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On the Thermal Field Characteristics and Evaluation Method of Intelligent Logistics Storage Space

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ABSTRACT

Intelligent logistics can effectively improve the intelligent analysis and decision-making and automatic operation execution capabilities of the logistics system. In order to optimize the design of the thermal environment of the intelligent logistics storage space and ensure the quality of stored goods and the physical and mental health of logistics and warehousing workers, it is especially important to analyze the thermal field characteristics of the intelligent logistics storage space and work out a reasonable and scientific evaluation method. This paper studies the thermal field characteristics and evaluation method of intelligent logistics storage space. First, based on the five characteristic factors of the thermal environment, a derivation process of the principle of heat transfer in the thermal field of the intelligent logistics storage space was demonstrated. Then, a specific research framework was given for evaluating the thermal environment of storage space, the average number of votes predicted was selected as the main evaluation indicator, and an adaptive model considering factors such as psychology, behavior, and physiology of the workers in the storage space was constructed. Finally, the corresponding analysis and evaluation results were provided.

1. INTRODUCTION

With the gradual advancement of automation, digitalization, and intelligent upgrading, intelligent logistics has become one of the mainstream trends in the development of the logistics industry [1-6]. Through intelligent technical means such as intelligent software and hardware, Internet of Things, and big data, intelligent logistics can achieve refined, dynamic, and visualized management on each link of logistics and effectively improve the intelligent analysis and decision-making and automatic operation execution capabilities of the logistics system [7-10].

Intelligent logistics storage management plays a core role in intelligent logistics management [11-16]. The logistics storage of special items such as fine wine, fur, antiques and prescription drugs is demanding on temperature control, and what is more, in traditional logistics storage space, there are problems such as high energy consumption and poor thermal environment, so it is necessary to equip modern intelligent logistics warehouses with temperature control systems [17-19]. Therefore, in order to optimize the design of the thermal environment of the intelligent logistics storage space, and ensure the quality of the stored goods and the physical and mental health of the logistics and warehousing workers, it is particularly important to analyze the thermal field characteristics of the intelligent logistics storage space, and work out a reasonable and scientific evaluation method.

Lan et al. [20] took the logistics storage environment as an example, and built a temperature and humidity detection system based on wireless sensor network. It simulated and analyzed the routing with the movement of nodes, and realized real-time detection of temperature and humidity in the logistics environment. Sun et al. [21] studied the impact of temperature fluctuations on the quality change of refrigerated large yellow croakers in the logistics process and evaluated the quality of large yellow croakers under different temperature environments. Lin [22] analyzed the mobile logistics warehousing with warehousing temperature control by the Internet of Things (IOT) technology, thermal technology and logistics unified information system (UIS), introduced the actual requirements for supply chain logistics circulation and warehousing and fixed logistics warehousing, and implemented the integrated design of logistics UIS temperature control perception system. The output of the system test results by the data factor analysis method shows that the IOT-based logistics storage temperature control UIS is feasible. In order to explore the effect of the goods stacking method on the temperature field of the cold storage, Tang [23] used the computational fluid dynamics (CFD) method to simulate the effects of different types of stacking arrangements on the temperature field of the cold storage under a new air outlet design. The simulation results show that the temperature distribution in the cold storage is the most uniform when the goods are stacked along the Z axis and filled with a 10cm thick pad in each layer. Simulations of this arrangement are highly consistent with measurements. This work revealed the temperature distribution characteristics of cold storage with ventilation holes.

Through review of the existing research results at home and abroad, it can be seen that there has been little research on the thermal environment evaluation of logistics storage space, that the evaluation methods for non-uniform thermal environment need to be developed, and that the spatial characteristics of the thermal field of logistics storage space need to be further discussed. This paper studies the thermal field characteristics and evaluation methods of intelligent logistics storage space. Section 2 shows the derivation process of the principle of heat transfer in the thermal field of intelligent logistics storage space based on five characteristic factors of thermal environment. Section 3 gives a specific research framework for evaluating the thermal environment of storage space, selects the predicted average number of votes as the main evaluation indicator, and establishes an adaptive model that considers the psychology, behaviors and physiology of the workers in the storage space. At last, the corresponding analysis and evaluation results are given.

