3D Transient CFD Modelling of a Museum Showcase with Environmental Air Exchange

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Keywords: CFD, Transient Analysis, Museum Showcase, Air Exchange Rate.

Abstract: A 3D transient CFD model is established to characterize heat and mass transfer phenomena in a museum showcase with environmental air exchange in Chongqing China Three Gorges Museum. The model is able to give detailed information about air temperature and velocity distributions in the showcase at different time points during the periods investigated. In order to evaluate the model's accuracy, experiments are performed in two typical days in summer and winter, while the temperature variation data is collected. The model is validated with the experimental data and shows satisfactory accuracy with average deviation within 0.1°C. A numerical method to calculate air exchange rate (AER) of museum showcases with environmental air exchange is proposed for as an application of this model. The method simulates the carbon dioxide tracer dilution process in the showcase, and the simulated tracer concentration curves are used to calculate the air exchange rate of the showcase successfully. Calculation results in both cases show that AERs increase with environmental temperature. This work proves CFD to be a powerful tool in the modelling of museum showcases.

1 INTRODUCTION

Preventive conservation is a significant methodology for long-term preservation of cultural heritage(Getty Institute, 1994). The key thought of preventive conservation is to protect cultural heritage from the environmental risks(Kissel, 1999). Environmental risks are determined by parameters including air quality, temperature and humidity, so monitoring and controlling of these parameters are significant tasks of preventive conservation(Ankersmit & Stappers, 2017). Museum showcases are significant preserving and displaying facilities for the cultural heritage in museums, so the effects of showcases on the preserving environmental parameters should be carefully evaluated, which makes a performance model for the showcases significant. A parametric model has been proposed to characterize air exchange performance of museum showcases with a single parameter, i.e. air exchange rate (AER)(Thomson, 1977). However, the one-parameter model is not enough to give detailed description of the coupled air flow, heat transfer and mass transfer phenomena in 3D space. Recently, researchers started to apply computational fluid dynamics (CFD) to the modelling of museum showcases. CFD can visualize in detail the physical process occurring in the museum showcases, thus can help with their design and optimization(Liu et al., 2008; Wang et al., 2013.).

CFD is a type of computer aided engineering tool capable of describing fluid flow, heat transfer and mass transfer processes. It is widely used in various fields such as aerospace, automotive and building ventilation(Peng et al., 2016; Xia et al., 2010; Yi et al., 2021). Some researchers attempted to apply CFD methods to the field of cultural heritage preservation, especially the preservation of some historic buildings(Balocco et al., 2014; D'Agostino et al., 2014; D'Agostino & Congedo, 2014; Oetelaar, 2016; Pasquarella et al., 2013). For example, D'Agostino et al. applied CFD to describe the airflow and salt crystallization process in a historical church in Italy(D'Agostino et al., 2014; D'Agostino & Congedo, 2014). Oetelaar applied CFD to simulate the thermal environment inside a set of ancient Roman baths(Oetelaar, 2016). Balocco et al. applied

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CFD to simulate the heat and moisture transfer process in a historical library room with people movements considered(Balocco et al., 2014; Pasquarella et al., 2013). Nevertheless, only a few studies applied CFD to the modeling and analysis of museum showcases. Wang(Wang et al., n.d.) applied CFD to simulate the air temperature and flow velocity distributions in two showcases with lamps as heat sources. Different air exchange flowrates were imposed to investigate the effects, while the heat transfer between the showcases and the environment was not taken into account. Liu(Liu et al., 2008) built a 2D CFD model to simulate the heat transfer between the showcase and the environment under summer and winter conditions. Constant environment temperatures were imposed in the model, while real-time temperature variation during the days was not taken into account.

Although the studies above applied CFD to model museum showcases, they all adopted major simplifications to the models which limited scope of the models' applications. The modelling method could be further improved if the following two aspects are taken into account. Firstly, real-time transient temperature variation needs to be imposed to the model, so that the simulation results are comparable to the experimental data, which makes the experimental validation of the model possible. Secondly, the coupled air flow, heat transfer and mass transfer process needs to be taken into account for the museum showcases as well as the environment. With the points above taken into account, this work is dedicated to build and validate a 3D transient CFD model for a museum showcase with varied environmental temperature imposed, while the air exchange between the showcase and environment is modelled simultaneously.

