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Diffusion analysis of carbon dioxide released by egg respiration at different storage temperatures based on FLUENT

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Abstract

Temperature is an important factor affecting the changes in the amount of gas exchanged between eggs and the surrounding during storage. The effect of temperature changes on the release of carbon dioxide (CO_2) from eggs was studied using eggs from the same breed. The experimental samples were divided into three groups, and placed in a storage box at 4, 25, or 35°C with 65% relative humidity for 20 days, and a breathalyser was used to measure the amount of CO_2 released by the eggs. The FLUENT software was used to simulate the diffusion at different temperatures. The conclusion from the present work was that as the temperature decreased, the amount and speed of CO_2 released by the eggs also decreased. The simulation results show that the diffusion of CO_2 released by egg respiration can be divided into the following sequential stages: initial, descending, mixing, and turbulence. When the storage temperature was 4°C, the CO_2 cloud of eggs was the lowest, followed by 35°C, and finally 25°C. The results show that the direction of gas diffusion was mainly affected by temperature, diffusion volume, and diffusion velocity, and that temperature mainly affected vertical gas diffusion. The present work thus provides a theoretical basis for egg respiration related research.

Introduction

Egg freshness mainly depends on storage temperature and storage time (Jones and Musgrove, 2005; Samli *et al.,* 2005; Yuceer and Caner, 2014). The freshness period of egg gradually decreases with increasing temperatures which increase the egg's internal physiological activity, and accelerate the exchange of moisture, gas, and other substances with the external environment, thereby leading to the decrease in egg quality (Tabidi, 2011; Liu *et al.,* 2016; Yimenu *et al.,* 2018). The decrease in of egg quality is manifested by thin albumen, loss of moisture and carbon dioxide (CO_2), and increased protein pH (Hammershoj *et al.,* 2002). These parameters are more affected by storage temperature than by storage time. The increase in protein pH may be due to the loss of CO_2 from the egg (Özlü *et al.,* 2018). Hence, there is a close relationship between the amount of CO_2 released by the egg and the storage temperature (Jones *et al.,* 2002; Bhale *et al.,* 2003; Rocculi *et al.,* 2011). It has been demonstrated that during storage, higher temperatures accelerate CO_2 diffusion through the pores on the surface of the eggshell, thus resulting in an increase in the pH of egg (Banerjee and Keener, 2012). The conclusion drawn from some studies is that using cryogenic CO_2 cools eggshell in order to maintain egg quality and improve the functional properties of its ingredients (Keener *et al.,* 2000; Rocculi *et al.,* 2009). Therefore, storage temperature is the most important factor in studying CO_2 released by egg respiration.

With the development of fluid mechanics, researchers in food process engineering have applied inverse finite element methods to specifically analyse egg parameters (Conradi *et al.,* 2019; Shen *et al.,* 2020). Perianu *et al.* (2010) simulated both the dynamic characteristics of eggshell and the force of the fluid inside eggshell. Sellés *et al.* (2019) took advantages of finite element to describe the different stress patterns in several egg types, and analysed the stress on the eggshell in free fall impact. Fabbri *et al.* (2011) determined the amount of CO_2 diffusion in various egg parts such as thin and thick albumen, and yolk by using the finite element model. Nonetheless, studies concerning CO_2 diffusion released by egg by

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finite element methods are very few. In the present work, fresh Hy-Line eggs of the same breed were studied using a breathalyser to monitor the CO_2 release under different conditions. The present work used UG software to establish a three-dimensional model of egg and determine the fluid domain, ICEM CFD software for structural meshing, and FLUENT software to complete the emulation of the model. The emphasis in the analysis was on the CO_2 diffusion at different time points and the spread of the distribution of CO_2 released by the egg at different temperatures. The present work provides not only a theoretical basis for gas exchange between egg and external surrounding, but new ideas for related research on egg respiration.

Materials and methods

Test materials

The fresh Hy-Line pink hen eggs used in the present work were laid within 24 h, and supplied by Wuhan Jiufeng Chicken Farm. Around 210 eggs with clean eggshells were selected as test objects. The eggs were randomly divided into three groups, and stored in a box with constant temperature and humidity at 4, 25, or 35°C with 65% RH for 20 d. Ten eggs were taken from each group every day to measure the amount of CO_2 released.