2. HEAT TRANSFER ANALYSIS OF THE THERMAL FIELD IN INTELLIGENT LOGISTICS STORAGE SPACE

Solar radiation, heat transfer of the enclosure structure of the logistics warehouse, heat dissipation from the indoor heat source equipment and personnel, and internal air flow are the five main characteristic factors of thermal environment that affect the thermal field of the intelligent logistics storage space simulated in this paper. Based on the above five characteristic factors, this paper shows the derivation process of the principle of heat transfer in the thermal field of the intelligent logistics storage space.

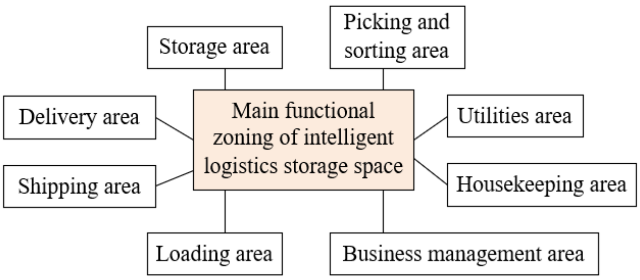

Figure 1. Functional zoning map of intelligent logistics storage space

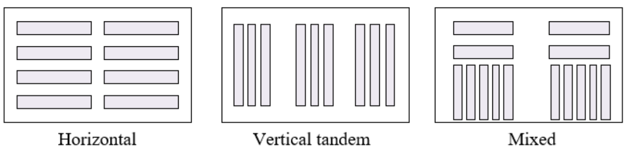

Figure 2. Shelf arrangement in intelligent logistics storage space

Figure 1 shows the functional zoning of the intelligent logistics storage space. It can be seen from the figure that 3/5~4/5 of the area of the intelligent logistics storage space is for goods storage, where the shelves are arranged. Figure 2 shows three kinds of shelf arrangements in the intelligent logistics storage space.

In this paper, signals were collected by wireless temperature and humidity sensors. Figure 3 shows the hardware connection of the indoor temperature measurement system in the storage space, where the temperature data are usually collected at the same time with the humidity data. Figure 4 shows the operation interface of the indoor temperature and humidity detection system in the storage space.

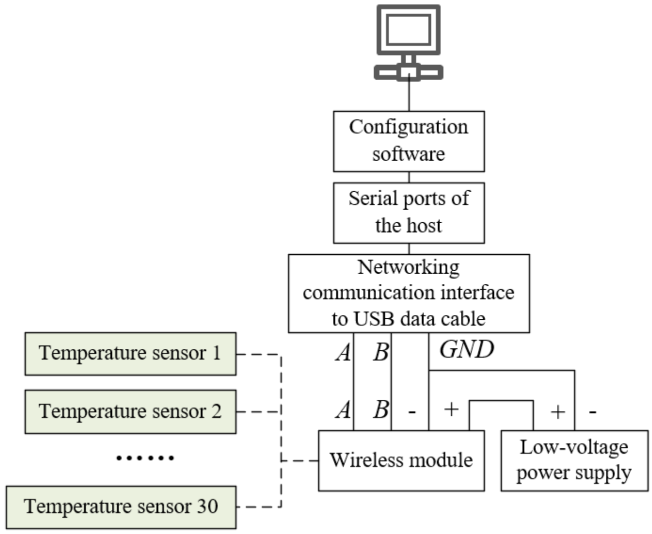

Figure 3. Hardware connection of the indoor temperature measurement system in the storage space

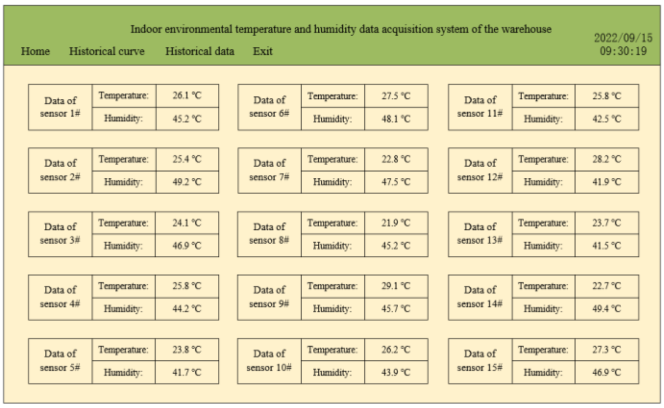

Figure 4. Operation interface of the indoor temperature and humidity detection system in the storage space

