Ethylene distribution and ventilation strategies of apple cold storage

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Abstract. Ethylene is a kind of plant hormone that may affect storage quality of fruit and corresponding ventilation strategies of cold storage. The purpose of this study was to explore the emission characteristics of ethylene and put forward ventilation strategies to reduce ethylene concentration. A real 230 t cold store for apples in Fufeng County of China was taken as the research object, Gas Chromatograph analysis (GC analysis) was applied to test ethylene concentration in the cold room, it was found that the indoor ethylene release rate peak appeared at 70 d. A 3-D, unsteady, incompressible and viscous numerical calculation model was developed and the component transport model was applied to numerically study the complicated phenomenon of heat transfer and mass transfer in the cold storage room. The results show that the ethylene concentration formed a tendency of diffusion from the apple zone to the air zone, and the highest ethylene concentration did not appear in the center of the apple zone, but appeared near the bottom of the apple zone. Furthermore, the air cooler was recommended to be running during ventilation for shorter ventilation time of 40 min and better temperature stability for cold storage.
1 Introduction

Cold store plays an important role in maintaining fruits and vegetables in good quality and prolonging storage period. Apples are still ‘living bodies’ and do not stop respiration after harvest, which results in apple quality degradation, and gradually becoming inedible. O₂, CO₂ and ethylene concentration influence the postharvest respiration intensity of apples.

In previous studies, scholars mainly focused on O₂ and CO₂ concentration on the physiological characteristics of apples. Lowering O₂ level during apple storage maintains higher flesh firmness[1], and limits superficial scald, but too low level may develop symptoms of low O₂ damage such as increase the production of volatile compounds. High CO₂ percentage would increase the accumulation of acetaldehyde and ethanol in the fruit[2].

However, there was little research on the emission characteristics of ethylene in cold storage. Ethylene is a plant hormone in fruit and vegetables, which can induce negative effects including senescence and over-ripening during postharvest storage. Apple is a typical climacteric fruit which is characterized by a sudden increase of respiration rate[3]. Studies have shown that the content of ethylene in fruit increased significantly before the respiratory jump was going on or about to start[4]. It was believed that the climacteric change of fruit is due to the peak of ethylene. Therefore, it is necessary to delay the period of the ethylene peak.

Relevant measures can be taken to delay the peak of ethylene, such as the use of 1-Methylcyclopropene (1-MCP). However, some private small cold stores built by farmers from apple production area in Shaanxi, China do not take any measures towards ethylene control. The simplest and most effective method to deal with this situation is ventilation by introducing fresh air outside the store to dilute the ethylene concentration.

We took a real cold room for apples as research object, the combination of experimental research and numerical simulation are carried out to study the temporal and spatial emission characteristics of ethylene during cold storage of apples. Furthermore, the influence of turn-on and turn-off mode of the air cooler on ethylene concentration and temperature stability of the cold room were studied. The research may be helpful to thoroughly understand the phenomenon of ethylene emission and accumulation in the cold storage for fruits, and provide some guidance for determining practical ventilation measure for apple cold storage.

2 Experiment and Numerical model

2.1 Experimental investigation

2.1.1 Experimental design

One 230 t real cold store for apples in Fufeng County of Shaanxi Province were chosen for study. Apples were stored under the condition that the temperature was 0±0.5°C and the relative humidity was 85-90%.

In this study, the method of Gas Chromatograph analysis (GC analysis) was introduced to measure the ethylene concentration and ethylene release rate in the cold store. The specific operation was to take the air from the cold store every 10 d and transport to the laboratory immediately, to analyze the ethylene composition by gas chromatograph.

2.1.2 GC analysis

A GC 6890N (Agilent Technologies, Palo Alto, CA, USA) instrument was applied in the study. Chromatographic peaks were quantified automatically by means of the MSD ChemStation software.

