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Article

The Carbon Reduction Mechanism and Adaptive Planning Strategies of TOD Neighborhood Form Regulation for Microclimate Effects

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Abstract: Adapting to climate change and controlling carbon emissions have emerged as significant challenges confronted by the international community. The high-quality pedestrian space system of TOD neighborhoods, as an essential means for carbon reduction and sink enhancement in cities, has exhibited a demonstration effect of green intensification, low-carbon sustainability in urban spatial development. The intersectional research of low-carbon block creation and urban microclimate was conducted, along with microclimate simulation (CFD) calculation of the pedestrian space morphology of typical TOD neighborhoods in Qingdao. The correlation between the simulation experiment results and the measured data was compared and comprehensively evaluated to quantitatively analyze the coupling relationship between the block morphology and the comprehensive microclimate environment of wind, heat, and carbon. Summarize and extract the adaptive planning strategies of TOD block space for low-carbon purposes, aiming to realize the low-carbon transformation of cities through the creation of a healthy microclimate environment.

Keywords: TOD neighborhoods; low carbon; microclimate effects; CFD; Qingdao city

1. Introduction

With the increasingly serious problem of climate change, low-carbon development has become a common goal pursued by the international community [1]. By constructing a TOD development model with "rail as the main and slow pedestrian as the auxiliary", it is conducive to shortening urban commuting distance, reducing automobile dependence and thus slowing down traffic carbon emissions [2-3]. As a system node connecting the subway hub station and the public field, the pedestrian space of the block is not only manifested in the interoperability of physical space and function, but also covers the correlation influence of local microclimate on pedestrian comfort and ventilation and carbon reduction efficiency [4-5]. Under the guidance of "dual-carbon" goal, TOD development should focus on the transition between rail transit and pedestrian space environment, emphasize that rail transit station is the core of urban development, and build a green intensive, low-carbon and sustainable block model within its 800m walking range [6-7].

Under the influence of microclimate, pedestrian space in TOD neighborhood is faced with problems such as poor ventilation and local heat island effect, which significantly weakens CO_2 diffusion and dilution capacity [8-9]. At present, China's research and practice in related fields are still relatively lagging behind: there is a lack of scientific and systematic correlation studies on neighborhood microclimate using corresponding simulation methods [10]; there is a lack of research results on the analysis and planning of neighborhood microclimate environment from the perspective of low-carbon [11]; there is a 1lack of comprehensive research methods and strategies for spatial form optimization and microclimate improvement of blocks [12].

In summary, this paper takes Qingdao City as an example to carry out a cross-over study between low-carbon neighborhood construction and microclimate environment, emphasizing not only the role of dynamic distribution of microclimate on street spatial environment, but also the influence of walking spatial pattern layout on CO_2 diffusion. Combined with microclimate simulation technology (CFD) and measured data, on the basis of accurately quantifying and evaluating the

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microclimate effect of walking space, we summarize and refine the adaptive strategies of spatial form optimization to mitigate and adapt to urban microclimate problems, and fully apply them in the planning and construction of pedestrian space in TOD neighborhoods in Qingdao City, which provides a decision-making basis for the practice of urban area renewal and decarbonization.

2. Methodology

2.1. Study Area

Neighborhood characteristics vary depending on the location of the rail transit station, the type of surrounding land, and the functions of the city [13].Neighborhoods under the TOD model can be divided into three categories: commercial, residential, and landscape neighborhoods, which combine the functions of commercial and entertainment, community commuting, and landscape corridors, and together they construct the city's commercial and social networks [14-15]. Accordingly, the kernel density and standard deviation analysis method in ArcGIS is used to summarize the development of the three types of points of interest (POIs) in Qingdao, namely, "shopping and consumption", "residential neighborhoods" and "tourist landscape". The development and agglomeration differences of the three types of POIs in Qingdao are summarized by the analysis of variance [16-17], and the subway stations adjacent to high-density POIs are screened out (Fig. 1). Field research and sampling were carried out in neighborhoods with large passenger flow within 800m of the station to finalize the study area and the location of measurement points, and the specific distribution is shown in Table 1.