To be specific, the following key points are discussed in this paper:

1) The 3D CFD model with transient environmental conditions is established for a museum showcase with environmental air exchange.

2) Experiments are performed for the showcase in two typical days in summer and winter.

3) The model is validated with the experimental temperature data and the accuracy is evaluated.

4) The validated model is applied to calculate the air exchange rate of the showcase in summer and winter.

2 EXPERIMENTAL SETUP

2.1 The Showcase

The museum showcase investigated is located in the Chongqing China Three Gorges Museum, and is shown in Figure 1(a). The showcase consists of three parts: the upper part which is an aluminium box with a set of lamps installed, the middle part made of glass in which the artifacts are preserved and displayed, and the bottom part made of aluminium sheet which acts as base of the showcase. A wooden table is placed in the middle part on which the artifacts are displayed. It should be noted that there are 18 openings and two gaps at bottom of the middle part as shown in Figure 1(b). The showcase is well sealed except for the openings and gaps mentioned above which connect the air inside to the environment. There is no individual temperature control and ventilation system for this showcase, so the temperature distribution inside is indirectly determined by surrounding environment.

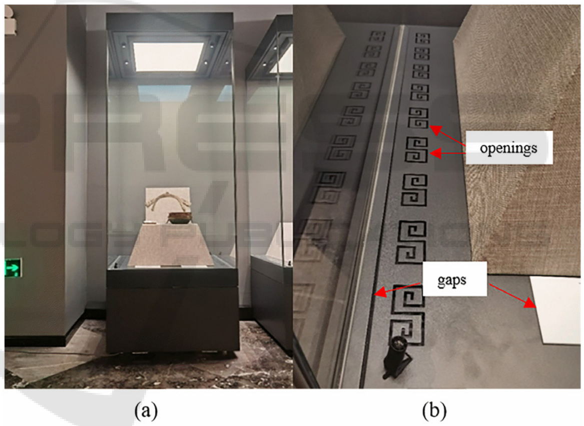


Figure 1: The museum showcase: (a) Overall structure; (b) Openings and gaps in the middle part.

2.2 Monitoring Device

The monitoring device in this work consists of seven Testo 160TH sensors which can measure and record parameters including temperature and humidity. One sensor (sensor A in Figure 2) is placed inside the showcase to measure the temperature inside. The other six sensors (sensors B, C, D, E, F, and G in Figure 2) are placed outside the showcase to record the environmental temperature. The temperatures are recorded every 1 minute for sensor A and every 15 minutes for the other six sensors.

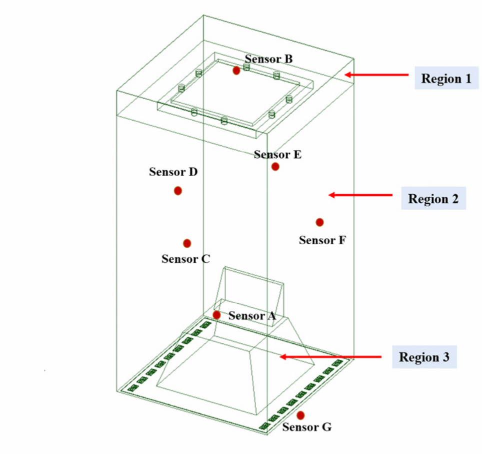


Figure 2: Geometry of the model and the sensor placement.

3 NUMERICAL METHOD

3.1 Geometry

The upper part and middle part of the showcase are chosen as the computational domain. As shown in Figure 2, the 3D geometry is 0.9m in length, 0.9m in width and 1.8m in height, which are in line with actual dimensions. Three fluid regions are created for air flow in this computational domain as shown in Figure 2: one for the upper part of the showcase (Region 1), one for the wooden table (Region 2) and one for the middle part of the showcase (Region 3). There is no direct mass transfer between the three fluid regions, but the former two regions effect heat transfer process in the showcase, thus they need to be taken into account in this model, even though Region 2 is of our most concern. It should be noted that only region 2 connects to the environment through the openings and gaps mentioned previously. Solid regions in the showcase model are defined to be solid materials including aluminium, glass and wood to take into account their effects on heat and mass transfer.