All objects in the intelligent logistics storage space, including goods and personnel, emit radiant heat to their surroundings due to their own temperature. Assuming that the emissivity of an object in the storage space is denoted by φ and that the Stefan-Boltzmann constant is denoted by ρ, when the temperature of the object is O, the following formula shows how to calculate the maximum value of radiant heat emitted by the object per unit area:

$$P = \phi \rho O^4 \tag{1}$$

If there is radiation heat transfer between an object with a higher temperature and one with a lower temperature in the intelligent logistics storage space, suppose that the temperatures are represented by O_1 and O_2, respectively, the formula for calculating the heat flux density between the two is given as follows:

$$w = \phi \rho \left(O_1^4 - O_2^4 \right) \tag{2}$$

The indoor heat source equipment and personnel inside the intelligent logistics storage space mainly exchange heat with the environment of the intelligent logistics storage space through convection and radiation. Under the ambient conditions of an ordinary warehouse without any temperature control system, since the temperatures of the indoor heat source equipment and personnel are usually higher than the average indoor radiant temperature, the air velocity in the warehouse is generally negligible. Therefore, according to the proportions of the radiation heat dissipation, convective heat dissipation, and evaporation heat dissipation from the indoor heat source equipment and personnel in the total dissipation, the radiant heat exchanges between the indoor heat source equipment and personnel and the indoor environment of the intelligent logistics storage space can be calculated, and further, the total heat dissipation from the indoor heat source equipment and personnel in the indoor storage environment can be obtained.

Assuming that the radiant heat exchange between the indoor heat source equipment and personnel and the storage indoor environment is represented by W_S, that the effective radiation area of indoor heat source equipment and personnel X_{pgg}, that the Stefan-Boltzmann constant ρ, that the average temperature of the outer surfaces of indoor heat source equipment and personnel O_{WB}, that the average ambient temperature O_{GD}, that the average emissivity of the outer surfaces of the indoor heat source equipment and personnel φ_e, that the average emissivity of the indoor storage environment φ_R, and that the total indoor area covering the indoor heat source equipment and personnel X_R, then the radiant heat transfer between the indoor heat source equipment and personnel and the thermal environment of the warehouse can be calculated by the following equation:

$$W_S = \frac{X_{pgg\rho}\left(O_{WB}^4 - O_{GD}^4\right)}{\frac{1}{\phi_e} + \frac{X_{pgg}}{X_R}\left(\frac{1}{\phi_R} - 1\right)} \tag{3}$$

Since the indoor environment area of the warehouse is much larger than the surface area of the indoor heat source equipment and personnel, the second term in the denominator of Eq. (3) can be ignored. Considering that the unit surface area is generally used in the calculation of the heat dissipation from indoor heat source equipment and personnel, assuming that the surface area coefficient is represented by g_{dk}, and that the effective radiation area coefficient of indoor heat source equipment and personnel g_{pgg}, the equation to calculate the radiant heat transfer is given as follows:

$$W_S = \phi_e g_{dk} g_{pggf} \rho\left({O_{WB}}^4 - {O_{GD}}^4\right) \tag{4}$$

By calculation, there is:

$$W_S = 3.625\times10^{-8} g_{dk}\left(O_{WB}^4 - O_{GD}^4\right) \tag{5}$$

During the normal activities of intelligent logistics storage, the average radiant temperature of the indoor storage environment, and the temperatures of indoor heat source equipment and personnel do not vary greatly. In order to simplify the above calculation process, the linear radiant heat transfer coefficient is represented by f_s, the quartic temperature difference is replaced with the linear temperature difference, and the relationship between the indoor heat source equipment and personnel and the environment of the warehouse is represented by f_s, and then:

$$f_s = \phi_t g_{pgg} \rho \frac{\left({O_{WB}}^4 - O_{GD}^4\right)}{O_{WB} - O_{GD}} \tag{6}$$

Accordingly, there is:

$$W_S = f_s g_{dk}\left(O_{WB} - O_{GD}\right) \tag{7}$$

Based on the calculated radiant heat transfer, the total heat dissipation from indoor heat source equipment and personnel in the indoor storage environment can be further obtained through calculation.