Determination of the amount of carbon dioxide released by eggs

The amount of CO_2 released by the eggs was measured using a respiration apparatus for fruits and vegetables. The model of the respiration measurement equipment purchased was SY-1022, is shown in Figure 1.

Before the analysis, the end of the rubber tube that connected to the breathing chamber was placed in an open space for calibration for 21 min. When the calibration was completed, the end of the rubber tube was reconnected to the breathing chamber. Then the valve was opened while the flow meter recorded a constant flow rate of 1.5 L/min. After CO_2 level stabilised, the eggs were numbered, weighed (*M*), and placed into the 0.25 L breathing chamber which was securely sealed. The CO_2 level (C_0) and temperature (T_0) in the breathing chamber were recorded at this time. After 0.5 h measurement, the CO_2 level (*C*) and temperature (*T*) were recorded.

Setting of initial conditions

During storage, the amount of CO_2 released by the eggs declined gradually. The specific changes (on day 0) of CO_2 released by the eggs are illustrated in Figure 2. Within 1800 s, the amount of CO_2 increased with time, and the trend was nearly linear ($R^2 = 0.9538$). Therefore, the present work simulated the diffusion of CO_2 released by the eggs in 1800 s (on day 0).

The size of the breathing chamber used in this test was 0.25 L, and its molar concentration basis formula (R) was calculated using Eq. 1 (Wang *et al.*, 2021):

$$R = (m_i - m_0) \times \frac{M}{22.4} \times \frac{273}{273+T} \times \frac{Pa}{101.325} \quad \text{(Eq. 1)}$$

The quality flow (Q) was calculated using Eq. 2:

$$Q = \frac{R}{t} \times V \quad \text{(Eq. 2)}$$

The velocity (v) was calculated using Eq. 3:

$$v = \frac{Q}{r \times \tau \times \pi^2 \times \mathrm{a} \times \mathrm{b}} \quad \text{(Eq. 3)}$$

where, Q (g/s) = quality flow; t = diffusion time; V = volume of the closed device; and r = CO_2 density (standard CO_2 density is 1.977 g/L, and it changes with temperature and pressure); 'a' = short

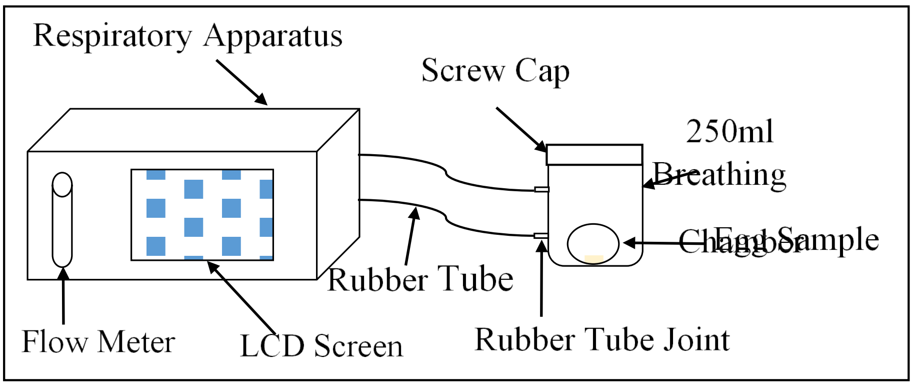

Figure 1. Respiration intensity measuring device.

