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# Numerical Modelling of Heat and Mass Transfer Processes in Chinese Cabbage Cold Storage Chamber

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## ABSTRACT

This paper is devoted to the numerical modelling of heat and mass transfer phenomena in the cold storage chambers of vegetables. The main objective of the paper is to work out the model relating cooling capacity of the cooling unit to the transpiration and respiration in the bed of Chinese cabbage, and to the other processes in the chamber. The thermal non-equilibrium model of heat transfer in porous media was applied both to the bed of vegetables and to the heat exchanger of the cooler. The heat and mass transfer coefficients in the bed of cabbage and in the cooler, and other thermal quantities were considered as field quantities. The results of calculations were compared to the experimental data. Good agreement between simulated and measured temperature in the bulk of vegetables was achieved. Improvements to the model as regards to the flow pattern were indicated.

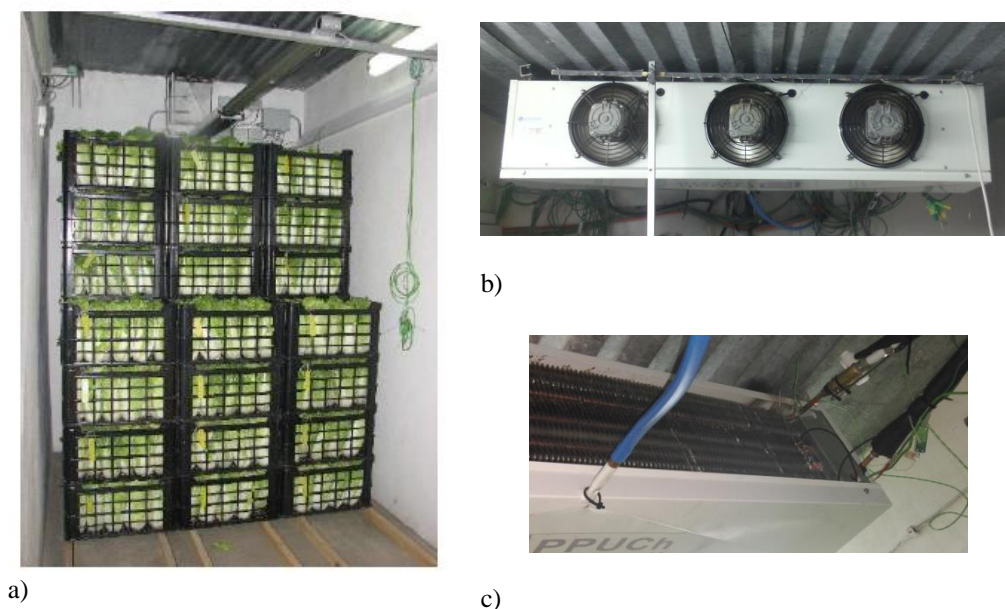
## 1. INTRODUCTION

Cold storage of fruits and vegetables may induce quantitative and qualitative losses due to unfavorable heterogeneity of storage environment. The macroscopic energy balance, usually used to design cold stores, cannot give the answers to the questions where storage conditions are going to produce the excessive drying or chilling injuries of the commodity. For this reason the CFD simulations of heat and mass transfer in the cold rooms occur to be very promising alternative to investigate the environmental conditions affecting the produce quality. The conditions in the bulk of vegetables depend mostly on velocity, temperature and humidity of air from the cooling unit, load arrangements and physical properties of vegetables and fruit. The numerical modelling of the impact of all these factors is less expensive, more convenient and can give the deeper insight into heat and mass transfer in the bed of vegetables than, for example, the experimental studies.

A distinctive feature of the storage chamber is a great variation in sizes of objects making its geometry. There are large empty spaces in the chamber, filled only with moist air, in contrast to very large areas occupied by huge number of small objects (pieces of produce in boxes or pallets, finned coils of a heat exchanger in the cooling unit). A geometric model of the cold store cannot maintain all the shapes of its relatively small details. For this reason a porous media approach is usually applied to model the air flow through the bulk of vegetables and the cooler.

In CFD modelling of the cold storage chambers the air cooler is usually simplified as to geometry and physics. In the paper by Nahor *et al.* (2005) the fan, making the air circulation, and the cooler were represented by body forces and resistance, taken from characteristics of these devices and distributed in a block of cooler dimensions. Hoang *et al.* (2000) took the effects of pressure rise in the fan and pressure drop in the cooler into account as a combined dynamic source in momentum equation, obtained from performance curves, applied in the direction of the local flow in the cooler. Hoang *et al.* (2015) modelled the swirling air jets from the fans by means of manufacturer data and measurements of air velocity at the outflow of the fans. In the papers by Delele *et al.* (2009a, 2009b) the cooler was regarded as porous medium, with dominant inertial resistance obtained from wall friction, entrance and exit, acceleration and deceleration effects.