2.2 CFD model

2.2.1 Geometry

Cold store geometry model was shown in Fig. 1. The cold store was 13 m×10 m×7.1 m (length×width×height). Size of the air cooler in the cold room is 1.92 m ×0.61 m×0.65 m (length×width×height), and has two round air outlets at a diameter of 0.5 m. Apples in the cold store were placed in two stacks, each of which was 11 m×4 m×6 m (length×width×height).


Fig. 1. Schematic diagram of cold store geometry model.

2.2.2 Governing equations

A series of assumptions were made in the numerical modeling of this paper. Apple zone was assumed as a porous domain consisting of a solid phase (apple) and a fluid phase (air in the gap)[5]. The thermal physical properties of apples were assumed to be temperature independent. The radiation heat exchange between apples was neglected. The enclosure structure was well sealed, regardless of the influence of external osmosis.

The internal flow field of the whole cold room could be simplified as a 3-D, unsteady, incompressible and viscous turbulent flow field. The turbulence model was calculated by using SST K-ε model combined with the continuity equation, momentum equation and energy equation to obtain the distribution characteristics of the flow field.
Meanwhile, this study simulated the change of component concentration, so the component transport model was used. The components defined in the mixture include O₂, CO₂, ethylene and nitrogen.

(1) General differential equation
\[
\frac{\partial (\rho U)}{\partial t} + \text{div}(\rho U \phi) = \text{div}(\Gamma \text{grad} \phi) + S_\phi
\]  
(1)

Where \( \rho \) is the density of the fluid; \( \phi \) is the general variable; \( U \) is the velocity vector of the fluid; \( \Gamma \) is the generalized diffusion coefficient corresponding to \( \phi \); and \( S_\phi \) is the generalized source term corresponding to \( \phi \).

(2) Apple zone resistance

When apple zone was treated as a porous medium, the resistance in the flow process must be considered, including viscous resistance and inertial resistance [8].

(3) Source item in energy equation

The source term of the energy equation can be expressed as:
\[
S_e = \rho_a (1 - \varepsilon) Q_r / \eta
\]  
(2)

Where \( \rho_a \) is the apple density, \( \text{kg m}^{-3} \); \( Q_r \) is the apple respiratory heat, \( \text{W kg}^{-1} \); \( \eta \) is the conversion coefficient of respiratory heat converted into heat, \( \% \).

The source term of ethylene concentration was obtained by experimental study on ethylene release rate during cold storage.

2.2.3 Boundary and initial conditions

All walls adopted the static wall surface without slip condition, the envelope and roof adopted the third type boundary condition, the ground was subject to the second type boundary condition. The air inlet of the air cooler adopted the speed inlet condition, where the air supply speed was 8 m s\(^{-1}\). The return air outlet adopted the outflow boundary condition. The initial condition of ethylene during apple cold storage was equal to zero and the temperature was 273.15 K.

2.2.4 Simulation setup

In this paper, a separation solver (Pressure Based) was used, and the solution process used an implicit format. Moreover, in order to obtain higher calculation accuracy in the simulation process, the second order upwind was adopted.

Grid independence proved that the optimum grid was 431,698 cells for the whole domain. By comparing several time step sizes (900s, 240s, 60s, 10s), 240 s with 200 iterations was selected as the optimum for requiring calculation accuracy without wasting calculation time.

3 Results and discussion

3.1 Ethylene release rate

Fig. 2 showed the measured characteristics of ethylene release rate with storage time in a real cold room for apples. The ethylene release rate peaked at 70 d of storage with a peak of 14.0 \( \mu \text{L kg}^{-1} \text{ h}^{-1} \). The sharp increase of ethylene will lead to the emergence of the respiration peak, in order to maintain the apple quality, it is necessary to control ethylene concentration in the storage atmosphere, that is to ventilate before the appearance of peak of ethylene release rate.

![Fig. 2. Measured results of ethylene release rate.](https://doi.org/10.1051/e3sconf/202235601060)

3.2 Model validation

The experimental and simulation results of ethylene concentration were compared as shown in Fig. 3. The simulation results show the same trend as the experimental results, when stored for 70 d, the relative error between them is 15.8\%, which is within the allowable error range of experimental verification.