Considering that there are differences in the thermal conductivity of different enclosure materials for intelligent logistics storage, and that there is usually a temperature difference between the two sides of the enclosure structure of an intelligent logistics warehouse, factors such as temperature difference, material thermal conductivity, and enclosure structure were all taken into account in this paper for the calculation of the flowing heat on both sides of the enclosure structure. The following formula shows the heat conduction equation for the enclosure structure of an intelligent logistics warehouse built based on Fourier's law and the law of energy conservation. Assuming that the heat flux density of the heat transferred per unit time is represented by w, that the thermal conductivity l, and that the temperature gradient at a certain point $\partial O/\partial A$, then:

$$w = -l\frac{\partial O}{\partial A} \tag{8}$$

Assuming that the heat inflow and outflow through the boundary and the heat generated by the enclosure structure of the warehouse are represented by W_I, W_O, and W_u respectively, the equation of the energy conservation law is given as follows:

$$\Delta P = W_I - W_O + W_u \tag{9}$$

If the heat flow per unit time is equivalent to the change in the internal energy of the warehouse enclosure structure, then:

$$\frac{dP}{do} = W_I - W_O + W_u \tag{10}$$

Suppose that the specific heat, density, volume, and calorific value per unit volume of the warehouse enclosure structure are represented by SH, σ, U, and w_u, respectively, and that the enclosure structure is made of only one single type of material with a volume of U, then its heat flow per unit time can be calculated by the following formula:

$$SH\sigma U\frac{dO}{do} = W_I - W_O + Uw_u \tag{11}$$

Assuming that any micro-element of the target object in the intelligent logistics storage space is represented by *da-db-dc*, to achieve heat balance of the micro-element of the target object within the time interval of $\triangle o(r)$ in the Cartesian coordinate system, based on the law of energy conservation, there is the following equation:

$$\begin{aligned}&\sigma SH\Delta O dadbda = \\ &\left(w_a dbdc + w_b dbdc + w_c dbda\right)\Delta o - \\ &\left(w_{a+da} dbdc + w_{b+db} dbdc + w_{c+dc} dbda\right)\Delta o \\ &+ w_b dadbdc\Delta o\end{aligned} \tag{12}$$

Let $\beta=l/(\sigma SH)$. With Fourier's law introduced, the heat conduction equation is given as follows under the conditions that $\triangle o \to 0$ and that l is a constant:

$$\frac{\partial O}{\partial o} = \beta\left(\frac{\partial^2 O}{\partial a^2} + \frac{\partial^2 O}{\partial b^2} + \frac{\partial^2 O}{\partial c^2}\right) + \frac{w_u}{\sigma SH} \tag{13}$$

When the temperature difference by default is the only factor affecting the heat transfer of the air inside the intelligent logistics storage space, then it can be deemed that the air temperature change in the storage space is caused by natural convection. At this time, the air temperatures at different positions inside the storage space can be calculated. Under natural convection of the air in the warehouse, its density can be regarded as a function of temperature, where temperature is the independent variable. Based on Archimedes' principle, the buoyancy of the air fluid per unit volume in the warehouse can be calculated as follows:

$$\left(\sigma\left(O_p\right) - \sigma\left(O\right)\right)h = \sigma\left(O_o\right)h\gamma\left(O - O_p\right) \tag{14}$$

Ideally, the air satisfies

$$\gamma = \frac{1}{O_p + 273} \tag{15}$$

Substitute Eq. (14) and (15) into the momentum equation, and there is the basic temperature control equation under the condition of natural air convection in the indoor storage space:

$$\frac{\partial v}{\partial a} + \frac{\partial u}{\partial b} = 0 \tag{16}$$

$$v\frac{\partial v}{\partial a} + u\frac{\partial u}{\partial b} = \alpha\frac{\partial^2 v}{\partial b^2} + h\gamma\left(O - O_p\right) \tag{17}$$

$$v\frac{\partial O}{\partial a} + u\frac{\partial O}{\partial b} = \beta\frac{\partial^2 O}{\partial b^2} \tag{18}$$

3. THERMAL ENVIRONMENT EVALUATION OF INTELLIGENT LOGISTICS STORAGE SPACE

Figure 5 shows the specific research framework for the thermal environment evaluation of storage space conducted in this paper. In order to explore the changes in the indoor thermal environment of storage space under different intelligent logistics warehousing activities, the predicted average number of votes was selected as the main evaluation indicator. This indicator fully considers the energy metabolism rate of indoor heat source equipment and personnel, the mechanical work done by indoor heat source equipment and personnel, the air temperature, partial pressure of water vapor and air velocity in the warehouse, the average radiation temperature of indoor heat source equipment and personnel, and the thermal resistance of the outer surfaces of indoor heat source equipment and personnel, etc.

