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Research Article

Research on Application of Composite Facades for Civilian Reconstruction of Industrial Heritage in Cold Regions Based on Thermal Buffering Effect

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Abstract

Previous studies on the civil transformation of industrial heritage have been conducted mainly from the perspective of architectural history, culture and aesthetics, but rarely focus on energy-saving and the comfort of the new users. Most industrial heritage facades are of high conservation value, but efforts to preserve the authenticity of the facade can lead to the application of limited energy-saving technologies, ultimately resulting in poor indoor thermal environments. Therefore, it is valuable to research how to solve the contradiction between protecting the authenticity of the preserved facades of industrial heritage and improving the indoor environmental performance. This paper proposes two composite facade application strategies based on thermal buffer effects, takes two composite facades renovation methods of Shenyang Dongmao No. 2 Warehouse as an example, utilizes the natural environmental resources to enhance the spatial quality of industrial heritage. With the help of DesignBuilder software modelling simulation analysis, in-depth comparative analysis of the two types of composite facades on the indoor thermal environment of the industrial heritage of the impact and scope. Key findings show that the application of two different composite facade retrofitting techniques not only protects the skin texture of the wall, but also effectively increases the indoor temperature and reduces the indoor energy consumption of the industrial heritage. The composite facade of the external solid wall and the internal glass is more stable in raising the indoor temperature, more effective in reducing the building energy consumption, and more suitable for the civilian transformation of industrial heritage in cold areas. The research findings provide reference for studies on the civil transformation of industrial heritage, and serve as technical references for architects.

Keywords

Thermal Buffering Effect, Composite Facade, Industrial Heritage

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1. Introduction

1.1. Research Background

As an important issue in the current stage of urban construction in China, the envelope interface of industrial building heritage is usually an important exhibit showing the background information of the historical era at that time, which has a high value and will be retained as much as possible in the transformation of industrial heritage. The industrial heritage located in the cold area also cause that the thermal insulation performance of the external protection interface usually cannot meet the requirements of users for indoor thermal comfort after functional replacement [1]. In order to meet the indoor thermal comfort requirements of new users and blindly transform the enclosure interface of industrial buildings, it will destroy the authenticity of industrial buildings and fail to implement the principle of reversibility of architectural heritage, such as Figure 1. Therefore, in the face of the contradiction between the preservation of architectural form and the inefficiency of indoor environmental performance, this paper proposes the application of two kinds of composite facades to renew and transform the external protection interface of industrial buildings in cold regions, so as to fill the new thermal comfort requirements after civilian renewal and retain the architectural authenticity.

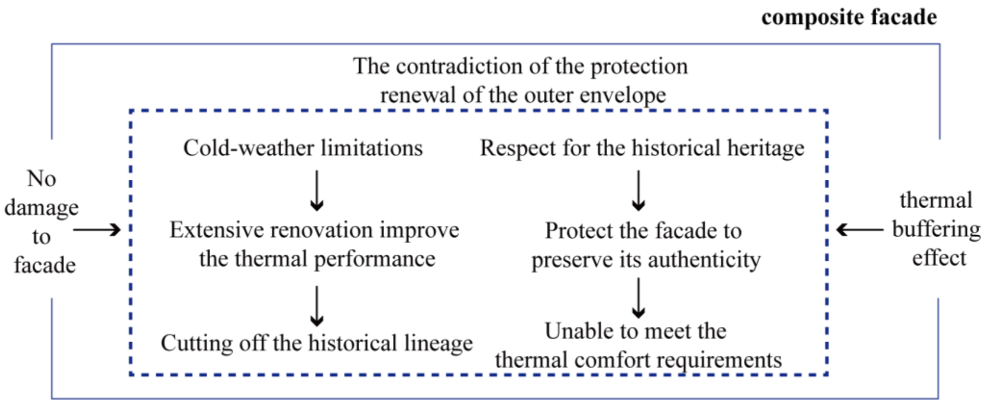


Figure 1. *Contradictions in the renewal of the envelop interface.*

1.2. Current Status of Research

1.2.1. Research on Thermal Buffering Effects

Most of the spatial types of thermal buffering effect were courtyards, patios and cold alleys in the traditional buildings [2]. In 2016, the space types of thermal buffer effect are increasing, and research on thermal buffer space such as side court, tunnel, closed balcony and auxiliary function space has appeared [3]. From 2020 to the present, the researches on thermal buffer space on the small scale, such as stairwells and composite boundaries, have appeared in succession [4]. There are many spatial names of thermal buffer effect, such as “cavity”, “intermediate space” and “thermal buffer layer” [5]. Chen Xiaoyang considered that the thermal buffer effect is to adjust the indoor microclimate through the two effects of “greenhouse effect” and “chimney effect”, such as Figure 2.