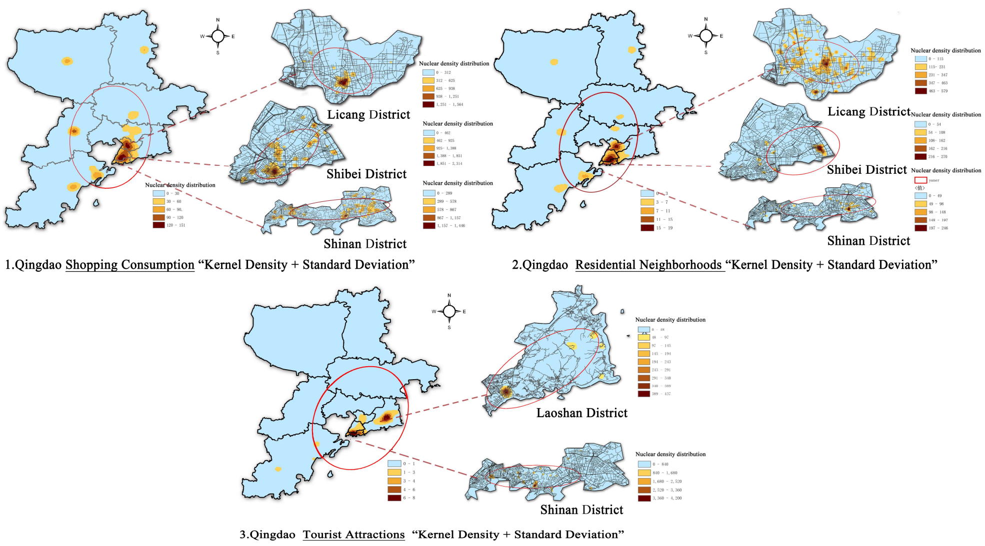
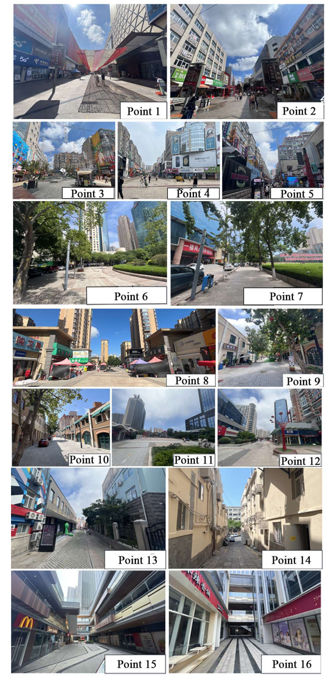


Figure 1. Differential Distribution of Three Types of POI Clusters in Qingdao City.

Table 1. Distribution of study area and field sites.

Type of station	Name of station	Measurement point distribution	Schematic of the scene
Shopping and consumption	Licun Station		
	Taidong Station		
	Wusi Square Station		

Residential neighborhoods	Xiawangbu Station		
	Zhongshan Road Station		
	Yan'erdao Road Station		
Tourist landscape	Qingdao Station		
	Miaoling Road Station		

2.2. Climatic Data for Analysis

The neighborhood pedestrian space is mainly a narrow street valley formed by the road and the buildings on both sides, and its geometry will also indirectly control the flow field by affecting the radiation balance in the space [18]. According to the above characteristics, the measured content includes the temperature (°C), wind speed (m/s), CO_2 concentration (ppm), as well as the street width (D) and the height of the buildings along the street (H) at the same time period during the daytime from July to August. Considering that the measured instantaneous wind speed, CO_2 concentration and other data are highly contingent, the actual measurements were taken at a frequency of three to four rounds in a day, and the average value of the data intercepted multiple times at each measurement point was taken.

2.3. Urban Microclimate Simulation Analysis

Data measurement and on-site research is the most direct way to grasp the current environmental conditions, but mesoscale research is often limited by the number of equipment can be measured point data is limited, completely take the measured way is more difficult, CFD simulation has a short calculation cycle, visualization and other advantages, and through the setting of the boundary conditions and then quickly simulate the numerical environment similar to the status quo, the measured data to play a better complementary role [19-20].

