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Study on Optimization of Air Infiltration at Entrance of a Commercial Complex in Zhejiang Province

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***Abstract*—**In the past decade, with the rapid development of China's economy, the purchasing power and physical demand of residents have been improved, which results in the vast emergence of public buildings like large shopping malls. However, the architects usually focus on the internal functions and streamlines of these buildings, ignoring the impact of the environment on the subjective feelings of building users. Only in Zhejiang province, the infiltration of cold air in winter frequently occurs at the entrance of sizeable commercial complex buildings that have been in operation, which will affect the environmental comfort of the building lobby and internal public spaces. At present, to reduce these adverse effects, it is usually adopted to add active equipment, such as setting air curtains to block air exchange or adding heating air conditioners. From the perspective of energy consumption, the infiltration of cold air into the entrance will increase the heat consumption of indoor heating equipment, which will indirectly cause considerable economic losses during the whole winter heating stage. Therefore, it is of considerable significance to explore the suitable entrance forms for improving the environmental comfort of commercial buildings and saving energy. In this paper, a commercial complex with apparent cold air infiltration problem in Hangzhou is selected as the research object to establish a model. The environmental parameters of the building entrance, including temperature, wind speed, and infiltration air volume, are obtained by Computational Fluid Dynamics (CFD) simulation, from which the heat consumption caused by the natural air infiltration in the winter and its potential economic loss is estimated as the objective metric. This study finally obtains the optimization direction of the building entrance form of the commercial complex by comparing the simulation results of other local commercial complex projects with different entrance forms. The conclusions will guide the entrance design of the same type of commercial complex in this area.

***Keywords*—**Air infiltration, commercial complex, heat consumption, CFD simulation.

I. Introduction

In recent years, with the rapid development of China's economy and the continuous improvement of people's consumption level, the business has experienced a substantial increase. From 2007 to 2017, the gross domestic product of the tertiary industry increased from 1,1,110.07 billion Yuan to 42,703.15 billion Yuan. The proportion of GDP increased from 42.9% to 51.6% [1]. Under such a background, modern commercial buildings are gradually moving from a single type, single function, scatter layout to a composite type, composite function, and centralized layout. Large-scale commercial complexes have gradually become the development trend of commercial buildings in first- and second-tier cities. The stock and construction volume are huge. By the end of 2017, the total number of large-scale commercial complexes in the country has exceeded 3,500, and the total number of commercial complexes in Zhejiang Province is about 256. The national total of 8% is the fourth in the country, and Hangzhou, as the capital city of Zhejiang Province, has added more than 20 large commercial complexes in 2017 [2], as shown in Figs. 1and 2.

Fig. 1 Map of commercial complexes in China in 2017

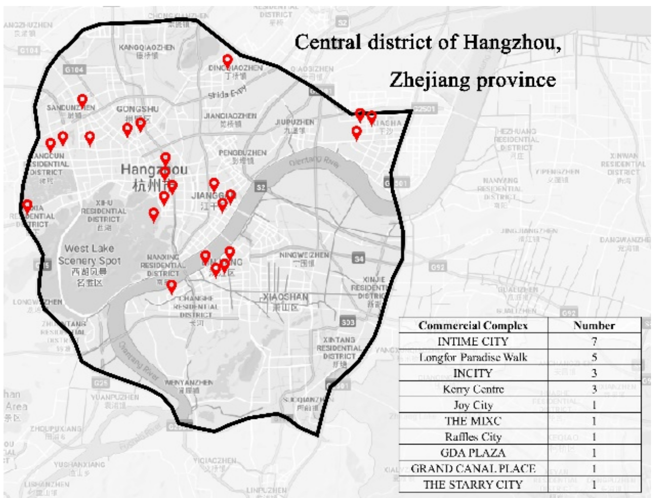

Fig. 2 Map of commercial complexes of Hangzhou in 2017

Compared with traditional commercial buildings, large-scale commercial complexes are characterized by diverse functions, complex space, numerous equipment, and dense personnel [2]. Therefore, such buildings usually have large building volume,

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open indoor space, and multiple entrances and exits. Its energy consumption is 5-15 times that of ordinary houses [3], and it also has a great impact on its indoor comfort. As China's urbanization construction enters a new stage, the future construction focus will be biased towards the airport. In high-speed railway stations and other buildings with large space and complex systems [4], the building energy-saving situation is urgent. At the same time, the indoor thermal environment comfort is also an essential factor affecting the operation of commercial buildings, and it has a connection with users' psychology and behavior.

