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Research on Quantitative Relationship between Body Design Parameters of Residential Buildings and Energy Saving in Cold Regions

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Abstract

The research on quantitative relationship between design parameters of residential buildings and energy saving conducted in the paper is to update and correct the previous related research results and is the supplement and perfection of the building energy-saving design. The effect of length and width and height of building on energy saving in cold area under all-weather conditions especially when considering the effect of solar radiation on the building energy consumption are carried out. And the change trend of building energy consumption with design variables, the influence of the variables on the energy consumption and the quantitative relations with energy consumption are obtained using statistical method, providing a basis for further theoretical and experimental research.

Keyword

Building energy-saving, Body design parameters, Energy consumption simulation, Quantitative relation.

1. Introduction

In the world's growing energy consumption, building energy consumption accounts for a large proportion of total social energy consumption whether in developing countries or developed countries. Building energy consumption refers to the energy consumed in the whole process from the process from production of building materials, construction, normal use until being dismantled [1]. The largest proportion of building energy consumption is created during the daily operation, accounting for more than 80%, mainly for air conditioning, heating, lighting, hot water, cooking, laundry and so on. With the industrialization and the improvement of people's living standards, the rapid development of construction, especially residential construction leads to an increasing proportion of building energy consumption in total energy consumption. At present, our society is be developed rapidly and people's living standard is being improved gradually. People's demand for residential thermal environment is also increasing, so the residential construction must be strictly in accordance with the relevant standards and conduct energy-saving. The situation of building energy saving in our country is very grim, and the state has given great attention and done a large number of work. A series of residential building design standards and norms and regulations have been promulgated one after another. At the same time, the state has adopted industrial policies that are aimed at construction energy-saving and are helpful to promote energy-saving and accelerated the research of energy-saving technology [2]. The promotion and application of energy-saving of residential buildings still have many deficiencies. The vast majority of our existing buildings are high energy consumption building. There are still many problems in energy saving of residential buildings and the situation is not optimistic. More work is required to truly achieve energy-saving effect.

This paper first analyzes the characteristics of body design of residential buildings in cold areas, extracts body design parameters that has impact on building energy-saving including plane length, width and building height. with the statistical method, the change trend of building energy consumption with design variables, the influence of the variables on energy consumption and the quantitative relations with energy consumption are obtained.

2. Overview of energy-saving related factors in residential building design in cold region.

Heating energy consumption of residential buildings in the cold area accounts for a larger proportion of the total building energy consumption, and the heating energy saving potential can be said to be the largest energy consumption of all kinds of buildings in our country, so it should be the focus of building energy-saving design and research. According to the characteristics of cold climate, in the design process of residential buildings, it should first meet the thermal insulation requirements in winter, then meet the thermal protection requirements in summer. This requires that in residential design, building facade design and window settings should first meet the sunshine and wind and other requirements. In addition, body parameters of buildings should also be strictly controlled, and select reasonable building plane, profile form and size, determine the appropriate ratio of window to wall. These factors are the issues that should be concerned about by architects in the first phase of design. And architects should carefully consider the parameters including building plane shape, body coefficient in order to design an energy-efficient construction program.

There is a clear definition to body parameters of residential buildings in the standard of energy-saving design of residential buildings in cold regions (JGJ26-2010) [3]: the ratio of building volume and outer surface area in contact with outdoor air. In the outer surface area, the floor, the interior wall and the door of non-heating stairs home area are not included, It could be expressed with the formula:

$$S = F / V \quad (1)$$

In the formula, S—building body parameter

F—building outer surface area (m^2)

V—volume surrounded by the building outer surface area(m^3)

By the above definition and formula it could be seen that the shape coefficient is expressed by building outer surface area in each volume, it directly reflects the complexity of the building shape and the size of the envelope.

When building volume is given, the larger the shape coefficient, the larger the contact surface of enclosure structure and air, so more heat is dissipated and more energy is consumed by the building. So control building body parameter is one of the important issues in the design of building energy saving. However, for architects, in the design stage, building body parameter could not be controlled directly. Instead it is controlled through adjusting the plane size of the building program (length and depth), building height and layer number and so on. From the formula (1) it is known that body parameter S is related to outer surface of building S and the surrounded building volume V. While for rectangular buildings with the uniform section, there are the following formulas:

$$F = L \times H + A \quad (2)$$

$$V = A \times H \quad (3)$$

L—Perimeter of building cross section(m)

H—Building height(m)

A—Area of building cross section(m^2)

For building with rectangular plane, the two parameters, perimeter and area of building cross section are both determined by the two design parameters, length (a) and depth (b) . The height of the building is related with the height per layer (H) and the layer number (n), so in the process of design the influence of building body parameters on energy-saving design could be controlled by determining building height, depth, height per layer and number of layers.