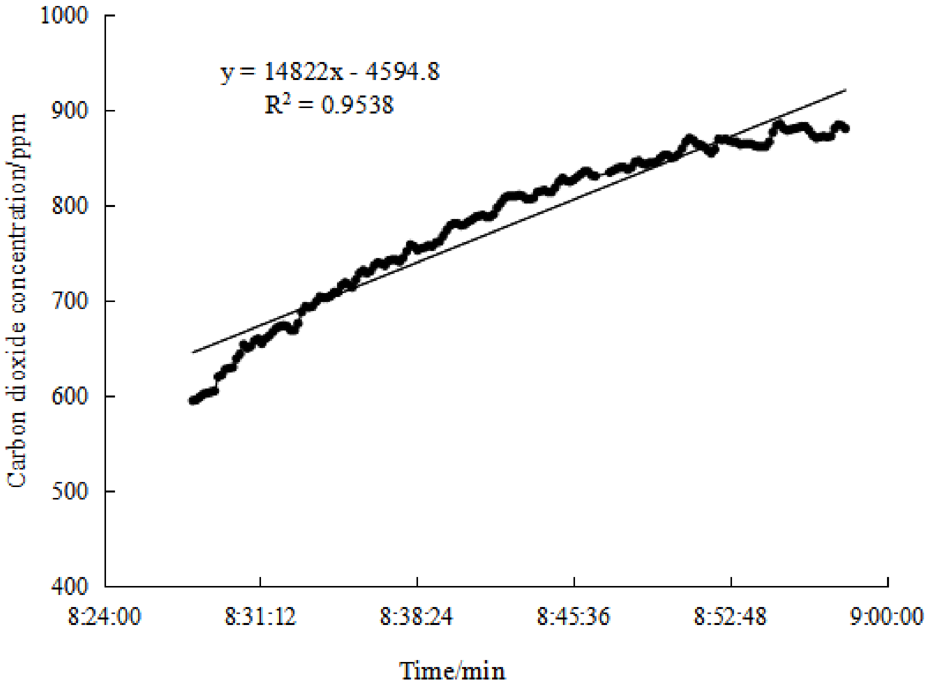

Figure 2. Amount of carbon dioxide released by eggs in 1800 s.

semi-axis; 'b' = long semi-axis; and = porosity (Wang *et al.,* 2018).

Model establishment and meshing

Egg long axis ranged from 53.29 to 60.42 mm. Egg short axis ranged from 41.27 to 44.6 mm. Egg shape index ranged from 1.25 to 1.36. A restricted space outside the egg was set in order to observe the process of CO_2 release from the eggs, which was a cuboid (126.43 × 108.66 × 108.66 mm). The fluid domain of the model was meshed hexahedral structurally by ICEM CFD software with no overlap in the divided meshes. The mesh quality was 0.7. The total number of divided grids was 431884, which met the calculation requirements.

The divided model was imported into Fluent 15.0 software. Then the corresponding parameters and boundary conditions were set according to the CFD theoretical method to numerically simulate the process of CO_2 released by the eggs.

Basic diffusion equations

The basic equations for CO_2 diffusion from eggs included a momentum equation, energy conservation equation, continuous equation, and component equation.

Continuous equation (Eq. 4):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \qquad \text{(Eq. 4)}$$

where, ρ= density of mixture; and u_j= speed in three directions of (x, y, z).

Momentum conservation equation (Eq. 5):

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(u\frac{\partial u_i}{\partial x_j}\right) + (\rho - \rho_a)g_i \qquad \text{(Eq. 5)}$$

where, μ= dynamic viscosity of fluid; g= acceleration of gravity; p= absolute pressure; and ρ_a= density of the air.

Energy conservation equation:

$$\frac{\partial(\rho T)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i T) = \frac{\partial}{\partial x_j}\left(\frac{k}{c_p}\frac{\partial T}{\partial x_j}\right) + S_T \qquad \text{(Eq. 6)}$$

where, c_p= specific heat capacity; T= temperature; k= heat transfer coefficient of the fluid; and S_T= internal heat source of the fluid and the viscous dissipation term.

Component transport equation (Eq. 7):

$$\frac{\partial(\rho c_s)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j c_s) = \frac{\partial}{\partial x_j}\left(D_s\frac{\partial(\rho c_s)}{\partial x_j}\right) \qquad \text{(Eq. 7)}$$

where, c_s= volume concentration of component s; ρc_s= mass concentration of the component; and D_s=

diffusion coefficient of the component.

Choices of appropriate computing model and operating environment

The processed mesh file was imported into FLUENT software. It was necessary to select a solver for the calculation model and set the running environment after checking the meshes. Since the present work simulated CO_2 released by the eggs in three-dimensional space, the mould created was a three-dimensional model; 3D was selected in the Space option. The present work used a single-precision solver and an uncoupled implicit solution method. Considering the time-dependent variables during diffusion, the non-steady-state calculation mode was selected. The corresponding time-dependent term calculation method made use of the first-order implicit calculation method.

The present work was designed to study the diffusion of CO_2 from the surface of the eggshell. When CO_2 began to diffuse, there was no phase change involved. During diffusion, a small amount of heat exchange was allowed to take advantage of the single-phase flow model. Therefore, the Energy Equation option was set to open. During the whole diffusion, Gravity was chosen in operating conditions as relative density of CO_2 needs to consider the effect of gravity. Considering that the eggs were pointed downward during storage, according to the three-dimensional model structure, a gravity acceleration of -9.8 was set in the X direction. The test opened the full buoyancy effects in the Viscous Model window on account of buoyant force influences.