In the winter, large-scale buildings in northern China often have a low inlet temperature. In this respect, many scholars have analyzed the entrances of typical buildings (shopping malls, airports, etc.) in the area through actual measurement and software simulation. It is found that the inlet cold air infiltration caused by the excessive temperature difference between indoor and outdoor is the main reason for the user to feel uncomfortable in the entrance space [5], [6]. By changing the primary entrance orientation of the building, the building entrance form, the envelope structure, the design strategy of auxiliary heating facilities and other factors can effectively alleviate this phenomenon. The buffer space at the main entrance plays a decisive role in controlling the inlet cold air penetration [7].

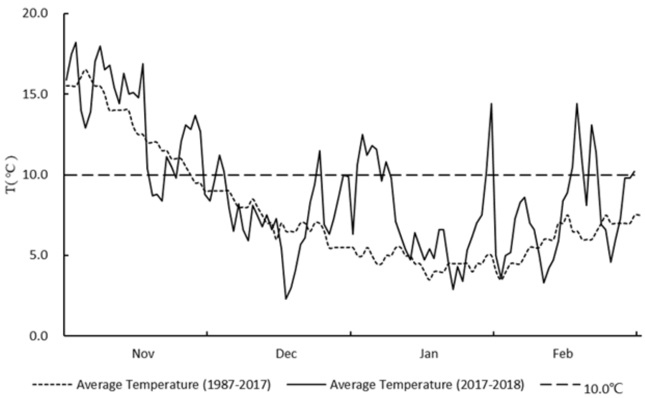


Fig. 3 The average temperature in winter in Hangzhou

There is also the problem of cold air infiltration in the entrance of large buildings in southern China. In the winter of 2017, the daily average temperature of Hangzhou below 10 °C accounted for two-thirds of the days of heating equipment operation, as shown in Fig. 3. The indoor commercial building temperature in winter is usually 22-25 °C. The indoor and outdoor temperature difference over 10 °C makes the problem of cold air penetration especially obvious. A large amount of cold air penetration not only affects the user's comfort level but also increases the heat consumption of the building heating and causes an inevitable economic loss. The heat consumption of the heating equipment in the hall causes a certain economic loss. Therefore, taking Zhejiang Province as an example, it is of great practical significance to explore the optimal design direction of the entrance form of sizeable commercial complex buildings for the problem of inlet cold air infiltration.

II. Methodology

A. Research Object

In this study, three large-scale commercial complexes (from now on referred to as A, B, and C buildings) newly built in the past five years in Hangzhou were selected as the research objects for indoor and outdoor environmental measurements and comparisons. The total construction area of Building A is about 220,000 square meters, and the general single-vestibule is set at the entrance; the total construction area of Building B is about 290,000 square meters, and the interior space of the vestibule is divided by the wind curtain; The area is about 200,000 square meters, and the double vestibule is provided at the entrance, as shown in Fig. 4.

Building A

Building B

Building C

Fig. 4 Entrance of research objects

B. Air Infiltration Rate

In previous studies, the test of osmotic air volume was usually performed by wind speed method, tracer gas method, or CFD simulation method. Among them, the tracer gas in the actual building is often CO_2 or H_2O. In the study of the osmotic wind at the entrance of the airport terminal by Liu [6], it was found that the indoor and outdoor CO_2 or H_2O were used in the large-scale buildings due to the influence of personnel density. The amount of permeate air obtained by the concentration calculation has a more massive error than other methods. Therefore, this study uses the wind speed method to calculate the average air velocity of the entrance door of the building to calculate the air penetration of the inlet. The calculation method is as shown in (1):

$$G_{infl.} = \sum_{i=1}^{n} A_i v_i \quad (1)$$

where G_{infil} represents the volume flow rate of air infiltration; n represents the number of inlets; A_i represents the area of the door opening; v_i is the average wind speed at the opening.

