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Analysis of Heat and Moisture Transfer and Thermal Comfort in Green Logistics Storage Space

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ABSTRACT

Regular logistics storage spaces suffer a very high temperature during summer. To build a green logistics storage space, it is truly necessary to optimize the thermal environment in summer. At present, there are few related studies on the energy consumption, thermal environment and human comfort of green logistics storage spaces. Therefore, this paper analyzes the heat and moisture transfer in and studies the impacts of the thermal environment of green logistics storage space. Based on the survey results, a coupled heat-moisture transfer model of green logistics storage space was constructed, which consists of three parts - the envelope structure, the hot and humid indoor environment, and the heating, ventilation and air conditioning (HVAC) system. Based on the idea of linear regression, a model was established to predict human body's subjective thermal sensation in green logistics storage space. The experiment showed the analysis results of heat and moisture transfer and thermal comfort in green logistics storage space, and verified the effectiveness of the proposed model.

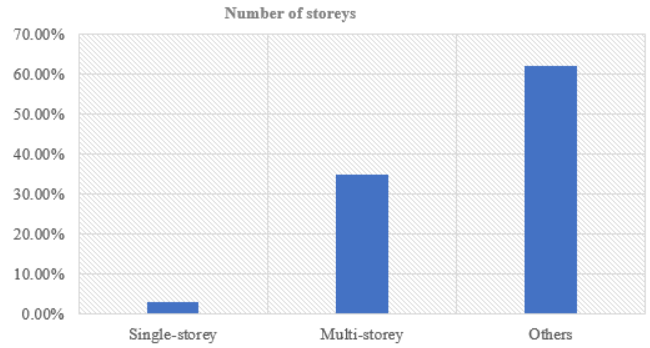
1. INTRODUCTION

With the rapid development of the e-commerce and logistics industry in China, the construction of logistics storage space has also increased significantly [1-10]. Along with this trend, people have begun to pay attention to environmental protection and energy conservation in the logistics and warehousing industry, and gradually accepted the concept of green warehousing [11-15]. Implementing green warehousing management can reduce the environmental pollution caused by warehousing while ensuring the quality and quantity of the stored goods, and improve the various problems of regular logistics storage space such as heavy environmental pollution, high energy consumption, large cargo loss, poor thermal environment and high transportation costs [16-21]. Among these problems, high temperature in summer is the most prominent one. To tackle this, it is necessary to optimize the thermal environment of green logistics storage space in summer, to obtain lower energy consumption of logistics storage space and maintain the physical and mental health of logistics and warehousing workers.

In order to predict and evaluate the moisture-heat performance of buildings, it is necessary to develop an accurate dynamic moisture-heat model for coupled heat-moisture transfer in porous building materials and envelopes. Dong et al. [22] fully validated the Künzel model and the Liu model, and the results of the two models simulated with Fortran code and COMSOL Multiphysics were compared with the analytical solutions, simulated solutions from other models, and data from two published experimental datasets. The simulation results of the two models were consistent with the results in the existing literature. To determine the effect of uncertainty on the values of the input parameters of the Künzel model, a local sensitivity analysis (LSA) was performed by adjusting the moisture-heat properties, surface transfer coefficient and initial conditions of the material by 5% [23]. The results show that the surface transfer coefficient and adsorption isotherm are the most influential parameters. However, due to the difference in the relative importance of the transfer, the conclusions are slightly different for the two materials. Hou et al. [24] constructed a reduced-order model simulating the optimization of heat and moisture transfer costs by combining the proper orthogonal decomposition (POD) and the discrete empirical interpolation method (DEIM). The POD-DEIM performance was evaluated through two applications: a relatively simple case of nonlinear heat transfer and a more complex case of nonlinear moisture redistribution. The results show that the POD-DEIM model is able to reduce the computational cost compared with POD and FVM when fairly accurate results are required. Borodulin and Nizovtsev [25] established a physical and mathematical model for calculating the thermal state and humidity of building facades with ventilation channels. This model is based on the joint solution to a system of non-stationary differential equations for heat and moisture transfer in multilayer porous materials. In addition, equations describing heat and mass transfer in air ventilation channels were considered in the model. Liu et al. [26] developed a six-dimensional semantic framework for outdoor thermal comfort assessment, including four descriptive dimensions “thermal sensation”, “humidity”, “wind” and “solar radiation”, and two emotional ones - “thermal pleasure” and “heat intensity”. The results indicate that the thermal sensation scale is insufficient to describe the outdoor thermal comfort. This study initiated a shift in biometeorological comfort research from rough one-dimensional descriptive thermal sensation scales to more refined, multidimensional description of subjective thermal states.

