NUMERICAL MODELLING OF HUMID AIR FLOW AROUND A POROUS BODY

Aneta BOHOJŁO-WIŚNIEWSKA*

*Division of Heat Engineering and Refrigeration, Białystok University of Technology, Białystok

a.bohojlo@pb.edu.pl

received 27 November 2014, revised 23 October 2015, accepted 26 October 2015

Summary: This paper presents an example of humid air flow around a single head of Chinese cabbage under conditions of complex heat transfer. This kind of numerical simulation allows us to create a heat and humidity transfer model between the Chinese cabbage and the flowing humid air. The calculations utilize the heat transfer model in porous medium, which includes the temperature difference between the solid (vegetable tissue) and fluid (air) phases of the porous medium. Modelling and calculations were performed in ANSYS Fluent 14.5 software.

Key words: Numerical Modelling, Heat Transfer, Air Flow, Mass Transfer, Chinese Cabbage

1. INTRODUCTION

Fresh vegetables and fruit are living tissues, which after being harvested undergo a number of biological processes. Most important of these – directly influencing the nutritional and commercial value – are: respiration, ripening, transpiration. The processes are greatly influenced by temperature and external air humidity. It is therefore essential for the product to be stored in optimal conditions - low temperature and adequate humidity - in order to minimize the product loss. Achieving such conditions in cold stores is possible thanks to cooling units with forced air circulation. Because of the number and complexity of the physical phenomena taking place in agricultural produce store chamber, this issue is a new and difficult field for Computational Fluid Dynamics (CFD).

Most of the publications concerning the cold storage, and the experimental data gathered in this field, suggest that air parameters in storage chambers are characterized by significant nonuniformity, both in the empty areas, as well as in areas occupied by storage containers (Moureh et at., 2009, 2009a, 2009b; Tapsoba et at., 2007; Ben Amara et at., 2004; Delele et at., 2009a, 2009b; Hoang et at., 2000; Than et at., 2008). This means that there are regions in the bed of vegetables where the temperature is too high, which causes the produce to dry, and areas where the temperature is too low, resulting in cold damages. Therefore there is a need to focus the research on finding a solution, which would eliminate, or at least significantly limit, this problem. Computational analysis done on an experimentally verified mathematical and computational model may serve as a tool for assessing the air parameters in cold storage, as well as the state of fruit and vegetable stored there, without the need to conduct time-consuming, expensive and complicated experimental analysis. It will be a relatively cheap and flexible tool for solving this problem.

Because of complex internal geometry of the vegetables bed in a cold store, and the scale difference between the storage chamber and a single vegetable, the most important element of the air flow model in a cold store is treating bed of vegetables as a porous medium. Direct modelling, i.e. modelling which includes the shape of vegetable is impossible in such a large space. The vegetables bed can be homogenized in two ways: taking into consideration the temperature difference between vegetables and flowing air, or disregarding it. In recent years there is a tendency in professional publications to include the temperature difference between the solid phase (vegetable) and the liquid phase (air) of the porous medium (vegetable load), because such a model of heat transfer better expresses the processes taking place in the load. The consequence of adopting this model of heat transfer is the need to determine the heat transfer coefficient on the boundary between solid and liquid phase of the porous medium.

The value of heat transfer coefficient depends on a number of factors, most important of which are: vegetable shape, load arrangement, pore velocity and local turbulence intensity (Kondjovan et al., 2006). Therefore it is a function of location within the load. Experimental determination of the heat transfer coefficient spatial distribution is very difficult, if not impossible. In this situation the Computational Fluid Dynamics (CFD) might prove useful. It allows us to model a small bed of vegetables directly, that is taking into consideration the shape of vegetables. This type of modelling does not require the knowledge of the heat transfer coefficients, provided that the model includes the heat conduction within the vegetables. The direct modelling allows us to determine surface heat flux between the vegetables and the flowing air, and consequently to determine the heat transfer coefficients at any point of the load treated as a porous medium.

The aim of this work is to present the preliminary stage of direct modelling on the example of humid air flow around a single element of the vegetable load (a head of Chinese cabbage) under conditions of complex heat transfer (i.e. including the heat conduction within the product). This will allow us to create a heat and humidity transfer model between the Chinese cabbage and the flowing humid air. Modelling and calculations were performed in ANSYS Fluent 14.5 software.