Because the perimeter of the building plane is also related to the twist degree of the plane, this is also one of the factors to consider when conducting the energy saving design. In previous studies, Cao Yiran et al from Shanghai Institute of building study the relationship between building height, width, length with body parameter by considering solar radiation and think that when building volume is given, the best building design size could be determined through comprehensively designing the ratio of length and width and building orientation [4].

In addition to body parameter, ratio of window to wall is one of the important parameters that is related to building energy-saving and need to be considered in the design of architectural scheme. On the one hand, radio of window to wall influences how much natural lighting and sunshine could shine into the room, on the other hand, there is a direct relationship between the size of the outer windows and energy consumption of heating in winter and air-conditioning energy consumption in summer, so it has a direct impact on the building total energy consumption. At the same time, ratio of window to wall is the ratio of outer window area to room elevation unit area (the area surrounded by building height per layer and the positioning line), and its value is a parameter that architect could directly change in architectural design, so it should also become one of the architectural energy-saving design factors.

3. Simulation analysis of energy consumption of residential buildings under different design parameters

Simulation and calculation of residential building energy consumption is related to climate conditions, thermal performance of building envelope, design parameters of building model, design of heating ventilation and air conditioning system and activity conditions of humans indoor, so the method of computer simulation could comprehensively consider all the factors and conduct accurate energy consumption simulation and calculation. Therefore, this paper employs DesignBuilder software combined with energy consumption simulation engine EnergyPlus to conduct building energy consumption simulation under different conditions, in order to analyze the relationship between different parameters of the architectural design and building energy consumption[5].

3.1. Relationship between building length (plane width) and energy saving

Physical model: When selecting the building length, a namely residential building combined plane length, the statistics results of residential survey in Tianjin area (Table 1) is referred to. For the plane type residential building, width of unit plane is determined as 14m-16m and 20m-24m. For the tower type residential building, plane length is determined as 20m-40m.

Table 1. Statistics results of plane size of residential unit

Building type		Unit plane width(m)	Plane depth(m)
Plane type	Few layers	15-20	11-15
	Many layers	14-16	11-15
	Small High-Rise	14-16/20-24	11-15
	High rise	19-20	15-17
Tower type	Few layers	12-18	10-12

	Small High-Rise	24-40	13-20
	High rise	24-40	13-20

When conducting simulation, residential standard layer is defined as unit combination plane. For the plane type residential building, it is the plane combined by two units. Therefore, the plane length of plane type residential unit is determined as 28m-32m. In the establishment of energy consumption model, residential plane length takes the construction modulus 0.3m as the difference to determine the value of each variable.

Residential plane width B is an auxiliary variable, when establishing energy consumption model, its value is set taking 3m as difference. Plane width of plane type residential building is 12m, 15m, and that of tower type residential building is 15m, 18m, 21m.

Simulation results and quantitative relationships: (1) first conduct energy simulation analysis of plane type residential building. For plane width (depth) b=12m, construction area changes in the scope from 338.4 m^2 -385.2 m^2, and building layer select 3 , 6 and 9. The simulation results of the total building energy consumption in different length (plane width) are shown in figure 1.

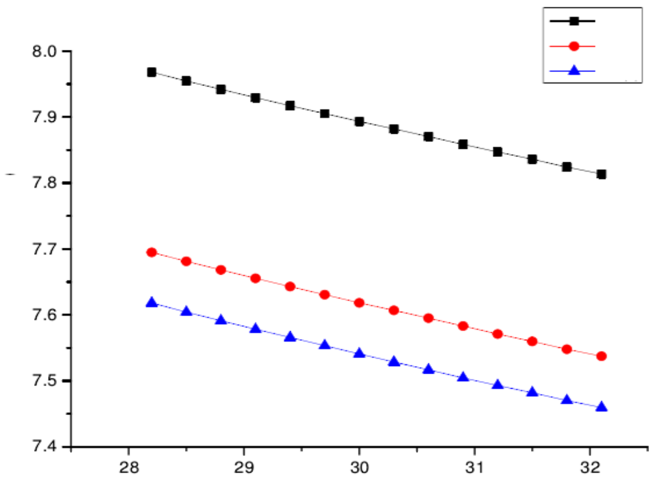

Figure 1. Change trend of unit building energy consumption of the plane type residential buildings with different heights with plane length