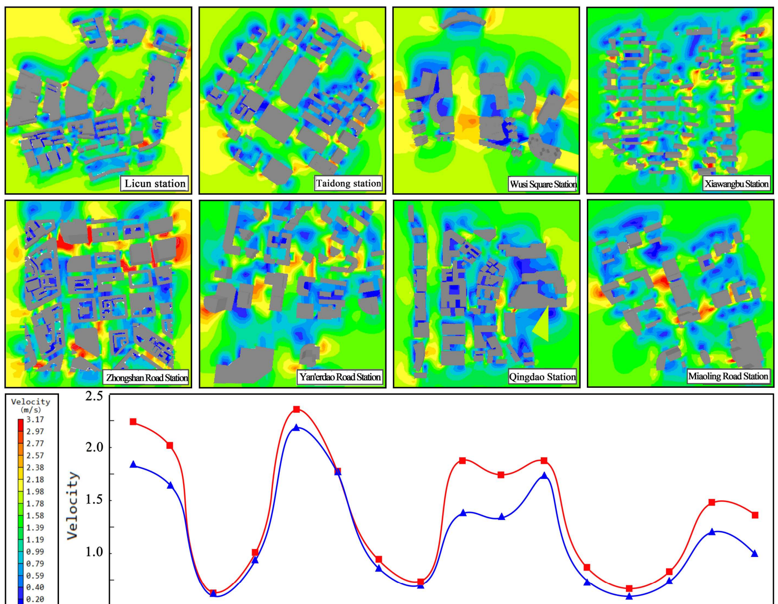
Focusing on the morphology and structure of the pedestrian space in TOD neighborhoods, based on the existing neighborhoods, taking the street width, the height of street-facing buildings, and the height-to-width ratio as independent variables, and taking the trend of the average wind speed and temperature as evaluation criteria, we quantitatively analyze the wind-heat environment through the simulation results of the CFD software [21]. To verify the role of walking space pattern on microclimate, and to propose improvement strategies for microclimate algorithm results and limiting elements.

3. Results

3.1. Wind-Heat Environment Simulation

3.1.1. Experimental Feasibility Verification

In order to evaluate the accuracy of this simulation experiment, it is necessary to analyze the fit between the measured data of the wind environment at the same site and the data measured by the software simulation under similar conditions [22]. It is known that the average wind speed of SSE wind direction at 1.5m from the ground is 2.1m/s, and the average temperature is 34.3°C. This set of values is measured in the open space without building and green shelter, and the other parameters are unchanged. The wind speed cloud at the pedestrian height was intercepted in the simulation results, and the corresponding mean values were calculated and counted (Fig. 2).



	Point 1	Point 2	Point 3	Point 4	Point 5	Point6	Point7	Point 8	Point9	Point10	Point11	Point12	Point13	Point14	Point15	Point16
Measured wind speed	2.241	2.050	0.225	0.983	2.355	1.776	0.797	0.383	1.859	1.733	1.872	0.661	0.293	0.574	1.474	1.332
Simulated wind speed	1.792	1.658	0.216	0.790	2.194	1.785	0.731	0.426	1.366	1.325	1.730	0.425	0.165	0.488	1.190	0.991

Figure 2. Comparison of simulation effect graphs and results.

Due to the idealized conditions, the modeling stage was simplified, and the influence of the building surface structure, green vegetation and other micro-factors were not considered, the simulated wind speed and the actual measured wind speed do not match exactly, but the numerical fluctuations are within the relative fitting interval, which shows that the simulation results have a certain degree of relevance to the actual measurements, i.e., the parameters used in the simulation of the wind environment are reasonable, and the results of the calculations are reliable.

3.1.2. Simulation Methods

Because the experiment mainly explores the influence of the narrow form of the walking space, i.e., the height and width scales on the microclimate, in order to ensure that the whole experiment has only two variables, namely, the height and width of the street, the length of the street is fixed as the average value of the depth of entry in the sampling of 50.0m, and according to the basis of the classification of the width of the walking street, the data of the current sampling are mainly distributed in the width ranges of the ideal-type walking street (14m ≤ D ≤ 24m) and the compact walking street (8m ≤ D ≤ 14m) [23]. So 16 models with different aspect ratios were numbered as ideal type A1～A7 and compact type B1～B9 for wind-heat environment simulation tests. Combined with the meteorological data of Qingdao's main urban area from July to August as the environmental

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parameters measured by the software simulation (dominant wind direction SSE, average wind speed of 3.0 m/s, average temperature of 33 °C), to explore the change rule of wind speed and temperature in the street with the change of aspect ratio (Figure 3).