3.2 Physical Models

The coupled air flow, heat transfer and mass transfer process in the model is calculated according to the following physical models.

Continuity equation:

$$\frac{D\rho}{Dt} + \rho\left(\nabla \cdot \vec{V}\right) = 0 \tag{1}$$

Momentum conservation equation, expressed by the Navier-Stokes equation:

$$\frac{D\vec{V}}{Dt} = \vec{f_b} - \frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2\vec{V} \tag{2}$$

Energy conservation equation:

$$\rho\frac{D}{Dt}\left(\hat{u} + \frac{V^2}{2}\right) = \rho\vec{f_b}\cdot\vec{V} + \nabla\cdot\left(\vec{V}\cdot\tau_{ij}\right) + \nabla(\lambda\nabla T) \tag{3}$$

where t is time, ρ is air density, $\vec{V}$ is velocity vector, $\vec{f_b}$ is volume force, p is pressure, μ is dynamic viscosity, $\hat{u}$ is internal energy, τ_{ij} is surface stress components, λ is thermal conductivity, T is temperature.

The standard $k-\varepsilon$ model is used to model turbulent flow, where turbulence kinetic energy (k) and its rate of dissipation (ε) can be obtained from the following equations:

$$\frac{Dk}{Dt} = P_k + G_k + D_k - \varepsilon \tag{4}$$

$$\frac{D\varepsilon}{Dt} = \frac{\varepsilon}{k}\left(C_{\varepsilon 1}P_k + C_{\varepsilon 3}G_k - C_{\varepsilon 2}\varepsilon\right) + D_\varepsilon \tag{5}$$

where P_k is the production term of k caused by average speed gradient, G_k is the production term of k caused by buoyancy, D_k is the diffusion term caused by k, D_ε is the diffusion term caused by ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ and $C_{\varepsilon 3}$ are model constants with values of 1.44, 1.92, and 0.09 respectively.

The one-dimension heat transfer equation is used to describe the heat transfer process in the solid regions with small thickness made of glass, aluminium and wood:

$$q = -\lambda\frac{dT}{dx} \tag{6}$$

where q is heat flux density, λ is thermal conductivity coefficient for certain material.

The thermal conductivity coefficients of the materials used in this model are listed in Table 1.

Table 1: Physical parameters of the materials in the model.

Name	Density(kg /m^3)	Specific Heat(J/kg ·K)	Thermal conductivity coefficients(W/ m· K)
Aluminium	2719	871	202.4
Glass	2500	840	0.77
Wood	200	50	0.05

3.3 Numerical Model Settings

As shown in Figure 3, the simulation mesh in CFD is generated based on the geometry mentioned above. Hexahedral and tetrahedral cells are applied and the total number of cells is 967873. The mesh is refined at the openings and gaps in order to improve robustness of the model. Temperature type boundary conditions are applied to the aluminium sheet and glass, while pressure-outlet type boundary conditions are applied to the openings and gaps in the model. Various environmental temperature is compiled into UDF (User-Defined-Function) files, which are adopted to the boundaries mentioned above. Thermal effects of glass in the showcase are taken into account with the shell model, in which the glass thickness, thermal conductivity coefficient and convective heat transfer coefficient with environment can be defined. Thermal effects of the wooden and aluminium sheet inside the showcase are taken into account with the wall thickness model on interfaces between the fluid regions. The coupled air flow, heat transfer and mass transfer process in the model is calculated according to the following physical models.