Through the above test data, the CFD simulation software is used to establish a numerical model that is consistent with the initial state. In the subsequent research, the simulation model can be used to obtain the inlet cold air infiltration under different conditions, to obtain the optimization design of the entrance of large commercial complex in Zhejiang area. All the CFD models of entrance were created with Ansys Fluent 19.0.

During the heating phase, the cold air infiltrated by the inlet tends to increase the heat consumption of the indoor heating equipment, as shown in (2):

$$Q = 0.28 \cdot C_p \cdot \rho_w \cdot G \cdot (T_n - T_w) \quad (2)$$

where Q represents heat consumption; C_p represents the specific heat capacity of air, which is usually taken as 1.01 kJ/(kg·K), and T_n and T_w represent the average temperature inside and outside the room, respectively. The corresponding additional economic expenditure for the increased heat consumption of cold air infiltration is estimated, according to (3):

$$C = Q \cdot h \cdot d \cdot p_{el} \quad (3)$$

where C represents the additional electricity cost corresponding to the increased heat consumption (yuan); h represents the number of hours of operation of the heating equipment throughout the day, 12 hours in the target building; d represents the total number of days of heating operation of the building in winter, taking 90 days; p_{el} represents the unit price of commercial buildings in Hangzhou (yuan/kWh).

III. On-Site Measurement

To confirm the current status of the thermal environment at the entrance of the building, the thermal environment of the entrances of buildings A, B and C were measured on a typical sunny day in the winter of 2018. The test contents included the temperature of the entrance space, the temperature of the hall, and the permeation wind speed of each door of the door. The test results are shown in Table I and the test instruments used are shown in Table II.

TABLE I
Measurement Result

	T_w (°C)	T_{entry} (°C)	T_{hall} (°C)	v_i (m/s)
Building A	9.5	10.3	17.1	2.43
Building B	10.3	12.1,15.7,19.7	19.7	0.30
Building C	9.7	14.9,15.3	18.9	0.24

TABLE II
Specifications of the Measurement Devices

Parameter	Device	Accuracy	Operational range
Air temperature	Pt PTD	0.1°C	0-50°C
Air velocity	Hot wire anemometer	0.03m/s	0-10m/s
Air pressure	Differential pressure	0.5Pa	0-2000Pa

From the test results, it is found that the infiltration air volume of the A building entrance reaches 19784 m^3/s, and there is an apparent cold air infiltration problem. The additional electricity cost of the building entrance due to cold air infiltration will reach 29,115 yuan in winter, and it will penetrate due to the large cold air. As a result of the low temperature in the foyer space, the test found that the average temperature at the entrance was only 10.3 °C. The problem is not evident in the B and C building entrances and exits. The construction scale of A, B, and C is similar to the internal functional division. The reason for the considerable difference in the entrance environment caused by the guess is the difference in the form of the entry. This assumption needs to be verified by using CFD simulation.

IV. CFD Simulation

A. Calibration Model

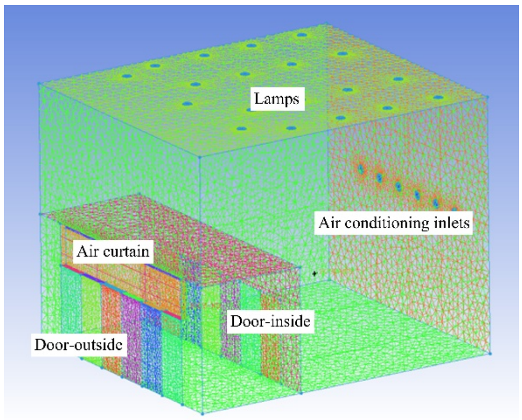


Fig. 5 CFD model

Fig. 5 shows the CFD model of the north entrance and foyer of building A. The model size is 11 m*15 m*14 m, and the measured indoor and outdoor environmental parameters are set to the model boundary conditions. To verify the accuracy of the model, the test is performed. At the same time, the temperature distribution of the fixed measuring point of the hall was obtained, as shown in Fig. 6. The comparison between the simulation result and the measured data is shown in Fig. 7. The error of each point is less than 0.5 °C, which effectively verifies the feasibility of the CFD simulation method.