Through review of the existing literature, it can be seen that domestic and foreign scholars have carried out a lot of simulated calculation and practical research on the comfort and energy conservation of civil buildings, such as houses and office buildings, and have also drawn valuable conclusions. Building type and thermal environment control method are the key factors to the energy consumption and thermal environment of indoor space, but there are few related studies on the energy consumption, thermal environment and human comfort of green logistics storage space. Therefore, this paper analyzes the heat and moisture transfer in and studies the impacts of the thermal environment of green logistics storage space. Based on the survey results, Section 2 constructs a coupled heat-moisture transfer model of green logistics storage space, which consists of three parts - the envelope structure, the hot and humid indoor environment, and the HVAC system. Based on the idea of linear regression, Section 3 establishes a model to predict human body's subjective thermal sensation in green logistics storage space. The experiment shows the analysis results of heat and moisture transfer and thermal comfort in green logistics storage space, and proves the effectiveness of the proposed model.

2. ANALYSIS OF THE COUPLED HEAT-MOISTURE TRANSFER IN GREEN LOGISTICS STORAGE SPACE



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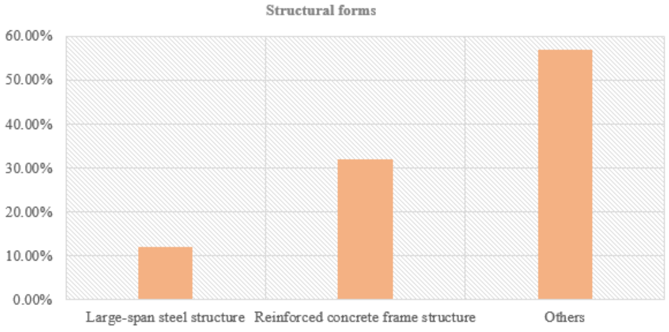

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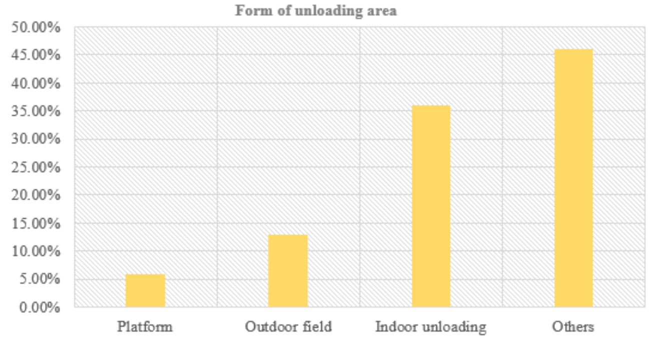

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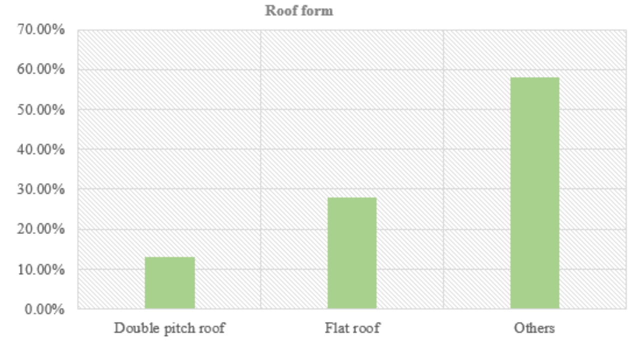

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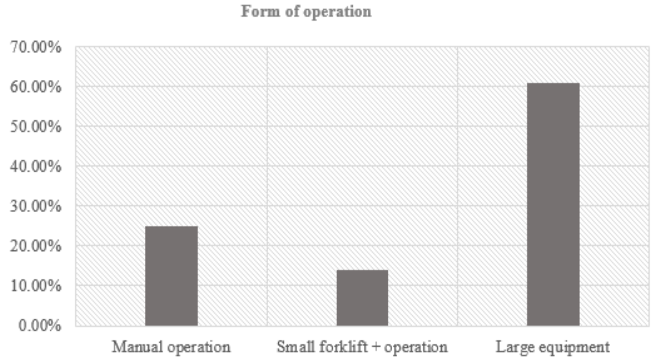