Analyze the above data and it could be seen from Figure 1 that with the increase of residential combination plane length (plane wide), the unit building energy consumption decreases linearly. At the same time, with the increase of building height, building energy consumption decreases. The slope of the three curves in the figure is approximately the same, and it could be seen that with the increase of plane length, the change trend of unit building energy consumption in different heights is basically the same.

Use the mathematical statistical software Origin[6] to conduct linear fitting of the curves in Figure 1 that indicates the relationship between the plane length of plane type residential building and energy consumption and calculate the regression equation to get the quantitative relation between plane length of the plane type residential building (plane wide) a and unit building energy consumption qb. From the fitting equation it could be seen that the slopes of the three curves have only 0.001 difference, which means that for the plane type residential building of different heights, the impact of plane length on building energy consumption is roughly the same; and also means that for the plane type residential building of different plane lengths, the trend of unit building energy consumption with height would not change with the change of plane length.

$$q_{b3} = 9.078 - 0.039 \times a \quad (4)$$

$$q_{b6} = 8.828 - 0.040 \times a \quad (5)$$

$$q_{b9} = 8.761 - 0.040 \times a \quad (6)$$

(2) For the tower type residential building whose combination plane width is 15m, the range of residential combination plane length is 20M-40M. Considering the range is relatively large, take 0.9m as difference to set different plane length, the variation range of building plane area is 301.5 m2 -598.5m2. Build residential models whose layer number are respectively 9, 18 and 25 for energy consumption simulation, and simulation results are shown in figure 2.

Figure 2 shows that for tower type residential building with the same plane width (depth), the total building energy consumption goes into a downward trend along with the increase of the plane length, and basically belongs to linear change. Energy consumption of 18 storey residential building is lower than that of 9 storey residential building,. But different with plane type residential building, when building layer number increases from 18 to 25, unit residential energy consumption of building with plane length of 21m and 21.9m would increase. So for buildings with specific plane, when height of the building increases to a certain extent, building energy consumption begins to rise. This is not conducive to energy saving.

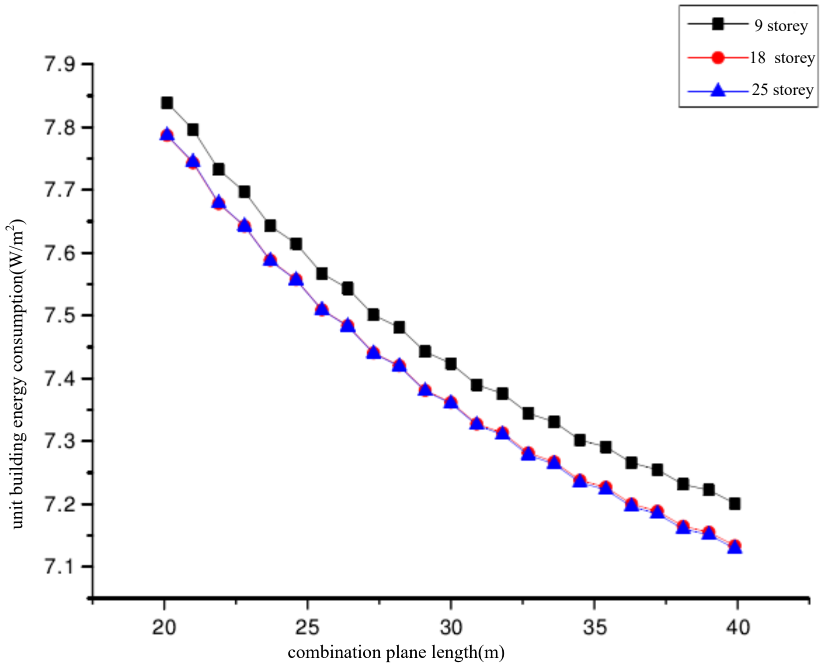

Figure 2. Change trend of unit energy consumption with plane length of tower type residential building with different heights