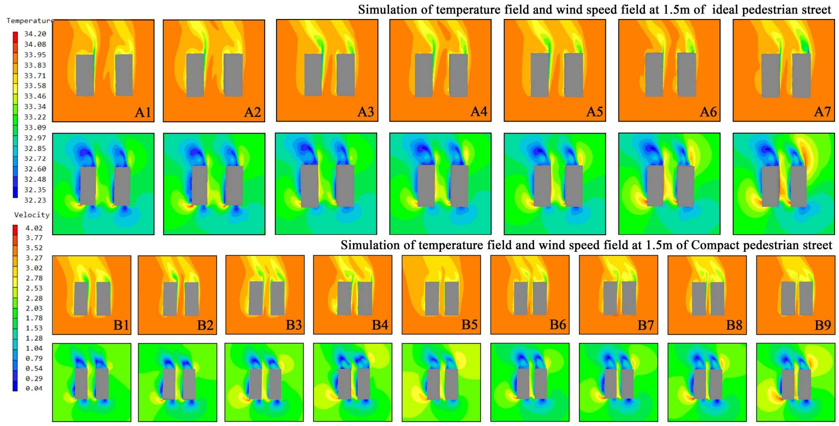

Figure 3. Simulation of temperature and wind speed at 1.5m in streets with different aspect ratios.

(1) Ideal type streets

Comparison of the data within the group found (Table 2): with the increase in aspect ratio, the average temperature within its streets showed a small decrease in the trend, the magnitude of which does not exceed 1%, indicating that increasing the aspect ratio of the street helps to improve the internal thermal environment in the summer, but the effect is very small, and has only a weak positive effect. Comparing the wind speed changes, the average wind speed inside the street maintains an increasing trend as the street aspect ratio increases, with a significant increase of 11.65% when the aspect ratio changes from 2.57 to 2.76. The potential reason for this is that the increase in the aspect ratio increases the positive and negative wind pressures of the building, which accelerates the air circulation rate and has an improving effect on the regional summer wind-heat environment.

Table 2. Ideal type street indicator simulation results.

Ideal type		A1	A2	A3	A4	A5	A6	A7
Height H (m)		26.1	32.2	34.1	36.1	38.4	47.5	43.3
Width D (m)		27.7	25.5	23.7	21.1	19.4	18.5	15.7
Height to width ratio H/D		0.96	1.26	1.44	1.71	1.98	2.57	2.76
Temperature (°C)	Street entrance	33.99	33.95	33.94	33.92	33.92	33.88	33.85
	Middle of street	33.96	33.94	33.92	33.91	33.95	33.86	33.80
	End of street	33.91	33.91	33.90	33.89	33.93	33.84	33.78
	Average	33.95	33.93	33.92	33.91	33.89	33.86	33.81
Temperature growth rate (%)		-	-0.06	-0.03	-0.03	-0.06	-0.09	-0.15
Wind Speed (m/s)	Street entrance	2.136	2.168	2.205	2.374	2.549	2.683	2.944
	Middle of street	1.975	2.079	1.937	2.138	2.236	2.347	2.725
	End of street	1.682	1.615	1.768	1.545	1.476	1.483	1.603
	Average	1.931	1.954	1.970	2.019	2.087	2.171	2.424
Wind speed growth rate (%)		-	1.19	0.82	2.48	3.36	4.02	11.65

Data source: software simulation.