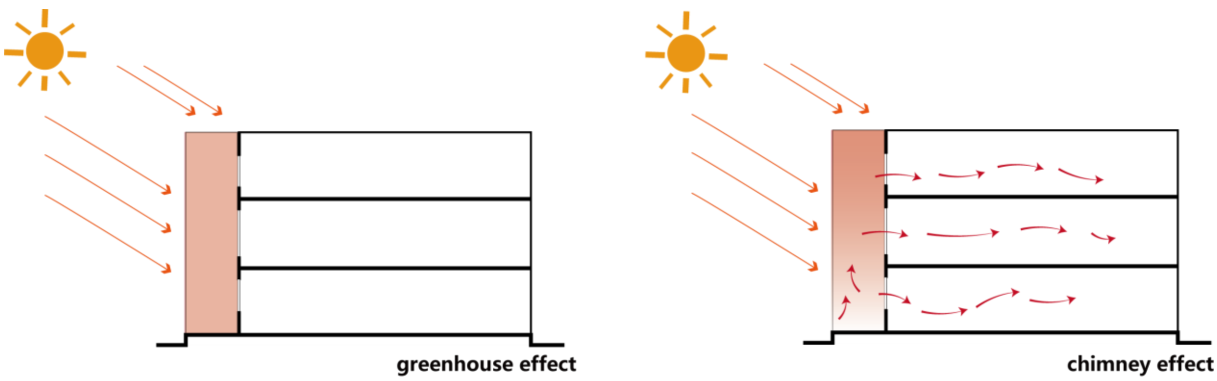


Figure 2. *Illustration of the principle of thermal buffering effect.*

1.2.2. Research on Composite Facade

The word of "composite facade" originates from "composite interface". Initially the composite interface refers to the demarcation space with transitional and composite characteristics that exists between the internal space of the building and the natural climate, which organically compounds the common characteristics of the space and the interface [6], such as Figure 3. In 2019 scholars subdivided composite elevations into the following three types based on the differences in the types of materials at the interface between the inside and outside of the elevation: double solid wall composite facade, external glazed internal solid wall composite facade and double glazed composite fa çade [7]. In the renovation methods of Shenyang Dongmao No. 2 Warehouse project that the author participated in in 2023, the designer used the thermal buffering effect of the composite facade. The specific method was a solid wall on the outside and U-shaped glass on the inside. Therefore, this research argues that the subdivision of composite facades can be divided into four types: Double solid wall composite facades, external glass internal solid wall composite facades, external solid wall internal glass composite facades and double glazed composite facades, such as Table 1. This paper proposes two kinds of composite facade for Shenyang Dongmao Warehouse No. 2, which are mentioned in the table as the type of solid wall with external glass and the type of internal glass with external solid wall.

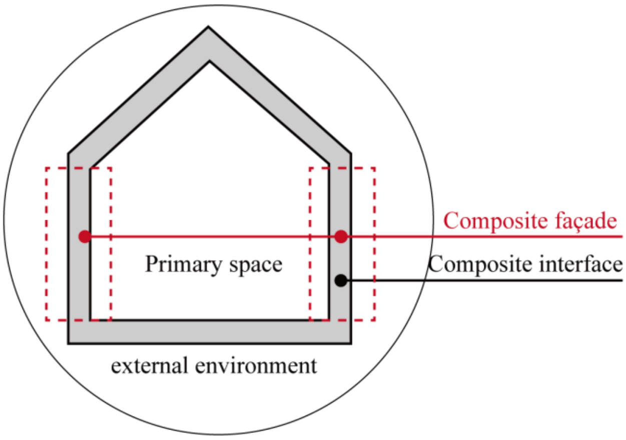
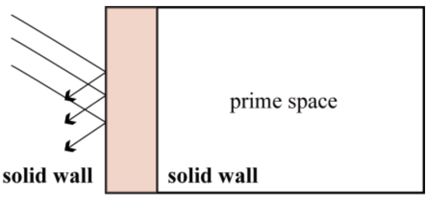
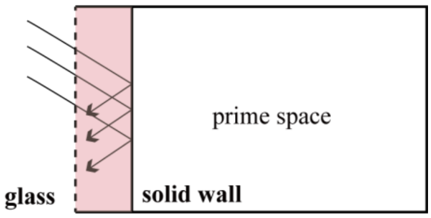
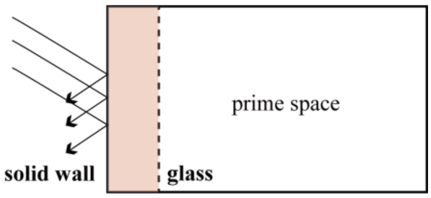
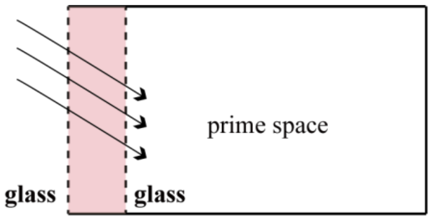


Figure 3. *Composite Interface and Composite facade Diagram.*

Table 1. *Composite facade space type classification.*

	Form classification	Schematic sketches	forms of representation
	Double solid wall		sunshade, hollow thick wall
composite facades	External glass internal solid wall		Side gardens, sunroom, trombe wall
	External solid wall internal glass		Border garden, buffer zone
	Double glazed		Double glazed curtain wall

1.2.3. Research on the Composite Facade Applications of Industrial Heritage

Zhao Wenyan proposed an intermediary space design strategy for green renovation of industrial buildings in 2019. In the article, the scholar pointed out that interface spaces such as double-layer skin cavity, sunroom, door space and overhead space can be used to adjust the lighting and thermal stability of industrial heritage. The article only stayed at proposing the design strategy without verifying its ideas [8]. Ri Na from the University of Delaware and the University of Nebraska-LincolnZhigang Shen. It is proposed to realize the problem of significantly reducing the energy consumption of old buildings by converting traditional cavity walls into passive ventilation cavity walls in 2020 [9]. At present, the research on composite facade after functional replacement of industrial relics mostly exists in practical projects, without specific demonstration of its effect.

