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Research Paper

Digital simulation of condensation and water loss in ventilated lychee packaging

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ABSTRACT

Lychee quality deteriorates rapidly post-harvest. Appropriately ventilated packaging can help maintain quality during the supply chain. However, interruptions in the cold chain can lead to temperature differences between the inside and outside of packages, increasing condensation and liquid water formation, which negatively affects lychee quality. This study used numerical simulations to analyse forced ventilation in different packaging structures, focusing on how the number of top openings affects internal temperature, humidity, condensation, and water loss. Additionally, the stacking of packaged lychee was modelled to predict water loss and condensation under actual supply conditions. The results showed that increasing the number of package openings reduces humidity differences and condensation, with eight openings resulting in 9.18 % less water loss rate compared to six openings. Six openings reduced condensation by 23.67 % compared to four openings. Furthermore, during storage and transportation, the amount of water loss and condensation varied by location, with lychees near the air outlet losing less water but experiencing more condensation. The findings of this study provide insights into reducing in-package condensation and water loss in the lychee supply chain, offering a reference for optimising storage and transportation strategies.

Nomenclature

Symbols	
c	Vapor concentration (mol m^{-3})
CHTC	Convective heat transfer coefficient (W m^{-2} K^{-1})
D	Water vapor diffusion coefficient of air (m^2 s^{-1})
d_{sat}	Humidity ratio of the saturated humid air (g kg^{-1})
E_i	Experimental result
g	Gravitational acceleration (=9.8 m s^{-2})
H	Specific enthalpy (J kg^{-1})
k	Heat conductivity coefficient (W m^{-1} K^{-1})
$\overline{T_l}$	Average fruit temperature (K)
M	Dynamic viscosity (kg m^{-1} s^{-1})
$m_{c,e}$	Evaporation rate (kg m^{-3} s^{-1})
ME	Mean error
MRE	Mean relative error
m_{wa}	Water loss rate of lychee (kg m^{-3} s^{-1})
$\overline{M_v}$	Molar mass fraction of water vapor

(continued on next column)

(*continued*)

Symbols	
n	The number of lychees inside the PET box (=18)
P	Static pressure (Pa)
P_{sat}	Saturated pressure (Pa)
P_v	Partial pressure of water vapor (Pa)
q	Latent heat of water (J kg^{-1}s^{-1})
q_l	Surface heat flux
Q_{resp}	Volumetric heat of respiration (W m^{-3})
RMSE	Root mean square error
S_h	Heat source term (W m^{-3})
S_i	Simulation result
S_v	Species source term (kg m^{-3} s^{-1})
T	Fluid temperature (K)
T_0	Initial temperature of lychee (K)
T_i	Instantaneous volume-averaged fruit temperature (K)
T_{ref}	Reference temperature (K)
V	Fluid velocity (m s^{-1})

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Symbols	
V	Air velocity in the surface at lychee (m s^{-1})
λ	Relaxation coefficient (=10)
ρ	Density (kgm^{-3})
σ	Coefficient of fruit temperature variation of lychee
ϕ	Relative humidity (%)
ω_{sat}	Saturated mass fraction of water vapor
ω_v	Mass fraction of water vapor

1. Introduction

Lychee is a fruit of Sapindaceae family grown in subtropical and tropical regions (Xiao et al., 2024), having popularity in the international market (Situ et al., 2023). However, lychee is harvested during the hot and humid summer, with a short shelf life after harvest and is susceptible to decay (Zhang et al., 2021).Storage environmental conditions such as temperature and humidity are important factors that directly affect fruit water loss and shelf life (Yang et al., 2022).For the reason of respiration and transpiration from the fruits and vegetables (Shao et al., 2020), the humidity and condensation in storage environment will rise while promoting the growth of microorganisms and accelerating the decay (Bizymis & Tzia, 2022; Du et al., 2022). Due to the water loss of the pericarp and surface condensation, the browning of lychee is exacerbated affecting the appearance of lychee and reducing its economic value (Sun et al., 2011).Therefore, using freshness packages to effectively delay the physiological and biological processes and extend the storage period (Shrivastava et al., 2023) is made of sense.

Open-cell polyethylene terephthalate (PET) packaging is often used as freshness packaging for fruits (Garavito et al., 2022; Giuffre et al., 2019). The headspace relative humidity of these packages is usually higher than 94 % because of their good water vapor barrier properties (Bai et al., 2019). However, higher relative humidity increases the risk of condensation on the packaging wall, which is not favourable for fruit storage (Bovi et al., 2019). Thus, a series of studies on packaging optimisation have been carried out. The opening of the clamshells had a significant effect on the quality maintain of the fruit during storage, increasing the openings helped to maintain the temperature inside the package, but decreased the relative humidity and increased the water loss of the fruit (Bai et al., 2019). Incorporating absorbing trays into the packaging can reduce the amount of condensation on the fruit while maintaining the relative humidity inside the packaging (Jalali et al., 2019).

The location, size, and number of openings in a package affect the flow field distribution (Delele et al., 2013; Han et al., 2015). Increasing the number of package openings facilitates the exchange of airflow between the inside and outside of the package, which improves the cooling efficiency and uniformity of the products and reduces the risk of condensation inside the package (Defraeye et al., 2013; Ferrua & Singh, 2011; Linke & Geyer, 2013). However, as the opening ratio increases, it not only reduces the mechanical strength of the package, but may also make it difficult to maintain humidity inside the package, resulting in more water loss (Zhao et al., 2016). Hence, a suitable fresh-keeping environment should be built by the package and ambient environment regulation together. To design a suitable package for certain products, the dynamic physiological characteristics and properties of packaging material, coupled with optimum headspace conditions for the given product should be considered. The most common way to predict the headspace environment within the package is mathematical modelling, by which the effects of package films, products and other factors on environment within the package can be obtained (Mangaraj and Goswami, 2011; Bovi et al., 2019; Fonseca et al., 2018).

Different fruits at different stages of the cold chain have different environmental requirements. For this reason, specific packaging is needed for different supply chains to guarantee package the quality of fruit (Schudel et al., 2022).However, experimental studies would take a great deal of cost, time and labour (Gou et al., 2023). In the last decades, computational fluid dynamics has been more and more widely used in the cold chain, especially in the evaluation of cooling performance. Yet other cold chain segments have been less simulated (Kelly et al., 2019).

In this study, numerical simulations were used to analyse temperature, humidity, lychee water loss, and condensation inside package wall during forced duct ventilation with varying numbers of package openings. The optimal packaging configuration was then identified and applied in simulations of the stacked storage process to predict water loss and condensation inside package wall. Experiments were conducted to validate the accuracy of the simulation models. The findings provide practical insights into optimising lychee packaging for improved storage and transport, helping to reduce water loss and condensation during the supply chain.

2. Materials and methods

2.1. Materials

2.1.1. Cold storage equipment

The cold storage equipment used in this study, developed by the College of Engineering at South China Agricultural University, operates on the principle of differential pressure. The chamber, measuring 1.9 m in length, 1.1 m in width, and 1.5 m in height, is fully insulated with polyurethane panels. It is divided into two sections: a fresh-keeping area and a refrigeration area. Negative pressure in the return air duct, located behind the fan, drives air from the fresh-keeping area to the refrigeration area, where it exchanges heat as it passes through the evaporator. The cooled air then returns to the fresh-keeping area through an open partition, completing the closed cycle. The ventilation air velocity can be adjusted by modifying the return air duct's airflow.

To study the pre-cooling process of lychee, an acrylic panel duct was constructed, measuring 600 mm in length, 275 mm in width, and 240 mm in height. This forced ventilation duct was placed within the cold storage equipment, with the pre-cooling temperature controlled by adjusting the preservation environment's temperature. The forced ventilation duct model and the lychee stacked storage model used in this study are shown in Fig. 1.