(2) Compact streets

Comparison of the nine sets of data found (Table 3): the aspect ratio in the 0.83 to 2.17 interval, with the increase in the street aspect ratio, the average internal temperature tends to decrease, the fluctuation interval within 1%; when the aspect ratio from 2.17 to 2.43, the temperature increases abruptly; when the aspect ratio in the interval of 2.43 to 2.79, with the increase in the aspect ratio, the average temperature continues to decrease, but the magnitude of the change is gradually slowed down; when the aspect ratio continued to rise from 3.29 to 3.51, the temperature no longer had a significant decreasing trend. Comparison of wind speed changes can be seen: the aspect ratio of 0.83 ~ 1.70 interval, with the increase in the street aspect ratio, the average wind speed inside the street is rising; when the aspect ratio of 1.70 to 2.17, the wind speed suddenly reduced, fluctuations reached 17%; in the 2.17 ~ 2.79 interval, with the increase in the aspect ratio, the average wind speed continues to increase; 3.29 ~ 3.51 interval, the wind speed has no obvious rising trend. There is no longer a clear trend of increasing wind speed in the interval of 3.29 to 3.51.

Table 3. Compact Street Metrics Simulation Results.

Compact type		B1	B2	B3	B4	B5	B6	B7	B8	B9
Height H (m)		11.4	15.3	17.1	19.2	20.3	21.0	23.4	25.3	24.9
Width D (m)		13.8	12.5	11.7	11.3	9.4	8.9	8.4	7.7	7.1
Height to width ratio H/D		0.8.	1.22	1.46	1.70	2.17	2.43	2.79	3.29	3.51
Temperature (°C)	Street entrance	33.79	33.83	33.87	33.74	33.68	33.84	33.81	33.79	33.74
	Middle of street	33.73	33.72	33.66	33.67	33.58	33.77	33.72	33.71	33.68
	End of street	33.70	33.64	33.54	33.45	33.42	33.61	33.45	33.39	33.44
	Average	33.74	33.73	33.69	33.62	33.56	33.74	33.66	33.63	33.62
Temperature growth rate (%)			-0.03	-0.12	-0.21	-0.18	0.54	-0.24	-0.09	-0.03
Wind Speed (m/s)	Street entrance	2.086	2.285	2.473	2.539	2.103	2.273	2.425	2.599	2.614
	Middle of street	1.973	2.163	2.386	2.481	1.982	2.096	2.184	2.426	2.377
	End of street	1.827	1.708	2.011	1.976	1.717	1.553	1.784	2.034	2.101
	Average	1.9362	2.052	2.290	2.332	1.934	1.974	2.131	2.353	2.364
Wind speed growth rate (%)			4.58	11.59	1.83	-17.07	2.07	7.95	10.42	0.47

Data source: software simulation.

3.2. CO_2 Concentration Diffusion Simulation

3.2.1. Correlation Analysis

According to the previous analysis, the pedestrian space morphology of TOD neighborhoods is closely associated with the regional wind-heat environment in which they are located, and presents autonomy and dynamics. Using the existing measured data, the Pearson correlation coefficient method in SPSS software was adopted to verify the coupling relationship between CO_2 concentration, meteorological effects, and architectural form [24-25]. The results of correlation analysis and interpretation are as follows (Table 4): The correlation between CO_2 and wind speed is -0.89, which shows a significant negative correlation. It indicates that the higher the wind speed, the stronger the ventilation effect, the gathered CO_2 is taken away and evacuated, and the concentration in the area is monitored lower; The temperature and CO_2 show a significant positive correlation, indicating that the higher the temperature, the CO_2 concentration increases accordingly; The correlation coefficient of the street aspect ratio and the CO_2 concentration is -0.95, with the significance level of 0.001, which indicates that there is a significant negative correlation between the aspect ratio and the CO_2.

It is especially necessary to analyze the correlation between CO_2 concentration and each index element, based on which to set up the effective conditions required for the establishment of the experiment, to provide a scientific basis for the next simulation analysis. With the help of Fluent19.2 software, the simulation experiment of CO_2 diffusion in the neighborhood was carried out to verify the correlation between CO_2 concentration and the spatial layout of the neighborhood more effectively [26-28].

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Table 4. Correlation of CO_2 concentration with wind speed, temperature, and street morphology indicators.