In summary, the civil transformation of industrial architectural heritage in cold regions of China faces the problem of poor indoor thermal environment performance after retaining the original authenticity, or catering for energy-saving norms will cause great damage to the external envelope of industrial remains, destroying their original authenticity [10]. The composite facade is mostly transformed in the form of double facades, only adding a layer of facade structure without destroying the original industrial heritage facade, and the increased interface is mostly transparent glass. By using its double effect, the indoor thermal environment can be improved after the transformation of industrial heritage civilization [11]. The author studied the application of Trombe walls on the external facade of industrial heritage in 2022 [12]. Therefore, based on the application of composite facades in the civil transformation of industrial architectural heritage with thermal buffering effect, compared the data with previous studies, and analyzed the differences in operation principles and effects of the two composite facades. In order to provide some reference for the research and practice of civilization transformation of industrial architectural heritage.

2. The Current Status of the Shenyang Dongmao Warehouse No. 2

2.1. Design Background

Dongmao Warehouse No. 2 is located in the south side of Shenyang East Railway Station in Dadong District of Shenyang City, which is the earliest and best-preserved civil storage buildings in Shenyang City. Its architectural techniques and art reflect the typical characteristics of warehouse buildings of the 1950s. Its architectural technology and art embody the typical characteristics of warehousing buildings in the 1950s. In 2018, the East Trade Complex was recognized as the fifth batch of historical buildings in Shenyang city, for the second category of historical buildings, but also for the Shenyang city industrial heritage. At the beginning of 2020, the government decided to preserve seven historical buildings with special characteristics and one railroad line after expert's argumentation. This research propose to use one of the seven characteristic historical buildings heritage, Dongmao Warehouse No. 2, which has a total depth of about 90 meters and is divided into three units of 30m×32m by the indoor load-bearing wall. The building unit is of brick and timber structure, consisting of platforms, red brick external walls, reinforced concrete beams and columns, timber roofing and roofing. In this paper, the civilization function of warehouse No. 2 is updated with the project practice consistently selected as a showroom, and the specific functional arrangement is as follows, such as Figure 4. The overall color of the exterior wall of the warehouse is dark red, 440mm thick load-bearing brick wall, which has a large thermal storage coefficient and high thermal stability coefficient. The bottom of the high windows is equipped with ventilation openings of 450mm×350mm, which also provides conditions for the implantation of composite facade. According to the definition of industrial heritage in the Convention Concerning the Protection of the World Cultural and Natural Heritage, Warehouse No. 2 reflects the special information of the historical era and the unique craftsmanship practices of the modern society, and its continuation of the historical lineage, scientific and artistic value is outstanding, and its red-brick facade form should be fully demonstrated in the renovation [13].

2.2. Preliminary Energy Conservation Measures

Warehouse No. 2 red brick exterior facade for the load-bearing exterior walls, in accordance with the requirements of the provisions of the conservation plan, the building facade of the window and door openings should not be changed in the form of the continuation of the history and nature of the original industrial warehouses. Therefore, it is necessary to meet the original facade form on the basis of retaining the No. 2 warehouse for preliminary energy-saving renovation, according to China's “General Specification for Building Energy Efficiency and Renewable Energy Utilization” (GB55015-2021) heat transfer coefficient limits to determine the minimum thickness of the wall insulation layer and roof insulation layer, according to this specification so that the two to meet the stipulated requirements of the thermal performance of the enclosure structure. At the same time, the indoor and outdoor pressure is used to increase air flow, and the space is combined with the original upward convergence profile form of the warehouse to form the "chimney effect" to improve ventilation. After the renovation, CFD simulation was used to verify that the main functional rooms of the building meet the area ratio requirements of the average natural ventilation frequency of no less than 2 times/hour in summer, such as Figures 5-6. Finally, the broken bridge aluminum window frame and single suspension film SCL-PS4. CPF glass were used to replace the existing double layer ordinary glass. The high side Windows of the roof are made of argon filled low-radiation double glass to meet the thermal requirements of the specification. To sum up, the implantation of composite facade cannot solve all the energy-saving problems of Dongmao Warehouse No. 2. Therefore, the original authenticity of Dongmao Warehouse No. 2 is not destroyed in the early application of composite facade. In the early stage of energy-saving transformation, the implantation of two kinds of composite facade is compared and analyzed on the basis of achieving energy-saving standards.