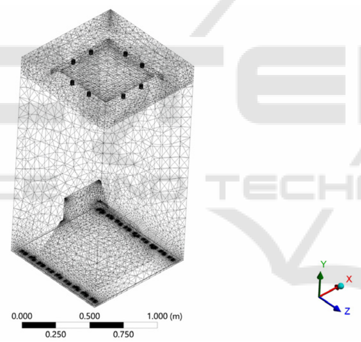
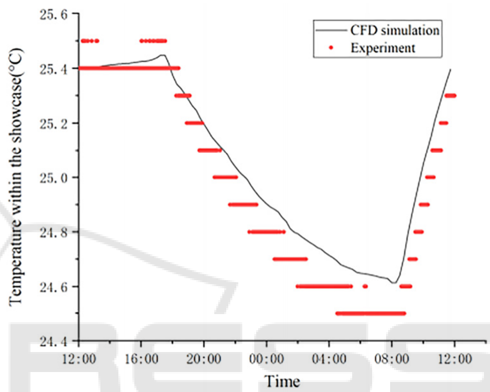


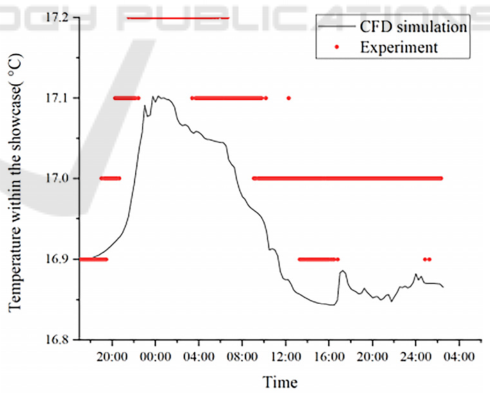
Figure 3: 3D Mesh for the simulation model.

4 EXPERIMENTAL VALIDATION

In order to validate the CFD model established, two sets of experiments are performed in two typical days in summer and winter, i.e., 14th August 2021 and 20th February 2022. The temperature data recorded by sensors outside the showcase are adopted in the UDFs as boundary conditions for the CFD model, so that the air flow and temperature distribution inside the showcase can be simulated. The measured and simulated temperatures in summer and winter are shown in Figure 4 as red points and black curves respectively. The data recorded by sensor A shows that the temperature decreases from 25.4 °C to 24.6 °C and then increases to 25.6 °C in summer, due to the environmental temperature variation. In the winter case, the temperature recorded by sensor A increases from 16.9 °C to 17.2 °C and then decreases to 16.9 °C. The measured temperature is compared with the simulated temperature, so that prediction accuracy of the model can be evaluated. The comparisons show that the CFD model can predict the temperature variation inside the showcase with satisfactory accuracy in both cases. In the summer case, the average and maximum deviations between measured and simulated temperatures are 0.09 °C and 0.20 °C, respectively. In the winter case, the average and maximum deviations between measured and simulated temperatures are 0.06 °C and 0.10 °C, respectively.



(a)



(b)

Figure 4: Experimental and simulated temperatures inside the showcase: (a) The summer case; (b) The winter case.

In the validation process mentioned above, the model gives detailed information about the temperature and air flow distributions inside the showcase simultaneously, and some examples are given and discussed as follows. Two planes, i.e., plane 1 and plane 2 in Figure 5, are created to visualize the temperature distribution.

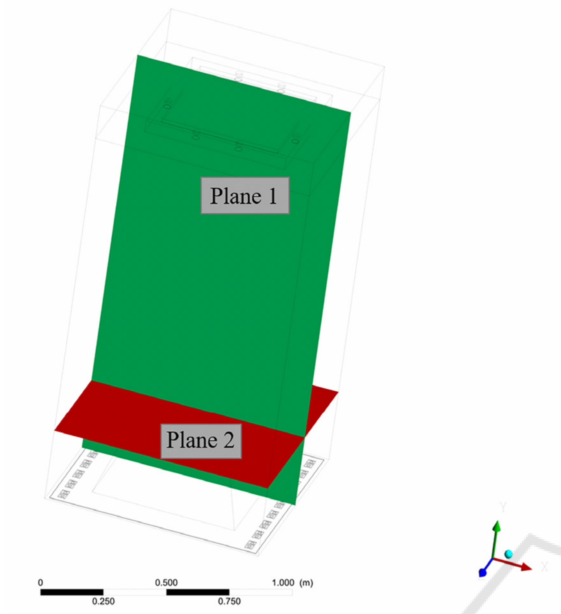


Figure 5: Planes for temperature visualization in the model.

