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Numerical modelling of heat and mass transfer in vegetables cold storage

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Abstract

Heat and mass transfer phenomena occurring in cold storage chambers for vegetables have been modelled in the paper on the example of the experimental Chinese cabbage cold store. Special attention has been given to the problem of modelling of interrelationship between phenomena occurring in the bulk of vegetables and in the heat exchanger of a cooling unit, accomplished through User Defined Functions UDF so that the cooling capacity and the transpiration and respiration in the bed of cabbage were closely related. The comparisons between simulation and experimental results were conducted in order to indicate further improvements to the model.

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Introduction

1. Introduction

Unfavorable storage conditions in cold stores of fruit and vegetables may induce drying of the commodity or its low temperature injuries. Quantitative and qualitative losses may occur due to non-uniformity of environmental condition in the bulk. The most important factors affected the homogeneity in the bulk are velocity, temperature and humidity of air from the cooling unit, load arrangements and physical properties of vegetables and fruit. The numerical modelling of the cold storage chambers may be of great assistance in studying so complex relationships affecting the storage conditions.

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Fig. 1. Experimental cold store of Research Institute of Horticulture in Skierniewice, Poland: the view from the cooler; (b) geometric model of the cold store

The heat transfer in the cold stores is modelled in various ways. Authors of [1] modelled only the airflow in the chamber, assuming temperature to be constant across the room. Researchers in [2] incorporated a lumped model of the heat exchange between the cooler and the air. In the papers [3, 4] the cooler was regarded as a porous medium, with dominant inertial resistance, obtained taking into account losses due to wall friction, entrance and exit, acceleration and deceleration effects. Heat transfer in the bulk of produce is usually modelled using thermal equilibrium, neglecting the temperature difference between the produce and the air, as in papers [3, 4]. Thermal non-equilibrium approach, considering temperature difference between product and cooling air, was used in [2], but with the simplest heat transfer model neglecting thermal conductivity in the bulk. Recently, the authors of [5] compared both approaches (with thermal conduction in a bulk) for experimental cold store of apples with good agreement to experimental results.

The objective of our study was to model the airflow, heat and mass transfer in the storage chamber of Chinese cabbage, considering the cooling unit and the bulk of vegetables as a whole, in order to predict non-uniformity of velocity, temperature and humidity distributions inside the commodity, and consequently to determine the unfavorable storage conditions. The close relationship between the phenomena occurring in the bulk and in the cooler (the transpiration and respiration of vegetables and the required cooling rate) has been achieved through the User Defined Functions (UDF) in ANSYS Fluent. The numerical model was examined on the example of the experimental cold store of Research Institute of Horticulture in Skierniewice, Poland, shown in Fig. 1a.

2. Modelling transfer phenomena

The view from the cooler side of the investigated experimental storage chamber is shown in Fig. 1a. Its geometric model is presented in Fig. 1b. The overall dimensions were 2.05 x 4.33 x 2.93m. The chamber was loaded with 2629 kg of Chinese cabbage, packed in plastic boxes, arranged in a block of dimensions 1.8 x 2.8 x 2.17m occupying most of the space. Boxes of cabbage were placed on wooden pallets. There was also a column of boxes in the antechamber to the room, seen in Fig. 1b. The nominal data of ceiling-type unit cooler operating on glycol solution were: capacity 1148W and air flow rate 1105 m³/h. The flow of air was generated by three axial fans of 20cm of diameter rotating at 1300 rpm, placed at the outflow of the cooler.

In modelling - the geometry of the cooling unit was simplified to the heat exchanger regarded as a box of porous medium and fans - being infinitely thin plates with pressure jump depending on the local normal velocity component according to the fan performance curve obtained from manufacturer data. The swirling jets of air coming from the fans to the room where visualized by means of yarn tufts and measured. The currents of air blown out by the fans took the shapes of divergent cones. The angle of divergence was measured to be 80°±90°. The inclination angle of velocity vector with respect to the circumference of the fans was equal to 15°±20°. These factors were used to define the radial and tangential components of velocity with the aid of UDFs. The fan motors and other solid parts of the unit were
excluded from the domain of calculations. The flow resistance for the heat exchanger of cooling unit was estimated from nominal plate pressure losses equal to 6.7 Pa.