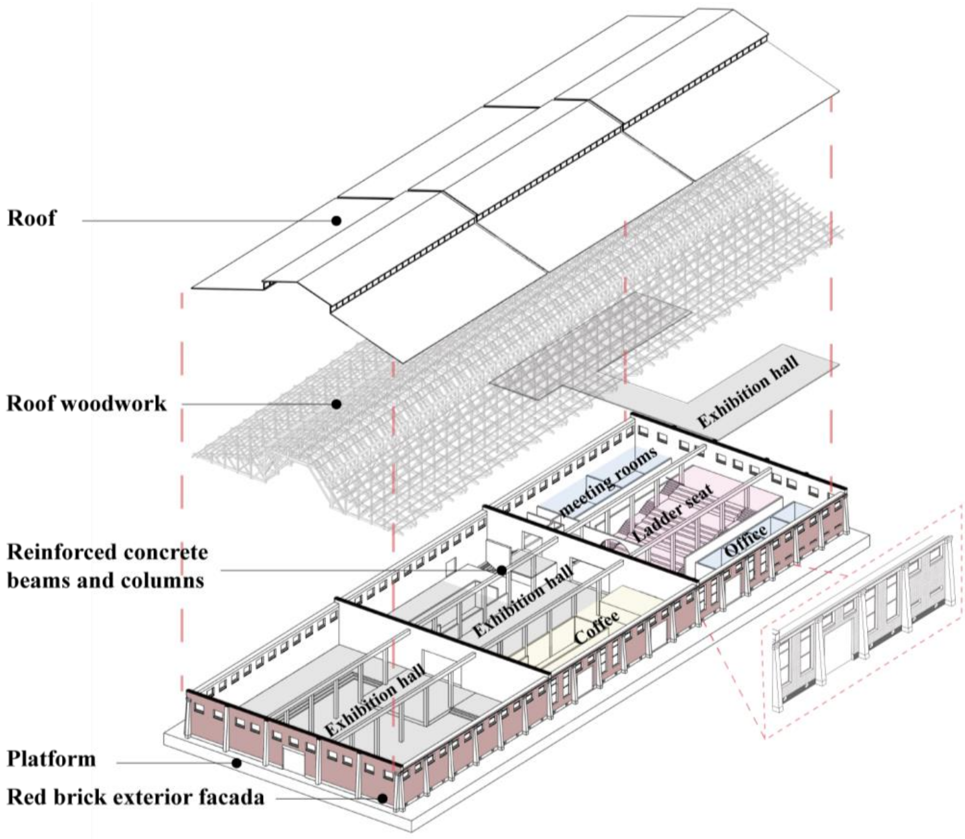


Figure 4. Functional diagram of the remodeled Warehouse No. 2.

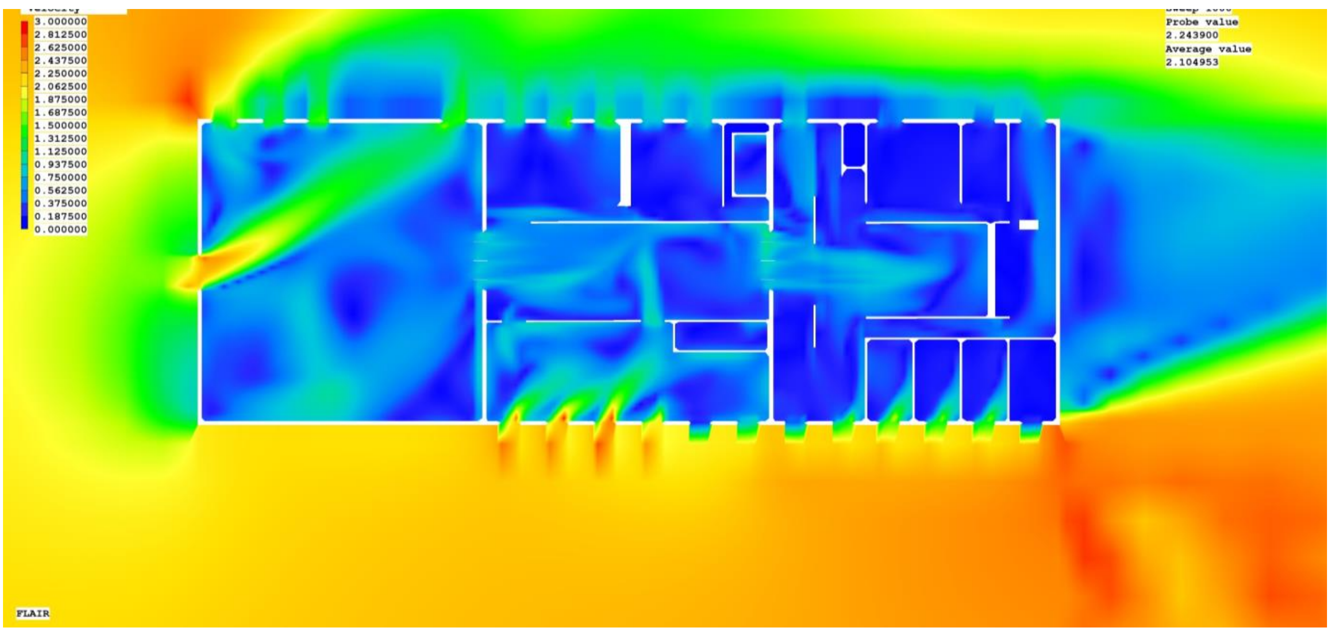


Figure 5. Schematic diagram of wind environment on the indoor floor.