Correlation coefficient	Width	Height	Height to width ratio	Temperature	Wind Speed
Temperature	-0.98(0.000***)	-0.93(0.003***)	-0.98(0.000***)		
Wind Speed	0.95(0.001***)	0.91(0.005***)	0.97(0.000***)	-0.98(0.000***)	
concentration	-0.96(0.001***)	-0.94(0.001***)	-0.95(0.001***)	0.83(0.020**)	-0.89(0.008***)

Note: ***, **, * represent 1%, 5%, and 10% significance levels, respectively.

3.2.2. Simulation methods

(1) Object Selection

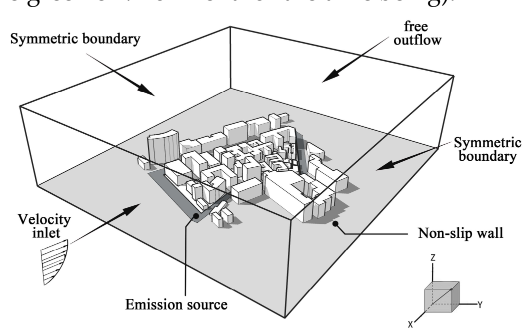
With Qingdao Station as the core, Yinyu Lane neighborhood is enclosed by Feicheng Road in the north, Hubei Road in the south, Tai'an Road in the west, and Surabaya Road in the east, covering an area of 26,000km2. The area is crowded, has a long history, and has a superior location, so it is necessary for the renewal and reconstruction to be more careful and comprehensive, in order to not only retain the historical sense of the buildings and neighborhoods, but also to enhance the overall livability level. Therefore, this experiment is oriented to alleviate the CO_2 concentration and improve the air quality in the main urban area, and through the simulation results and analyses, it aims to propose scientific and specific practical strategies for the renewal and transformation of the neighborhood.

(2) Carbon source determination

CO_2 is selected as the carbon source for the simulation experiment, and the wind speed field and CO_2 concentration field at each point in space are solved. Since the study area is a historical urban area, the carbon source is mainly the carbon emission brought by transportation, and the influence of pollution from industry, agriculture and life is weak, so the automobile exhaust in the urban neighborhoods is taken as the linear emission source, and other pollution sources are not considered for the time being. According to the relevant documents and synthesizing the existing research results, the source strength of CO_2 emissions from roads was determined by estimating the traffic flow and the rate of vehicle exhaust emissions and other indicators [29-30].

(3) Boundary conditions and convergence settings

For complex urban interfaces, the choice of unstructured grids can ensure the quality of the grids as well as simplify the complex urban space. Space claim is used to perform the unstructured grid Tetra/Mixed division. Local encryption is performed on buildings, roads and floors to accurately describe the flow field changes. At the same time, the boundary layer grid is divided in the proximity to strengthen the fluid change and description at the interface. The grids are imported into the software and simulated, and the boundary conditions are also set in combination with Qingdao's meteorological data, as shown in Figure 4 (the theoretical model mainly focuses on the building layout, and does not take into account the differences in the type of the sub-bedding surface and the influence of the green environment for the time being).



Boundary conditions	Setting content
(Inlet)	Wind profile: $U=U_0(Z/Z_0)^\alpha$ U_0 is the average wind speed (3m/s) at a standard height of 10m, Z_0 is the height of the area, α is the degree of roughness of the ground (taking the value 0.2) Wind direction SSE
(Outlet)	Free outflow boundary
(Wall-side)	Symmetric boundary
(Wall-up)	Symmetric boundary
(Wall-build)	Non-slip wall
Temperature	33
Sky Clouds	Sunny and cloudless

Figure 4. 3D modeling and numerical simulation of boundary conditions.

