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Applicability of different energy efficiency calculation methods of residential buildings in severe cold and cold zones of China

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Abstract. With the accelerated development of dynamic energy consumption simulation software, the accuracy and feasibility of steady-state calculation method for energy efficiency designs of residential buildings in severe cold and cold zones should be investigated. A six-story residential building model as a case study is introduced to be calculated and simulated by steady-state calculation method elaborated in 'Design standard for energy efficiency of residential buildings in severe cold and cold zones' and dynamic energy consumption simulation of EnergyPlus software respectively, in order to compare and analyze the differences between these two methods in five typical cities of China (Xi'an, Lhasa, Xining, Harbin and Hailar). The findings indicate that the index of heat loss of building obtained from both methods is different to typical cities with varied difference ratios. Especially in cities of high altitude, strong radiation and greater diurnal range, namely Lhasa and Xining, the difference ratio is as high as 43.83% and 16.63%. Thus, dynamic energy consumption simulation should be used for counting residential building energy efficiency instead of steady-state calculation method in above mentioned zones by analyzing main factors concerning the differences.

1. Introduction

The accelerated development of the building sector consuming a large amount of energy and natural resources leads to the energy crisis and climate change [1]. It has become the focus on different countries in the world, also China. At present, in order to control the excess heating energy consumption of residential buildings and its negative impact in northern heating zones, the Ministry of construction in China in 2010 promulgated the design code JGJ 26-2010, namely '*Design standard for energy efficiency of residential buildings in severe cold and cold zones*', which proposes steady-state calculation method for guiding architects to consider building energy efficiency in the initial design phase [2]. However, complex upgrades of buildings, progress of energy-saving technologies and climate change are gradually restricting the application of steady-state methods in the building sector which was proved [3]. Meanwhile, another dynamic energy consumption simulation by computer software is being widely adopted in central and southern China because of its high precision and good applicability to complex buildings. Few researchers compare the difference between steady-state method and dynamic simulation in the application of building energy efficiency.

Therefore, to further investigate the differences between above two methods, this paper utilizes EnergyPlus software to simulate a typical building in five typical cities for comparing with the steady-state method to identify the optimal method for sever cold and cold zones to improve the accuracy and efficiency of energy efficiency calculation.

2. Research methods

At present, there are two main calculation approaches used for analyzing and calculating the main energy consumption of residential buildings as follows.

2.1. Steady-state calculation method

At present, the effective heat transfer coefficient method is one of the steady-state calculation ways commonly used in China. The main building thermal energy efficiency design reference standard states that the effective heat transfer coefficient method is used to calculate IOHLOB based on the steady heat transfer theory, the specific formula is as follows:

$$q_{\mathrm{H}} = q_{\mathrm{HT}} + q_{\mathrm{INF}} - q_{\mathrm{IH}} q_{\mathrm{H}} \quad (1)$$

In equation (1), where q_{H} is index of heat loss of building. q_{HT} and q_{INF} is the heat transfer through the building envelope and building infiltration heat removal respectively, in a unit building area per unit of time. q_{IH} is the interior heat addition in a unit building area per unit of time and usually takes 3.8 $\mathrm{W \cdot m^{-2}}$.

2.2. Dynamic energy consumption simulation

Based on the unsteady heat transfer theory, dynamic simulation as an advanced method, including transfer function method, harmonic reaction method, and finite element difference method, uses computer simulation software to establish building models through introducing the hourly meteorological parameters, so that it can simulate and analyze dynamic change of building load under the constantly changing outdoor meteorological condition [4]. At present, there are all kinds of software with excellent performance developed by various countries to provide users with convenience. In addition, some researchers have verified the accuracy of EnergyPlus software and high precision of dynamic simulation method [5]. Hence, EnergyPlus 8.6 software is used in this study to simulate the typical buildings because of its mature system and wide application. It simulates dynamic loads of buildings by heat balance method and simulates transient heat transfer of building envelops based on the internal surface temperature of the wall by conduction transfer function (CTF) algorithm [6].