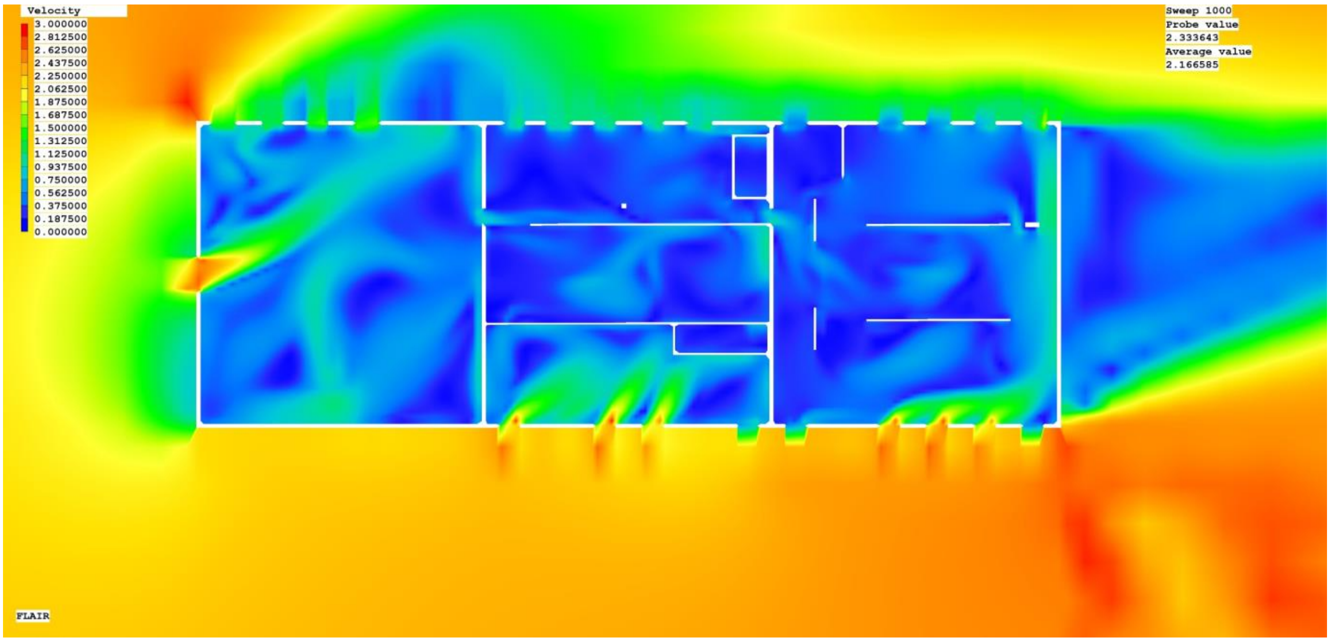


Figure 6. *Schematic diagram of the indoor wind environment on the second floor.*

3. Technical Measures

3.1. Two Operating Conditions of the Composite Facades

3.1.1. Operating Conditions of the Trombe Wall System

The application of external glass inside solid wall composite facade in Dongmao No. 2 can choose the Trombe Wall system. The Trombe wall consists of a certain thickness of dark-colored heat storage wall on the inner side and glass cover plate on the outer side [14], the solar heat through the glass is absorbed by the heat storage wall, part of the absorbed heat is transmitted to the indoor through conduction [15], part of the heat is transmitted to the air in the cavity through radiation, the radiation wavelength is longer than that through the glass, so the gas inside the cavity generates "greenhouse effect" [16], and the temperature of the air inside the hot channel rises. When there is no air vent, the cavity forms a sealed air insulation layer, which strengthens the thermal insulation performance of the facade. When there is a vent, the "chimney effect" drives the air flow in the cavity, and the air is heated by the heat channel to the interior, achieving the purpose of improving indoor thermal comfort. The operating conditions are shown in Figure 7.

3.1.2. Operating Conditions of the Buffer Zone System

The application of external glass inside solid wall composite facade in Dongmao No. 2 can choose the buffer zone system. Compared with the Trombe wall system, the operating conditions of the buffer zone system are relatively simple. The solar energy is absorbed by the heat storage wall and transmitted to the room through conduction.

The heat storage solid wall and the glass body form a heat insulation layer to resist the invasion of cold airflow. In summer, the bottom opening of the external wall of the solid wall and the original opening of the solid wall can be opened, and the "chimney effect" is used to drive the hot air in the cavity to rise, taking away the excess heat transmitted by the cavity and the heat storage wall. As the glass cover is placed inside the building, the thermal environment of the internal space of the building is less affected by the external environment, and the indoor thermal environment can be maintained in a relatively stable state for a long time. The operating conditions are shown in Figure 8.

Dongmao Warehouse No. 2 is located in Shenyang City, Liaoning Province, which belongs to Severe Cold Zone C. Therefore, this paper simulates two kinds of composite facade application research primary consideration of the exterior enclosure structure heat preservation performance enhancement, so the choice of heat storage wall room outside the glass cover plate upper and lower air vents are closed Trombe wall system as a typical model for the simulation of the composite facade of the outer glass inside the solid wall type. The buffer zone with closed air vents at the top and bottom of the thermal storage wall and at the top and bottom of the glass cover plate on the interior side of the thermal storage wall is selected as a typical model for simulation of a glazed composite facade in an exterior solid wall.

