Analysis of Residential Building Layout and Its Impact on Building Energy Consumption in Hefei Region

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Abstract. This article focuses on residential buildings in the Hefei region. Energy consumption simulations for different building layouts were conducted using ECOTECT and BECH software. Comparative analysis of simulation results was performed for three different conditions: winter, summer, and transitional seasons. The study aimed to identify the most energy-efficient building layout considering the local climate. The results indicate that for winter and summer conditions, the row-column layout is the most energy-efficient, saving 7.66% and 8.33% compared to enclosed and slanted layouts in winter, and 4.98% and 5.07% in summer. However, during the transitional season, an enclosed layout in April achieves the best energy-saving performance, while in October, the enclosed layout consumes 2.82% more energy than the row-column and slanted layouts. Overall, considering annual energy consumption, the row-column layout proves to be the most energy-efficient for residential buildings in the Hefei region, with energy savings of 4.28% and 3.5% compared to enclosed and slanted layouts, respectively, providing valuable in sights for energy-efficient design in residential buildings.

1 Introduction

Since the early 1970s, humanity has been consuming resources from the Earth at a rate that exceeds its sustainable capacity [1]. To achieve the goal of limiting global warming to below 1.5 degrees Celsius, the world needs to reduce global emissions by over 50% by 2030 and achieve carbon neutrality by 2050 [2]. In 2021, the global building sector accounted for over 34% of energy demand and approximately 37% of related carbon dioxide emissions[3]. Implementing effective energy-saving and emission-reduction measures is fundamental to achieving energy efficiency in buildings. Hassan Saeed Khan et al. [4] utilized ECOTECT software for energy modeling, demonstrating a 38% reduction in total energy demand for buildings constructed with sustainable materials compared to conventional buildings under local climate conditions. Shen Yan et al. [5] Simulated the outdoor wind environment formed by different building layouts in the Yangling area, concluding that the most energy-efficient layouts in Yangling during the summer are diagonal or parallel rows. Zhang Hao et al. [6], combining field surveys with ECOTECT software analysis, determined that the optimal layout for buildings in Lhasa is parallel rows oriented 15°east of south, with a recommended window-to-wall area ratio of 0.6.

Since 2005, Hefei has experienced rapid development, witnessing tremendous changes in its urban landscape. The city's economy has surged to new levels, accompanied by a sharp rise in population. Consequently, the energy consumption of residential buildings has naturally become one of the focal points of observation for people. Taking the Hefei region as an example and considering its climatic characteristics, this paper employs ECOTECT and BECH software for simulation to propose the most energy-efficient layout for residential buildings.

2 Model Building

2.1 Theoretical analysis

Building heat consumption includes the heat consumption of external windows, non-transparent enclosure structures, and heat consumption due to cold air infiltration.

$$Q = Q_{win} + Q_{non} + Q_{wind} \qquad (1)$$

In the equations:

Q represents the total building heat consumption in watts, W.

Q_{win} is the heat consumption of external windows in watts, W.

Q_{non} is the heat consumption of non-transparent enclosure structures in watts, W.

Q_{wind} is the heat consumption due to cold air infiltration in watts, W.

The heat consumption per unit building area through the heat transfer of enclosure structures should be calculated according to the following formula:

$$q_{HI} = (t_i - t_e)\left(\sum_{i=1}^{m} \varepsilon_i \times K_i \times F_i\right)/A_0 \qquad (2)$$

In the equation:

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t_i represents the average indoor calculated temperature for all rooms, typically set at 16 degrees Celsius for residential buildings.

t_e Average outdoor temperature in heating area℃.

ε_iCorrection factor for the heat transfer coefficient of the enclosure structure:

K_i The heat transfer coefficient of the enclosure structure [W/(m^2·K)], for external walls, should be taken as the average heat transfer coefficient: I'm sorry for the confusion, but it seems like your sentence is incomplete.

F_i The area of the enclosure structure(m):

A_0 building area(m^2).

2.2. Software analysis

ECOTECT's thermal environment analysis adopts the dynamic load calculation method—quasi-dynamic method[7], which is characterized by its simplicity in operation, fast calculation, and no quantity limit for the simulation and analysis of building models.

BECH's thermal load calculation is based on the principle of steady-state heat transfer, where the focus lies on the heat gained and lost by the area under calculation.