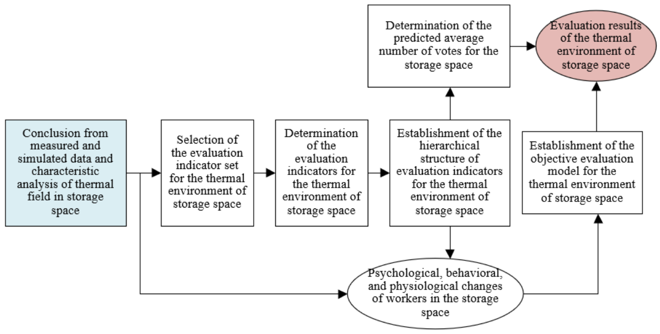

Figure 5. Research framework for the thermal environment evaluation of storage space

Assuming that the energy metabolism rate of the indoor heat source equipment and personnel is represented by N, that the mechanical work done by the indoor heat source equipment and personnel Q, that the partial pressure of water vapor E_x, that the ratio of the outer surface area of the indoor heat source equipment and personnel to the exposed outer surface thereof $f_{cl}g_{dk}$, that the outer surface temperature o_{dk}, that the convective heat transfer coefficient f_d, that the indoor air temperature o_x, that the average radiation temperature o_n, that the thermal resistance of the outer surface I_{dk}, and that the air velocity u, then the predicted average number of votes is calculated as follows:

$$\begin{aligned}&ENU = \left(0.303p^{-0.036N} + 0.028\right) \\ &\{N - Q - 3.05\times10^{-3} \\ &\left[5733 - 6.99\left(N-Q\right) - T_x\right] \\ &-0.42\left[\left(N-U\right) - 58.15\right] \\ &-1.7\times10^{-5}N\left(5867 - E_x\right) \\ &-0.0014N\left(34 - o_x\right) \\ &-3.96\times10^{-8}g_{dk}\left[\left(o_{dk}+273\right)^4\right. \\ &\left.-\left(o_n+273\right)^4\right] - g_{dk}f_d\left(o_{dk}-o_x\right)\}\end{aligned} \tag{19}$$

where,

$$\begin{aligned}&o_{dk} = 35.7 - 0.028\left(N-Q\right) \\ &-I_{dk}\{3.96\times10^{-8}g_{dk}\times\left[\left(o_{dk}+273\right)^4\right. \\ &\left.-\left(o_n+273\right)^4\right] - g_{dk}f_d\left(o_{dk}-o_x\right)\}\end{aligned} \tag{20}$$

$$\begin{aligned}&When\ 2.38\left(o_{dk}-o_x\right)^{0.25} > 12.1\sqrt{u}, \\ &f_d = 2.38\left(o_{dk}-o_x\right)^{0.25} \\ &When\ 2.38\left(o_{dk}-o_x\right)^{0.25} < 12.1\sqrt{u}, \\ &f_d = 12.1\sqrt{u}\end{aligned} \tag{21}$$

$$\begin{aligned}&When\ I_{dk} \le 0.078m^2 \cdot {}^oC/W,\\&g_{dk} = 1.00 + 1.290 I_{dk}\\&When\ I_{dk} > 0.078m^2 \cdot {}^oC/W,\\&g_{dk} = 1.05 + 0.645 I_{dk}\end{aligned} \tag{22}$$

The thermal environment is defined as the indoor environment characteristic of the warehouse that affects the heat dissipation from the heat source equipment and personnel in the intelligent logistics storage space, and the logistics warehousing operation temperature, vertical temperature difference of the storage space, air velocity inside the storage space, humidity of the storage space, the floor temperature of the warehouse, and the drift or ramp of the temperature inside the storage space, etc. are defined as the indicators of the thermal environment acceptable to the internal heat source equipment and personnel. In particular, the drift or ramp of the temperature inside the storage space refers to the maximum value of the change in the logistics warehousing operation temperature during different time periods.