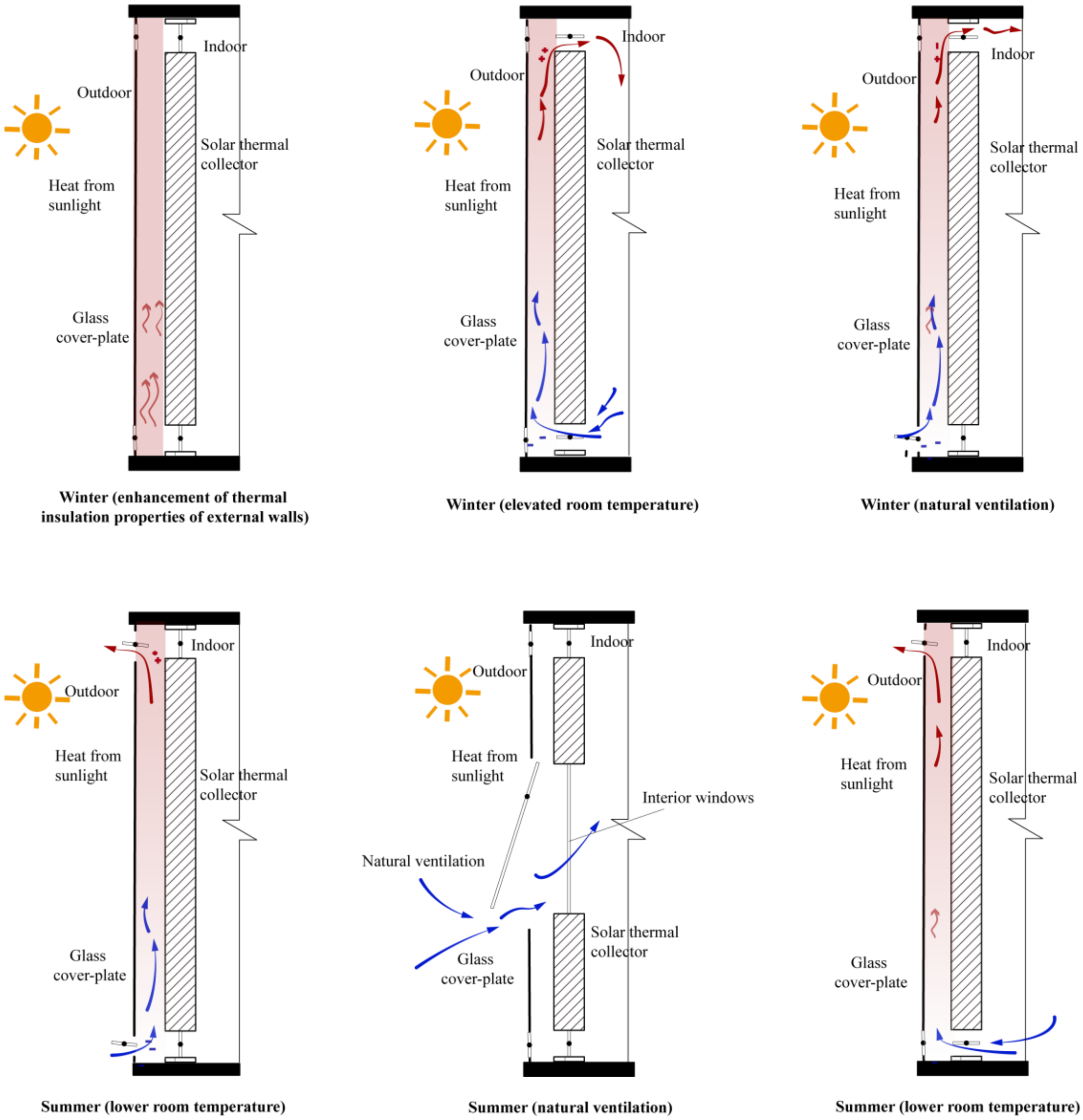


***Figure 7**. The operating conditions of the Trombe Wall principle.*

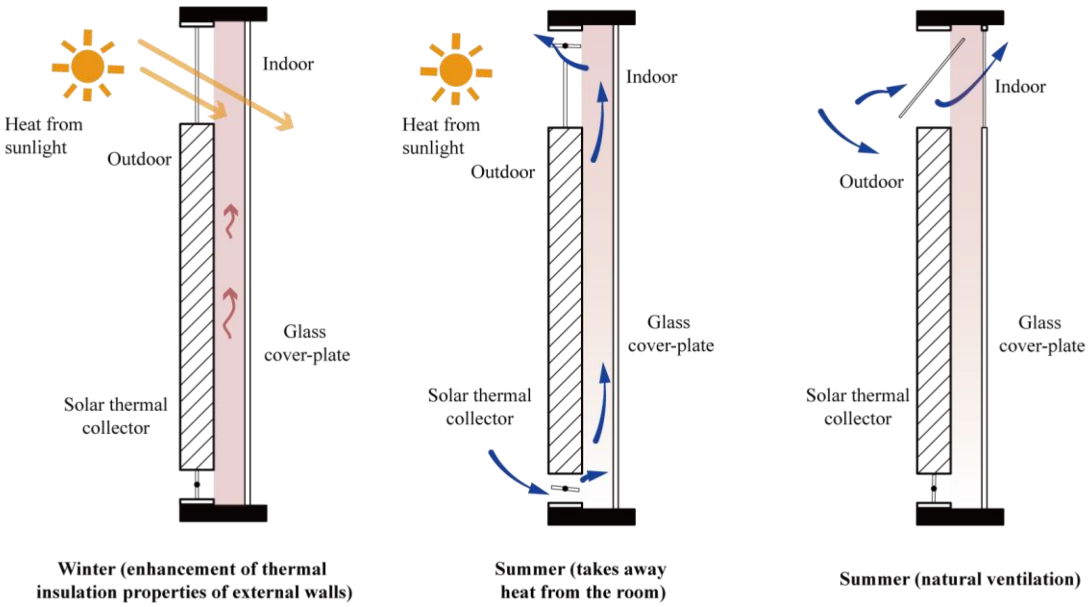


***Figure 8**. The operating conditions of the buffer zone principle.*

3.2. Simulation Modeling and Parameter Setting

The calculation model of this research uses DesignBuilder (Version7.0) to build a model for simulation calculations [17]. The climate data of typical meteorological years in Shenyang area provided by Weather tool are used. The model is established according to the scale of 1:1 of the prototype of the Dongmao warehouse No. 2, and the corresponding material of the enclosure structure is re-endowed in the software, and the simulation boundary conditions are limited according to the conditions of the use of exhibition halls from the aspects of meteorological data, simulation time and personnel rest time, such as Table 2. The boundary conditions of the simulation are limited in terms of meteorological data, simulation time and personnel. In the temperature simulation study, this paper intends to study the indoor thermal comfort under the condition of no equipment. In the energy consumption simulation study, this paper intends to study the reduction of energy consumption under the condition of heating and normal air conditioning. In order to ensure a more intuitive observation of the effect of the two composite facade, the simulation model to establish a total of four groups, The four groups are as follows: group a does not include a composite facade in the model and has no reference model for the preliminary energy conservation measures, group b adopts the preliminary energy conservation measures but has no reference model for the composite facade, group c adopts the preliminary energy conservation measures and includes a composite facade model of an exterior glass-interior solid wall type, and group d adopts the preliminary energy conservation measures and includes a composite facade model of an exterior solid wall with an interior glass facade, such as Figure 9. The above four groups of models are compared to ensure that the simulation results are more accurate. In order to better compare and study the effect of the two composite facade, model c and model d in addition to changes in the location of the glass cover plate, its materials and dimensions are the same, the material used double insulating glass, the use of carbon steel frame and the wall for articulation.

Table 2. Parameter settings for space partitioning simulations.

Functional partitioning	Exhibition hall	Coffee	Public space (Ladder seat)	Office space	Transportation space (halls, corridors)	Service space
Runtime setting	**Closed on Mondays Tuesday through Sunday 10:00-20:00**	**Monday through Sunday 8:00-20:00**	**Closed on Mondays Tuesday through Sunday 10:00-20:00**	**Monday through Sunday 8:00-20:00**	**Monday through Sunday 8:00-20:00**	**Monday through Sunday 8:00-20:00**
Person density / (person/m^2)	0.4	0.4	0.4	0.4	0.033	0.05