2.3. Modeling

According to local standards[8,9], for multi-story residential buildings arranged in parallel in the north-south direction or with a southward deviation of 15 degrees east (west) in the Hefei region, when the height of the above-ground building on the south side is below 18 meters (including 18 meters), the spacing between them should be no less than 1.23 times the height of the south-side building. If the south-side building exceeds 18 meters, the spacing should be no less than 1.26 times the height of the south-side building[10]. The model established in this paper has a building length of 12 meters, width of 10 meters, floor height of 3 meters, and 6 floors in total across 6 buildings. The orientation is towards the south, with a spacing of 6 meters between adjacent buildings and a front-back spacing of 26 meters. The selected enclosure structure parameters are as shown in Figure.1.The three layout models consist of six buildings, with their floor plans shown in Figure.2. Select the structural parameters of the building envelope as shown in Table 1.

Table 1. Construction and Thermal Properties of Building Envelope Materials

structure	Construction Method of Enclosure Structures (Thickness Unit: mm)	thermal conductivity (W/m^2·K)
wall	Plastic waterproof pendant 0 + extruded polystyrene board 20 + structural falsework 12 + reflective insulation layer 0 + mineral wool, rock wool, glass wool 2 50 + C-shaped steel keel 120 + gypsum board 12	0.55
roof covering	Tile-shaped steel plate color tile 0 + cold-formed steel hanging tile strip 0 + synthetic polymer	0.65
	waterproof coating 2 + cement mortar 120 + reinforced concrete 120 + mineral wool, rock wool, glass wool 2 65 + reinforced concrete 120 + lime, cement, mortar 10	
floor	C20 fine stone concrete 40 + extruded polystyrene board 10 + eco-friendly waterproof coating 0 + C15 concrete 80 + compacted clay 1 100	1.55
Floor slab	C20 fine stone concrete 40 + extruded polystyrene board 40 + eco-friendly waterproof coating 20 + C15 concrete 100	1.7

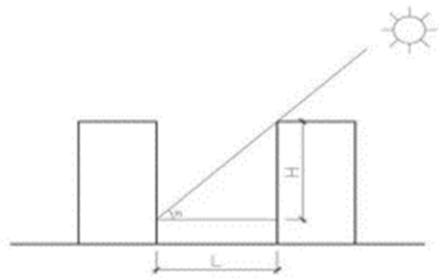
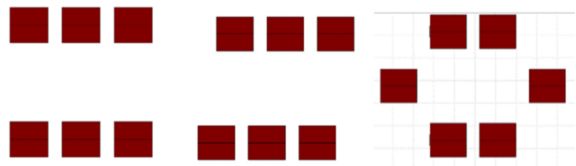


Fig. 1. Schematic diagram for calculating building spacing



A row-column B column C enclosed

Fig. 2 The three layout models

3 Software simulation analysis

3.1 The simulation results of ECOTECT

As depicted in Figure 3, in all three layouts, the peak month for heating energy consumption is January, while the peak month for cooling energy consumption is July. This aligns with the actual conditions in Hefei, where the average lowest temperature occurs in January at 4 degrees Celsius, and the average highest temperature occurs in July at 28 degrees Celsius. It is also noticeable that there is minimal cooling energy consumption in March and April, and some heating energy consumption in November. This is attributed to limitations in the ECOTECT software itself, which does not allow for the setting of segmented air conditioning schedules. To address this, a simulation of building energy consumption under the same conditions was conducted using the green building software (BECH).

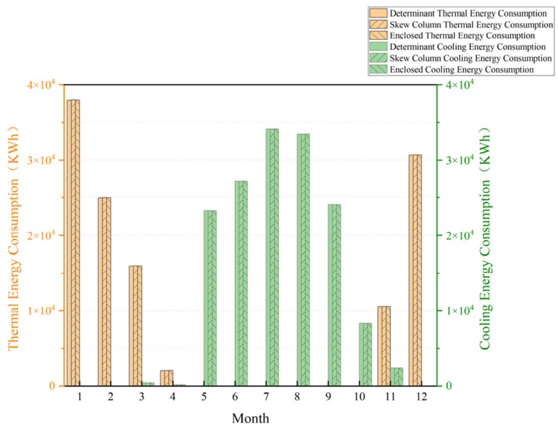


Fig. 3. Building energy enclosed configuration diagram based on enclosed configuration

3.2 The Simulation results for BECH

Based on Figure 4, it can be observed that the total energy consumption in January and July is the highest in both the oblique column and enclosure building layouts, exceeding 5×104 kWh and constituting the largest proportion of the annual energy consumption. In the row-column layout, although the total energy consumption in January and July does not reach 5×104 kWh, it still represents the highest proportion of the annual energy consumption. On the other hand, the total energy consumption in April and October has the smallest proportion, both being less than 5×103 kWh.