Use mathematical statistics software Origin to conduct fit regression of the three curves in Figure 2 and get the relationship between plane length of tower type residential building a and unit building energy consumption qt.

$$q_{t9} = 8.388 - 0.031 \times a \quad (7)$$

$$q_{t18} = 8.350 - 0.032 \times a \quad (8)$$

$$q_{t25} = 8.357 - 0.032 \times a \quad (9)$$

3.2. Relationship between building width (depth) and energy saving

Physical model: The plane design width common used in current residential building could be obtained through analysis of the research results of the design parameters of the existing residential building shown in Table 1[7]. For plane type residential building it is within the range of 11m-14m, and for tower type residential building it is within the range of 14m-17m. During the statistics of the width, the distance between outer surfaces of the building envelope is taken as calculation size, not including building facade projections including the balcony, bay window and air conditioning board. In the study of quantitative relationship between different plane width (depth) and building energy consumption, several different building height will be chosen for comparative analysis and ensure the rationality of research conclusion.

Table 2. Size selection of residential plane width with plane length as 30m

Plane type residential building			Tower type residential building		
3 storey	6 storey	9 storey	9 storey	18 storey	25 storey
11.1	11.1	11.1	14.1	14.1	14.1
11.4	11.4	11.4	14.4	14.4	14.4
11.7	11.7	11.7	14.7	14.7	14.7
12.0	12.0	12.0	15.0	15.0	15.0
12.3	12.3	12.3	15.3	15.3	15.3
12.6	12.6	12.6	15.6	15.6	15.6
12.9	12.9	12.9	15.9	15.9	15.9
13.2	13.2	13.2	16.2	16.2	16.2
13.5	13.5	13.5	16.5	16.5	16.5
13.8	13.8	13.8	16.8	16.8	16.8
14.1	14.1	14.1	17.1	17.1	17.1
14.4	14.4	14.4	—	—	—
14.7	14.7	14.7	—	—	—
15.0	15.0	15.0	—	—	—

As shown in Table 2, building storey of plane type residential building is selected as 3, 6 and 9, and that of tower type residential building is selected as 9, 18, 25. Take building module 0.3m as difference for residential plane width to conduct energy consumption simulation. The residential plane takes the common 4 households combination as a reference, the length of combination plane is set uniformly as 30m, the plane area is 333m^2-513 m^2. Build energy consumption model.

Energy consumption simulation and analysis :(1) First conduct energy consumption simulation to plane type residential building. Building height of model is set to 3m, the ratio of window to wall is set according to the specified limit from building energy saving design standards, and plane width (depth) is set from 11m-15m with 0.3m as difference, building height is 9m ,18m, 27m. A total of 42 sets of simulation experiments are carried out and the obtained simulation results are shown in Figure 3.

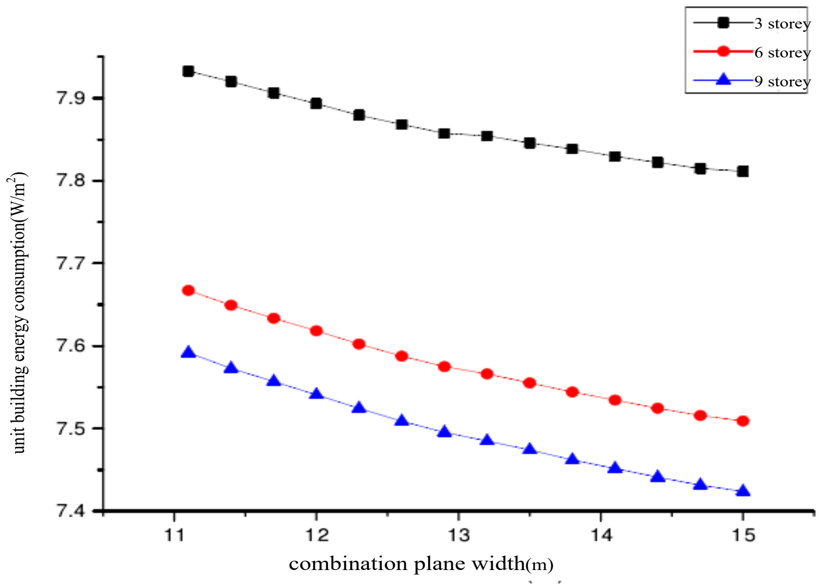

Figure 3. Change trend of unit energy consumption with plane width of plane type residential building with different heights

It could be seen from Figure 3 that with the increase of building plane width (depth), unit building energy consumption is reduced linearly. At the same time, with the increase of building height, residential energy consumption will be reduced. Conduct significant difference analysis to the three curves obtained in the above figure and obtain that it is significantly different at the 0.05 level. This shows that when the plane type residential building is with different heights, the change trends of unit building energy consumption with plane width are different. At the same time, for tower type residential building with different depths, the change trends of energy consumption with height are also different.