2.1.2. Sample of lychee and packing

Lychee fruits were picked at 6:00 a.m. and immediately transported to the College of Engineering at South China Agricultural University. The lychees were fresh, full in appearance, firm in texture, with minimal mechanical damage, and uniform in size and maturity. They were packaged in commercial PET boxes designed for fruits and vegetables, featuring top and side vents, with a weight capacity of 500 g.

2.2. Geometry and meshing

This study investigated the impact of the number of PET openings on temperature and humidity inside and outside the package under forced ventilation conditions, as well as the effect of temperature fluctuations on lychee water loss and condensation within the package during stacked storage. Temperature fluctuations were found to directly affect lychee physiological traits, leading to increased weight loss and quality deterioration, while also exacerbating condensation and bacterial growth within the package, which accelerates spoilage. A corresponding three-dimensional model was developed using CATIA software. The forced ventilation model included three PET boxes with different numbers of top openings, each with a diameter of 8 mm. Lychee fruits were modelled as spheres with a diameter of 32 mm within an isotropic continuous medium. Each PET box contained 18 lychees, arranged in two uniform layers. The various package configurations are shown in Fig. 2.

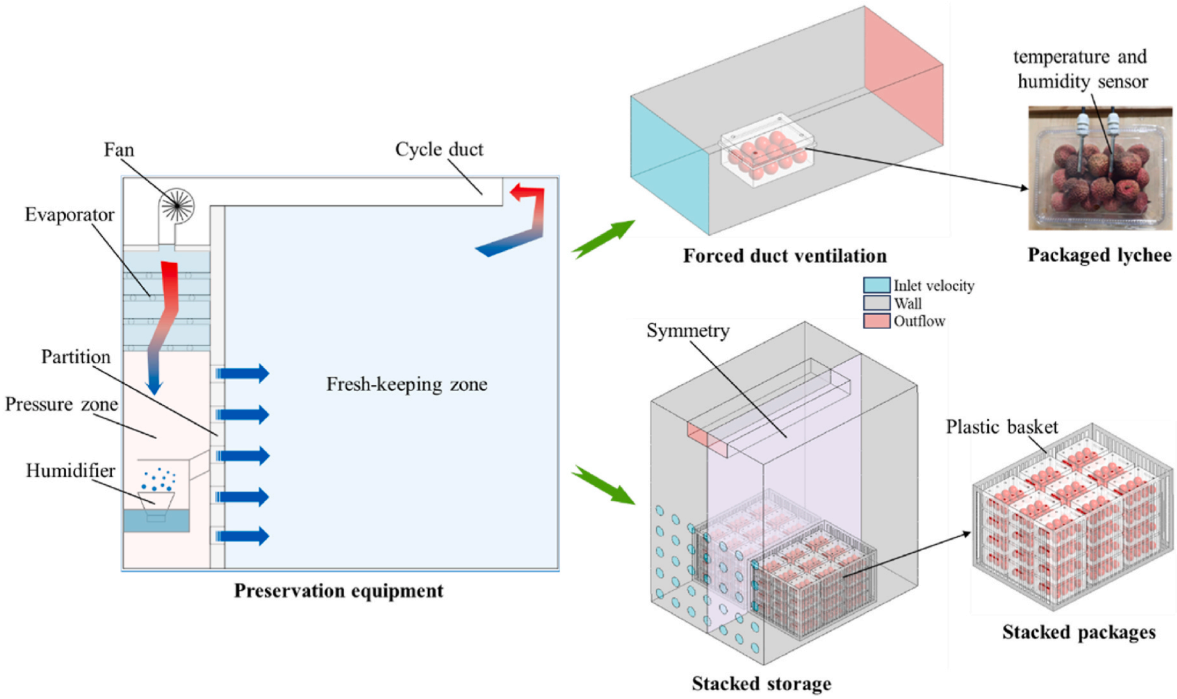

Fig. 1. Schematic diagram of the cold storage equipment and the models of lychee duct forced ventilation and stacked storage.

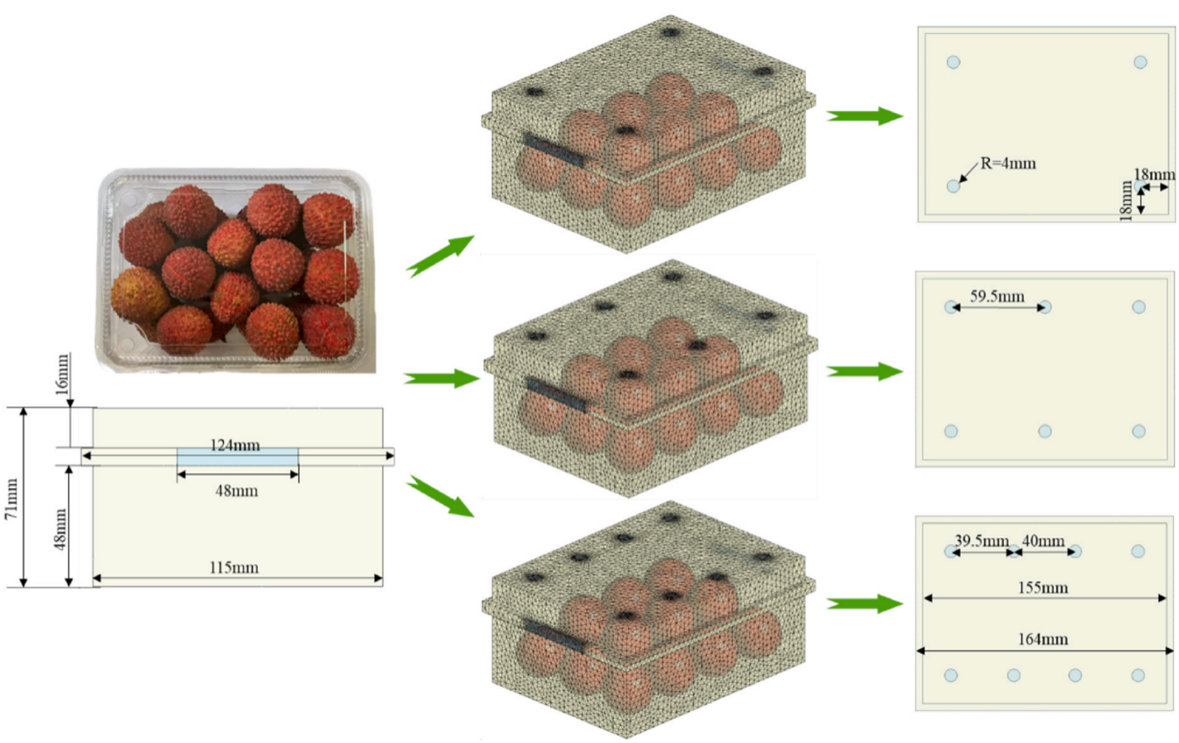

Fig. 2. Models and mesh for different packages.

The model was discredited into a tetrahedral unstructured mesh using CFD-ICEM. Since the simulation results and computation time are influenced by mesh size and number, an appropriate mesh size was investigated to ensure simulation accuracy. Five different mesh densities were tested, ranging from 6×10^5 cells to approximately 3.55×10^6 cells, representing a spectrum from coarse to fine. To enhance computational accuracy in specific regions, such as exits, entrances, package openings, and lychees, local mesh refinement was applied. As shown in the grid-independence validation results in Fig. 3, air temperature and relative humidity inside the package fluctuated slightly with increasing mesh density. When the mesh count was between 2.01×10^6 and 3.55×10^6 cells, the temperature and humidity curves stabilised, indicating that further mesh refinement had minimal impact on the results. Based on accuracy, reliability, and considerations of computational efficiency and cost, a mesh size of 2.01×10^6 cells was selected for the final calculations.