Figure 6 shows the temperature distribution at a time point in the simulation case in summer. At 12:00 of the day, the environmental temperature is higher than the temperature inside the showcase, thus the air inside is heated up. There are three ways of heat transfer into the showcase in this case as follows. Firstly, environmental air with relatively higher temperature enters the showcase through the openings and gaps, causing a temperature rise around these areas. Secondly, heat transfers from the environment into Region 1 through the aluminum sheet enclosing this region. Due to the higher thermal conductivity of aluminum sheet than glass, the air temperature in Region 1 is relatively higher than that in Region 2, which leads to the heat transfer from Region 1 to Region 2 through the aluminum sheet between them. Thirdly, heat transfers from the environment into the showcase through glass and the bottom aluminum sheet of Region 2.

The air in Region 2 has pretty uniform distribution, which can be explained by the fact that the convective heat transfer caused by the air flow circulation inside this region (as shown in Figure7) is of much higher intensity than the heat transfer into this region caused by the three ways mentioned above.

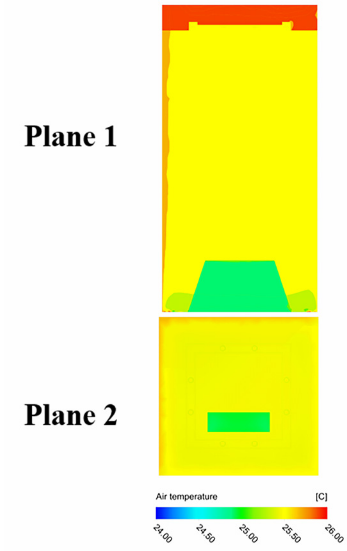


Figure 6: The temperature distribution at 12:00 in the summer case.

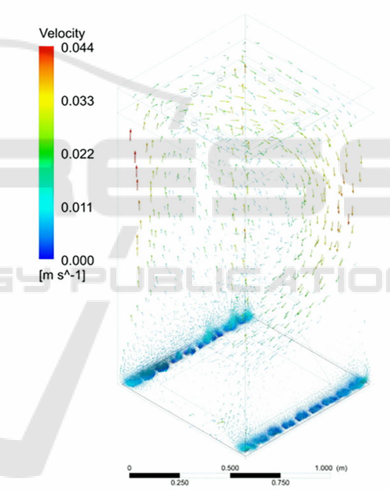


Figure 7: The air flow distribution at 12:00 in the summer case.

Figure 7 shows the air flow distribution in the showcase at a time point in the simulation case in summer. At 12:00 of the day, air in the environment enters and mixes with the air inside the showcase around the openings and gaps, so intense air flow and temperature gradient form around these areas. The temperature gradient leads to natural convection of air, thus a convective air circulation inside the showcase, which transfers heat simultaneously. In this way, a coupled mass and heat transfer process is formed.

5 AIR EXCHANGE RATE ANALYSIS

The CFD model established and validated characterizes the coupled heat and mass transfer process, so it is capable of evaluating air tightness performance of the showcase with numerical calculation. In order to characterize the air exchange process between the showcase and the environment, the carbon dioxide (CO_2) tracer gas dilution method(Xu et al., 2012) is simulated in this work. In the CFD model, the initial CO_2 concentration in Region 2 is set to be a value higher than the environment. As air enters and exits through the gaps and openings, the CO_2 in Region 2 is continuously diluted. Figure 8 shows CO_2 concentration distributions at different time points during the simulation case in summer. As shown in Figure 8(a), the CO_2 concentration in Region 2 decreases with time, and is distributed uniformly at a certain time point, which can be explained by the air circulation inside the showcase. Figure 8(b) shows the non-uniform CO_2 concentration distribution around the openings, and the CO_2 concentration is lower than the rest part of Region 2, which can be explained by the process of air exchange with different CO_2 concentrations.