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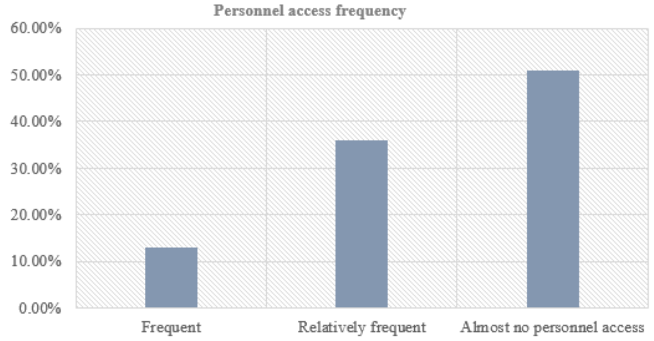

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Figure 1. Preliminary survey results of green logistics storage space

Figure 1 shows the preliminary survey results of green logistics storage space. The figure shows the survey results of 6 aspects of green logistics storage space, namely the number of storeys, structural form, form of unloading area, roof form, form of operation, and personnel access frequency. Based on the survey results, this paper established a coupled heat-moisture transfer model for green logistics storage space. This model consists of three parts - the envelope structure, the indoor heat-moisture environment, and the HVAC system. The indoor personnel activities and the effect of the heat and humidity transfer process of the wall make the indoor temperature and humidity highly uncertain, which needs calculation by the heat-mass balance equation. This section introduces the coupled heat-moisture transfer mechanism of the wall and the coupled heat-moisture model of green logistics storage space.

The law of continuity is applicable to the heat and moisture transfer in green logistics storage space. Assuming that the total enthalpy is represented by F, that the heat flux density w, and that the heat source or heat sink R_f, the heat transfer equation in green logistics storage space envelope can be expressed as follows:

$$\frac{\partial F}{\partial o} = -\nabla w + R_f \tag{1}$$

Assuming that the enthalpy of the building material is represented by F_r, and that the enthalpy of the moisture contained in the material F_q, the total enthalpy of the green logistics storage space envelope consisting of F_r and F_q: as follows:

$$F = F_r + F_q \tag{2}$$

Assuming that the density of the material is denoted by τ_r, that the specific heat capacity of the material SH_r, that the total moisture q, the frozen moisture q_g, that the specific heat capacity of liquid water SH_q, that the specific heat capacity of frozen water SH_g, that the enthalpy of melting f_g, and that the temperature O, then F_r and F_q can be calculated as follows:

$$F_r = \tau_r SH_r O \tag{3}$$

$$F_q = \left[\left(q - q_g \right) SH_q + q_g SH_g - f_g \frac{dq_g}{dO} \right] \cdot O \tag{4}$$

Assuming that the thermal conductivity of the wall material is represented by μ, that the temperature gradient ∇O, and that the heat flow density w is in direct proportion to the product of μ and ∇O, based on Fourier's law, there is:

$$w = -\mu \nabla O \tag{5}$$

Assuming that the heat source or heat sink generated by evaporation or condensation is denoted by R_f, that the latent heat of phase change f_u, and that the water vapour transfer rate h_u, the enthalpy flux generated by moisture transfer and phase change in the heat balance equation can be characterized by the source term in the following equation:

$$R_f = -f_u \nabla \cdot h_u \tag{6}$$

The heat transfer equation is given as follows:

$$\left(\tau SH + \frac{\partial F_q}{\partial O} \right) \cdot \frac{\partial O}{\partial o} = \nabla \cdot \left(\mu \nabla O \right) + f_u \nabla \cdot \left(\xi_e \nabla \left(\varphi e_{sat} \right) \right) \tag{7}$$

Suppose that the moisture content of the wall material layer is represented by Q, that the liquid water transfer rate h_q, that the water vapour transfer rate h_u, and that the moisture source R_q. Similar to the heat balance control equation, the following formula shows how to express the moisture transfer equation in green logistics storage space:

$$\frac{\partial Q}{\partial o} = -\nabla \cdot \left(h_q + h_u \right) + R_q \tag{8}$$

Suppose that the liquid water permeability coefficient is denoted by l_q and that the capillary pressure e_q, the transfer rate of liquid water is given as follows:

$$h_q = l_q \nabla e_q \tag{9}$$

Assuming that the liquid water conductivity is denoted by C_ϕ, that the capillary transmission coefficient C_q, that the relative humidity ϕ, and that the volumetric moisture content of the material q, the formula for calculating the liquid water transfer rate is given as follows:

$$h_q = -C_\varphi \nabla_\varphi = -C_q \frac{\partial q}{\partial \varphi} \nabla \varphi \tag{10}$$