DOI 10.1515/ama-2015-0027

2. HEAT AND MASS TRANSFER MODEL BETWEEN A HEAD OF CHINESE CABBAGE AND THE FLOWING HUMID AIR

The flow of air around a single head of Chinese cabbage will be analysed in a test tunnel because in the said tunnel, the experiments of the heat and mass transfer between the suspended cabbage and the stream of humid air will be conducted. The geometric model of the cabbage and the tunnel is presented in Fig. 1.

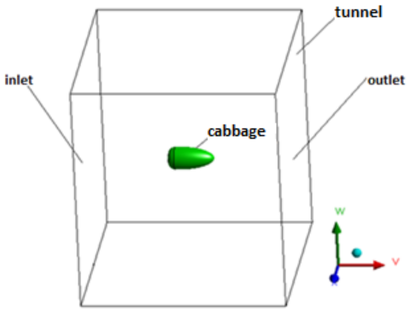

Fig. 1. Geometric model of the tunnel with a single element of the Chinese cabbage load, and the calculation domain

The actual shape of the Chinese cabbage (Fig. 2) and its internal structure are very complex.

Fig. 2. Chinese cabbage head

Fig. 3. Cross-section of a Chinese cabbage

Fig. 3 presents the cross-section of a Chinese cabbage. The photographs presented show that only 2 or 3 external leaves are slightly open at the top of a head. The rest of the leaves form a separate, porous structure, which is almost completely isolated from the surrounding air. Therefore in the proposed model we treat the inside of a Chinese cabbage as porous medium and assume that the airflow within the porous medium has a velocity close to zero, i.e. we assumed a very high resistance of the medium. The calculations do not take into account the porous structure of vegetable tissue (cabbage leaves).

The domain of solution is divided into subdomain occupied by the air flowing around the cabbage head (tunnel) and the subdomain of cabbage itself, modelled as a porous medium. The calculations utilize the heat transfer model in porous medium, which includes the temperature difference between the solid (vegetable tissue) and fluid (air) phases of the medium.

The porosity of the medium is defined as the ratio of the pore volume V_p to the total volume of the porous medium V (Strzelecki et at., 2008):

$$\varepsilon_m = \frac{V_p}{V} = 1 - \frac{\rho_p}{\rho_s}, \qquad 0 \le \varepsilon_m \le 1. \tag{1}$$

In the equation (1) ρ_p is the apparent density of the porous medium, and ρ_s is the true density of a solid (cabbage leaf). Porous medium is a fictitious continuum, with flow resistance equal to the resistance of a real obstacle. This resistance is included in the balance equation by adding an additional source term to the momentum equation (ANSYS FLUENT 14.5):

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|v|\,v_j\right), \tag{2}$$

where: i, j is the spatial direction (x, y, z), D_{ij} and C_{ij} are the resistance coefficient matrices, viscous and inertial respectively, μ – is the viscosity of fluid phase of the porous medium, including the turbulent viscosity, v_j – denotes the respective velocity component. In the model proposed, because of the Chinese cabbage internal structure, the convection within the medium is negligible. Therefore we assumed a very high resistance value, which almost eliminates motion of the medium.

The operating medium in the tunnel subdomain was humid air, treated as a non-compressible ideal gas, being a mixture of oxygen (O_2), nitrogen (N_2) and water vapour (H_2O) (species transport model without chemical reactions). The thermo-physical properties of O_2, N_2 and H_2O are dependent on the temperature according to the 4th order polynomial, according to ANSYS Fluent theory Guide 14.5. The cabbage subdomain was treated as a porous medium, where the solid material is the cabbage leaf tissue, whilst the fluid phase is the humid air. Within the porous medium we adopted a heat transfer model which includes the temperature difference between solid and fluid phases.

The flow in the computational domain is described by the continuity equation:

$$\frac{\partial(\varepsilon_m\rho_m)}{\partial t} + \nabla \cdot (\varepsilon\rho_m\vec{v}_m) = 0, \tag{3}$$

where: ε_m – is the porosity (for the *tunnel* subdomain ε_m= 1), ρ_m is the mixture density, v_m – its velocity, and the momentum equation which includes the natural convection term:

$$\frac{\partial(\varepsilon_m\rho_m\vec{v}_m)}{\partial t} + \nabla \cdot (\varepsilon_m\rho_m\vec{v}_m\vec{v}_m) = (\rho_m - \rho_0)g - \varepsilon_m\nabla p + \nabla \cdot \left(\varepsilon_m\mu_m(\nabla\vec{v}_m + \nabla\vec{v}_m^T)\right) + S, \tag{4}$$

where: p is the pressure, ρ_0 – reference density, and S – an additional source term resulting from the use of porous media model.