Personnel heat dissipation (W/person)	108	134	108	134	134	134
Winter temperature / ℃	12~22	12~22	12~22	12~22	12	12
Summer temperature / ℃	26~28	26~28	26-28	24-28	26-28	28-30
Minimum fresh air volume / [m^3/(h·P)]	30	30	30	30	20	20
Lighting power density (W/m^2)	9	9	9	9	5	6
Equipment power density (W/m^2)	15	15	15	15	15	15

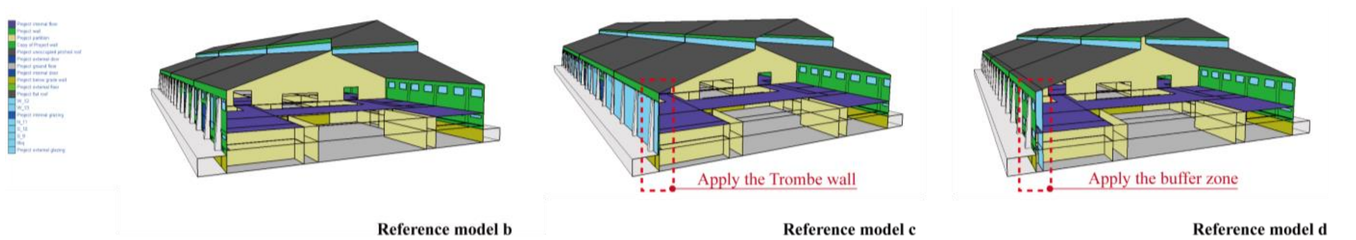


Figure 9. Schematic diagram of the simulation model.

4. Results and Discussion

4.1. Comparison of Temperature Simulation

The simulation comparison uses natural room temperature as an example. The simulation assumes that the air conditioning system is not turned on in the house to compare the conditions before and after the two composite facades are installed in Warehouse 2. The simulation calculates the hourly average indoor temperature data for 8760 hours throughout the year to compare the influence of the two composite facades. The two kinds of composite facades make the internal temperature tend to be stable, and the extreme heat and cold in the house are reduced. It can be seen that the application of the Trombe wall can effectively improve the problem of low room temperature in the civil renovation of industrial heritage, and has an obvious effect on improving the indoor thermal environment in winter. By comparing the two kinds of composite facades, there is little difference in the effect of indoor thermal environment adjustment between the two kinds of composite facades.

Compared to the buffer zone system, the application of the Trombe wall is more effective in regulating the indoor thermal environment. That means the composite facade of the external glass and the internal solid wall is more effective in improving the indoor thermal environment, and the best regulating effect occurs in February-April and November-December when solar radiation resources are more abundant in the Shenyang area, such as Figure 10. This is due to the fact that the Dongmao Warehouse No. 2 is located in an open field with little shading from the surrounding trees, and the thermal storage walls and glass coverings allow the Trombe wall system to maximize heat collection efficiency. But compared to another composite facade, the external solid wall and the internal glass is more stable in raising the indoor temperature. Compared with other months, especially in summer, the impact of the two types of composite facades on the indoor thermal environment is not much different.

4.2. Comparison of Energy Consumption

In order to facilitate the comparison of the energy consumption of the two composite facades, all energy supply units of the annual energy consumption simulation calculation results of Dongmao Warehouse No. 2 warehouse are converted into electric units for comparison, and the total energy consumption is integrated into heating energy consumption, cooling energy consumption and other energy consumption for statistical and comparative analysis. The simulation calculation results obtained are shown in the Table 3.