The bed of vegetables was modelled as a porous medium. In order to derive pressure losses coefficients due to viscosity and inertia the Ergun equation for non-spherical particles was applied, following Verboven formulation [6], containing the effective diameter (0.146cm) and the shape factor of the cabbage head equal to 1.42. The flow resistance through the cabbage bed was taken into considerations as an added momentum sink in the governing momentum equation. Density, specific heat and thermal conductivity of cabbage heads were regarded as temperature dependent. Defining functions were determined based upon composition data for cabbage found in ASHRAE Guide [7] and porosity of a cabbage head assumed 0.391 after [8].

Humid air supposed to be a mixture of oxygen, nitrogen and water vapour described by the species transport model without chemical reactions. The air was regarded as an ideal incompressible gas with physical properties being the fourth degree polynomial functions of temperature with coefficients taken from Fluent library.

In the case of heat generation inside a porous medium (the bed of vegetables and the heat exchanger of the cooler) solid and fluid phases are not in thermal equilibrium, so conservation equations of energy are solved separately for solid and fluid zones. They are connected by the heat exchanged through the fluid/solid interface and require the heat transfer coefficients to be determined. The most important factors affected heat and mass balance in a room are respiration and transpiration.

The respiratory heat generation rate was calculated by the formula taken from [9] \( W = \frac{10.7f}{3600}(\frac{a}{5} + 32)^g \), where \( t \) stands for temperature in °C. The respiration coefficients \( f \) and \( g \) for cabbage are equal to \( f = 6.0803 \times 10^{-04}, g = 2.6183 \) [7]. The model of transpiration is based on the equation [9]:

\[
m = k_t (VPL p_s - p_v),
\]

following the assumption that the driving force for the process is a difference in water vapour pressure between the surface of a vegetable and the surrounding air. The expression \( VPL \) stands for the water vapour pressure deficit. The water vapour pressure on the vegetable surface is lower than the water vapour saturation pressure at the commodity surface temperature \( p_s \) due to dissolved substances. The vapour pressure lowering coefficient \( VPL \) was evaluated after [9] at 0.99. The transpiration coefficient \( k_t \) is related to the convective mass transfer coefficient \( h_a \) according to the perfect gas law \( k_t = \frac{1}{h_a} \), where \( T \) – is the local absolute temperature of the boundary layer. The convective mass transfer coefficient \( h_a \) can be determined from Lewis correlation \( h_a = \frac{h_{tc}}{\rho c_p L e^{1/3}} \) assuming that \( Le = 1 \).

In this formula symbol \( \rho \) denotes humid air density, \( c_p \) stands for specific heat of humid air. The convective heat transfer coefficient \( h_c \) can be calculated from the Nusselt-Reynolds-Prandtl correlation [10] \( Nu = 2.19 Re^{\frac{1}{3}} Pr^{\frac{1}{3}} \) and the definition of Nusselt number \( Nu \) as \( h_{tc} = Nu \frac{k}{d_{pe}} \), were \( k \) stands for thermal conductivity of humid air.

In the case of heat exchanger of cooling unit the convective airside heat transfer coefficient \( h_{tx} \) was derived from the total heat transfer rate \( \dot{Q} \) (cooling capacity):

\[
h_{tx} = \frac{\dot{Q}}{A\eta (T_a-T_c) + L \frac{\rho c_p}{T_a} (p_v - p_s)^2},
\]