The logistics warehousing operation temperature reflects the combined effect of the air temperature and average radiant temperature in the storage space on the indoor heat source equipment and the thermal sensation of the indoor personnel. Assuming that the logistics warehousing operation temperature is represented by o_0, that the average radiation temperature o_s, that the air temperature o_x, that the radiant heat transfer coefficient f_s, and that the convective heat transfer coefficient f_x, then there is the following calculation formula:

$$o_0 = \frac{f_s o_s + f_d o_x}{f_s + f_d} \tag{23}$$

The subjective feeling of indoor personnel is also an important aspect of the objective evaluation on the thermal environment of the logistics warehouse. This paper chooses an adaptive model that considers the psychological, behavioral, and physiological factors of the workers in the storage space as the objective evaluation model for the thermal environment of the logistics warehouse, which takes neutral temperature as the evaluation criterion. Assuming that the thermal neutral temperature that makes the indoor workers feel comfortable in the logistics warehouse is represented by o_{SU}, and that the monthly average outdoor temperature of the warehouse $o_{x.LP}$, there is the following equation:

$$o_{SU} = 0.31 o_{x,LP} + 17.8 \tag{24}$$

4. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 6 compares the temperatures at different measuring points in the intelligent logistics storage space. It can be seen that the temperatures at the 5 measuring points, namely 1-1, 2-1, 3-1, 4-1, and 5-1, exhibited a similar general trend - rising from 8:30 to 14:00 and reaching the highest value around 14:00, and then slowly decreasing from 14:00 to 17:30.

Table 1 lists the specific average temperature at each measuring point in the intelligent logistics storage space. It can be seen that the temperatures obtained at measuring point 1-1 were higher than those at measuring points 3-1 and 2-1, and that the lowest average temperature appeared at measuring point 5-1. Per analysis, the enclosure structure on the south side of the logistics storage space received strong solar radiation throughout the day, so the average temperatures at measuring points 1-1 and 3-1 on the south side rose fast and dropped slowly.

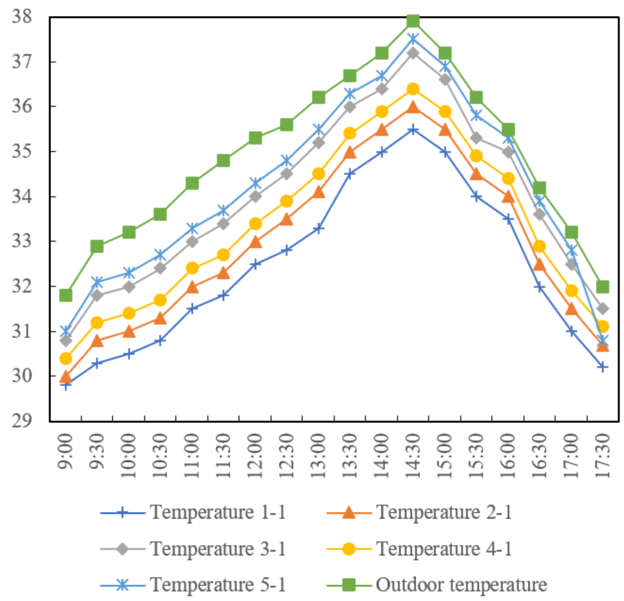

Figure 6. Comparison of temperatures at different measuring points in the intelligent logistics storage space

Table 1. Average temperature at each measuring point (MP) in the intelligent logistics storage space

Time	MP 1	MP 2	MP 3	MP 4	MP 5
9:00-10:00	32.52	37.42	36.19	25.19	37.42
10:00-11:00	36.97	39.18	33.52	37.42	39.61
11:00-12:00	31.24	31.26	37.46	31.29	30.58
12:00-13:00	39.61	35.29	39.02	35.61	32.46
13:00-14:00	38.57	37.46	37.42	37.58	39.27
14:00-15:00	30.69	39.15	31.26	30.62	36.29
15:00-16:00	34.61	32.68	39.42	39.26	31.42
16:00-17:00	38.42	37.74	31.05	37.24	38.62
17:00-17:30	39.64	31.59	39.26	30.58	34.07