The monthly total energy consumption difference between the oblique column layout and the enclosure layout is not significant. Moreover, there is a trend of increasing monthly total energy consumption for the row-column, oblique column, and enclosure layouts, especially in the winter months of January and February and the summer months of July and August. The total energy consumption in the row-column layout is significantly lower than that in the oblique column and enclosure layouts during these winter and summer months. All three building layouts share a commonality in that the building cooling energy consumption reaches its peak in July, which is the hottest month of the summer season. Air conditioning, as the dominant component of energy consumption during the summer, experiences high usage rates among occupants. In the transitional months of April and October, when the climate conditions are mild, the overall building energy consumption is generally lower due to lower utilization rates of air conditioning and heating, with normal usage of lighting, cooking, and laundry-related energy consumption.

3.2.1 Annual Energy Consumption Comparison

The annual total energy consumption results, as shown in Figure 5, indicate that the row-column layout remains the most energy-efficient among the three layouts, followed by the oblique column layout, with the enclosure layout being the least efficient. In comparison to the row-column layout, the oblique column layout consumes 4.28% more energy, and the enclosure layout consumes 3.5% more energy. The additional energy consumption in the enclosure layout is primarily concentrated in the cooling energy consumption during summer conditions. Compared to the row-column layout, the cooling energy consumption in the enclosure layout increases by 5.96%, significantly increasing the overall energy burden.

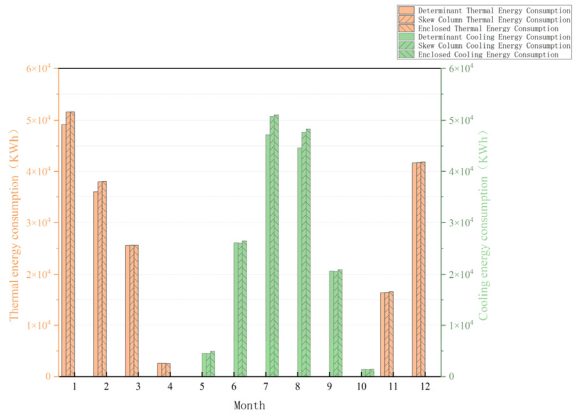


Fig. 4. Bar Chart of Building Energy Consumption for Three Layouts

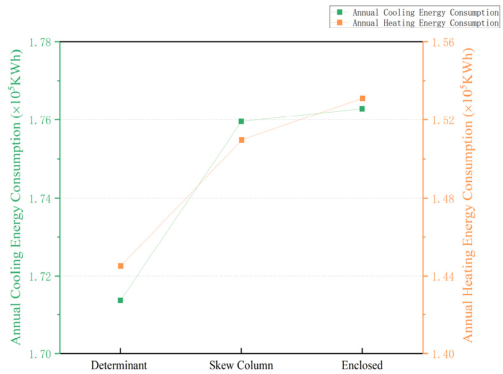


Fig. 5. Annual Total Energy Consumption Chart for Three Layouts

3.2.2 Analysis of Simulation Results Across Different Seasons

The total energy consumption of the three architectural layouts in January and July, representing winter and summer, respectively, is illustrated in Figures 6 and 7. In January, the energy consumption of the row-column layout, diagonal-row layout, and enclosed layout increases sequentially. The row-column layout is the most energy-efficient among the three, with the enclosed layout being the least efficient. In comparison to the row-column layout, the diagonal-row layout requires an additional 4.98% energy in January, while the enclosed layout requires 5.07% more energy. In July, the energy consumption pattern follows a similar trend, with the row-column layout being the most energy-efficient and the enclosed layout being the least efficient. In this case, the diagonal-row layout requires an extra 7.66% energy in January compared to the row-column layout, and the enclosed layout requires 8.33% more energy.

The overall energy consumption of the three architectural layouts during the transitional seasons of April and October is depicted in Figures 8 and 9.

Transitional seasons are characterized by variable weather conditions and significant temperature differences between morning and evening. In April, the energy consumption of the row-column and diagonal-row layouts is nearly identical, while the enclosed layout surprisingly emerges as the most energy-efficient among the three layouts. Although the difference is not significant, it saves approximately 50 kWh compared to the row-column and diagonal-row layouts. In October, the energy consumption of the row-column and diagonal-row layouts is again nearly identical, with both layouts consuming almost the same amount. In comparison to the enclosed layout, these layouts are 2.82% more energy-efficient.