which contains sensible and latent heat transfer rates. The heat exchange surface area \( A=5.703 \text{ m}^2 \) was taken from nominal data of the cooler; \( \eta \) stands for averaged overall surface efficiency equal to 0.81 under wet conditions [11]; latent heat of water vapour condensation \( L \) was dependent on temperature. The quantities of the flow, temperatures \( T_a \) and \( T_c \), vapour pressure of surrounding air \( p_v \), and pressure in the boundary layer under saturation \( p_s \) were taken at each iteration from Fluent solver. The coefficient of condensation in the heat exchanger was calculated in the same way as the coefficient of transpiration in bed. In the presented model of heat and mass transfer in porous media, Reynolds Re and Prandtl Pr numbers were computed for local interstitial parameters of the flow, taken at each iteration from Fluent...
solver, so heat transfer coefficients in the cabbage bed and in the heat exchanger as well as heat of respiration rate were the functions of local flow parameters, and required communication with solver in order to acquire the actual quantities of the flow. The required cooling capacity $\dot{Q}$ was calculated from macroscopic heat balance, performed at the beginning of each solver iteration, by summing up in all computational cells of the cabbage bed heat generation rates due to transpiration/condensation effects, respiration of vegetables and due to heat gains/losses through boundaries of the store, computed based upon the flow quantities taken from the previous iteration. This data exchange and communication with Fluent solver was completed via specialized UDFs and User Defined Memories (UDM).

Heat and mass transfer phenomena in a cold store are governed by the continuity equation for the humid air, the Navier-Stokes momentum equation, two energy equations for fluid and solid zones of porous media and two species transport equations for oxygen and water vapour. The mass fraction of nitrogen is calculated as a supplement to 1. The governing equations are transformed to Reynolds Averaged Navier-Stokes RANS equations and closed by the realizable $k$-$\varepsilon$ model of turbulence. It was decided not to insert detailed conservation equations in the paper because of the lack of space. They can be easily found in ANSYS FLUENT Theory Guide.

Computational grid of 22736 163 control volumes was obtained in ANSYS Workbench 16.0 using cut cell method. The Parallel Fluent 16.0 with twelve parallel calculation processes was applied in the calculations. The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm was used because of its lower memory requirements. Calculations were carried out on the computer equipped with processor Intel (R) Xeon (R) 2.7 GHz with 256 GB RAM.

3. Results and discussion

During the post-harvest storage in the investigated cold room an experimental study was conducted in order to get environmental information required to examine the computational model. Velocity and relative humidity of air measurements were carried out in the mid-plane of the store above the load using mobile measuring system seen in Fig.1a. Velocity and humidity sensors travelled along the horizontal linear guide carried by a slide moving automatically between points of the measuring grid shown in Fig. 1b. Velocity was measured at elevations $V_1$-$V_4$ and relative humidity – at RH level. The data were collected at 8 verticals during 10 min. of rest at each position with frequency of 1 Hz. The air temperature measurements in the bulk of cabbages were also performed at 7 points marked in Fig. 1b in yellow.

Omni-directional transducers Delta Ohm HD103t were applied to measure the magnitude of velocity vector with air speed accuracy of $\pm 0.04 \text{m/s}$ in the range of $0\text{-}0.99 \text{m/s}$ and $\pm 0.2 \text{m/s}$ in the range of $1\text{-}5 \text{m/s}$. Relative humidity
was measured with an EE Elektronik sensor of J type with accuracy of 2.7% in the range above 90% RH and 1.5% below 90% RH. Air temperature in the bulk of cabbage was measured with T-type thermocouples Czaki (precision ±0.2°C).

Fig. 3. (a) Velocity distribution in the mid-plane of the chamber; (b) distribution of the convective cabbage-air heat transfer coefficient in the bulk in the section through the fan and antechamber

In the Fig. 3a the experimental and calculated results obtained at V1 and V2 levels are presented drawn as solid lines. There is also the range of changes of each measurement depicted as dots showing the lowest and the highest velocity readings at each grid point. The computed data extend beyond this range in many positions. Velocity distribution in the mid-plane of the chamber, shown in Fig. 3a, presents the air jet attached and detached to and from the ceiling. Its shape strongly affects the results at V1 level. Results obtained for V2 level, placed in less dynamic region, seem to be in better agreement with experimental ones. It is clearly seen from Fig. 2 that the range of velocity readings taken at the same position is fairly wide, so the airflow in the current blown out by the fans is highly turbulent and unstable. Three swirling jets interfere with each other, with ceiling of the room, walls, rough and changing in time (because of waving leaves of cabbages) top surface of the bed and with supports of measuring system. It can be stated that further work has to be undertaken in modelling the current of air from the cooler, and that the realizable k-ε model of turbulence proved to be insufficient in this case and other time dependent models should be taken into account.