Because of the use of species transport model for describing the humid air flow, the system of equations is supplemented with two transport equations for oxygen and water vapour of the form:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho\,\vec{v}_m Y_i) = -\nabla \cdot \vec{J}_i + S_i, \tag{5}$$

where i-denotes the species, Y_i– is the „ i" species mass fraction, S_i –user defined source of „ i" species (Nitrogen mass fraction is defined as the supplement to 1). J_i is the diffusion flux of species „i" due to temperature and concentration gradients. In turbulent flow it is expressed as:

$$\vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right) \nabla Y_i - D_{T,i} \frac{\nabla T}{T}, \quad (6)$$

where: $Sc_t = \mu_t/\rho D_t$ is the effective Schmidt number for turbulent flow (μ_t – turbulent viscosity, D_t – the effective mass diffusion coefficient due to turbulence), $D_{i,m}$ – is mass diffusion coefficient for species „i", $D_{T,i}$ – is the thermal diffusion coefficient, T – temperature.

The species transport model allowed us to include the moisture source due to transpiration from the inner leaves of the cabbage (Si source in (5) equation for water vapour), as well as its diffusion.

Within the cabbage subdomain we will therefore solve two energy equations – one for air (7) and one for cabbage leaves (8):

$$\frac{\partial}{\partial t}(\varepsilon_m \rho_m E_m) + \nabla \cdot (\vec{v}_m(\rho_m E_m + p)) = \nabla \cdot (k_m \nabla T_m) - \sum_i h_j J_i + (\bar{\bar{\tau}}_{eff} \cdot \vec{v}_m) + S_m^h + h_{fs} A_{fs}(T_f - T_s), \quad (7)$$

$$\frac{\partial}{\partial t}((1-\varepsilon_m)\rho_s E_s) = \nabla \cdot ((1-\varepsilon_m) k_s \nabla T_s) + S_s^h + h_{fs} A_{fs}(T_s - T_f), \quad (8)$$

where: $E_m = h_m + p/\rho_m + v_m^2/2$ is the fluid phase (humid air) total energy and E_s – solid phase (Chinese cabbage leaves) total energy; T_m and T_s – the temperature of humid air and cabbage leaves, respectively; k_m is the fluid phase thermal conductivity (including the turbulent contribution); ρ_s, k_s – density and conductivity of the solid phase (leaves); h_{fs} – the heat transfer coefficient for the leaves-humid air interface; A_{fs} – is the interfacial area density, that is the ratio of the contact area between leaves and air to the volume of the porous medium (cabbage head), S_m^h, S_s^h – fluid and solid enthalpy source terms, respectively.

The heat transfer coefficient for the interface between vegetable tissue and the air within the cabbage was determined from the correlation for natural convection (Wiśniewski and Wiśniewski, 2000):

$$Nu = 0.13 Ra^{1/3}, \quad (9)$$

where the Nusselt number is defined as:

$$Nu = \frac{hl}{k}, \quad (10)$$

l – the length scale, k – heat conductivity, h – convective heat transfer coefficient.

Rayleigh number is given as:

$$Ra = GrPr. \quad (11)$$

Grashof number is defined as:

$$Gr = \frac{g\beta(T_s - T_\infty) l^3}{\nu^2}, \quad (12)$$

where: g – acceleration due to gravity, β – volumetric thermal expansion coefficient, ν – kinematic viscosity, T_s – surface temperature, T_∞ – bulk temperature.

Prandtl number is defined as:

$$Pr = c_p \frac{\mu}{k}, \quad (13)$$

where: c_p – specific heat, μ – dynamic viscosity.

The proposed model includes heat processes taking place in the vegetable, biological process – the heat of respiration, being the positive source in equation (8) and the heat of transpiration being the negative source in equation (7), due to evaporative cooling. In the water vapour transport equation (6) we include the positive source, due to transpiration from the surface of the cabbage leaves. They were placed in cabbage subdomain treated as a porous medium. In the presented model both heat and mass sources are treated as being constant.