3. Case study

In order to investigate the applicability and difference between steady-state calculation and dynamic simulation method in energy efficiency design of residential buildings in severe cold and cold zones, there are five typical cities, namely Xi'an, Lhasa, Xining, Harbin, and Hailar, selected in this analysis. The selection principle is that this five cities not only belong to each climate sub-zone of residential building energy efficiency design, but also are located in different provinces and at different altitudes. In addition, for further quantitative and qualitative analysis of the two methods, each typical city's heating period for calculation (HPFC) and mean outdoor temperature during heating period (MOTDHP) in dynamic simulation need to be the same as in steady-state calculation from building specification. Hence, relevant information and comparison group of each city are shown in Table 1. Steady-state calculation I (SCI) is defined that all HPFC, MOTDHP and relevant climate data used in steady state calculation are derived from design standard JGJ 26-2010. Steady-state calculation II (SCII) is defined that HPFC is identified in according with the design standard, and MOTDHP is identified as a constant value by CSWD hourly meteorological data. Dynamic simulation II (DSII) is defined that HPFC used in dynamic simulation is identified in according with the above standard, outdoor temperature with the dynamic change is obtained from CSWD hourly meteorological data but the calculated MOTDHP is consistent with SCII.

Table1. Heating period for calculation and mean outdoor temperature during heating period in typical cities

Climate zone	Climate sub-zone	Province	City	Altitude (m)	Comparison group	HPFC (d)	The heating period time (day/month)	MOTDHP (ºC)
Severe cold zone	II(A)	Shaanxi	Xi'an	398	SCI	82	/	2.10
					SCII, DSII	82	01/12-20/02	0.90
	II(B)	Tibet	Lhasa	3650	SCI	126	/	1.60
					SCII, DSII	126	01/11-06/03	1.08
Cold zone	I(C)	Qinghai	Xining	2296	SCI	161	/	-3.00
					SCII, DSII	161	22/10-31/03	-2.91
	I(B)	Heilongjiang	Harbin	143	SCI	167	/	-8.50
					SCII, DSII	167	22/10-06/04	-10.26
	I(A)	Inner Mongolia	Hailar	611	SCI	206	/	-12.00
					SCII, DSII	206	01/10-24/04	-12.36

3.1. Introductions to the building model

A six-story residential building model is chosen to conduct the comparative study by steady-state method and dynamic simulation method. The typical floor plan of building model is shown in Figure1, and Figure 2 describes the corresponding SketchUp model for subsequent simulation. There are two households per floor sharing with stairs and being South-North orientation. The building area is 1430.76 m^2, the building height is 16.8 m (2.8 m×6), and the building volume is 4006.13 m^3. The ratio of window to wall area of each direction is 0.37 in the south, 0.06 in the east and west, and 0.21 in the north, respectively. In addition, the thermal performance parameters of the main envelope meet the requirements of the building code JGJ 26-2010 as shown in table 2.

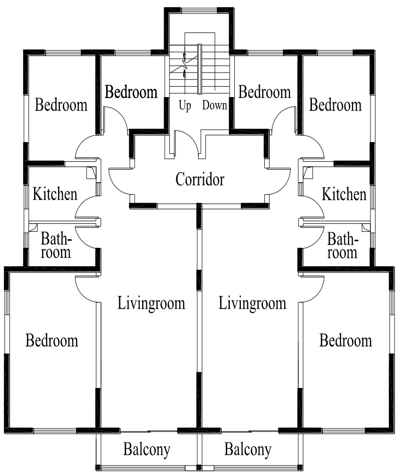


Figure 1. Typical floor plan of building model.

Figure 2. Simplified SketchUp building model.

3.2. Steady-state calculation and dynamic simulation process

According to the parameters setting in Table 1 and Table 2, the building model is calculated and simulated by steady-state calculation and dynamic simulation methods mentioned above. To be specific, based on JGJ 26-2010, the building is adopted continuous heating running system, and the indoor heating air temperature in common rooms is required to reach 18ºC and in stairwell is required to be 12ºC. Meanwhile, the total internal heat gains from people, lights, and electrical appliances etc. are formulated to be 3.8 W·m^{-2}, and the average air change rates equal to 0.5 aches. In addition, Ideal Loads

Air System is used in dynamic simulation to calculate the ideal load and the heat gains of the sample building [7]. Moreover, the dynamic simulations are carried out based on hourly data of typical meteorological year (TMY) of each typical city in the Chinese Standard Weather Date (CSWD) format downloaded from the EnergyPlus official website [8].

Table2. Thermal performance value of the building model envelope.