(4) Simulation results

The wind speed field and concentration field maps at a horizontal plane intercepted at a height of 1.5 m represent the air quality situation at the breathing level of pedestrians (Figure 5). According to the correlation study, the distribution of wind velocity field has a direct influence on the distribution of CO_2 concentration in the area, and the smooth air flow can increase the air renewal rate, promote the diffusion of CO_2, and improve the air quality; on the contrary, the obstruction of the air flow will cause the CO_2 can not be eliminated smoothly and thus form the deposition, and the correspondence between the two is significant. From the results of the concentration field simulation, it can be seen that the diffusion of CO_2 in the pedestrian height is slow, and the spatial distribution of pollution has obvious differences. Since CO_2 is mainly emitted from vehicle exhaust in the surrounding streets, the average concentration at the source locations is high, especially in the buildings along the streets. In addition, the downstream neighborhoods are subject to different degrees of air pollution, with the downstream neighborhoods of Feicheng Road being the most seriously polluted. The reasons for this are as follows: high density of buildings at pedestrian height, less open space, and strong enclosure of existing open space, which lacks inlets for incoming winds; long length of continuity of street-facing buildings, which blocks the clean incoming flow from the upstream neighborhood into the interior of the street; and large angle between the orientation of the buildings and the direction of the incoming winds, which increases the bypassing of the incoming winds. Under the combined effect of the above factors, the block clean incoming flow is blocked, the air flow is slow, and an effective ventilation corridor is not formed, so that the street and the downstream block form a large static wind area and thus a large amount of CO_2 stagnation.

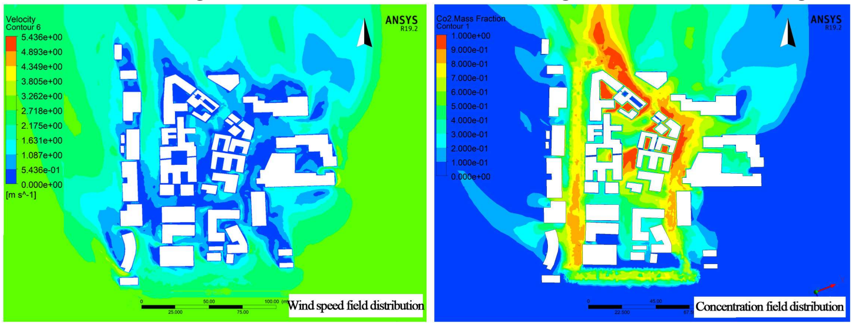


Figure 5. Wind velocity field and concentration field at 1.5m height in the Silverfish Lane neighborhood.

Secondly, the distribution of CO_2 concentration was observed by intercepting the vertical cross-section highlighting the features at different horizontal distances in the north-south direction (Fig. 6). Comparing the same cross-section, it can be seen that the CO_2 concentration in the street is roughly inversely proportional to the aspect ratio: when the aspect ratio is too low, the CO_2 is easy to accumulate underneath the building and circulate internally in the corner of the street valley, which is not easy to be diluted; the larger the aspect ratio, the more favorable it is for the increase of the wind speed and the decrease of the CO_2 concentration. However, there are some limitations: when the height of the building is high, its leeward area has a large area of static wind, thus forming a high concentration aggregation area. Comparing different cross sections, it is found that under the same aspect ratio, the degree of concentration diffusion varies, which is mainly due to: the higher height of the buildings along the street in the upwind direction, which forms a vortex effect on the center area leading to higher CO_2 concentration in the central area; the more sheltered wake area in the central area is not conducive to the diffusion of CO_2; and there are mostly low-rise buildings downwind from the block, which have insufficient heights and poor diffusion effects.

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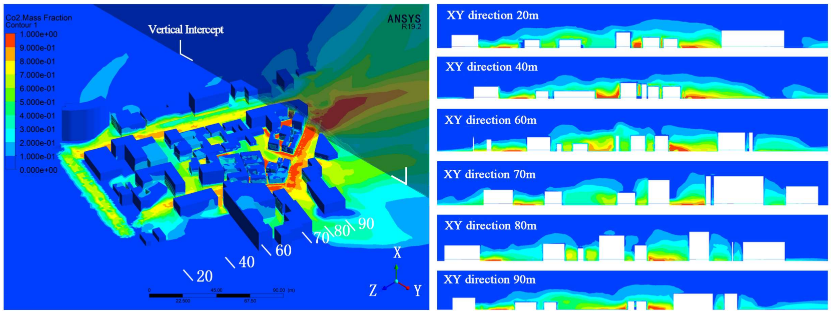