Conduct regression fitting to the three curves in the figure and obtain three regression equations to express the quantitative relationship in different building heights between the plane width (depth) of the plane type residential building and the energy consumption.

$$q_{b3} = 8.266 - 0.031 \times b \tag{10}$$

$$q_{b6} = 8.102 - 0.040 \times b \tag{11}$$

$$q_{b9} = 8.055 - 0.043 \times b \tag{12}$$

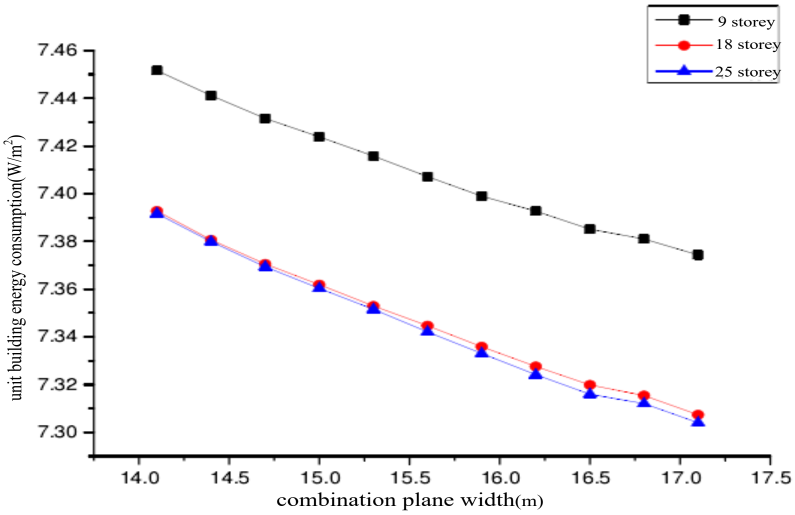

Figure 4. Change trend of unit building energy consumption with plane width of tower type residential building with different heights

(2) Secondly conduct energy consumption simulation to tower type residential building. The energy consumption model uses the same parameters with plane type residential building including plane length (width), height, and ratio of window to wall. The range of plane length is 14m-17m, and building storey is selected as 9,18 and 25. A total of 33 sets of energy consumption simulation experiment are conducted. The simulation results are shown in figure 4.

It could be seen from the figure that similar with plane type residential building, the energy consumption level of tower-type residential building decreases with the increase of residential plane width (depth). With the increase of building height, unit energy consumption of residential building gradually decreases. The regression equation of the quantitative relationship between the plane width of the tower type residential building and the unit building energy consumption is obtained by using the statistical software to conduct fitting regression the of the three curves in the picture above.

$$q_{t9} = 7.809 - 0.026 \times b \quad (13)$$

$$q_{t18} = 7.784 - 0.028 \times b \quad (14)$$

$$q_{t25} = 7.798 - 0.029 \times b \quad (15)$$

3.3. Relationship between building height (storey number) and energy saving

Physical model: In architectural plane design, in order to simulate the rationality of contrast experiment, the plane area of residential standard floor are uniformly set as 360 m^2, namely residential combination is four household layout[8]. In this experiment, the plane of energy consumption model is chosen as a rectangular plane. And according to the different characteristics of residential plane size of plane type residential building and the tower type residential building, plane width of the former (depth) is set as 12m, and that of the latter is set as 15m. In addition, in order to study the influence of different plane changes on the relationship between building height and energy consumption, the area of the residential plane and the length-to-width ratio of the plane are changed respectively, and model is built to simulate the energy consumption [9].

Energy consumption simulation and analysis:(1) First in the case of the building plane unchanged, conduct energy consumption of plane type residential buildings with different heights, the number of building storey is in the range of 3-13. The simulation results is shown in figure 5.