In the present work, an implicit separation solver was used to calculate the discrete equations. Using the simple algorithm of pressure velocity coupling, the continuity equation was used to connect the velocity field and pressure field for calculation and correction. The first-order upswing style was selected as the discrete format of momentum, volume fraction, and turbulent kinetic energy. The pressure relaxation factor, momentum relaxation factor, turbulent kinetic energy relaxation factor, dissipation rate relaxation factor, and turbulent viscosity relaxation factor were set to 0.3, 0.7, 0.8, 0.8, and 1, respectively, and the revised standard pressure revised equations were used to settle. Before performing iterative calculations, it was necessary to initialise the parameters. In the present work, the boundary conditions of the initial flow field were used to calculate from the egg surface. The speed at the beginning of the diffusion was set to 0.08 m/s and the temperature to 298.15 K. The iteration time step was set to 1. The data file was automatically saved every 10 s. The total number of steps was 1800, and the transient diffusion of CO_2 within 30 min was continuously calculated.

Results and discussion

The present work simulated the diffusion of CO_2 released by the eggs stored at temperatures of 4, 25, and 35°C. The simulation of diffusion is shown in Figures 3, 4, and 5. The CO_2 diffusion was analysed at different time points. Since the density of CO_2 is greater than that of air, the effect of gravity was taken into consideration. It is known that the diffusion of CO_2 released by the eggs is in accordance with the characteristics of heavy gas diffusion from Figures 3, 4, and 5, and accordingly, this could be roughly divided into four stages: initial, descending, mixing, and turbulence.

In the initial stage, CO_2 fluctuated slightly and adhered to the surface of the eggs owing to being affected by the flow of external ambient air under the diffusion effect of diffusion source from the moment the diffusion of CO_2 began. In the descending stage, after a transitory float in the initial stage, CO_2 began to decline significantly due to the effect of gravity, and it diffused horizontally after spreading to the edge of the confined space. In this process, CO_2 continuously mixed with the air, and there was a small amount of energy exchanged with the atmosphere due to atmospheric turbulence. In the mixing phase, heavy gas clouds gradually transformed into non-heavy gas clouds. Further mixing of CO_2 clouds and the atmosphere resulted in a continuous decrease in the relative density of CO_2, and the effect of gravity continued to weaken. The CO_2 diffusion was sustained. The turbulent stage is the last part of diffusion during which CO_2 fully mixed with the air. The CO_2 cloud spread with the direction and speed of air flow, and further mixed with the air to completely diffuse into the surrounding atmosphere due to the effect of atmospheric turbulence.

The following rules were summarised as shown in Figures 3, 4, and 5, according to simulation analysis of CO_2 released by the eggs at different temperatures. The amount of CO_2 released by the eggs within 30 min was 40, 300, and 400 ppm at storage temperatures of 4, 25, and 35°C, respectively.

When the diffusion time was 60 s, the CO_2 dispersion was in the initial stage, so CO_2 was attached to the surface of the egg. There was no significant difference in CO_2 distribution of the