Table 3. *Results of energy consumption data for the optimized scenario.*

	The original model	Energy efficiency retrofit modeling		
		Pre-optimization	Application of the Trombe Wall system	Application of the buffer zone system
Heating energy consumption per unit area/(kW·h/m^2)	168.47	110.83	99.95	93.26
Trombe Walls Energy Efficiency Rates		1	-9.80%	15.8%
Total energy savings from energy efficiency retrofits	1	-34.20%	-40.60%	-44.64%
Refrigeration energy consumption per unit area/(kW·h/m^2)	21.54	14.87	14.94	13.21
Trombe Wall Energy Efficiency Rates		1	0.60%	11%
Total energy savings from energy efficiency retrofits	1	-30.96%	-30.64%	-38.6%
Other energy consumption per unit area/(kW·h/m^2)	26.51	25.82	25.95	25.89
Total energy savings from energy efficiency retrofits	1	-2.60%	-2.10%	-2.33%
Building energy consumption per unit area/(kW·h/m^2)	216.52	151.52	140.84	129.95
Trombe Wall Energy Efficiency Rates		1	-7.04%	-14.20%
Total energy savings from energy efficiency retrofits	1	-30.02%	-34.95%	-37.98%

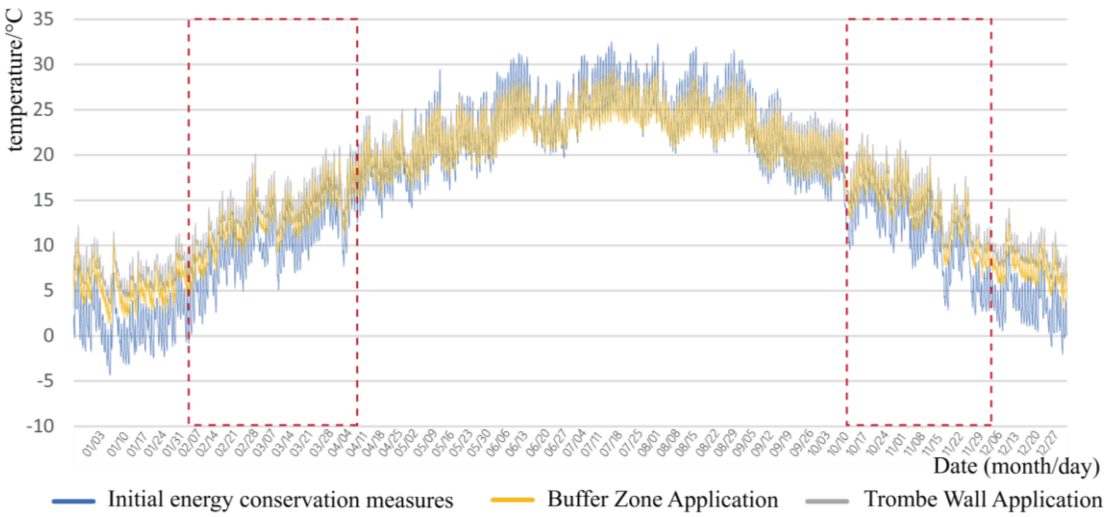


Figure 10. *Composite facades Temperature Simulation Comparison graph.*

It can be seen from the table that the application of two different composite facade retrofits can effectively reduce the indoor energy consumption of the industrial heritage. After the application of two types of composite facade, the heating energy consumption decreased significantly, while the cooling energy consumption did not change significantly. Especially, the cooling energy consumption increased after the application of the Trombe wall, which also confirmed that the composite facade without openings was only suitable for the winter in the cold area, and the improvement of its summer energy consumption was not obvious. Compared to two kinds of composite facades, it can be seen that the use of the external solid wall and the internal glass can more effectively reduce the energy consumption of the building, and its impact on the cooling energy consumption is lower, which is more suitable for the civilization of the industrial heritage. But there are also some disadvantages of using the external solid wall and the internal glass, such as it occupies the indoor utility area of the industrial heritage, and the process is more cumbersome compared to the another composite interface.

5. Conclusion

Based on the thermal buffering effects, applying the Trombe Wall system and the buffer zone system, this paper analyzes and studies transformation process of the envelope structure of Shenyang Dongmao Warehouse No. 2, and explores the operating conditions and the application effect of the two composite facades. It aims to investigate the design strategies and methods to meet the needs for optimizing the thermal performance of the interior and preserving the originality of the facade after the civilization and renovation of the industrial heritage. As verified by DesignBuilder software modelling simulation analysis, the average indoor temperature of the industrial building heritages after the application of two different composite facade renovation have different magnitude of increase, and effectively reduce the indoor energy consumption of the building. The composite facade of the external solid wall and the internal glass is more stable in raising the indoor temperature, more effective in reducing the building energy consumption, and more suitable for the civilian transformation of industrial heritage in cold areas.

The application of passive design strategies to the renewal and optimization of industrial heritage in the process of civilized renovation will comprehensively enhance the level of protection of historical and cultural heritage as well as the realization of the goal of energy conservation and emission reduction of the whole society. This study provides an in-depth comparative analysis of the impact and scope of the two composite facades renovation methods on the indoor thermal environment of industrial heritage, with a view to providing a certain reference for the study of civil renovation of industrial heritage.

Abbreviations

CFD Computational Fluid Dynamics

Author Contributions

Mengru Zhang: Data curation, Software, Formal Analysis, Writing – review & editing, Visualization, Resources

Yong Huang: Conceptualization, Methodology, Resources, Supervision

Rui Zhang: Investigation, Resources, Formal Analysis

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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