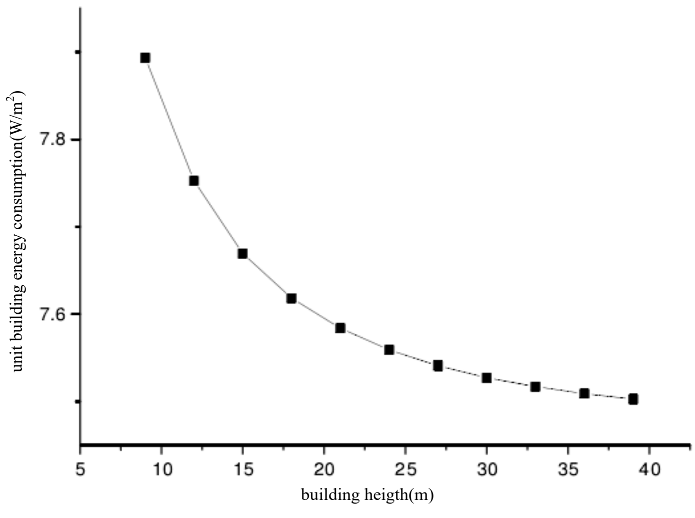

Figure 5. Change trend of energy consumption of plane type residential building with the same plane size with the building height

It could be seen from the figure that for plane type residential building there is an inverse proportional change relation between building height and unit building energy consumption, and with the increase of building height, decrease of building energy consumption gradually slows down, and the turning point appears when the height is 20m, about 6 storeies. So for plane type residential building, the building's energy saving effect is more significant with building storey number increasing from 3 to 6, and when from 6 to 13, the energy-saving effect is very general. The curve of the relationship between building height and energy consumption is fitted, and the regression equation is obtained:

$$q_{bH} = 7.502 + 1.296 \times 0.874^{H} \tag{16}$$

(2) Then the energy consumption of tower type residential building is simulated in order to study the relationship between building height and energy consumption. The result is shown in figure 6.

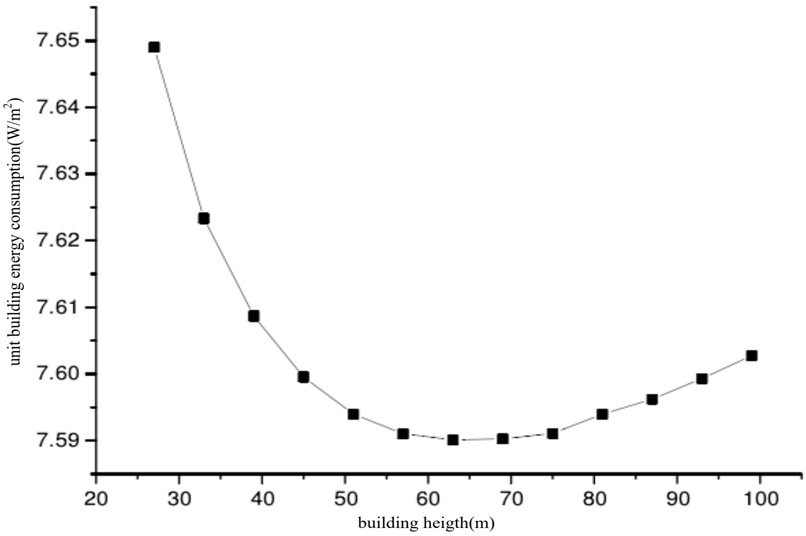

Figure 6. Change trend of energy consumption of tower type residential building with the same plane size with the building height

From the figure it could be seen that with the increase of height of the tower type residential building, unit building energy consumption increases firstly and then decreases, generating an inverted parabola curve in figure. The lowest point of the curve is the turning point. When the building height is above this point, the building energy consumption begins to show an upward trend. Conduct fitting regression of the curve in the above figure and equation (17) is obtained, which indicates the quantitative relationship between the height of tower type residential building and unit building energy consumption [10].

$$q_{tH} = 7.544 + 5.821\times10^{-4} \times H + 0.474\times0.940^{H} \qquad (17)$$

(3) Relationship between building height and energy consumption under the influence of different building plane.

From the above study it could be seen that as the height of the building increases, the residential unit building energy consumption decreased first and then increased, the plane size of the residential 15m*24m, 63.2m turning point for the construction of high energy consumption changes. In order to study the different dimensions in residential building height change trend of the lowest energy consumption level, on the same floor area, different level of ratio of length to width and the same plane length width ratio, different plane area of residential energy consumption simulation research.