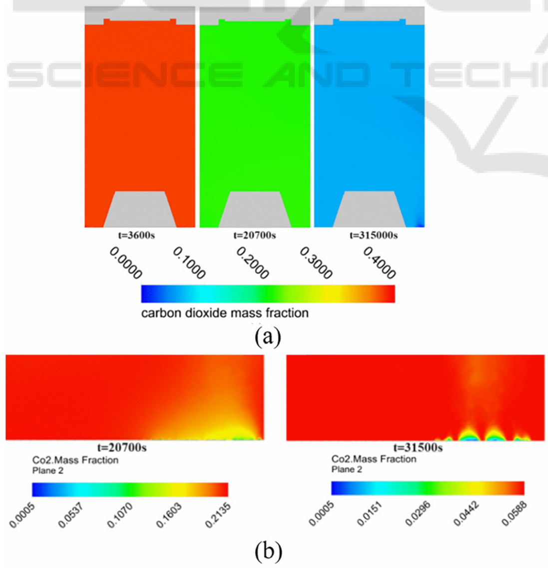


Figure 8: CO_2 concentration distributions: (a) On plane 1; (b) Around the openings.

To characterize the CO_2 dilution process, the CO_2 concentration evolution data points are plotted with time as black squares for the summer case and the winter case in Figure 9. As shown in Figure 9, the CO_2 concentration decreases with time in both cases, while an exponential relationship can be observed, which means the rate of dilution decreases with time. This phenomenon can be explained by the constant and low environmental CO_2 concentration, which leads to a decreasing CO_2 concentration difference between the showcase and the environment, i.e., the driving force for the CO_2 dilution process.

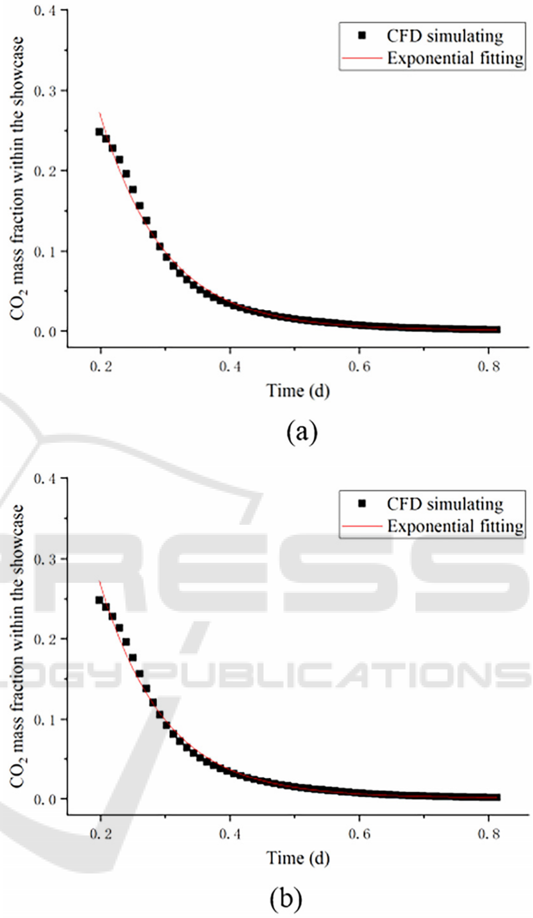


Figure 9: Simulated CO_2 concentration data and fitting curves: (a) In the summer case; (b) In the winter case.

Air exchange rate is the parameter used in the one-parameter model proposed in previous publications to evaluate air tightness performance of a showcase(Brimblecombe & Ramer, 1983; Calver et al., 2005). With the data shown in Figure 9, this parameter can be calculated and compared for the both cases. Schematic diagram for the one-parameter air exchange model is shown in Figure 10. Thought of the one-parameter model is to assume that the air exchange rate is a constant, while the air inside the showcase is well mixed during the time period investigated. Given the initial CO_2 concentration in the showcase and the environmental CO_2 concentration, the air exchange rate of the showcase can be calculated, and the calculation process is illustrated as follows.