Assuming that the water vapour diffusion coefficient of the material is denoted by ξ_e, and that the partial water vapour pressure e, and the water vapour transfer rate is given as follows:

$$h_u = -\xi_e \nabla e \tag{11}$$

Assuming that the water vapour diffusion coefficient in the air is represented by ξ, and that the water vapour diffusion resistance coefficient λ, the water vapour diffusion coefficient of the material can be calculated by the following formula:

$$\xi_e = \frac{\xi}{\lambda} \tag{12}$$

By combining the above equations, the following equation of moisture transfer in a green logistics storage space envelope can be obtained:

$$\frac{dq}{d\varphi} \cdot \frac{\partial \varphi}{\partial o} = \nabla \cdot \left(C_q \frac{dq}{d\varphi} \nabla \varphi + \xi_e \nabla \left(\varphi e_{sat} \right) \right) \tag{13}$$

In this paper, the heat exchange of walls and solar radiation, the heat production of storage equipment, the heat exchange through doors and windows, and the heat exchange of indoor space ventilation are considered as the main factors in the establishment of the indoor heat balance equation of green logistics storage space. A change in the indoor thermal environment of the green logistics storage space is determined by the abovementioned heat transfer processes. Assuming that the air density is represented by τ, that the specific heat capacity of air SH_o, that the room volume U, that the indoor air temperature O_i, that the outdoor air temperature O_x, that the surface area of the wall X_j, that the surface heat transfer coefficient β_j, the inner surface temperature of the wall O_j. that the heat gain from solar radiation entering the room through doors and windows W_{sun}, that the heat generated by the personnel, lights and equipment indoors W_{EQ}, that the heat gain generated by ventilation W_{wind}, and that the air change rate per hour m, the following formula shows how to express the heat balance equation for indoor air:

$$\begin{aligned} \tau \cdot SH_o \cdot U \cdot \frac{dO_i}{do} &= \sum_j X_j \beta_j \left(O_j - O_i \right) + W_{sun} + W_{EQ} \\ &+ m \cdot U \cdot \tau \cdot SH_o \left(O_o - O_i \right) + W_{wind} \end{aligned} \tag{14}$$

The moisture absorption and desorption flux on the inner surface of the wall is the main influencing factor considered in the establishment of the indoor humidity balance equation of green logistics storage space in this paper. In addition, humidification and dehumidification of storage equipment, moisture production of personnel indoors, moisture penetrating through doors and windows, and other moisture sources in green logistics storage space are also related to the indoor moisture content. Assuming that the outdoor air moisture content is represented by HW_t, that the indoor air moisture content of the green logistics storage space HW_i, that the moisture gain into the room from the inner surface of the wall h_{ij}, that the moisture production of the personnel indoors and other humidity sources in the green logistics storage space CS_i, and that the humidification and dehumidification of the air conditioner CS_{AC}, the following formula is given below as the indoor humidity balance equation:

$$U \cdot \frac{dHW_i}{dHW} = \sum_j X_j h_{ij} + m \cdot U\left(HW_o - HW_i\right) + CS_i + CS_{AC} \tag{15}$$

For green logistics storage space in areas where summer is hot and winter is cold, air convection and rainfall are the manifestations of outdoor humidity sources. Suppose that the moisture flows through the inner and outer surfaces of the envelope structure are represented by h_i and h_p, respectively, that the convective mass transfer coefficients of the inner and outer surfaces of the wall γ_{in} and γ_{out}, that the partial pressures of water vapour on the inner and outer surfaces of the wall $e_{wp,in}$, and $e_{wp,out}$, respectively, that the partial pressure of water vapour in indoor and outdoor air e_{in} and e_{out} respectively, and that the moisture source brought by rainfall is represented by h_s, the moisture flow through the outer surface of the envelope is expressed by the following formula:

$$h_p = \gamma_{out}\left(e_{out} - e_{wp,out}\right) + h_s \tag{16}$$

When the boundary conditions in the green logistics storage space are relatively stable, the moisture flow on the inner surface of the envelope structure can be calculated as follows:

$$h_i = \gamma_{in}\left(e_{in} - e_{wp,in}\right) \tag{17}$$

Suppose that the coefficients of the convective heat transfer between the inner and outer surfaces of the envelope and the air are represented by f_{in} and f_{out}, respectively, that the temperatures of the inner and outer surfaces of the envelope $O_{st,in}$ and $O_{st,out}$, respectively, that the indoor and outdoor air temperatures O_{in} and O_{out}, that the latent heat of vaporization of water vapour f_u, that the solar radiation absorption coefficient of the outer surface of the wall β, and that the solar radiation intensity EM, the calculation formula of the heat flow w_p on the outer surface of the envelope is given below:

$$w_p = f_{out}\left(O_{out} - O_{st,out}\right) + f_u \gamma_{out}\left(e_{out} - e_{wp,out}\right) + \beta EM \tag{18}$$