In the paper the model SST $k-\omega$ was used. SST model utilizes the advantages of both models: $k-\varepsilon$ and $k-\omega$. The use of a k-ω model in the inner parts of the boundary layer makes the model directly usable all the way down to the wall through the viscous sub-layer, therefore the SST $k-\omega$ model can be used as a Low-Re turbulence model without any extra damping functions. The SST formulation also switches to a k-ε behavior in the free-stream and thereby avoids the common $k-\omega$ problem that the model is too sensitive to the free-stream turbulence properties.

The model is to be applied to the study of phenomena on the border of the bed – empty space in the cold storage then it is to be extended and used for modeling the whole cold storage. For this type of calculation model SST $k-\omega$ works better than other models (Delele et at., 2009a, 2009b, 2012; Norton et at., 2007).

3. COMPUTATIONAL MODEL

The grid was created in ANSYS Meshing 14.5 software. It consists of 2 126 006 control volumes, including: 10896 tetrahedrons, 105834 wedges, 9794 pyramids, 1927387 hexahedrons, 72095 polyhedrons. The grid was created using the cutcell method (Fig. 4).

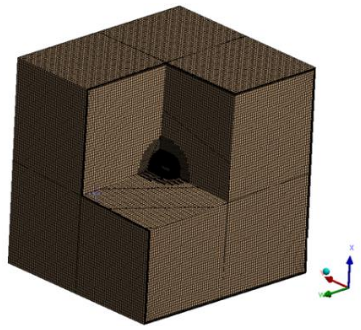

Fig. 4. Computational grid

Tab. 1. Volume, density and porosity of cabbage heads

	Mass	Volume	Volume of the leaves	Apparent density	Density of the leaves	Porosity
	[kg]	[l]	[l]	[kg/m³]	[kg/m³]	
Cabbage #1	0.86483	1.76265	1.12183	490.6419	770.91	0.363555
Cabbage #2	0.7495	1.29366	0.861	579.364	870.4994	0.334446
Cabbage #3	1.1135	1.997	1.19945	557.5864	928.3422	0.399374
Cabbage #4	0.6365	1.465	0.781836	434.471	814.1094	0.466324
			Mean values	**515.5**	**846**	**0.391**

The stability and precision of calculations are strongly affected by the computational grid quality. Cutcell is described by orthogo-

DOI 10.1515/ama-2015-0027

nal quality which ranges from 0 to 1, where values close to 0 correspond to low quality. Our minimum orthogonal quality was 0.296257.

a)
b)
c)

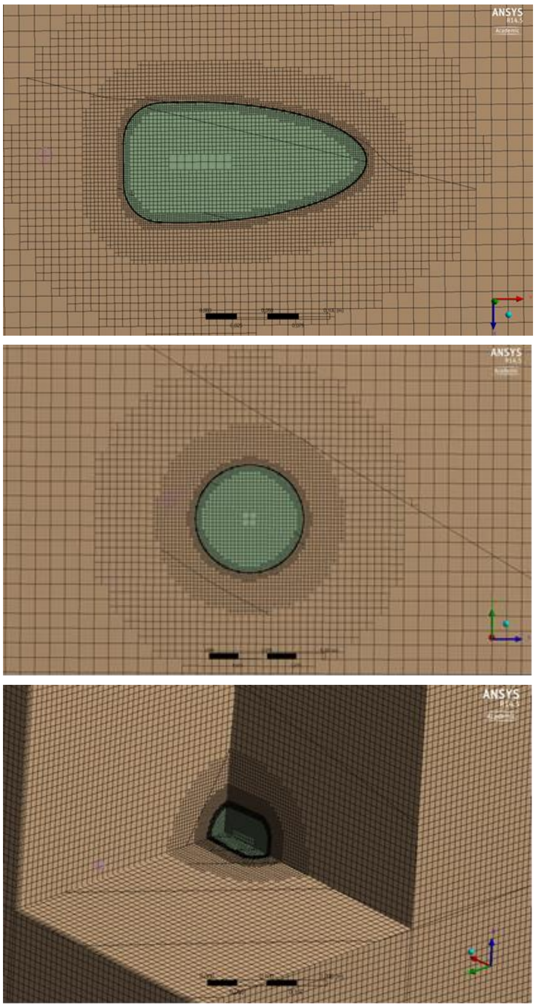

Fig. 5. The meshing of computational model: a) The grid in the symmetry plane of the *cabbage* domain, b) The grid is the cross – section of the *cabbage* domain, c) The grid of the *tunnel* and *cabbage* subdomains

Tab. 2. The area of the cabbage leaves (the interface between leaves and air)