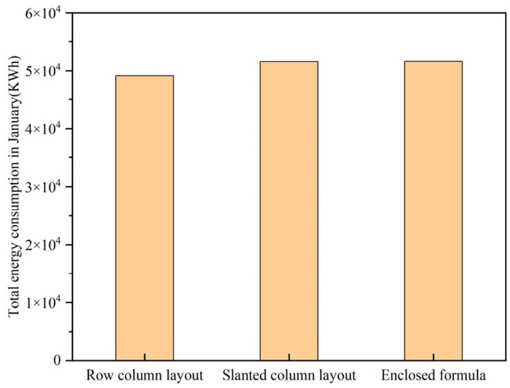


Fig. 6. The total energy consumption of buildings in January

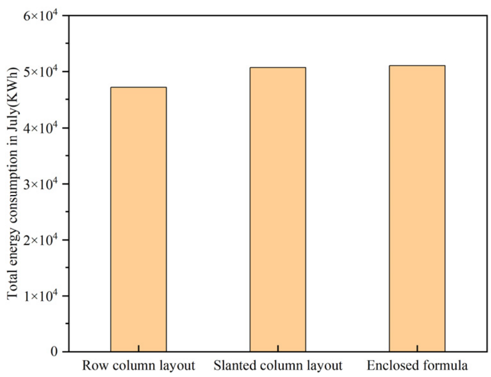


Fig. 7. The total energy consumption buildings in July

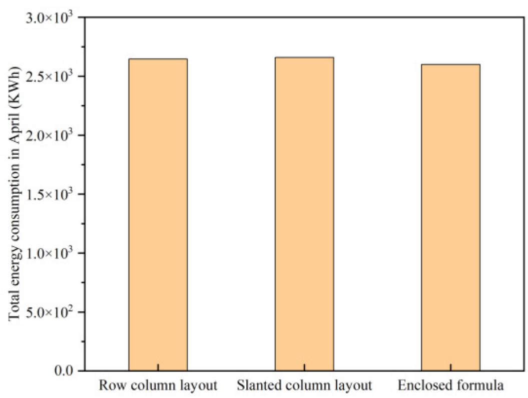


Fig. 8. The total energy consumption of buildings in April

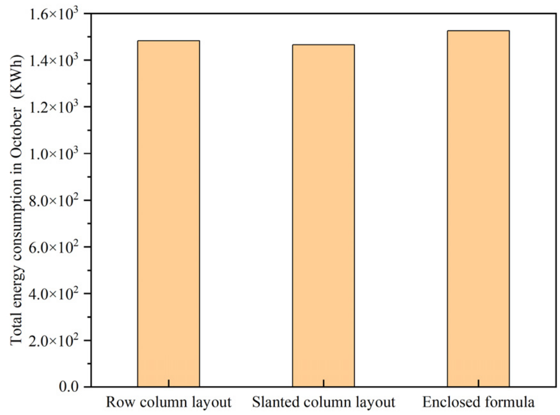


Fig. 9. The total energy consumption of buildings in October

3.2.3 Simulation analysis of the coldest and hottest days

As shown in Figures 10 and 11, the simulation analysis of the total building energy consumption on the coldest day and the hottest day reveals that on January 9th, the matrix layout is the most energy-efficient among the three layout forms, while the enclosed layout performs the worst. However, the overall difference in total building energy consumption among the three layouts is not significant on the coldest day. On the hottest day, August 23rd, the matrix layout proves to be the most energy-efficient again, while the enclosed layout remains the least efficient. In contrast to the coldest day, both the diagonal row layout and the enclosed layout have significantly higher building energy consumption than the matrix layout, with an increase of up to 16.8%. This discrepancy can be attributed to inherent flaws in different building layouts, such as variations in sunlight exposure between buildings and poor ventilation effects. Additionally, specific meteorological conditions on the hottest day, coinciding with the peak solar radiation intensity, contribute to the widening of the energy consumption gap. In summary, the optimal building layout for both the coldest and hottest days is the matrix layout.