The formula for calculating the heat flux w_i on the inner surface of the envelope is given below:

$$w_i = f_{in}\left(O_{in} - O_{st,in}\right) + f_u \gamma_{in}\left(e_{in} - e_{wp,in}\right) \tag{19}$$

Considering the human thermal comfort in confined space and the thermal environment requirements of green logistics and warehousing in summer, Table 1 lists the indicators of the thermal environment requirements for green logistics storage space, including thermal environment requirement of human body, that of goods storage and the overall temperature, humidity and air velocity requirements.

Table 1. Thermal environment requirements for green logistics storage space in summer

Type of requirements	**Temperature (℃)**	**Humidity (%)**	**Air velocity (*m*/*s*)**
Thermal environment requirement of human body	23℃~28℃	52%~62%	2.3*m*/*s*-3.8*m*/*s*
Thermal environment requirement of goods storage	≤27℃	56%~78%	Dry and ventilated
Overall thermal environment requirement	23℃~27℃	53%~69%	2.2*m*/*s*-3.9*m*/*s*

3. ANALYSIS OF HUMAN THERMAL COMFORT IN GREEN LOGISTICS STORAGE SPACE

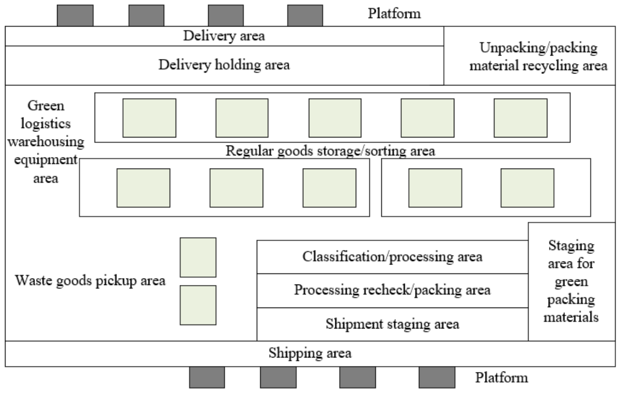

Figure 2. Functional distribution map of green logistics storage space

Green warehousing requires reasonable warehouse site selection and scientific warehousing layout to maximize the utilization of the warehousing area. Figure 2 shows the functional distribution of a green logistics storage space. As can be seen, the main functional areas include the delivery area, the delivery holding area, the unpacking/packing material recycling area, the regular goods storage/sorting area, the green logistics warehousing equipment area, the waste goods pickup area, the classification/processing area, processing recheck/packing area, shipment staging area, staging area for green packing materials and shipping area.

Warehousing staff are mainly concentrated in the unpacking/packing material recycling area, sorting area, classification/processing area, and processing recheck/packing area. For areas where people stay for a long time, it is necessary to focus on the human thermal comfort in the storage space. In order to improve the thermal environment quality in summer in such areas and create a relatively comfortable working environment for warehousing workers, it is necessary to analyse the dynamic and steady thermal sensations of warehousing workers and the index parameters that affect their thermal comfort in the areas where they stay. It is also necessary to evaluate the subjective thermal sensations of warehouse workers under different working conditions. Based on the idea of linear regression, a prediction model of human's subjective thermal sensations in green logistics storage space was established.

Assuming that the energy metabolism rate of the human body is represented by N, that the mechanical work done by the human body Q, that the heat dissipated from the outer surface of the human body to the surrounding environment through convection and radiation *D* and *S*, that the heat taken away from the human body through exhalation of water vapour and evaporation of sweat *P*, and that the heat storage rate of the human body *R*, then the heat balance equation characterizing how the human body maintains normal body temperature is expressed as follows:

$$N - Q - D - S - P - R = 0 \tag{20}$$

In addition to the influence of environmental factors, the body's own thermoregulatory function also has a great impact on the thermal comfort of the human body. When the skin temperature and sweat rate are in the best state, the warehousing workers in the green logistics storage space can obtain the most comfortable experience. When the heat storage rate *R* of the human body is 0, there is the following heat balance equation:

$$N - Q - D - S - P = 0 \tag{21}$$

Suppose that the convective heat transfer coefficient is represented by f_d, that the surface temperature of clothing o_{dk}, that the air temperature o_x, that the thermal resistance of clothing TH_{dk}, that the partial pressure of water vapour around the human body E_x, that the ratio of clothing area to skin area g_{dk}, the average radiation temperature $\bar{o}_s$, and that the relative air velocity U_x. Substitute *D*, *S* and *P* into the heat balance equation, and the following thermal comfort equation can be obtained:

$$\begin{aligned}(N-Q) &= g_{dk} f_d (o_{dk} - o_c) + 3.88\times10^{-8} g_{dk}\left[(o_{dk}+273)^4 - (\bar{o}_s+273)^4\right] \\ &+ 2.89\left[5.655\text{-}0.005(N\text{-}Q) - E_x\right] + 0.38(N - Q - 59.1) \\ &+ 0.0159\mathrm{N}(5.698\text{-}E_x) + 0.0021N(32.5 - o_x)\end{aligned} \tag{22}$$

Among the 8 variables in the formula, Q is 0, and g_{dk} and o_c are dependent on TH_{dk}. Therefore, the above thermal comfort equation can reflect that when the worker in the green logistics storage space are in a state of thermal equilibrium, N, o_c, E_x, $\bar{o}_s$, TH_{dk} and u determine the value of the variable – human thermal comfort.

4. EXPERIMENTAL RESULTS AND ANALYSIS

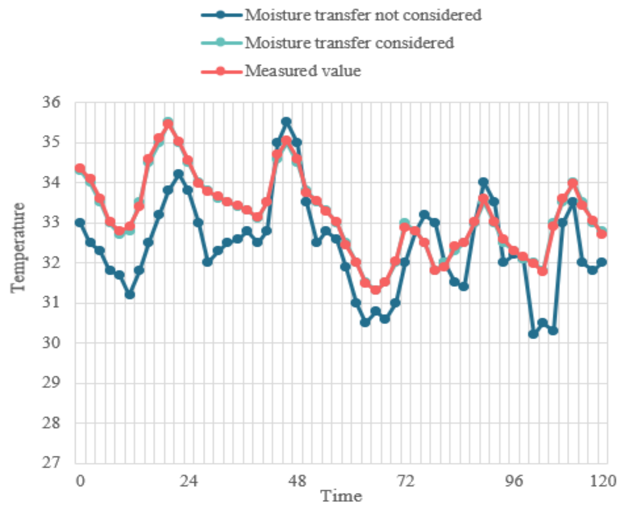

Figure 3. Indoor temperature of green logistics storage space

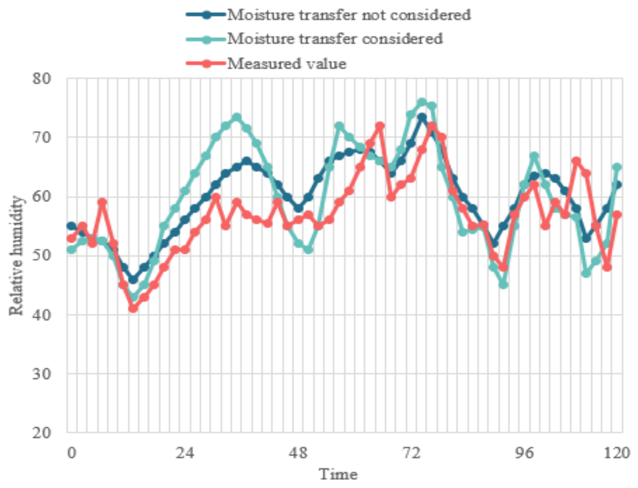

Figure 4. Indoor relative humidity of the green logistics storage space

Table 2. Heat flow of the green logistics storage space with different inner materials

		Max	Min	Indoor heat loss	Indoor heat gain
Gypsum	Moisture not considered	4.62	-7.16	-10653.74	4693.75
	Moisture considered	4.27	-6.25	-14271.63	4852.37
Tetraethyl orthosilicate	Moisture not considered	4.53	-7.19	-16325.95	4751.36
	Moisture considered	3.41	-6.57	-16235.85	4127.15
Composite material	Moisture not considered	4.69	-7.58	-14257.36	4847.69
	Moisture considered	4.85	-6.29	-11427.84	4625.38

Table 3. Heat flow in the green logistics storage space with different thermal insulation materials