Table 1. Comparison of experimental and calculated results

<table>
<thead>
<tr>
<th>Relative humidity at RH level [%]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental</td>
<td>88.4</td>
<td>88.2</td>
<td>88</td>
<td>87.9</td>
<td>87.2</td>
<td>89.1</td>
<td>89.7</td>
<td>88.8</td>
</tr>
<tr>
<td>calculated</td>
<td>84.9</td>
<td>84.9</td>
<td>85.1</td>
<td>85.3</td>
<td>85.3</td>
<td>85.3</td>
<td>85.3</td>
<td>85.3</td>
</tr>
<tr>
<td>δ_{RH} [%]</td>
<td>3.9</td>
<td>3.8</td>
<td>3.4</td>
<td>3.0</td>
<td>2.1</td>
<td>4.3</td>
<td>5.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature in the bulk [K]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental</td>
<td>274.36</td>
<td>274.36</td>
<td>274.13</td>
<td>273.93</td>
<td>273.93</td>
<td>274.00</td>
<td>273.94</td>
</tr>
<tr>
<td>calculated</td>
<td>274.41</td>
<td>274.44</td>
<td>274.28</td>
<td>274.3</td>
<td>274.29</td>
<td>274.28</td>
<td>274.26</td>
</tr>
<tr>
<td>δ_{T} [%]</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.14</td>
<td>0.13</td>
<td>0.10</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Comparison of experimental and calculated relative humidity at RH level and temperature in the bulk is presented in Table 1. Symbols δ_{RH} and δ_{T} mean relative differences of measured and computed quantities. Airflow in the chamber strongly affects the temperature and moisture content. The best agreement between calculated and experimental RH occurs to be at 5 vertical, at which the best coincidence in velocity magnitudes has been obtained. The other factors influencing relative humidity of air are models of transpiration and respiration of vegetables and their coupling with processes occurring in the cooler. Other correlations than used in this study may prove better in terms of agreement between
computed and experimental results. Despite the fairly poor agreement between experimental and simulation results of velocity and relative humidity, the air temperatures occur to be in good concurrence. Apparently, the airflow outside the bulk affected the conditions inside not as much as it was expected.

4. Conclusions

Modelling of so complex and dynamic airflow as in the cold room along with heat and mass transfer occurring in a bulk and in a cooler is a difficult task. The model of the flow presented in this paper allows for the coupling of heat and mass transfer phenomena in the bed of vegetables and in the cooler. It relates the capacity of the cooler to the heat gains/losses in the chamber and prevents relative humidity from uncontrolled growth, as it sometimes occurs during calculations near 100%RH and in the presence of water vapour generation. The excess of moisture condenses in the cooler. Non-equilibrium model of heat transfer in the porous medium and dependence of criterial numbers on local parameters of the flow enabled us to compute the spatial distribution of the convective cabbage-air heat transfer coefficient (Fig. 3b) in the bulk.

Although the present model allows us to have only qualitative insight into the flow patterns in the cold room, the predictions of temperature in the bulk and relative humidity of air can to be considered as very promising. Further work has to be undertaken in order to adjust model parameters to experimental data, mainly, in modelling the outflow from the fans. The other elements of the model have to be also developed and validated. The further works are going to involve more sophisticated model of determination of cooling capacity, including heat transfer between airside and the inside of the exchanger tubes and the frosting on the tubes and fins. More work has to be done in order to model biological processes in the vegetables. Additional problem which has to be solved is the generation of turbulence inside the bed of vegetables and on the boundary between the bulk and the chamber which has the great impact on the flow patterns and, in consequence, on conditions and heterogeneity in the bulk.

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References