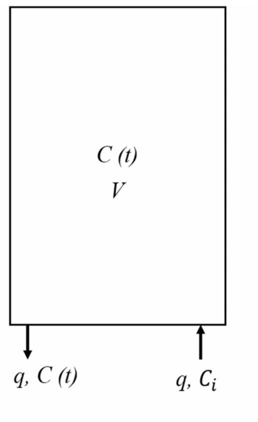


Figure 10: Schematic diagram for the one-parameter air exchange model of museum showcases.

The CO_2 dilution process in the showcase can be mathematically expressed by a differential equation in Eq. (7), with consideration of mass balance.

$$V\frac{dC(t)}{dt} = q \cdot C_i - q \cdot C(t) \tag{7}$$

where V is the volume of air inside the showcase, $C(t)$ is the average CO_2 concentration in the showcase at time t, C_i is the environmental CO_2 concentration, q is the volumetric air flow rate of the air exchange process.

Eq. (7) can be rewritten as:

$$\frac{dC(t)}{dt} = \frac{q \cdot C_i}{V} - \frac{q \cdot C(t)}{V} \tag{8}$$

For simplicity, let:

$$K_0 = \frac{q}{V} \text{ and } K_1 = \frac{q \cdot C_i}{V} \tag{9}$$

Substituting Eq. (9) into Eq. (8) gives:

$$\frac{dC(t)}{dt} = K_1 - K_0 \cdot C(t) \tag{10}$$

Integrating Eq. (10) gives:

$$\int_{C_0}^{C(t)} \frac{dC(t)}{K_1 - K_0C(t)} = \int_0^t dt \tag{11}$$

where C_0 is the initial CO_2 concentration in the showcase when $t = 0$

Thus,

$$\frac{K_1 - K_0C(t)}{K_1 - K_0C_0} = e^{-K_0t} \tag{12}$$

Rearranging Eq. (12) leads to:

$$K_1 - K_0C(t) = (K_1 - K_0C_0)e^{-K_0t} \tag{13}$$

and:

$$C(t) = \frac{K_1}{K_0} - \left(\frac{K_1}{K_0} - C_0\right)e^{-K_0t} \tag{14}$$

Substituting Eq. (9) into Eq. (14) gives the final equation, which describes the CO_2 dilution process as a function of time as Eq. (15):

$$(t) = C_i - (C_i - C_0)e^{-K_0t} \tag{15}$$

The exponential relationship between the CO_2 concentration and time agrees with the observation in Figure 7. K_0 represents the air exchange rate of the showcase with the unit of s^{-1}. AER can be calculated from K_0 with the unit transfer from s^{-1} to d^{-1}, since AER is defined to quantify the times of air exchange per day.

Regression calculations based on Eq. (15) are performed with the simulated CO_2 concentration evolution curves to get the parameters K_0 and AER, and the AERs calculated for both cases are listed in Tab. 2. As shown in Tab. 2, the AER in summer is higher than that in winter, which indicates that AER of the showcase increases with environmental temperature. The R^2 values are higher than 0.99 for both cases, which proves the model in Eq. (15) to reflect the CFD simulation data quite well.

Table 2: Regression results for air exchange rates of the showcase.

Condition	AER/d^{-1}	R^2
Summer	10.8	0.99857
Winter	10.0	0.99319

6 CONCLUSIONS

A 3D transient CFD model is established to characterize the coupled air flow, heat transfer and mass transfer phenomena in a museum showcase with environmental air exchange in Chongqing China

Three Gorges Museum, and the following points can be concluded:

(1) The CFD model is successfully established and can provide detailed information about the air flow velocity and temperature distributions in 3D space of the showcase at different time points during the simulated time period.
(2) The model is validated to have high prediction accuracy by comparing the simulated temperature inside the showcase with experimental data, and the average deviations are within 0.1°C.
(3) A novel numerical CO_2 tracer gas dilution method is proposed using the model established, and the air exchange rates of the showcase can be calculated with the method.
(4) The AER of this showcase is simulated to be 10.8 d-1 in summer and 10.0 d-1 in winter, indicating an increase of AER with environmental temperature.

The points above prove CFD to be a powerful tool to model a museum showcase with environmental air exchange, and future development of this methodology can be expected.

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