<table>
<tr><th colspan="4">The total area of the leaves [m²]</th></tr>
<tr><td colspan="2">Leaves of cabbage #1</td><td colspan="2">0.95636</td></tr>
<tr><td colspan="2">Leaves of cabbage #4</td><td colspan="2">0.76182</td></tr>
<tr><td colspan="4">$interfacial\ area\ density = \frac{total\ area\ of\ the\ leaves}{volume\ of\ the\ cabbage\ head}$ [m²/m³]</td></tr>
<tr><td>Cabbage #1</td><td>542.5694</td><td rowspan="2">Mean value</td><td rowspan="2">531.293</td></tr>
<tr><td>Cabbage #4</td><td>520.0169</td></tr>
</table>

Some of the cabbage physical properties were taken from various publications, others were determined in experiments. Tab. 1 presents the volume, density and porosity determined experimentally for 4 different Chinese cabbage heads. The average of apparent density, the density of vegetable leaves and porosity were used as input data in numerical calculations. Specialized publications do not contain data for interfacial area for Chinese cabbage (Sadik et at., 2011, Uzokwe et at., 2012, Olfati et at., 2010), so the measurements were performed with a polar planimeter for two heads of Chinese cabbage. The calculations of the average interfacial area density inside the cabbage head is presented in the Tab. 2.

– The following data were used as the input data in the calculations:
– Inlet mass flow rate 3.938 kg/s (maximum mass flow measured experimentally in the channel in which in the future the experiment is planned), relative humidity 80%, air temperature 0.5 °C,
– Heat of respiration for Chinese cabbage at 0.5°C – 3590 kJ/ton/24h (Murata et al. 1992),
– Daily mass loss caused by transpiration, assumed as for white cabbage (no data available for Chinese cabbage) 0.233 % (Watkins and Nock, 2012),
– Thermophysical properties of Chinese cabbage at 0.5°C and relative humidity of 80%:
  - The density of the tissue 846 kg/m^3 (Tab. 1),
  - Density of the entire cabbage head (apparent density) 515,5 kg/m^3 (Tab. 1),
  - Moisture mass fraction for cabbage m=0.92 (Niesteruk, 1996),
  - Specific heat c_p= 1402+2785·m, c_p=3964.2 J/(kg·K) (Niesteruk, 1996),
  - Thermal conductivity k=0.8 W/(m·K) (Niesteruk, 1996),
  - Porosity ε=0.391 (Tab.1),
  - The mass loss of the load treated as a volume water vapour source: 1.39 x10^{-5} kg/m^3·s ,
  - The heat of respiration, treated as a volume heat source: 21.42 W/m^3,
  - The volume of the cabbage was 1,12·10^{-3} m^3,
  - Heat transfer coefficient 1.98 W/(m^2·K),
  - Interfacial area density 531,293 1/m (Tab. 2).

4. RESULTS OF CALCULATIONS

The calculations were performed on a PC computer with Intel Xeon 3,47 GHz CPU, 24 GB RAM with ANSYS Fluent 14.5 code and the Couple algorithm. The parallel environment with 4 parallel processes was used and calculations were done in double precision. The calculations lasted around 1800 iterations. The residual convergence was presented in Fig. 6.

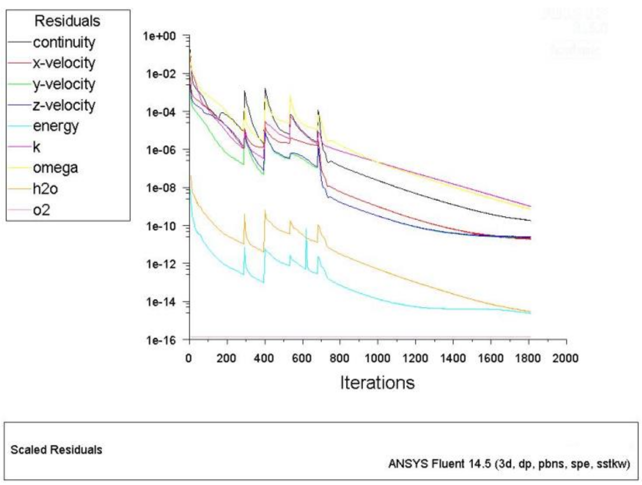

Fig. 6. Residual convergence

The result of calculations were presented in graphic form in Figs. 7-10. Fig. 7 shows the velocity distribution in symmetry plane of the tunnel. The maximum value was 3.84 m/s. A characteristic wake behind the cabbage can be clearly seen in the picture – it was the area of the lowest velocity. Inside the cabbage the velocity was almost equal to zero. The distribution of pressure was presented in the Fig. 8. Around leading edge of the cabbage there is a small area of higher pressure – around 1.5 Pa more than in the trailing area. In the area around the poles of the cabbage the pressure is at its lowest – approx. – 10 Pa. Inside the cabbage the pressure is equal to 0.36 Pa.