		Max	Min	Indoor heat loss	Indoor heat gain
Extruded polystyrene board	Moisture not considered	4.02	-7.69	-13627.51	4152.85
	Moisture considered	3.74	-6.95	-9142.57	4036.42
Polystyrene board	Moisture not considered	4.15	-7.49	-13265.85	4152.47
	Moisture considered	3.27	-6.51	-9142.57	4174.62
Rock wool board	Moisture not considered	4.58	-7.03	-14274.15	4336.69
	Moisture considered	3.95	-6.48	-9253.84	4517.28

Table 4. Average value of the human thermal comfort under different working conditions

Condition	Predicted average rating	Predicted percentage of the unsatisfactory rating	Temperature
29℃	-0.0651	12.69	21.3
28℃	-0.1147	19.37	26.5
27℃	-0.3596	25.58	28.4
26℃	-0.9582	27.52	26.9
25℃	-1.5285	36.39	27.3

Figure 3 shows the indoor temperature of the green logistics storage space. It can be seen that when moisture transfer is not considered, the average deviation between the simulated and measured values of the indoor temperature in the green logistics storage space is 0.77°C. When moisture transfer is considered, the average deviation between the simulated and measured values of the indoor temperature in the green logistics storage space is 0.81°C. The simulated and measured values of the indoor temperature in the green logistics storage space in both cases are within the ideal range.

Figure 4 shows the indoor relative humidity of the green logistics storage space. The three curves drawn based on the calculated and measured values with and without the moisture transfer considered show similar fluctuations. The average relative deviations between the simulated and measured values of indoor relative humidity in the green logistics storage space with and without moisture transfer considered are 2.96% and 2.09%, respectively. When moisture transfer is considered, the simulated value is more consistent with the measured one. The main reason for the relative deviation is that there is a delay in the change of indoor temperature and humidity in the green logistics storage space.

Table 2 shows the heat flow in the green logistics storage space with different inner layer materials. According to the analysis of the heat flow and moisture flow in the green logistics storage space and on the inner surface of the wall, the total heat flow is lower when the moisture transfer is considered. The heat exchange between the indoor environment and the wall of the green logistics storage space mainly consists of heat conduction and heat convection. If the coupled heat and moisture transfer of the wall is fully considered, the heat transfer between the interior environment of the green logistics storage space and the wall will be greatly affected by the phase change process of the humid air. Table 3 shows the heat flows in green logistics storage space with different thermal insulation materials. It can be seen that the fluctuation range of the heat flow in the green logistics storage space is smaller when the moisture transfer is considered than that when it is not considered.

The thermal comfort values of human body under various working conditions under the operation of the air-conditioning-fan-based thermal environment control system were collected, as listed in Table 4. It can be seen that the predicted average ratings under different working conditions under the operation of the thermal environment control system were all below 0, and that the predicted average percentage of unsatisfactory ratings were all greater than 10%. When the preset conditioned temperature was 29°C, the predicted average rating was the highest, and the predicted average percentage of unsatisfactory rating the lowest; and when the present conditioned temperature was 25°C, the predicted average rating was the lowest, and the predicted average percentage of unsatisfactory rating the highest. Judging from the range of change, the absolute value of the human thermal comfort increased under the working condition of 25-29°C.

Figure 5 shows the change trends of the two human thermal comfort indicators - predicted average rating and predicted percentage of unsatisfactory rating. It can be seen that at the same temperature, when the operation energy consumption of the thermal environment control system increased, the predicted average rating kept decreasing, and the predicted average percentage of unsatisfactory rating kept increasing. When the preset conditioned temperature was 29°C and 28°C, the predicted average rating fell to the comfortable range. When the preset conditioned temperature was 27°C, the predicted average rating was around -1.25, and the predicted percentage of unsatisfactory ratings was greater than 25%. When the preset conditioned temperature was 26°C and 25°C, the predicted average rating finally stabilized at around -1.75, and the predicted percentage of unsatisfactory ratings at 45%, showing that after the energy consumption of the thermal environment control system increased, the warehousing workers participating in the test felt colder, which is consistent with the result of the actual thermal sensation voting. It can be seen from the analysis that, after the operation of the thermal environment control system, the inner surface temperature of the envelope structure of the green logistics storage space was effectively reduced, and then the average indoor radiation temperature of the green logistics storage space was rapidly reduced. The combined cooling form of air conditioner and fan enhanced the convective heat transfer on the skin surfaces of the workers, and thus the human thermal comfort rapidly increased.