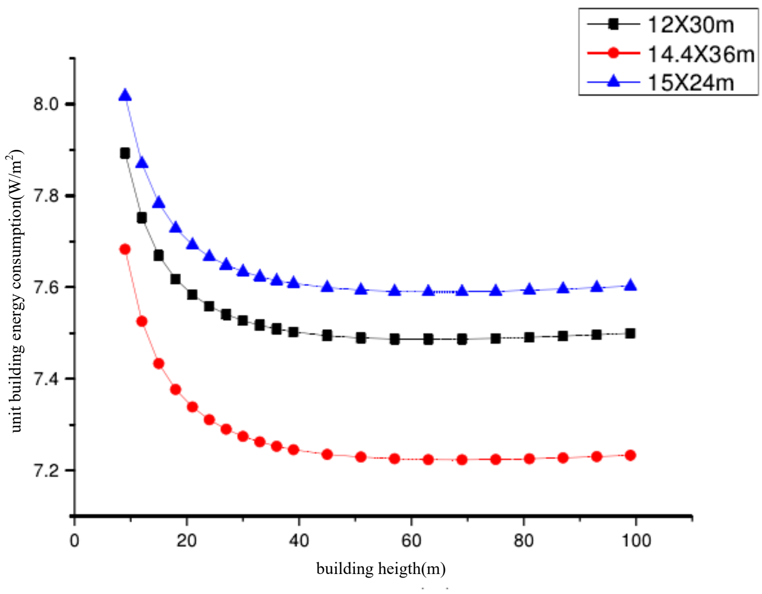

Figure 7. Change trend of energy consumption of residential building with the different plane size with the building height

So choose the residential buildings with plane size separately as 12m*30m, 15m*24m, 14.4m*36m and conduct energy consumption simulation of different heights. The building height is set to 3m, and the results is shown in figure 7.

Through the simulation experiments, we could see from figure 7 that when the building plane size changes, the trend of residential unit building energy consumption with building height also changes. When the plane length-width ratio of residential building is the same, the larger the plane area, the lower the level of building energy consumption; when the residential plane is the same, the larger the length-width ratio of the plane, the lower the level of building energy consumption, and the building is more energy-saving. Conduct fitting regression of the three curves in Figure 7 and solve the minimum of function. The following equations are obtained:

$$q_{H1} = 7.494 + 2.054\times10^{-5}\times H + 1.211\times0.882^{H} \quad (18)$$

$$q_{H2} = 7.242 + 1.816\times10^{-4}\times H + 1.340\times0.882^{H} \quad (19)$$

$$q_{H3} = 7.601 + 7.358\times10^{-5}\times H + 1.277\times0.881^{H} \quad (20)$$

Through conducting energy consumption simulation of residential building with the same building standard plane area and different building height, and analyzing the obtained experimental data, it is concluded that for both plane type residential building and tower type residential building, along with the increase of building height, the whole building energy consumption decreases. Specifically, for the plane type residential building with plane size as 12m*30m, 6 storey is the first cut-off point, namely when building storey is more than 6 and the height is more than 20m, with the further increase of height, the decrease trend of building energy consumption gradually gentle. For the tower type residential building with plane size as 15m*24m, 21 story is the second cut-off point, when building height is more than 63.2m, the further increase of height will lead to the increase of building energy consumption, not conducive to building energy saving. For residential buildings with different plane size, when length-width ratios are the same, the larger the plane area, the smaller the change trend of building energy consumption with building height, and the lower the overall building energy consumption, the more the building energy saving; and when the plane area is the same, the larger the plane length-width ratio, the gentler the change trend of building energy consumption with building height, the lower the overall building energy consumption, and more conducive to energy conservation.

4. Conclusion

In this paper, the effects of different design parameters on the energy consumption of residential buildings are studied. Simulation analysis is carried out with sufficient samples. According to the different residential types, simulation analysis is conducted and the conclusion is that residential unit energy consumption would decrease with the increase of combination plane length (plane width direction) and width (depth direction), and would decrease with the increase of building height, and there will be the minimum value. When the height is more than the value, building energy consumption would increase. In addition, according to the data of energy consumption simulation, the function expressions of each parameter and the energy consumption are given, providing a basis for further theoretical and experimental research.

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