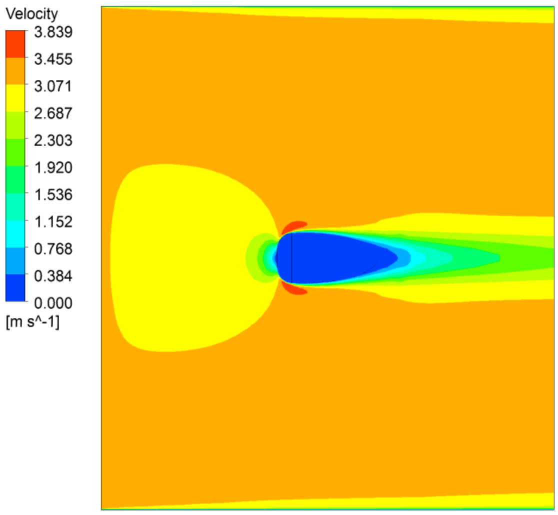

Fig. 7. Velocity distribution in the symmetry plane of the *tunnel*

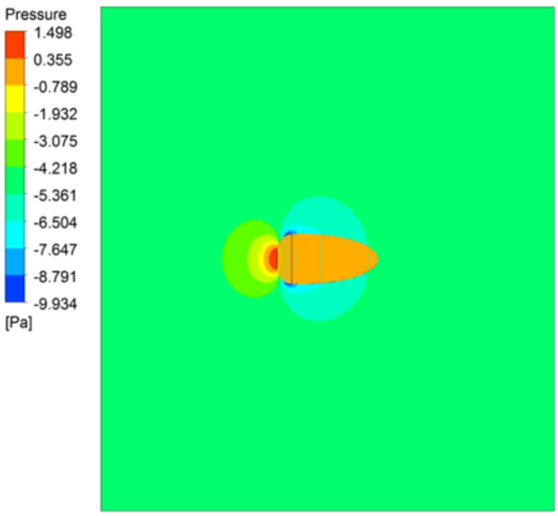

Fig. 8. Pressure distribution in the symmetry plane of the *tunnel*

The temperature contours in the symmetry plane of the tunnel are given in Fig. 9. The distributions of temperature in the tunnel and in the air inside the cabbage are presented in Fig. 9a, whilst in the tunnel and inside the vegetable tissue- in Fig. 9b. Each plot uses a separate temperature scale in order to present the relations in more detail. The highest temperature was observed in the solid phase (leaf tissue) of the cabbage of the porous medium – 0.536°C. The lowest temperature detected was 0.5°C – it was the temperature on the inflow and in the tunnel itself. Both figures clearly show the rise of temperature in areas near the Chinese cabbage head – which is caused by the heat source (heat of respiration). The total heat of respiration for the entire volume of the Chinese cabbage was 86.364 J/h.