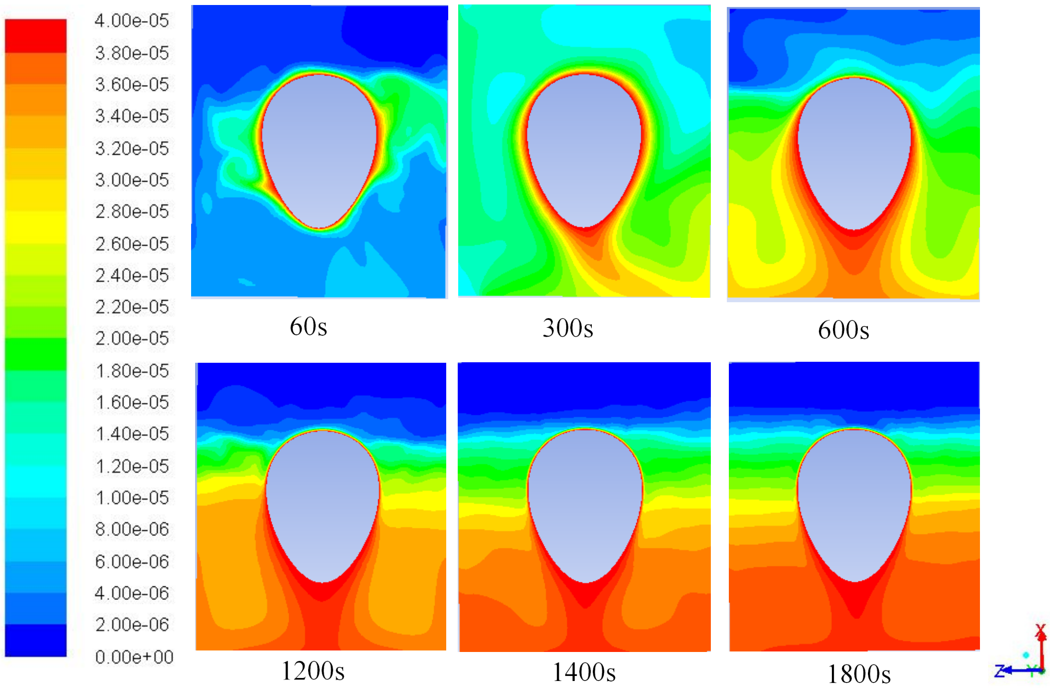

Figure 3. Simulation of carbon dioxide diffusion by eggs at different time points at 4°C.

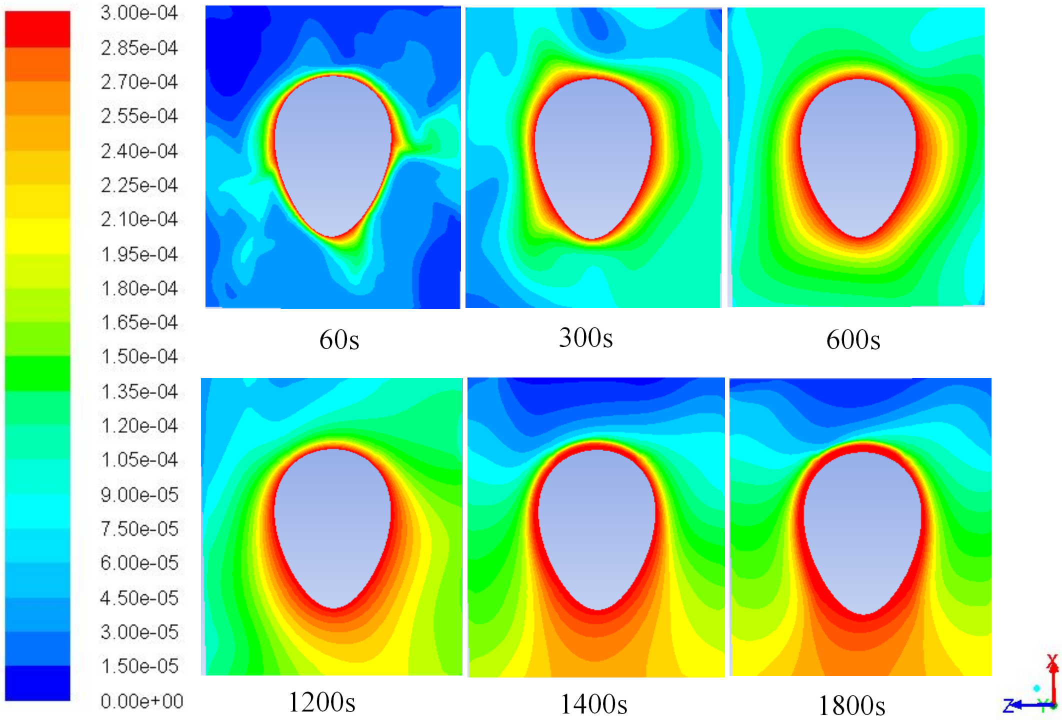

Figure 4. Simulation of carbon dioxide diffusion by eggs at different time points at 25°C.

three CO_2 temperature fields. When the diffusion time was 300 s, CO_2 distribution at storage temperature of 25 and 4°C was attached to the surface of egg, which was still in the initial stage of spread. Nevertheless, the diffusion of CO_2 at storage temperature of 4°C had entered a declining phase, and began to deposit downward. Temperature mainly affected the vertical direction of gas diffusion. It was clear from the simulation results that when the temperature was low, the time for the gas adhering to the surface of the egg was ephemeral, and it quickly descended. At a diffusion time of 600 s at 4°C, the CO_2 continued to deposit downward, and was about to enter the mixing stage. At the same time point, CO_2 spread at 25°C was still in the initial stage, and it adhered to the surface of the eggs, while at 35°C, it was entering into the decline stage. When the diffusion time was 1200 s,

