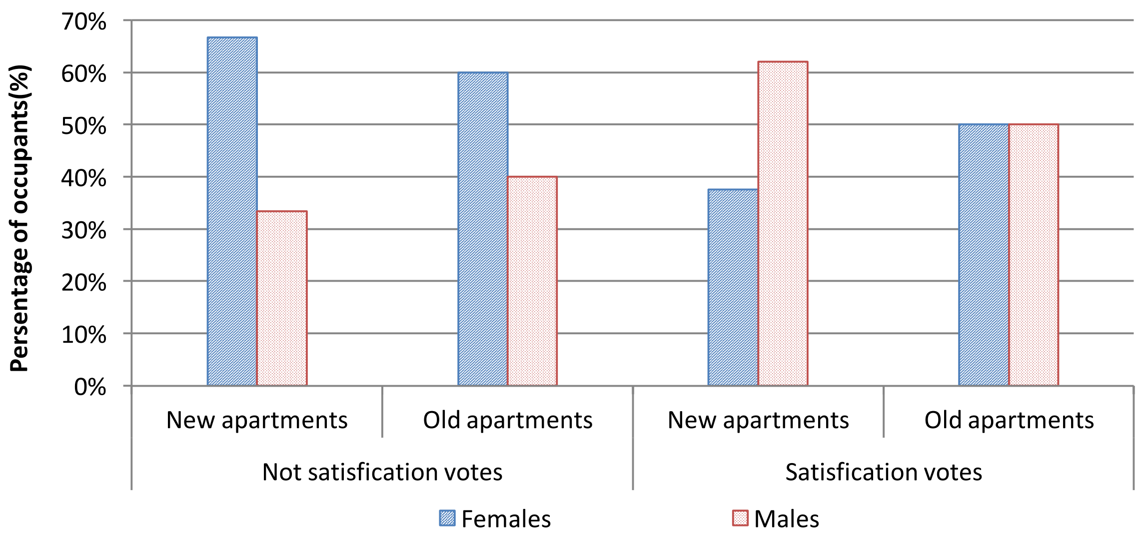



Figure 7. Distribution of thermal acceptability for females and males in old and new apartments

## 4 Conclusions

This experiment is based on subjective responses of 28 occupants that provided thermal sensation data from survey in the old and new apartments according to updated standards during winter season in North China. The conclusions are as follow:

- According to the results, the indoor temperature differences between old and new apartments were obvious. The mean indoor temperature in all old apartments is 22.5°C and the indoor air temperature in new one is 20.7°C which is respectively 1.8°C lower than the value measured in old apartments.
- The study investigated that the correlations between clothing insulation level and indoor temperature. From liner correlation the coefficient of determination $R^2$ can be observed as 0.12 for old apartments and 0.08 for new apartments.
- The greater number of occupants in old apartments voted the range from slightly warm (+1) hot (+3). Furthermore, thermal preference scales from occupants' survey show that 57% occupants in old apartments want to change their indoor environment to be cooler.
- A main issue to consider when reducing building energy consumption is not to sacrifice indoor thermal comfort. With the finding of energy consumption, adjustment of indoor set point temperature by using TRVs in new apartments, they provide better thermal responses than those in old ones. Evidence concluded in this study show that new building standard lead to better thermal comfort of occupants compared with old one.
- Overall there are over 57% of satisfactions for thermal environment in the new apartments higher than that of 29% in old apartments. The sensation differences in old and new apartments might be caused by occupants' psychological expectation. Furthermore, overall females have much higher complaint than males in both types of apartments.

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