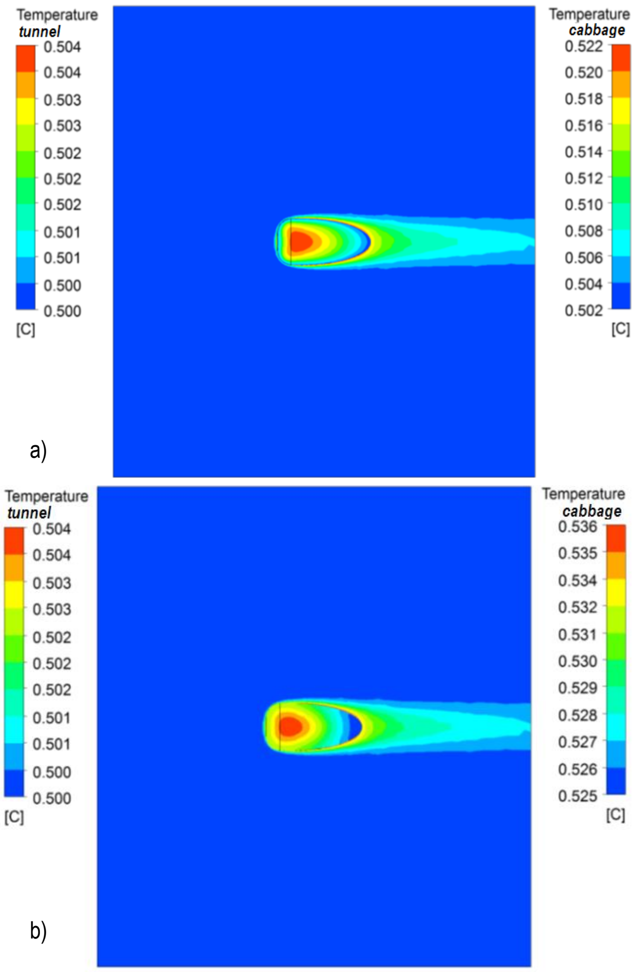

Fig. 9. Temperature distribution in the symmetry plane
a) in the *tunnel* and in the fluid phase (air) of a *cabbage*,
b) in the *tunnel* and in the solid phase (leaves of the cabbage)

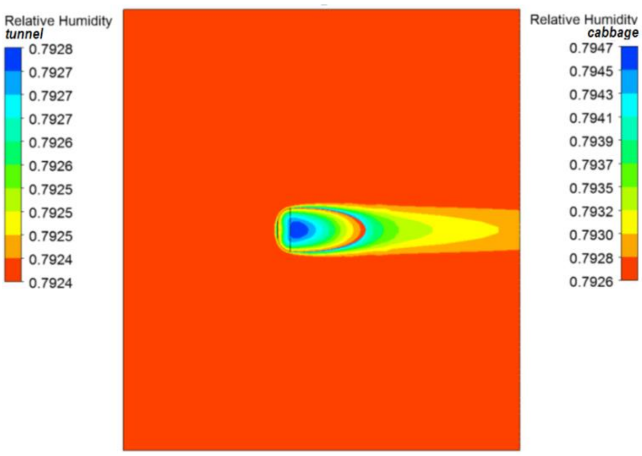

Fig. 10. Relative humidity distribution in *tunnel* and *cabbage* subdomains

Fig. 10 presents the distributions of relative humidity in the symmetry plane. The relative humidity distribution was presented in two different scales – one for air in the tunnel and one for air in the porous medium. In the picture we can see that the relative humidity rises near the cabbage; it is caused by the water vapour

DOI 10.1515/ama-2015-0027

mass transfer from the cabbage in the transpiration process. The water vapour seen on the outer surface of the cabbage is a result of transfer within the product. The water vapour emitted by the Chinese cabbage head was equal to 0.056 g/h.

5. CONCLUSIONS

In the paper preliminary computational model is presented which includes the temperature difference between the solid (vegetable tissue) and the fluid (air) phases of the porous medium representing the Chinese cabbage head. This model is able to calculate velocity, pressure, relative humidity and surface and inner temperature evolution of the vegetable. The temperature and relative humidity differences between the air and the cabbage are very small. Such differences are very difficult to measure in the experiment neither for one nor for a few cabbage heads. Experimentally it is possible to measure such small differences only in larger beds. Unfortunately for such a large space it is impossible to perform numerical computations by direct modelling approach. In the submitted computational model we are able to verify by experiment only velocity of the air.

In the future research it is planned to make the calculations on a larger number of heads of the Chinese cabbage in the test channel . In addition, in the computation model taking into account the intensity of the processes of evaporation and respiration dependent on the temperature and humidity by adding the UDF (User Defined Function) is planned. Unfortunately, the data on the Chinese cabbage are either difficult to reach or do not exist. They are incomplete, ambiguous and therefore some values (porosity of the cabbage head, interfacial area density, total area of the cabbage leaves) were determined experimentally. These processes require further experimental research.

The numerical calculations presented in the paper allowed us to test the computational model and helped to determine the important factors in the analysed problem. Further stages of the analysis will lead us to determine the spatial distribution of the heat transfer coefficient on the outer surface of the vegetable as a result of calculations of heat surface flux.