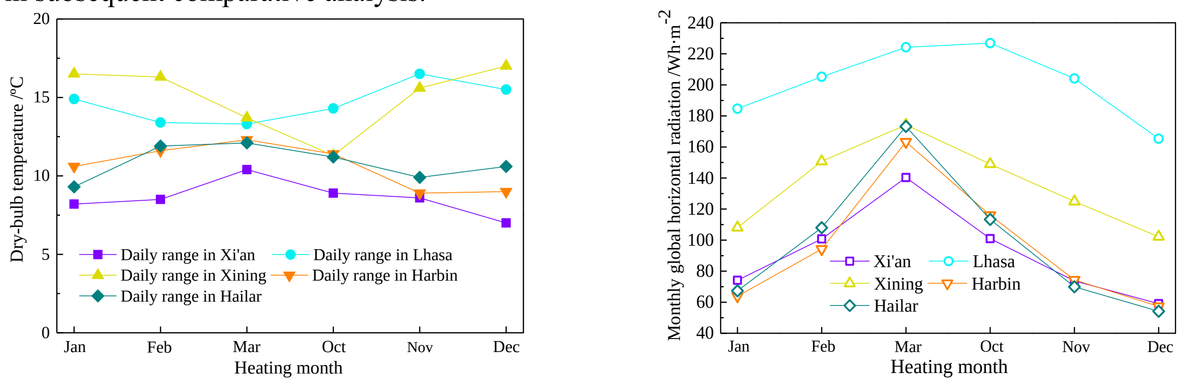
City	Heat transfer coefficient of building envelop ***K*** (W·m^{-2}·°C^{-1})									Thermal resistance ***R*** (m^2·°C·W^{-1})
	External wall	Roof	Window (S)	Window (E, W, N)	Outside door	Partition panel in balcony		Internal wall	Floor	Ground slab （Insulation layer）
						Wall	Window			
Xi’an Lhasa	0.60	0.42	2.50	2.80	2.80	0.60	2.50	2.05	0.63	1.02
Xining	0.42	0.31	1.60	1.75	1.75	0.42	1.60	1.36	0.41	1.02
Harbin Hailar	0.32	0.20	1.60	1.75	1.75	0.32	1.60	1.15	0.35	1.50

Note: S-South, E-East, W-West, N-North.

4. Results and discussions

4.1. Meteorological data of typical cities

Air temperature and solar radiation as meteorological parameters are the relatively primary cause influencing the heating energy consumption which was proved [9].Therefore, daily range and global horizontal radiation of five typical cities in main heating months are shown in Figure 3 in order to assist in subsequent comparative analysis.



(a) (b)

Figure 3. Daily range and global horizontal radiation of typical cities in severe cold and cold zones.

Figure3 illustrates that both the daily temperature ranges and global horizontal radiation in Lhasa and Xining are obviously higher than in other typical cities, followed by Harbin and Hailar, and finally Xi'an. Particularly in Lhasa, the highest monthly hourly global horizontal radiation in heating period can reach 226.88 Wh·m^{-2}. In addition, comparing with Table 2, it is an interesting finding that those cities with strong radiation and greater daily range possess higher altitude than others. The reason why this phenomenon happens is that high altitude zones, such as Lhasa and Xining, with thin air and low cloud amount can enhance solar radiation which results in the increase of daytime temperature in the zones. It leads to large temperature difference between day and night compared with low radiation zones, and unstable outdoor air temperature into a dynamic change over time. In contrast, the cities with low solar radiation and low daily range, such as Hailar, Harbin, and Xi’an, are also relatively low in altitude.

4.2. Comparative analysis of the methods

After the above processes, the building model was used to study differences between steady-state calculation method and dynamic energy consumption simulation in the value of IOHLOB by manual computation and software simulation. The results of IOHLOB of residential buildings in above 5 typical cities obtained by SCI, SCII, and DSII are shown in Figure 4. Firstly, all of the results of each city got from either the steady-state method or the dynamic simulation meets the requirement of building energy efficiency design for IOHLOB as specified in the standard JGJ 26-2010. Figure 4 represents that the results vary greatly from city to city but the trend is basically similar by comparing the IOHLOB of different cities no matter which method is used. To be specific, the value of IOHLOB in Hailar is the highest about 19 $W \cdot m^{-2}$. Second, the value in Harbin ranges from 15.63 $W \cdot m^{-2}$ to 18.22 $W \cdot m^{-2}$, followed by Xi'an and Xining, and finally Lhasa, which has the lowest value less than half that of Hailar. The reason for these results can be found by combing Table 1 that there is a linear relationship between IOHLOB and heating period, and outdoor temperature, for most cities except of Lhasa and Xining with high altitude and strong radiation. However, Lhasa and Xining breaks this linear relationship which indicates that the height of altitude and the intensity of solar radiation have a strong impact on IOHLOB. Furthermore, SCI and SCII selects different climate data and specific date of heating period that leads to the different MOTDHP involved in calculation although both methods uses the same theoretical algorithm and same HPFC from design standard.