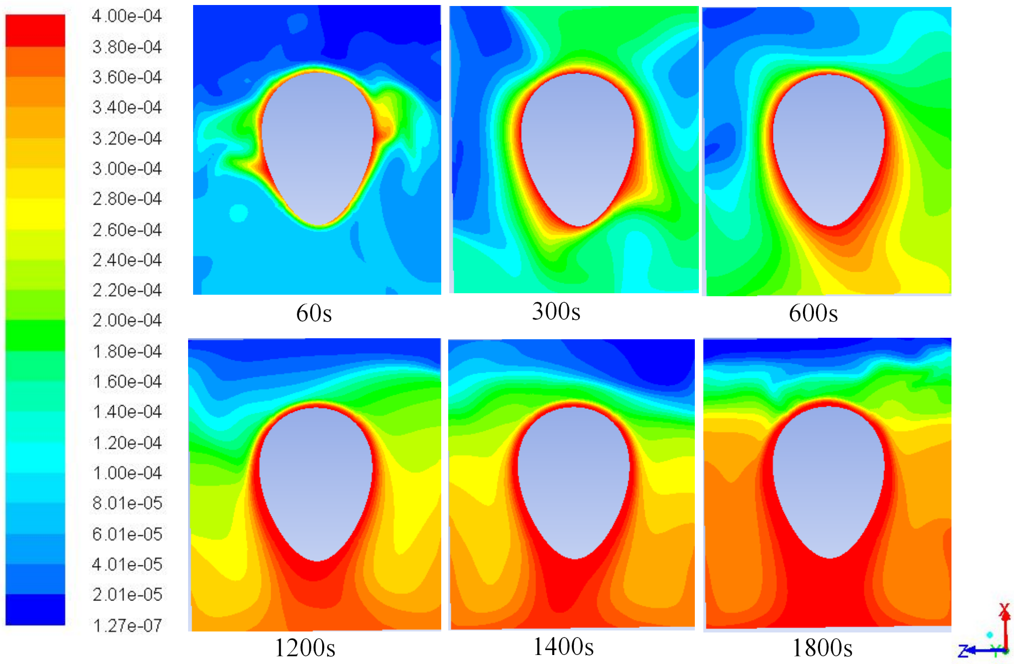

Figure 5. Simulation of carbon dioxide diffusion by eggs at different time points at 35°C.

the CO_2 diffusion at 4°C continued to deposit downward, ready to enter the turbulent phase, mixing with the air gradually and completely. At this time point, the pervasion of CO_2 at 25 and 35°C entered the decline stage, and deposited downward progressively. It was concluded that the amount and velocity of diffusion influenced the direction of spread.

By 1400 s, the CO_2 diffusion at 4°C was in the turbulent phase, in which clouds began to diffuse with the direction of air flow, and further mixed with air. The diffusion of CO_2 at 25°C entered the descending phase and CO_2 deposited downward step by step. The CO_2 pervasion on the egg surface at 35°C reached the turbulent stage. When the diffusion time reached 1800 s, the CO_2 pervasion at 4°C and 35°C were in the turbulent state, and gradually mixed with the air as the air flowed. The CO_2 spread at 25°C was still in declining phase and progressively deposited downward.

Conclusion

The present work simulated the diffusion of CO_2 released by the eggs stored at different time points and different temperatures based on a parallel set of actual respiration data. The spreading of CO_2 released by the eggs accorded with the characteristics of heavy gas diffusion. The CO_2 first spread on the surface of egg, then deposited downward on account of gravity, and finally rose gradually with the air flow until it was completely mixed with the air. The amount and speed of CO_2 released by the eggs was influenced by the storage temperature. Notably, when the CO_2 distribution at 25 and 35°C was in the initial stage, the CO_2 pervasion at 4°C had started to deposit downward, and enter the decline state. Our analysis suggests that the amount of CO_2 released by eggs at 4°C is low, so low temperature had an effect on vertical gas diffusion. The time point at which CO_2 diffusion at 35°C entered the decline stage was earlier than that at 25°C, which indicated that the amount and speed of CO_2 released by the eggs affected the vertical direction to a certain extent.

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