REFERENCES

1. **ANSYS FLUENT** Theory Guide.
2. **Ben Amara S., Laguerre O., Flick D.** (2004), Experimantal study of convective heat transfer during cooling with low air velocity in a stack of objects, *International Journal of Thermal Science*, 43, 1213-1221.
3. **Delele M. A., Vorstermans B., Creemers P., Tsige A. A., Tijskens E., Schenk A., Opara U.L., Nicolaï B.M., Verboven P.** (2012), CFD model development and validation of a thermo nebulisation fungicide fogging system for postharvest storage of fruit, *Journal of Food Engineering*, 108, 59-68.
4. **Delele M. A., Schenk A., Ramon H., Nicolai B. M., Verboven P.** (2009b), Evaluation of a chicory root cold store humidification system using computational fluid dynamics, *Journal of Food Engineering*, 94, 110-121.
5. **Delele M. A., Schenk A., Tijskens E., Ramon H., Nicolai B. M., Verboven P.** (2009a), Optimization of the humidification of cold stores by pressurized water atomizers based on a multiscale CFD model, *Journal of Food Engineering*, 91, 228-239.
6. **Hoang M. L., Verboven P., De Baerdemaeker J., Nicolai,** (2000), Analysis of the air flow in a cold store by means of computational fluid dynamics, *International Journal of Refrigeration*, 23, 127-140.
7. **Kondjoyan A.** (2006), A review on surface heat and mass transfer coefficients during air chilling and storage of food products, *International Journal of Refrigeration*, 29, 863-875.
8. **Moureh J., Tapsoba M., Flick D.** (2009a), Airflow in a slot-ventilated enclosure partially filled with porous boxes: Part I – measurements and simulations in the clear region, *Computers & Fluids*, 38, 194-205.
9. **Moureh J., Tapsoba S., Derens E., Flick D.** (2009), Air velocity characteristics within vented pallets loaded in a refrigerated vehicle with and without air ducts, *International Journal of Refrigeration*, 32, 220-234.
10. **Moureh J., Tapsoba S., Flick D.** (2009b), Airflow in a slot-ventilated enclosure partially filled with porous boxes: Part II - measurements and simulations within porous boxes, *Computers & Fluids*, 206-220.
11. **Murata S., Miyauchi K., Wang Y.** (1992), *Respiration Rate of Thirteen Kinds of Japanese Fresh Vegetables*, Laboratory of Agricultural Process Engineering, Faculty of Agriculture, Kyushu University 46 - 05, Fukuoka 812, Japan.
12. **Niesteruk R.** (1996), *Thermophysical properties of food*, Part 1 (in Polish), Wydawnictwo Politechniki Białostockiej.
13. **Norton T., Sun D., Grant J., Fallon R., Dodd V.** (2007), Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: A review, *Bioresource Technology*, 98, 2386–2414.
14. **Olfati J.A., Peyvast G. , Shabani H., Nosratie-Rad Z.** (2010), An Estimation of Individual Leaf Area in Cabbage and Broccoli Using Non-destructive Methods, *Journal Of Agricultural Science And Technology*, 12, 627-632.
15. **Sadik S. K., AL-Taweel A. A., Dhyeab N. S.** (2011), New Computer Program for Estimating Leaf Area of Several Vegetable Crops, *American-Eurasian Journal of Sustainable Agriculture*, 5(2), 304-309.
16. **Strzelecki T., Kostecki S., Żak S.** (2008), *Modeling Flow Through Porous Media* (in Polish), Dolnośląskie Wydawnictwo Edukacyjne.
17. **Tapsoba M., Moureh J., Flick D.** (2007), Airflow patterns inside slotted obstacles in a ventilated enclosure, *Computers & Fluids*, 36, 935-948.
18. **Than V. T., Vranken E., Berckmans D.** (2008), Data-based mechanistic modeling of three-dimensional temperature distribution in ventilated rooms filled with biological material, *Journal of Food Engineering*, 86, 422-432.
19. **Uzokwe E., Borokini T., Lawal I., Audu I., Adams A.,** (2012), Estimating the Leaf Area of Irvingia Gabonensis (Aubry-Lecomte ExO' Rorke) Baill from Linear Measurement, *Journal of Plant Studies*, 1(2), 2012.
20. **Watkins Ch. B., Nock J. F.** (2012), *Production Guide for Storage of Organic Fruits and Vegetables*, Department of Horticulture, Cornell University.
21. **Wiśniewski S., Wiśniewski T. S.** (2000), *Heat Transfer* (in Polish), Wydawnictwo Naukowo-Techniczne.

The paper was supported by project No. PBS1/A8/7/2012.