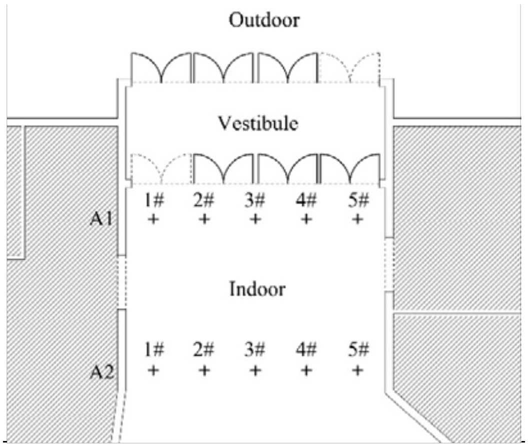


Fig. 6 Measuring points

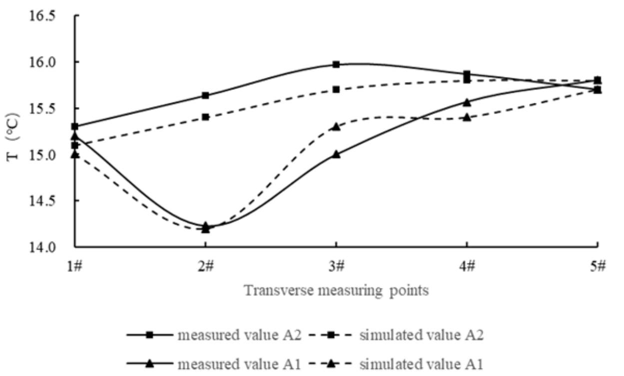
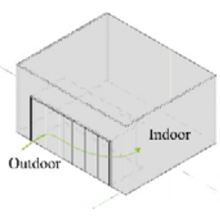


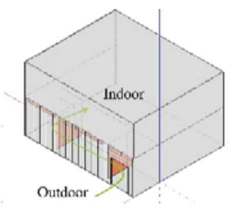
Fig. 7 Comparison of simulation results

B. Different Forms of Entry

The B building entrance uses a wind curtain to divide the single-vestibule into multiple horizontal spaces, while the C building has a double-vestibule. Using CFD simulation to verify whether these two types of measures are equally effective in the A building, only the different door bucket forms are selected as a single variable without changing the indoor and outdoor environmental parameters and the size of the A building hall, as shown in Fig. 8.



(a)



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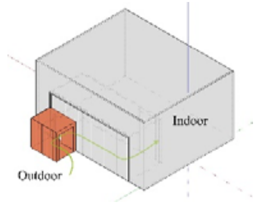
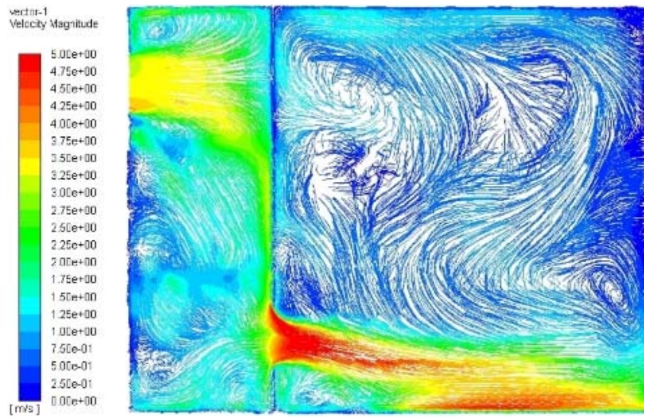


(c)

Fig. 8 Different forms of entry

The simulation results are shown in Fig. 9 and Table III. From the simulation results, it can be concluded that the two measures are used to improve the cold air infiltration problem of the A building entrance, and the improved additional electricity cost is reduced by at least 64%. Under the premise of not considering the construction cost, the two improvement measures have apparent optimization effects for the cold air infiltration of large commercial complex inlets.