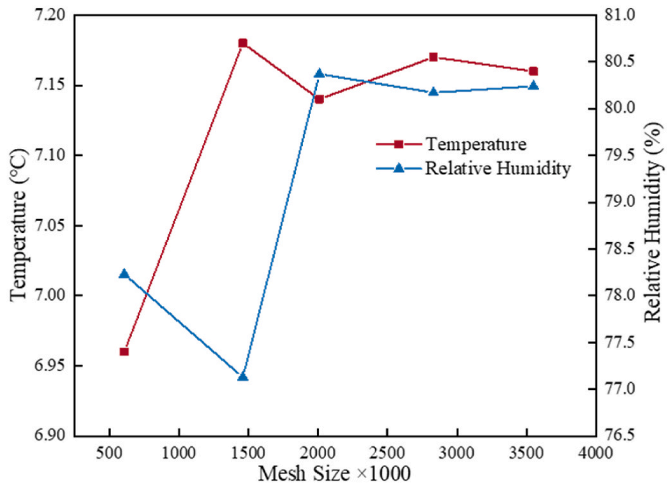

Fig. 3. Results of mesh-independence study.

2.3. Model solving

2.3.1. Model assumptions

The unsteady heat and mass transfer in lychee fruits during forced air cooling is very complex and includes not only sensible heat exchange dominated by convection, but also latent heat transfer through heat conduction, radiation, transpiration, and respiration. Therefore, to simplify the calculations and describe the experimental system correctly, the following assumptions were made.

(1) All the materials are isotropic.
(2) The air is Newtonian fluid and satisfies the Boussinesq assumption.
(3) Neglect radiative heat transfer from all objects.
(4) Thermophysical parameters of lychee fruits are uniform, and the rate of water loss remains unaffected by the physiological characteristics of the lychee.
(5) The water lost by lychees is directly sublimated into water vapor.

2.3.2. Governing equations

The computational domain of the model in this paper was segmented into three distinct zones: the free airflow zone (air inside and outside package), the product zone (lychee), and the solid zone (PET, wall, and plastic basket). The unique flow and heat transfer characteristics of each zone were elucidated through their respective governing equations.

(1) In the free airflow zone, the airflow distribution and temperature field could be approximately described as follow(Novotny & Pokorny, 2021; Soodmand et al., 2022; Wang & Wang, 2023):

$$\frac{\partial \rho_a}{\partial t} + \nabla.(\rho_a\, V_a) = 0 \tag{1}$$

$$\frac{\partial(\rho_a V_a)}{\partial t} + \nabla.(\rho_a V_a) = -\nabla.(P) + \mu_a \nabla^2 V_a + \rho_a g \tag{2}$$

$$\frac{\partial}{\partial t}(\rho_a H_a) + \nabla.(\rho_a V_a H_a) = \nabla.(k_a \nabla T_a) + S_h \tag{3}$$

where the subscript a identifies properties of air, ρ (kg m^{-3}) is the density, V (m s^{-1}) is the fluid velocity, P (Pa) is the static pressure, μ (kg m^{-1} s^{-1}) is the dynamic viscosity, g (=9.8 m s^{-2}) is the gravitational acceleration, T (K) is the fluid temperature, H(J kg^{-1}) is the specific enthalpy, k (W m^{-1} K^{-1}) is the heat conductivity coefficient, S_h (W m^{-3}) is the heat source term.

The moisture transport in the free airflow zone could be described as follow:

$$M_v V_v \cdot \nabla c_v + \nabla.(-M_v D_v \nabla c_v) = S_v \tag{4}$$

where the subscript v identifies properties of water vapor, M (kg mol^{-1}) is the molar mass of water vapor, c (mol m^{-3}) is the vapor concentration, D_v (=2.4 × 10^{-5} m^2 s^{-1}) is the water vapor diffusion coefficient of air (Schudel et al., 2022), S_v (kg m^{-3} s^{-1}) is the species source term represents the addition of moisture within the domain.

The variation of water vapor content in the air was affected by water loss from lychee. Condensation and evaporation, which were defined by the following equation (Li, 2020):

$$m_{wa} = \frac{8.322 - 5\phi^2 - 0.003247\phi + 29.2V - 2T^2 - V^2 - 0.32432V\cdot\phi}{3600000} \tag{5}$$

$$\phi = \frac{P_v}{P_{sat}} \tag{6}$$

$$P_{sat} = \exp\left(9.3876 - \frac{3826.36}{T - 45.47}\right) \times 10^6 \tag{7}$$

$$P_v = (P + 101325) \times \overline{M_v} \tag{8}$$

$$\overline{M_v} = \frac{\omega_v/18}{\omega_v/18 + (1-\omega_v)/29} \tag{9}$$

where m_{wa} (kg m^{-3}s^{-1}) is the water loss rate of lychee, ϕ is the relative humidity; V (m s^{-1}) is the air velocity in the surface at lychee; T (K) is the air temperature inside the package; P_v (Pa) is the partial pressure of water vapor; P_{sat} (Pa) is the saturated pressure; $\overline{M_v}$ is the molar mass fraction of water vapor; ω_v is the mass fraction of water vapor.

The driving force for water vapor condensation is the difference between the partial pressure of water vapor in the air and the saturation pressure of water vapor at the surface temperature of the package (Han et al., 2015).

$$m_{c,e} = \lambda \cdot \rho_a \cdot |\omega_v - \omega_{sat}| \tag{10}$$

$$\omega_{sat} = \frac{d_{sat}}{1 + d_{sat}} \tag{11}$$

$$d_{sat} = 0.622\frac{P_{sat}}{P - P_{sat}} \tag{12}$$

where $m_{c,e}$ (kg m^{-3}s^{-1}) is the evaporation rate or condensation rate; λ is a relaxation coefficient (=10); ω_{sat} is the saturated mass fraction of water vapor; d_{sat} (g kg^{-1}) is the humidity ratio of the saturated humid air. Condensation occurs only when ω_v is greater than ω_{sat}.

The latent heat of water q (J kg^{-1}s^{-1}) could be calculated by the following equation (Garavito et al., 2021):

$$q = 2502.535 - 2.386(T_a - 273.15) \tag{13}$$

(2) In solid zone, the energy equation was written as follows:

$$\frac{\partial}{\partial t}(\rho_s H_s) = \nabla.(k_s \nabla T_s) \tag{14}$$

where the subscript s identifies properties of solid.

(3) In the product zone, the heat conduction inside individual lychee was considered, and the energy equation could be written as follows (Guo et al., 2016):

$$\frac{\partial}{\partial t}(\rho_l H_l) = \nabla.(k_l \nabla T_l) + Q_{resp} \tag{15}$$

$$Q_{resp} = 3.0049 \times 10^{11} \exp\left(\frac{-8528.57}{T_l}\right)\rho_l \tag{16}$$

where the subscript l identifies properties of water vapor, Q_{resp} (W m^{-3}) is the heat source term represents the volumetric heat of respiration.

2.3.3. Initial and boundary condition

In the model of forced duct ventilation for packaged lychee, the inlet was set as a velocity-inlet with 1.0 m s^{-1}, temperature for 275.15 K, and relative humidity for 80 %. The outlet was set as a pressure-outlet. The wall was configured as the convective heat transfer boundary, and the external ambient temperature was 293.15 K. The initial temperature in the computational domain was 293.15 K, and the relative humidity was 40 %.

In the model for stacked storage of packaged lychee, the boundary type settings were the same as those in the forced ventilation model. The inlet air velocity was 0.85 m s^{-1}, the temperature was 273.15 K, the relative humidity was 90 %, and the ambient temperature was maintained between 275.15 K and 279.15 K. The external ambient temperature was 301.15 K. The temperature in the computational domain was initialised to 278.15 K, and the relative humidity was 90 %. The specific values set in the model are derived from actual measurements. The schematic of initial condition is shown in Fig. 4.

2.3.4. Solving solution

The models in this paper were numerically simulated by the software Ansys Fluent 18.2. Pressure-base solver type with absolute velocity, transient time, Standard k-epsilon model, and Component Transportation model was selected. The SIMPLE algorithm-based implicit scheme for pressure-velocity coupling was chosen. The Least Squares Cell Based method was used in the gradient calculations, the pressure, momentum, and energy were solved by using Second Order Implicit, and the turbulent kinetic energy and turbulent energy dissipation rate were solved by using First Order Implicit. The physical parameters of the product are shown in Table 1 and some of them are described in detail. The time step was chosen to be 1 s considering the calculation stability and convergence.