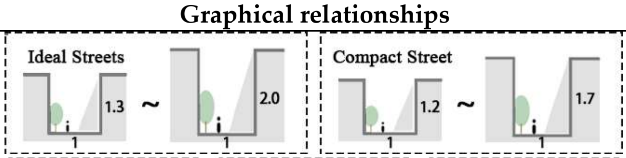
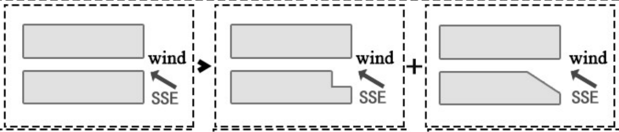
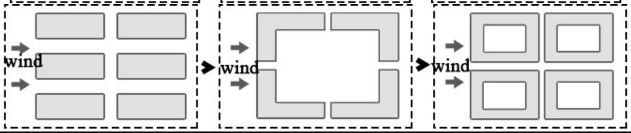
Figure 6. Vertical Interface Interception and Concentration Distribution in the Silverfish Alley Neighborhood.

It can be seen that the increase of aspect ratio has a positive effect on the enhancement of CO_2 reduction rate, but there are also constraints: when the height of the building facing the street is certain, the open space formed by the wider street is more favorable for diffusion; when the open space is certain, it is easier to diffuse in the area facing the wind than in the area facing the leeward side.

4. Discussion

The results of the wind-heat-carbon integrated environment simulation are summarized, and it is found that different street aspect ratios have different effects on the wind-heat environment and the diffusion rate of CO_2 concentration, so it is reasonable to define the appropriate aspect ratio interval, control the height of the buildings, and appropriately increase the distance between the buildings in order to effectively improve the microclimate of the local area. In addition, by adjusting the spatial pattern of the neighborhood, increasing the internal ventilation corridor can effectively promote air circulation and dilute the CO_2 concentration. When the angle between the urban ventilation corridor and the dominant wind direction is too large, the ventilation effect is often poor, and the air intake can be increased by changing the shape of its entrance. The number and location of open space should be controlled in planning and design, and the degree of enclosure should be considered in combination with the incoming wind, and the layout of the surrounding buildings should be controlled, so as to effectively guide the incoming wind into the neighborhood. A certain amount of open space can also be set up in the leeward direction of high-rise buildings (CO_2-enriched area) to enhance the ventilation capacity with the help of the dual attributes of spatial development intensity and spatial morphology on the overall intensity and local distribution of wind speed, open and breezy spaces to increase ventilation, complemented by various forms of parks and green spaces are preferred (Table 5).

Table 5. Definition of Aspect Ratio and Optimization of Spatial Form Indicators.

Type	Optimization measures	Graphical relationships
Aspect ratio range	Ideal: 1.3 to 2.0; Compact: 1.2 to 1.7	
Entrance Forms	Design of entrance forms at right angles or cut corners	
spatial openness	Open enclosure for greater air permeability	

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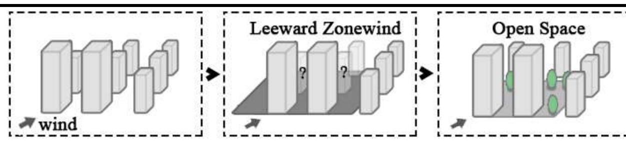
multistory building complex	Installation of certain open spaces in the leeward direction of high-rise buildings	

5. Conclusions

Pedestrian space can effectively connect metro stations and urban functions, and in the process of livable urban renewal and development, it is important to summarize the microclimate influence of the spatial form of neighborhoods, and to give full play to the low-carbon development mode of TOD, which is “Railway Transportation + Slow Pedestrian System”. This paper combines the actual situation of Qingdao subway development and urban renewal construction, conducts on-site research and dynamic measurement on the screening object, takes microclimate simulation (CFD) and correlation theoretical model as the technical support, points out that the spatial morphology of the neighborhood space faces the problem of incoordination between spatial morphology and planning, and gives the corresponding low-carbon design strategy, which will help the urban renewal and the “dual-carbon” urban renewal process. It also gives corresponding low-carbon design strategies to help urban renewal and the realization of the “dual-carbon” goal.

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