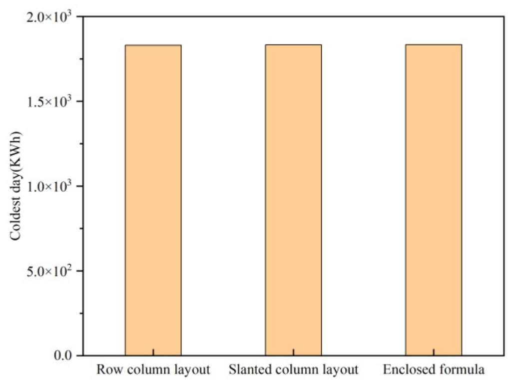


Fig. 10. Total building energy consumption on the coldest day

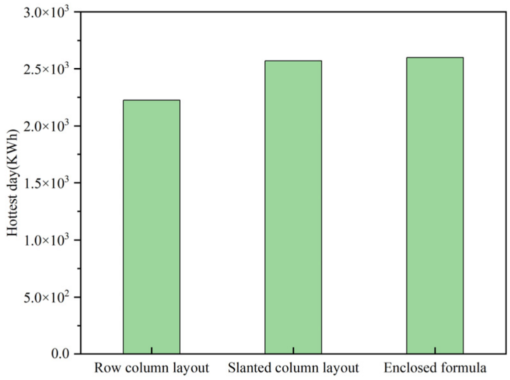


Fig. 11. Total building energy consumption on the hottest day

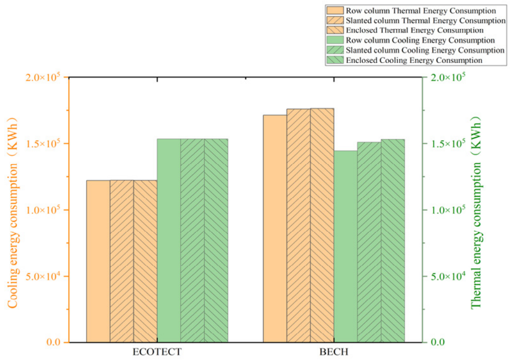


Fig. 13. Comparison of Cooling and Heating Energy Consumption Software

4 Comparative Analysis of Two Software Simulations

Although ECOECT and BECH software were used for building energy consumption simulations under the same conditions, the differences in the platforms used for model creation can easily lead to deviations. As shown in Figure 12, the total building energy consumption calculated by BECH is slightly higher than the results simulated by ECOTECT. However, the simulation results for different layouts show little variation. This can be attributed to the differences in the calculation principles of the two software tools. BECH employs steady-state heat transfer principles, while ECOTECT uses the quasi-steady-state method. Additionally, ECOTECT has lower accuracy in simulating air conditioning systems, resulting in slightly lower simulation results.

In Figure 13, there is a significant difference between the two software tools in terms of thermal energy consumption calculation results, while the difference in cooling energy consumption calculation results is minimal. This discrepancy arises because BECH, when calculating heat loads, accumulates various heat loads, while ECOTECT cannot calculate fresh air loads and moisture loads, leading to calculated values that are always smaller than the actual conditions. However, the overall trend in building energy consumption for different layouts remains consistent—enclosed > diagonal row > matrix. The cross-validation between the two software tools plays a crucial role in clarifying the energy-saving trends.

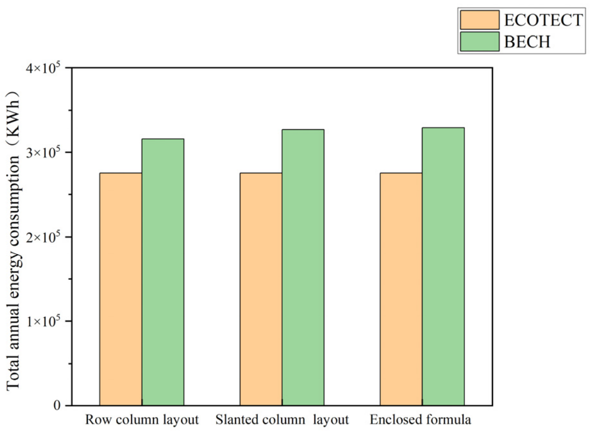


Fig. 12. Comparison of Building Total Energy Consumption Software

5 Conclusion

Based on the above analysis, the conclusion is drawn that, in the residential buildings' total annual energy consumption in the Hefei region, row-type layout buildings are the most energy-efficient, while enclosed layout buildings are the least energy-efficient, with staggered layout buildings falling in between. The specific analysis of energy consumption during various time periods, including January in winter, July in summer, transitional seasons in April and October, as well as the coldest and hottest days, reveals that except for the optimal building layout being enclosed in April, the optimal building layout for other time periods is row-type.

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