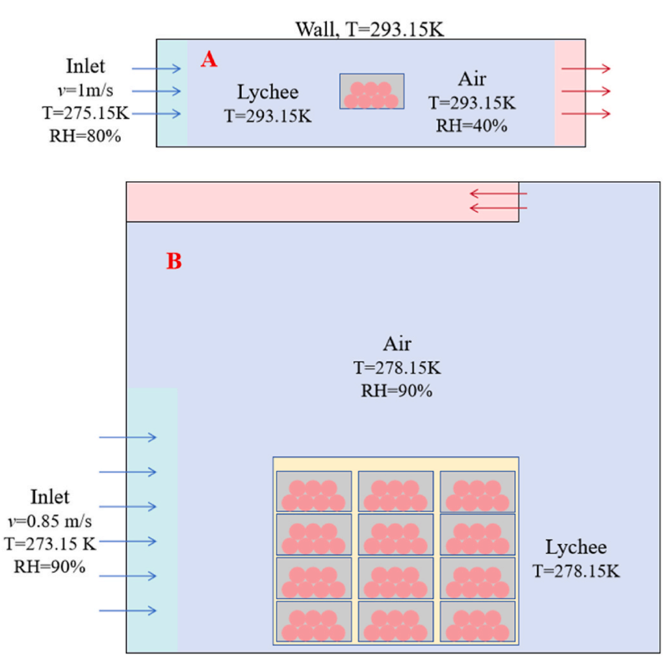

Fig. 4. The schematic of initial condition.

Table 1
Specification of physical parameters.

Name	Phase	Parameter	Value
Air	Gas	Density/(kg m^{-3})	1.225
		Specific heat/(J kg^{-1} K^{-1})	1006
		Heat conductivity coefficient/(W m^{-1} K^{-1})	0.0225
		Viscosity/(Pa s)	1.79×10^{-5}
Water	Liquid	Density/(kg m^{-3})	998
		Specific heat/(J kg^{-1} K^{-1})	4182
		Heat conductivity coefficient/(W m^{-1} K^{-1})	0.6
Lychee (Guo et al., 2016)	Solid	Density/(kg m^{-3})	932.89
		Specific heat/(J kg^{-1} K^{-1})	3710
		Heat conductivity coefficient/(W m^{-1} K^{-1})	0.51
PET (Guo et al., 2016)		Density/(kg m^{-3})	1000
		Specific heat/(J kg^{-1} K^{-1})	2200
		Heat conductivity coefficient/(W m^{-1} K^{-1})	0.47
Plastic basket (Li, 2020)		Density/(kg m^{-3})	220
		Specific heat/(J kg^{-1} K^{-1})	1700
		Heat conductivity coefficient/(W m^{-1} K^{-1})	0.048
Wall (Guo et al., 2016)		Density/(kg m^{-3})	1612
		Specific heat/(J kg^{-1} K^{-1})	2004.44
		Heat conductivity coefficient/(W m^{-1} K^{-1})	0.35

2.4. Experimental verification

The accuracy of the model was verified by separate tests in the cold storage equipment (maintenance temperature 5 ± 1 °C). Forced ventilation duct was placed into the cold storage equipment, the package was placed in the middle of the forced ventilation duct, 18 lychees were placed in the package, and 2 high precision temperature and humidity sensors were arranged in the package (ALMEMO FHA 646-R; temperature range: 30-100 °C, accuracy:±0.2 °C; humidity range: 5 %–98 %, accuracy:±2 %; AHLBORN, Germany) to measure the ambient temperature and humidity inside the package. Datalogger (ALMEMO 2590-4AS; data logging frequency: per second; AHLBORN, Germany) was used to record the temperature and humidity sensors data per second. Air velocity was measured by a hot-wire anemometer (Testo405i; measuring range:0–30 m s^{-1}; measurement accuracy: ± (0.1 m s^{-1} +5 % of the measured value for 0–2 m s^{-1}), ± (0.3 m s^{-1}+5 % of the measured value for 2–15 m s^{-1}); Testo, Germany).

Furthermore, two plastic baskets of packaged lychee were placed in the cold storage equipment to validate the packaged lychee stacked storage model. Each plastic basket contained 36 PET boxes, each containing 18 lychees. Temperature and humidity were monitored by wireless temperature and humidity sensors (Testo 174H; temperature range: 20-70 °C, accuracy:±0.5 °C; humidity range: 0 %–100 %, accuracy:±3 %; Testo, Germany), core temperature of lychee was monitored by thermocouples (WZP-031; measuring range: 50~200 °C; accuracy: ±0.1 °C; YINGLONG, China), and air velocity was measured by a hot-wire anemometer at the open partition. The layout of the lychees and the sensors are shown in Fig. 5.

2.5. Data analysis

2.5.1. Cooling rate

To eliminate the difference of initial conditions, define a dimensionless constant Y to describe the core temperature change during the pre-cooling process of lychee, as in Eq. (17). Seven-eighths cooling time (SECT, $Y = 0.125$) was the most common parameters used to evaluate cooling performance.

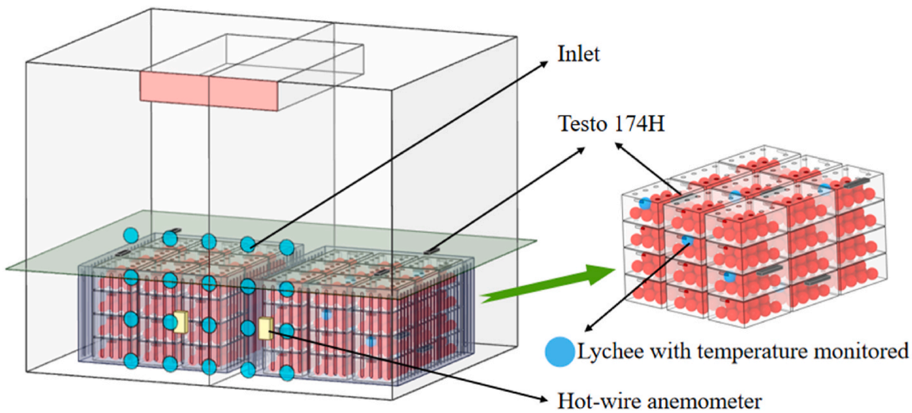

Fig. 5. The arrangement of temperature sensors in cold storage equipment.

$$Y = \frac{T_l - T_{ref}}{T_0 - T_{ref}} \tag{17}$$

where T_{ref} is the reference temperature, T_0 is the initial temperature of lychee.

2.5.2. Convective heat transfer coefficient

The convective heat transfer coefficient (CHTC, W m^{-2} K^{-1}) on the surface of lychee was an important parameter for the measurement of cooling rate, which was defined by Eq. (18).

$$\mathrm{CHTC} = \frac{q_l}{T_l - T_{ref}} \tag{18}$$

where q_l (W m^{-2}) is the surface heat flux in the direction normal to the air-lychee interface.

2.5.3. Cooling uniformity

The cooling uniformity (Guo et al., 2016) in precooling process can be measured by the coefficient of fruit temperature variation as follow:

$$\sigma = \frac{1}{\overline{\overline{T}}}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(T_i - \overline{T_l}\right)^2} \tag{19}$$

where σ is the coefficient of fruit temperature variation of lychee, n is the number of lychees inside the PET box (=18), T_i is the instantaneous volume-averaged fruit temperature of the lychee i, $\overline{T_l}$ is the average fruit temperature of the 18 lychees.

2.5.4. Error calculation

In order to assess the difference between the experimental and computational results, we introduced three quantitative metrics including mean error (ME), root mean square error (RMSE) and mean relative error (MRE). These parameters are summarised below:

$$ME = \frac{1}{n}\sum_{i=1}^{n}|E_i - S_i| \tag{20}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - S_i)^2} \tag{21}$$

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\frac{|E_i - S_i|}{E_i} \tag{22}$$

where S_i is the simulation result, E_i is the experimental data and n is the number of samples.