On the other hand, comparing DSII with SCI or SCII, Figure 4 also shows that the values of IOHLOB calculated by steady-state calculation method is higher than that by dynamic simulation in all the cities except Harbin, especially when DSII and SCII adopt same parameters but produce different results. The main reason is that the theoretical algorithms of two methods are different. For example, the conventional steady-state method only considers the steady state heat exchange without the unstable characteristics of building materials, such as thermal mass performance, which has been considered by dynamic simulation. Furthermore, thinking about the special result of Harbin, the reason may be excessive consideration of extreme conditions which leads to the unreasonable choice of run time during the dynamic simulation.

4.2.1. Difference ratios. In order to clearly compare the steady-state calculation and dynamic simulation method used in energy efficiency design in severe cold and cold zones, this research introduces the difference ratio, which is the ratio of differences between the two algorithms to dynamic simulation method in calculation results, usually expressed as a percentage. The difference ratio of IOHLOB in five typical cities between SCII and DSII are shown in Figure 5.

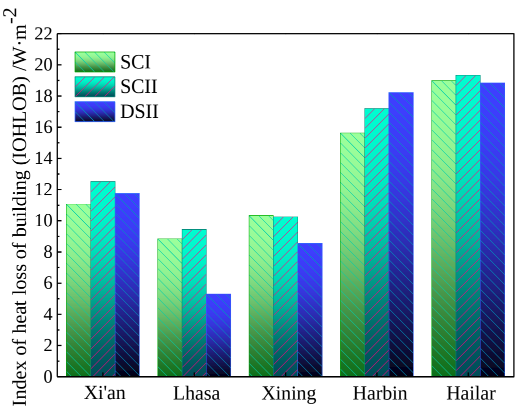


Figure 4. The IOHLOB calculated by steady-state calculation and dynamic simulation in severe cold and cold zones.

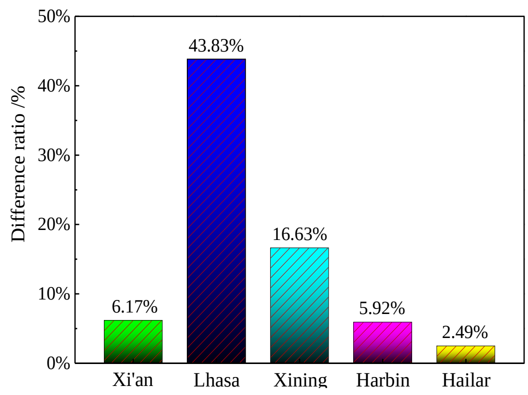


Figure 5. The difference ratio of IOHLOB compared between SCII and DSII in severe cold and cold zone.

Apparently, the difference ratios of IOHLOB between SCII and DSII differ greatly from city to city. More specifically, the difference ratio in Lhasa is up to 43.83%, which is the highest in all typical cities.

Next is Xining with a difference ratio of 16.63%. Both in Lhasa and Xining, the difference ratio between above two methods are much greater than 10%, indicating unreasonable application of the steady-state calculation method in residential building energy efficiency design in these two cities. Followed by Xi'an and Harbin, their difference ratio is 6.17% and 5.92%, respectively. Finally, Hailar has the lowest difference ratio of IOHLOB, only 2.49%. It implies that there is no significant impact on the energy efficiency calculation of residential buildings in this area whether or not whichever of the above two methods is chosen.

In addition, combining Figure 3 and Figure 5, it can be seen that the daily range and solar radiation are the main reasons for the difference between the steady-state calculation method and the dynamic simulation. The stronger the solar radiation and the greater the daily range in areas such as Lhasa and Xining, the higher the difference ratio of IOHLOB between the two methods. This is because the increase of solar radiation in strong radiation areas causes a large temperature difference between day and night, which makes a dynamic change trend in outdoor temperature with time. As a result, the steady-state method proposed by the building code to calculate building energy efficiency is not applicable to the areas with strong solar radiation and greater diurnal range, because MOTDHP involved in the calculation is constant. On the contrary, dynamic simulation is suitable for the above areas, namely Lhasa and Xining, because it uses hourly climate data which is dynamic and conforms to the actual weather situation in these areas.

5. Conclusions

In this study, besides of the difference in theoretical algorithm and different climate data selected for manual calculation and software simulation have significant impact on index of heat loss of building and its differences between the two methods for the same city. In addition, altitude, solar radiation, and daily range are the key factors causing obvious differences among different cities when comparing the two methods. Especially index of heat loss of building obtained from both methods vary widely in cities of high altitude, strong radiation and greater diurnal range, namely Lhasa and Xining, with a difference ratio is as high as 43.83% and 16.63%. Therefore, dynamic energy consumption simulation is recommended over steady-state method for building energy efficiency calculation in above mentioned zones.

Acknowledgments

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