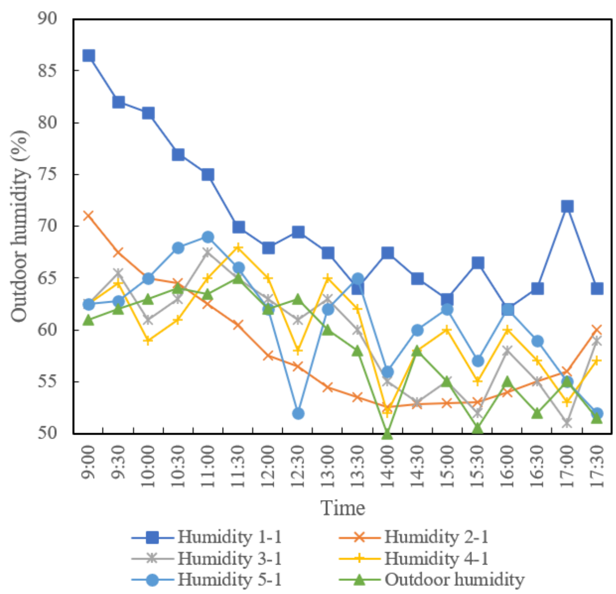

Figure 7. Comparison of humidity at different measuring points in the intelligent logistics storage space

Figure 7 compares the humidity obtained at different measuring points in the intelligent logistics storage space. The humidity obtained at the 5 points also exhibited a similar general trend – decreasing slowly from 87% to about 63% during the period from 8:30 to 14:00. The humidity at measuring points 2-1 and 5-1 was relatively high, mainly because there was less cargo stacked near the two measuring points, which are close to the middle of the aisle between the shelves in the logistics storage space. Around 14:00 in the afternoon, the humidity in the logistics storage space was the lowest overall, reaching about 53%. From 14:00 to 17:30 in the evening, the humidity at measuring point 2-1 showed a slow upward trend, from 53% to about 59%. The main reason lied in the indoor temperature drop of the logistics storage space.

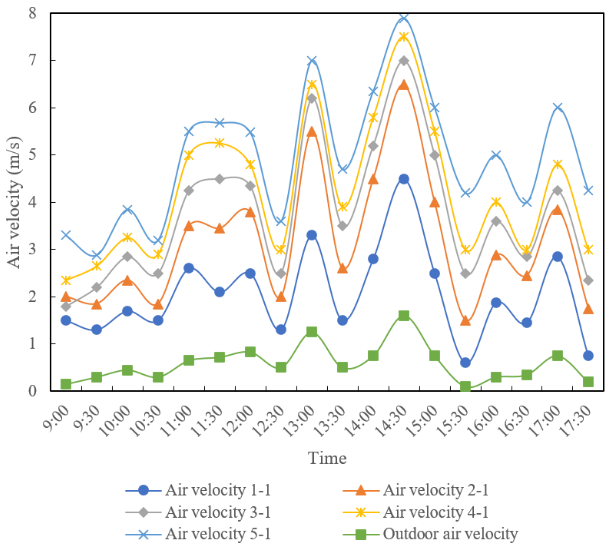

Figure 8. Comparison of air velocity at different measuring points in the intelligent logistics storage space

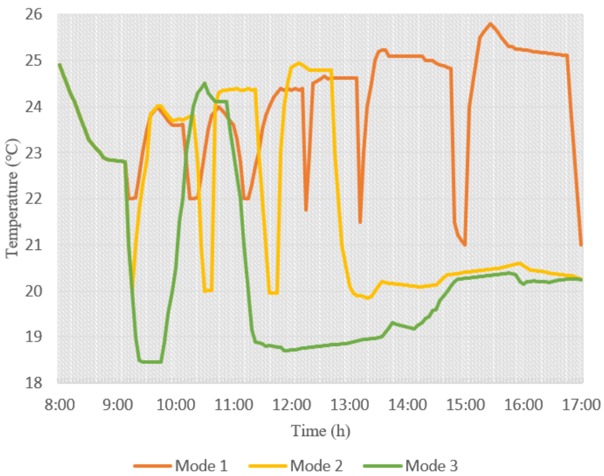

Figure 9. Average indoor air temperature of the storage space under different operating modes

Figure 8 compares the air velocity at different measuring points in the intelligent logistics storage space. The air velocity measured at the 5 points exhibited a similar trend. When the outdoor air velocity was low, the air velocity at measuring points 5-1 and 4-1 was relatively high, and the lowest appeared at measuring point 1-1. The main reason is that the logistics storage space was almost fully closed, with few windows, and that the main vent was only the warehouse door, which was quite far from measuring point 1-1, resulting in the extremely low air velocity.