3. Results

3.1. Model validation

The simulated and experimental values of air temperature and relative humidity in the single PET forced ventilation model are shown in Fig. 6.The root mean square error (RMSE) of the air temperature simulated and experimental values was 0.83, the mean absolute error (MAE) was 0.66 °C, the root mean square error (RMSE) of the simulated and experimental values of relative humidity was 2.28 and the mean absolute error (MAE) was 1.69 %.Therefore, the experimental and simulated values are in good agreement, which proves the credibility of the forced ventilation model.

Fig. 7 displays the simulated and experimental values for temperature and relative humidity in the stacked storage model for packaged lychees. The trends observed in the simulated and experimental data are generally consistent. The errors between the simulated and experimental values were calculated using equations (11)–(13), with the results presented in Table 2. The average relative error for in-package data is within 3 %, while the average relative error for ambient temperature is less than 10 %. These results indicate that the stacked storage model for packaged lychees aligns well with the experimental data.

3.2. Effect of the number of package openings under forced ventilation

3.2.1. Effect on temperature

Fig. 8A illustrates the trends in air temperature variation inside PET packaging with different numbers of openings. The figure shows that the number of openings at the top of the packaging has a relatively minor impact on air temperature variation inside the package. Nevertheless, the pre-cooling times were reduced to 124, 128, and 130 min, respectively. Fig. 8B presents the convective heat transfer coefficients (CHTC) and fruit temperature uniformity coefficients for lychees with varying numbers of package openings. As the number of openings increases from 4 to 8, the CHTC rises from 4.90 to 5.24 W m^{-2} K^{-1} while the uniformity coefficient decreases from 0.112 to 0.106.

The temperature distribution inside the package for different numbers of package openings is shown in Fig. 9 The air temperature at the core of the lychee stack decreased significantly with the increases in the number of openings, and the low-temperature region increased significantly.

3.2.2. Effect on relative humidity

Fig. 10 depicts the relative humidity distribution within the PET boxes. In these two cross-sections, PET box with 4, 6, and 8 openings exhibit minimum relative humidity levels of 50.1 %, 51.2 %, and 52.1 %, respectively.

Fig. 11A illustrates the changes in relative humidity within the

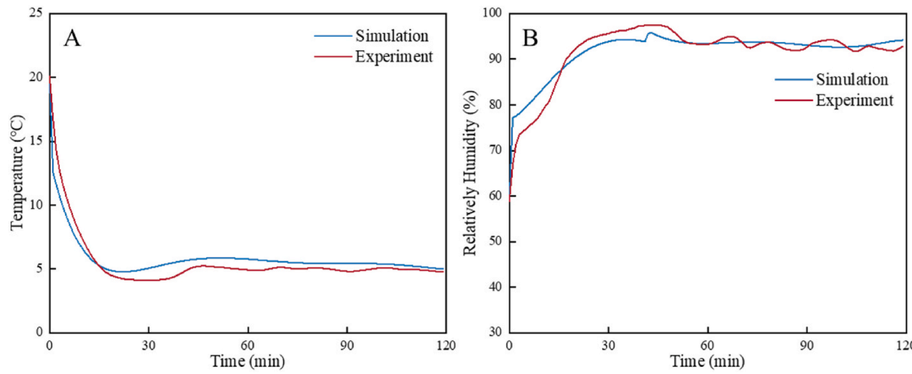

Fig. 6. Comparison of simulation for lychee forced ventilation model and experimental values: (A) Air temperature; (B) Relative humidity.

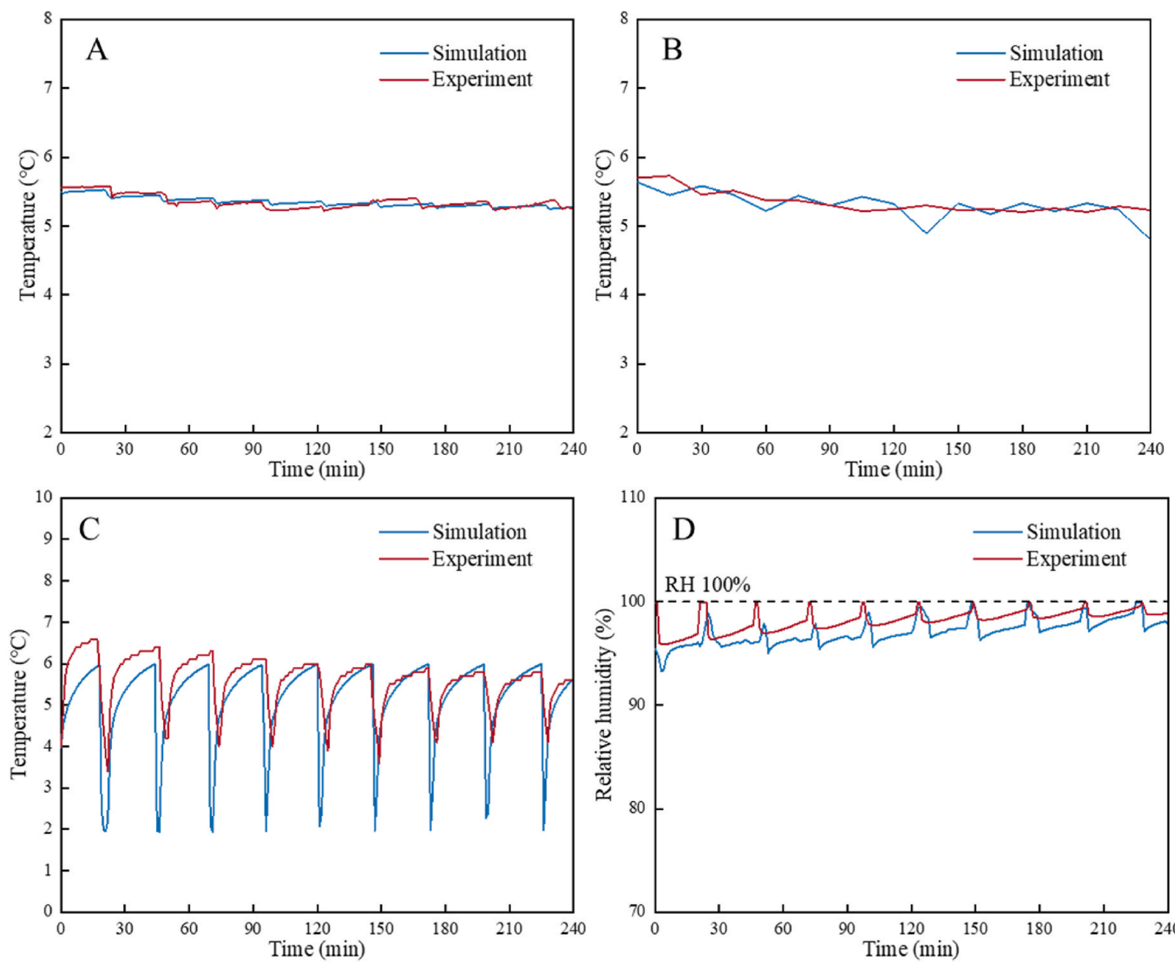

Fig. 7. Comparison of simulation for lychee stacked storage model and experimental values: (A) Core temperature in lychee; (B) Air temperature in package; (C) Air temperature in cold storage equipment; (D) Relative humidity in package.

Table 2
Difference between experimental and simulation values.

Validation Data	ME	RMSE	MRE
Core temperature in lychee	0.05	0.059	0.948
Air temperature in package	0.142	0.186	2.661
Air temperature in cold storage equipment	0.536	0.979	9.793
Relative humidity in package	1.227	1.433	1.269

packaging for different numbers of openings. The relative humidity in the packaging with 4 openings decreases to 57.6 % and then increases, which is significantly higher than that in the packaging with 6 or 8 openings. However, the rate of increase and decrease in relative humidity is faster for packaging with 6 or 8 openings.