![Fig. 3. Comparison between experimental and simulated values of ethylene concentration.](https://doi.org/10.1051/e3sconf/202235601060)

3.3 Ethylene Spatial distribution characteristics

This section study the spatial distribution characteristics of ethylene after 70 d storage. Representative sections (Fig. 1) were selected for further analysis, which were Y=7 m (X-Z plane) and X=2.5 m (Y-Z plane).

Spatial distribution characteristics of ethylene after 70 d storage were shown in Fig. 4. It showed that the ethylene concentration formed a tendency of diffusion from the apple zone to the air zone (Fig. 4A and Fig. 4B). Moreover, the highest ethylene concentration did not appear in the center of the apple zone, but appeared near the bottom of the apple zone (Fig. 4A) opposite to the door side (Fig. 4B). This is because the top and near door apple zone are close to air zone, and air zone is conducive to component diffusion due to its small airflow resistance and large flow space. However, the bottom apple zone and the place far away from the room door have a small diffusion space, which makes the diffusion difficult. During the apples storage process, apples from less mature batches can be placed in areas of the cold storage with higher ethylene concentrations to mitigate the effects of ethylene on apples storage quality.
3.4 Effect of air cooler operating mode on ethylene concentration

According to cold storage technology for apples, ethylene concentration inside the cold room for apples is recommended to be below 10 μL·L⁻¹ after ventilation (GB/T 8559-2008, 2008). The peak concentration of ethylene occurred at the 70th day of storage, thus 70th day was regarded as the start point of ventilation, and 10 μL·L⁻¹ of ethylene concentration was taken as the end requirement for the cold room.

Fig. 5 showed the variation of ethylene concentration during ventilation when the air cooler was turned on and turned off. The running of the air cooler made ethylene concentration in the room decrease faster when compared with the air cooler was turned off. When the air cooler was turned off, 60 min was needed for ventilation to meet storage requirement, whereas, 20 min was enough when the air cooler was turned on.

3.5 Effect of air cooler operating mode on temperature stability

The temperature fluctuation during storage should be no more than 0.5°C (GB/T 8559-2008, 2008). Initial conditions were as follows: Temperature in the room is 0°C, outdoor fresh air temperature is 10°C, supply air velocity of the air cooler is 8 m s⁻¹ and supply air temperature is -2°C.

Fig. 6 demonstrated the influence of the turn-on and turn-off of air cooler on temperature fluctuation after ventilation. When the air cooler was turned on, the fluctuation range was less than 0.5°C throughout the ventilation, which satisfied the storage requirement. However, the temperature fluctuation range exceeded 0.5°C after 2 min ventilation when the air cooler was turned off, which did not meet the storage requirement.

4 Conclusions

The spatial and temporal distribution characteristics of ethylene concentration and corresponding ventilation strategies in cold storage were studied by using the method of CFD simulation and GC analysis. The following detailed conclusions were obtained:

1. Concerning the studied 230 t apple cold storage room, the peak of ethylene release rate was found to be appeared at 70 d.

2. Ethylene concentration formed a tendency of diffusion from the apple zone to the air zone, and the highest ethylene concentration appeared at the lower part of the apple zone opposite to the door of the cold store.

3. In order to meet apple cold storage requirement, ventilation duration of the turn-on and turn-off of air cooler were 20 min and 60 min, respectively, when ethylene concentration was reduced to 10 μL·L⁻¹.

4. When the air cooler was turned on during ventilation, the fluctuation of indoor temperature was less than 0.5°C, which satisfies the storage requirement of cold storage for apples.

References


Fig. 4. Simulation results of ethylene concentration on Y=7 m plane (A) and X=2.5 m plane (B) after 70 d storage.

Fig. 5. Comparison of average temperature between the turn-on and turned-off of air cooler during ventilation.

Fig. 6. Comparison of average temperature between the turn-on and turned-off of air cooler during ventilation.