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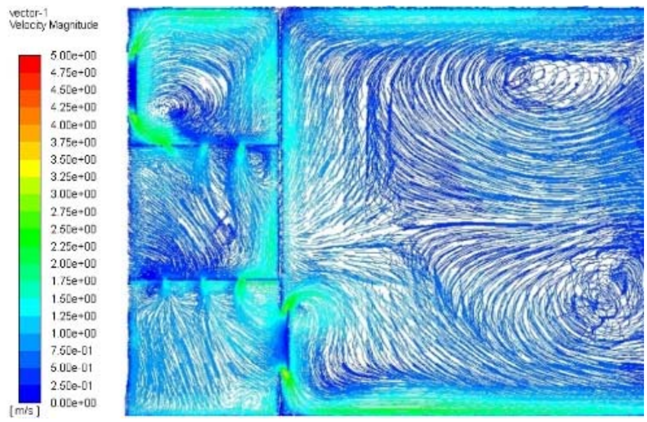

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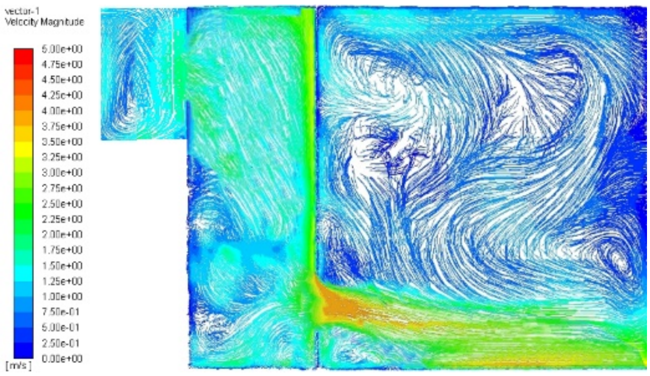

(c)

Fig. 9 CFD simulation results of airflow

TABLE III
COMPARISON OF SIMULATION RESULTS OF THREE CASES

	Basis for Comparison	G_{infil} (10^4 m^3/h)	Q (10^4 w)	C （10^4 yuan）
case 1	Single vestibule	1.98	6.28	2.91
case 2	Dividing spaces by curtains	0.61	1.95	0.88
case 3	Double vestibule	0.71	2.25	1.04

V. CONCLUSION

In this study, three typical large-scale commercial complex buildings in Hangzhou City, Zhejiang Province were selected as research objects. Among them, the entrance of A building was set up with ordinary single-layer door buckets. After the actual measurement, there was an apparent cold air infiltration problem. The B and C buildings avoid this problem by dividing the internal space of the vestibule and setting the double vestibule. Using the CFD simulation method, the measures adopted in the B and C buildings were applied to the A building, and the results showed that the cold air infiltration problem was improved.

The design strategies adopted by B and C buildings have commonalities and can be seen as adding buffer space based on single-layer door buckets. Therefore, in the southern cities of China, such as Zhejiang Province, it is difficult to avoid the problem of cold air infiltration in the entrance and exit of sizeable commercial complex buildings. The cold air infiltration not only affects the subjective feelings of users but also generates considerable economic losses. Adding buffer space based on the above two methods as the above two methods is especially important in future designs.

NOMENCLATURE

A_i opening area (m^2)
C electricity cost (yuan)
C_p heat capacity (kJ/(kg·K))
Ginfil volume flow rate of air infiltration (m^3/h)
Q heat consumption (w)
v_i wind speed (m/s)
ρ density (kg/m³)
h hours
d days
p_{el} the unit price of commercial buildings in Hangzhou (yuan/kWh)

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