Fig. 11B demonstrates the impact of different opening numbers on lychee water loss rate within the packaging. When the packaging openings are 4, 6, and 8, the lychee's water loss rete over 2 h is 3.48 %, 3.34 %, and 3.15 %, respectively. Water loss rate decreases with an increase in the number of openings, with variations in water loss between adjacent packaging openings at 4.02 % and 5.34 %, indicating a

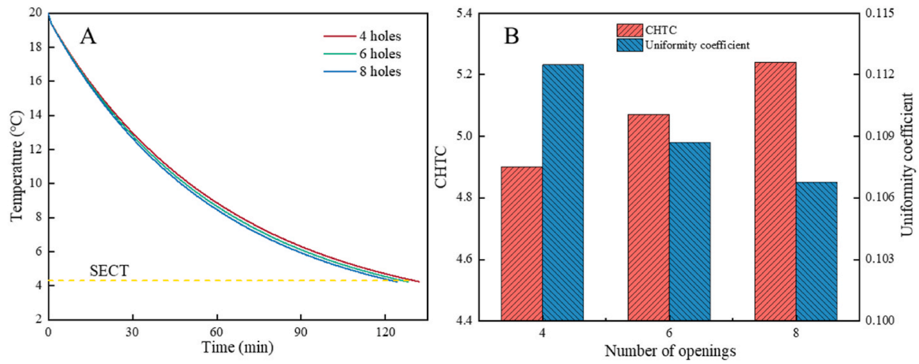

Fig. 8. Effect of number of package openings on cooling process: (A) Air temperature; (B) CHTC and uniformity coefficient.

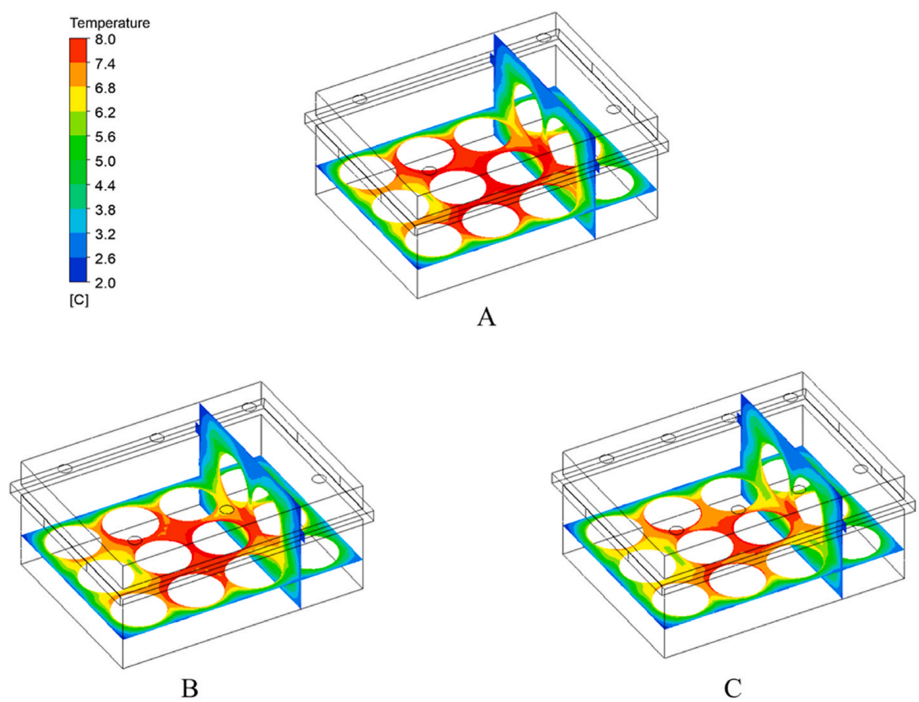

Fig. 9. Temperature distribution inside the package at the end of cooling with different numbers of openings.

significant effect of packaging opening numbers on lychee water loss rate.

Fig. 11C illustrates the impact of different numbers of packaging openings on the amount of condensation within the packaging. During pre-cooling, when the number of openings is 4, 6, and 8, the total condensation on lychees is 1.45 g, 1.11 g, and 1.03 g, respectively. When the number of openings exceeds 6, the variation in condensation stabilises. With packaging openings numbering 4 and 6, condensation decreases by 23.67 %, while for packaging openings numbering 6 and 8, condensation decreases by 7.40 %.

3.3. Numerical simulation of stacked storage of lychee

The air distribution in the fresh-keeping test platform and the airflow distribution in the stacked packaging are shown in Fig. 12 The cold air entering the fresh-keeping test platform is hindered by the plastic baskets, flows along the surface, and flows out from the outlet, forming eddies in the fresh-keeping test platform. Part of the airflow enters the interior through gaps in the plastic baskets or diffuses to other areas.

Fig. 12 illustrates the temperature distribution of stacked lychees during the fresh-keeping process. As shown in Fig. 13A, when the refrigeration unit is turned on, the temperature of the lychees on the windward side decreases the fastest, while those on the leeward side and at the centre decrease more slowly due to the low airflow rate and slow convective heat transfer between the lychees and the air. This observation aligns with the results depicted in the flow field distribution diagram. As can be seen in Fig. 13B, when the air temperature reaches the lower limit of the temperature control range, the refrigeration unit turns off, causing the temperature inside the cold storage equipment to rise due to the heat load.

Fig. 14 illustrates the relatively humidity distribution in the plastic basket. During cooling, incoming wet air creates near 100 % relatively humidity inside the packaging, leading to condensation, while the leeward side lychees experience lower relatively humidity due to airflow obstruction and higher temperature. After refrigeration turn off, air relatively humidity in plastic decreases rapidly because of the raise in temperature, while the relatively humidity inside package is little varied.

Fig. 15 shows the distribution of lychee surface water loss rates. During the temperature control process, the lychees on the windward side had the slowest rate of water loss (4.00×10^{-6} kg m^{-3} s^{-1}) when the refrigeration was on because this area was most affected by the inlet

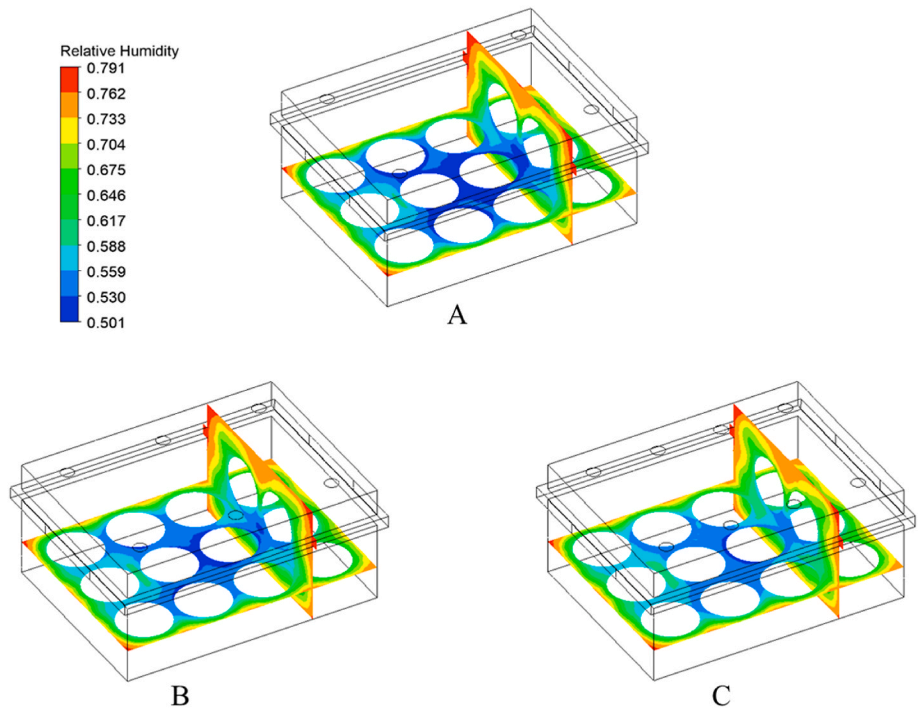

Fig. 10. Relative humidity distribution inside the package at the end of cooling with different number of openings.