In order to obtain the analysis results of the thermal field in the intelligent logistics storage space and accurate thermal environment evaluation results, comparative experiments were conducted under different operating modes in this paper. There were 3 operating modes, namely mode 1: when the average indoor air temperature of the storage space was lower than 25°C, the velocity of the air supplied by the cooling fan was set at 0m/s; when the indoor temperature was stable, and the indoor average air temperature was greater than 25°C, the velocity of the air supplied by the cooling fan was set at 0.5m/s; mode 2: when the average indoor air temperature of the storage space was lower than 30°C, the velocity of the air supplied by the cooling fan was set at 0.5m/s; when the indoor temperature was stable, and the average indoor air temperature was greater than 30°C, the velocity of the air supplied by the cooling fan was set at 1.0m/s; mode 3: when the average indoor air temperature of the storage space was lower than 35°C, the velocity of the air supplied by the cooling fan was set at 1.0m/s; and when the indoor temperature was stable, and the average indoor air temperature was greater than 35°C, the velocity of the air supplied by the cooling fan was set at 2.0m/s.

The average air temperature and air velocity in the storage space under different operating modes were compared and analyzed, with the experimental results shown in Figures 9 and 10. From the simulation results in Figure 9, it can be seen that the three operating modes could well meet the requirements of the indoor thermal environment of the storage space. When the outdoor air temperature rose from 25°C to 30°C, workers in the storage space would feel less comfortable in the early stage of mode 1 and the late stage of mode 3, while in mode 2, the average indoor air temperature was maintained at 25°C ±2°C during the working hours, which could keep the workers thermally comfortable in the storage space.

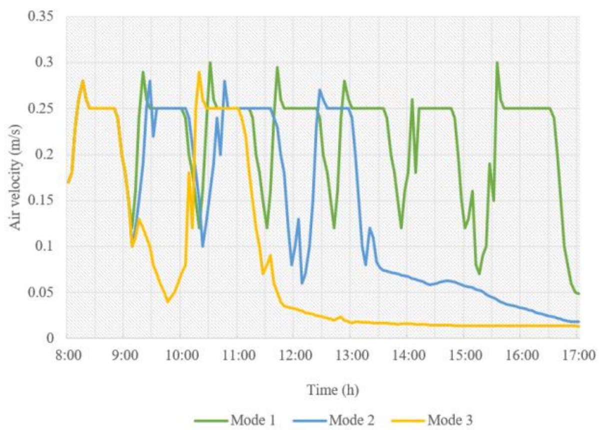

Figure 10. Effects of different operating modes on the air velocity measured

From the simulation results in Figure 10, it can be seen that before and after the cooling fan was turned on, the air velocity within 10 cm above the ground during the operation of mode 1 and mode 2 was both less than 0.25m/s, which basically met the requirements of thermal comfort, while the air velocity within 10cm above the ground exceeded 0.35m/s during the operation of mode 3, which would bring a draft sensation to the indoor workers, affecting their comfort.

In summer, workers working in the thermal environment of the intelligent logistics storage space usually feel thermally uncomfortable. In view of the situation where the outdoor temperature is higher than 35℃ and most of the storage space is closed and poorly ventilated, it is recommended more vents be added at locations far from the warehouse door, so as to improve the indoor thermal environment of the storage space through natural ventilation.

5. CONCLUSIONS

This paper studies the thermal field characteristics and evaluation methods of intelligent logistics storage space. Based on the 5 characteristic factors of thermal environment, the derivation process of the principle of heat transfer in the thermal field of the intelligent logistics storage space was demonstrated. A specific research framework for evaluating the thermal environment of storage space was proposed, and the predicted average number of votes was selected as the main evaluation indiocator. Also, an adaptive model considering factors such as psychology, behavior, and physiology of the workers in the storage space was constructed. Through experiments, the temperature, humidity and air velocity at different measuring points in the intelligent logistics storage space were compared, and the analysis results were given. The average air temperature and air velocity in the storage space under different operating modes were also compared and analyzed, with the thermal environment analysis results given and the corresponding optimization scheme proposed.

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