Figure 6 shows the relationship between the preset conditioned temperature and the thermal comfort of the human body under different working conditions. The two indicators are the predicted average rating and the average thermal sensation vote. It can be seen from the figure that there was a highly linear correlation between the measured thermal sensation and the preset conditioned temperature, that is to say, the thermal sensations of the warehousing workers participating in the test were very sensitive to the indoor temperature changes in the green logistics storage space. There is a certain difference between the fitted curves of the average thermal sensation vote and the predicted average rating in the figure. The average value of the thermal sensation votes was higher when the preset conditioned temperature was in the range above 25.4°C than that when the present conditioned temperature was below 25.4°C. Although the predicted average ratings were generally low, they could still predict the thermal sensations of the warehousing workers well.

5. CONCLUSIONS

This paper analyzed the heat and moisture transfer in and studies the impacts of the thermal environment of green logistics storage space. Based on the survey results, a coupled heat-moisture transfer model of green logistics storage space was constructed, which consists of three parts - the envelope structure, the hot and humid indoor environment, and the heating, ventilation and air conditioning (HVAC) system. Based on the idea of linear regression, a model was established to predict human body's subjective thermal sensation in green logistics storage space. Through an experiment, the indoor temperature and relative humidity of the green logistics storage space were given, from which it was concluded that the main reason for the relative deviation was the delay in the change process of the indoor temperature and humidity of the green logistics storage space. The heat flows in the green logistics storage space with different inner layer materials and thermal insulation materials were shown, and the corresponding analysis results given. The human thermal comfort values under various operating conditions under the operation of the air-conditioning-fan-based thermal environment control system were collected, and the change trends of two human thermal comfort indicators - the predicted average rating and the predicted percentage of unsatisfactory ratings - were shown. Finally, the relationship between the preset conditioned temperature and the human thermal comfort under different working conditions was established.

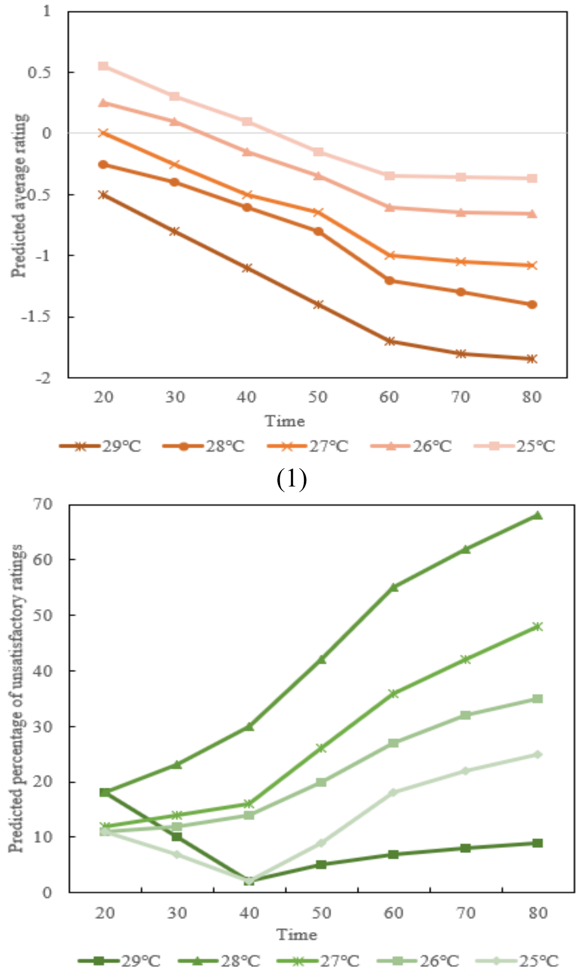

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Figure 5. Changes in human thermal comfort

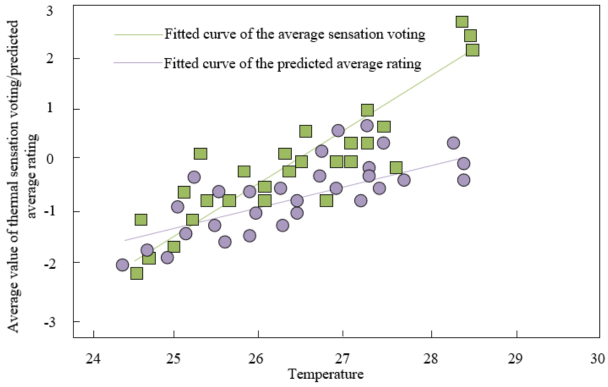

Figure 6. Fitting relationship between the preset conditioned temperature and human thermal comfort

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