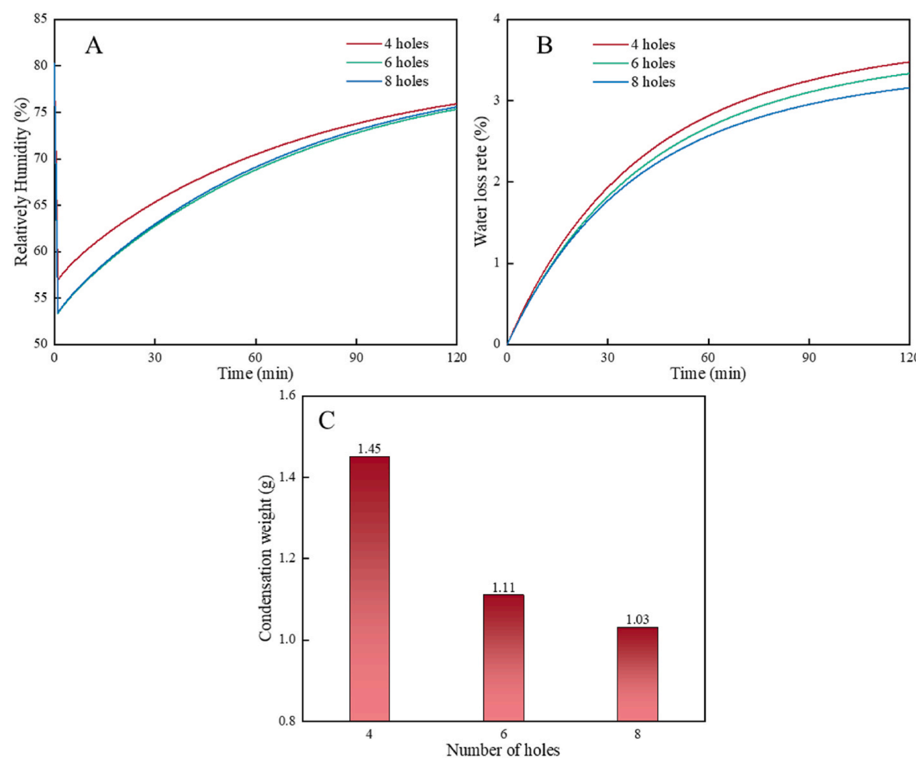

Fig. 11. Effect of packaging with different number of openings on moisture transfer: (A) Relative humidity; (B) Water loss rate; (C) Condensation weight.

cold air. When the refrigeration was switched off, the lychees near the wall warmed up the fastest due to the heat load, resulting in the fastest rate of water loss amount (2.45×10^{-5} kg m^{-3} s^{-1}).

Fig. 16A shows the condensation levels in stacked lychee packages, which increased with longer temperature control. Over 240 min, the average condensation was 2.39 g at windward side, 0.99 g at the middle, and 1.26 g at the leeward side, with 1.55 g per package. Higher condensation occurred near the entrance due to faster cooling and greater exposure to humidification, while the centre showed less due to stable temperature.

Fig. 16B illustrates the water loss rates of lychees at different positions within the plastic basket. The rates were 3.69 %, 4.58 %, and 4.88 % for the front, middle, and back, respectively. Lychees near the entrance experienced less water loss amount due to faster cooling and

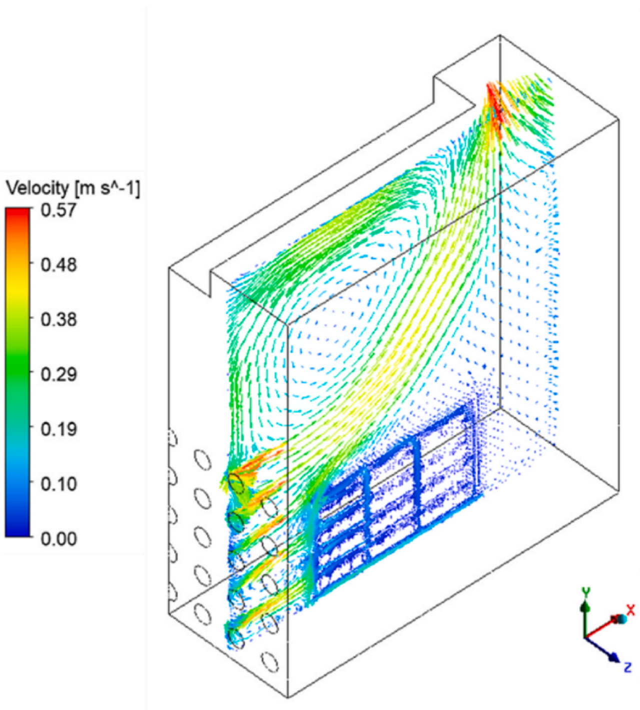

Fig. 12. Airflow distribution in the cold storage equipment.

higher humidity, which inhibited dehydration. Variations in water loss amount are influenced by factors such as air velocity, temperature, and relative humidity; cooling promotes water loss amount, while warming reduces it, resulting in minimal fluctuations during temperature control.

4. Discussion

In the numerical simulations examining the effect of varying the number of packaging openings, it was found that increasing the number of openings enhances the cooling rate of lychees, lowers the internal package temperature, and reduces both the water loss rate and condensation inside the package. These results align with prior studies showing that improved airflow through ventilation openings accelerates convective heat transfer, thereby reducing temperature gradients and moisture accumulation (Defraeye et al., 2013; Ferrua & Singh, 2011). For example, Bai et al. (2019) reported that increasing package openings reduces internal humidity but increases water loss amount in small fruits, whereas our study uniquely demonstrates that eight openings achieve a balance, reducing water loss amount by 9.18 % compared to six openings while minimising condensation. This discrepancy may stem from differences in fruit type (lychee *vs*. berry) and packaging geometry, highlighting the need for product-specific optimisation. Fig. 11 shows the airflow distribution within the cold storage equipment used in this study. The figure demonstrates that cold air entering the equipment is obstructed by the plastic basket, causing it to flow along the basket's surface and exit through an outlet, creating vortices within the test platform. Some airflow penetrates the interior through gaps in the plastic basket or disperses to other areas. Similar findings were reported by Ambaw et al. (2017). The low wind speeds observed inside the plastic basket and packaging box are therefore not effective for cooling the

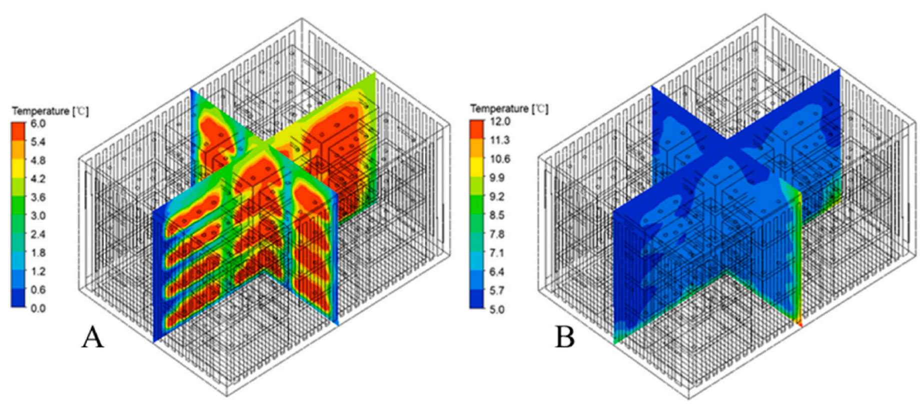

Fig. 13. Temperature distribution in the plastic basket: (A) switch on refrigeration; (B) switch off refrigeration.

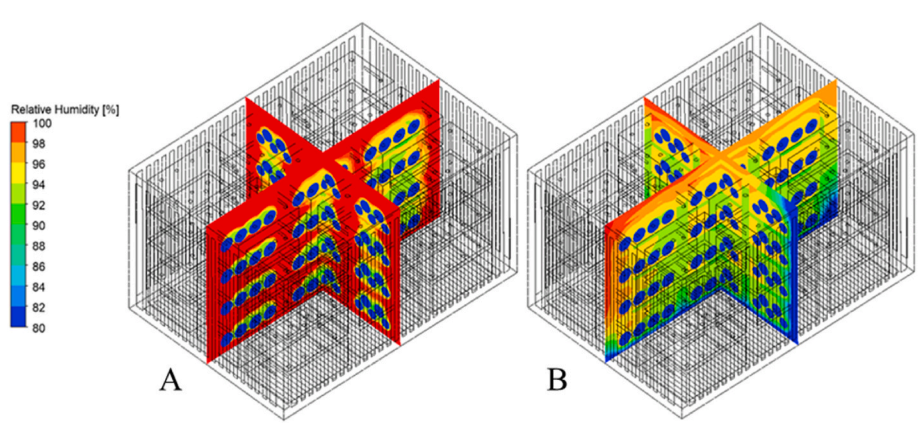

Fig. 14. Relative humidity distribution in the plastic basket: (A) switch on refrigeration; (B) switch off refrigeration.

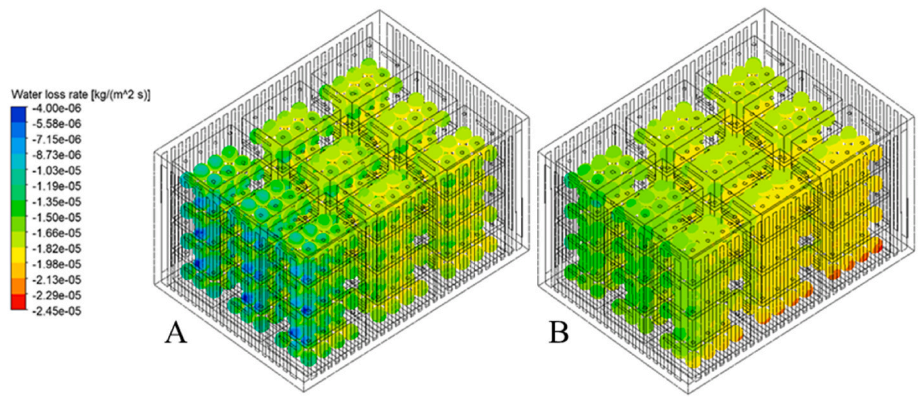

Fig. 15. Water loss rate distribution in the plastic basket: (A) switch on refrigeration; (B) switch off refrigeration.

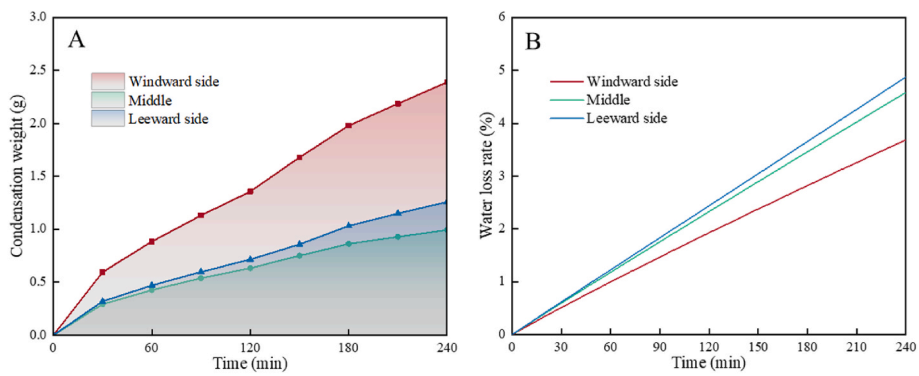

Fig. 16. (A) Condensation weight in packages at different locations; (B) Lychee water loss amount in packages of different positions.

lychees.

When the refrigeration unit is activated, the temperature distribution within the plastic basket corresponds to the airflow pattern: lychees facing the wind cool down the fastest, while those on the leeward side and in the middle cool more slowly due to lower air velocities and reduced convective heat exchange with the air. As temperature decreases, the saturation vapor pressure of the air also decreases, leading to higher relative humidity; thus, relative humidity is higher on the windward side than on the leeward side (Fig. 13A). The incoming airflow is cold and highly humid, exposing most of the stacked lychees to a high-humidity environment, with relative humidity approaching 100 %, indicating condensation within the packaging, as also observed by Schudel et al. (2022). Figs. 12–14 show that lychees on the windward side experience the lowest water loss amount due to low temperature and high humidity conditions. When the refrigeration unit is turned off, the stacked lychees warm up due to external heat loads from the platform and the respiration of the lychees. Lychees near the walls warm up the fastest, resulting in the lowest relative humidity and the highest water loss rates.

In Fig. 15A, the driving force for condensation is the difference between the mass fraction of water vapor and the saturation mass fraction of water vapor. The incoming high-humidity air increases the mass fraction of water vapor inside the package, exceeding the saturation level and causing condensation. On the windward side, the rapid cooling and significant temperature drop reduce the saturation mass fraction of water vapor, leading to the highest condensation levels. In contrast, the middle layer of the package maintains a more stable temperature, and the airflow is weaker due to obstruction from the windward-side package, resulting in the lowest condensation levels.

The water loss rate of lychees increases linearly during storage, suggesting that the on/off cycles of the refrigeration unit have minimal impact on water loss amount. Additionally, as the lychee position shifts towards the leeward side, the water loss rate increases, corresponding with the temperature distribution. This indicates that within the packaging box, airflow velocity is relatively low, making temperature the dominant factor influencing water loss amount.

5. Conclusion

In this paper, a model of cooling of single-PET packaged lychee in a forced-air duct and a model of stacked storage of packaged lychee were developed. And experiments were conducted to verify the reliability of the models. Through the numerical simulation of the forced ventilation process and the storage process, the following conclusions are drawn.

1) Increasing the number of package openings had a small effect on decreasing pre-cooling time of lychee but helped to improve internal airflow and pre-cooling uniformity.
2) The number of package openings significantly affected lychee's water loss rate, with the lowest rate observed when using 8 openings, leading to a 9.18 % reduction compared to 6 openings. More openings reduced internal humidity difference and condensation, especially with 6 openings resulting in a 23.67 % reduction in condensation compared to 4 openings.
3) In the actual storage and transportation process, there were differences in the water loss rate and condensation of packaged lychee at different locations, with less water loss amount but more condensation near the entrance. By maintaining the temperature at 5 ± 1 °C and relative humidity at 90 ± 5 %, condensation can be reduced, and water loss amount can be delayed.

The results of the study provide some references for the selection of external environmental parameters, packaging and temperature control strategies during the pre-cooling, storage, transportation, marketing, and preservation of lychee. However, this study only considered condensation on the package's inner wall, excluding that on the lychee surface and its effect on water loss amount, as well as condensate evaporation. Future models will incorporate these factors and visualise condensation regions, allowing for a more precise assessment of condensation impacts on lychee quality. This will aid in optimising packaging and storage to reduce quality loss and improve freshness preservation.

CRediT authorship contribution statement

Jicheng Lin: Writing – original draft, Validation, Methodology, Investigation, Data curation. **Xiaodan Zhang:** Validation, Software, Data curation. **Yihong Jiang:** Writing – review & editing, Software, Data curation. **Dongfeng Liu:** Validation, Data curation. **Wei Cai:** Validation, Data curation. **Guopeng Lin:** Validation, Data curation. **Zhiwu Ding:** Writing – review & editing. **Enli Lü:** Supervision, Funding acquisition. **Jiaming Guo:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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Data availability

The datasets used and/or analysis during the current study are available from the corresponding author on reasonable request.

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