The heat transfer in the cooler and in the bulk is modelled in many ways. Hoang *et al.* (2000) considered only the airflow in the chamber, assuming temperature to be constant in the whole room. Nahor *et al.* (2005) incorporated a macroscopic model of the heat exchange between the cooler and the air. Cooling capacity and condensation/evaporation effects in the cooler were also included into the model. Heat transfer in the bed of vegetables is usually modelled neglecting temperature difference between the produce and the air, e.g. in papers by Delele *et al.* (2009a, 2009b) and Chourasia *et al.* (2007). Thermal non-equilibrium model, considering temperature difference between the product and cooling air without conduction in the bulk was used by Nahor *et al.* (2005). In the paper by Xu and Burfoot (1999) the multi-scale model has been applied, including conduction inside separate products but neglecting conduction in a bed of vegetables. Hoang *et al.* (2015) compared the equilibrium and non-equilibrium models for experimental cold store of apples achieving a good agreement to experimental results. The conduction in the separate product was also introduced by the use of additional internal resistance.



**Figure 1:** The experimental storage chamber of Research Institute of Horticulture in Skierniewice, Poland; a) the view from the cooler side at the time of loading; b) the outlet from the cooler; c) the inlet to the cooler

The objective of this study is to develop a numerical model of the airflow in the storage chambers for vegetables on the example of the Chinese cabbage store of Research Institute of Horticulture in Skierniewice, Poland, considering the heat and mass transfer in the cooler in conjunction with processes occurring in the bulk of vegetables in order to investigate velocity, temperature and humidity distributions inside the commodity. The close connection between the transpiration and respiration of vegetables and the required cooling capacity of the cooler has been achieved through the User Defined Functions (UDF) in ANSYS Fluent. The model presented in the following section is the development of the model described by Kolodziejczyk *et al.* (2015). The results of simulation were compared with the results of measurements.

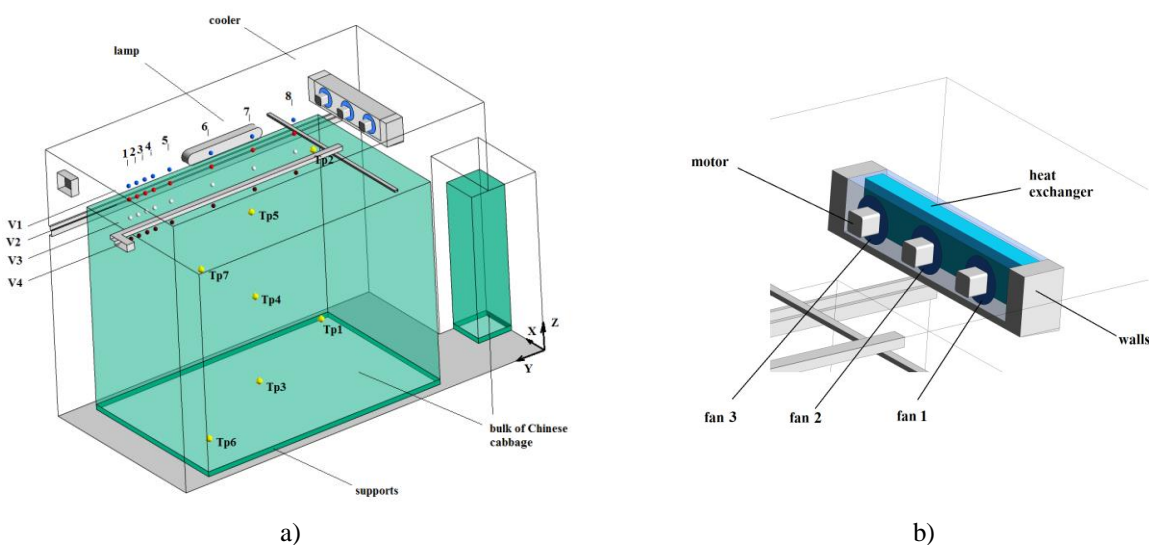
## 2. NUMERICAL MODEL

There is a view from the cooler side of the investigated experimental storage chamber in Fig. 1a. The geometry of the chamber and the load arrangement are shown in Fig. 2a. The overall dimensions were 2.05 x 4.33 x 2.93m. The room had an antechamber, seen in Fig. 2a. The chamber was loaded with 2629 kg of Chinese cabbage, packed in plastic boxes, arranged in one block of dimensions 1.8 x 2.8 x 2.17m occupying most of the space. Boxes of cabbage were placed on wooden supports. There was also a column of boxes in the antechamber, seen in Fig. 2. The ceiling-type unit cooler (Fig. 1b,c) was operating on glycol solution with nominal capacity of 1148W and nominal air flow

rate of 1105 m<sup>3</sup>/h. The airflow was generated by three axial fans of 20cm of diameter rotating at 1300 rpm, placed at the outflow of the cooler.

The geometry of the cooling unit was simplified (Fig. 2b) to the heat exchanger in the shape of a box of porous medium and fans - infinitely thin plates with pressure jump depending on the local normal velocity component according to the fan performance curve taken from manufacturer data. The rest of the unit was empty, filled only with moist air. The swirling jets of air coming from the fans to the room where visualized and measured. The currents of air took the shapes of divergent cones. The angle of divergence was equal to 80°÷90° and the inclination angle of velocity vector to the circumference of the fans was about 15°÷20°. On the base of these factors the radial and tangential components of velocity were defined by means of UDFs. The other solid parts of the cooling unit were excluded from the domain of solution. The flow resistance for the heat exchanger of cooling unit was estimated from nominal pressure losses equal to 6.7 Pa.

Moist air was modelled as a mixture of oxygen, nitrogen and water vapor described by 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 ANSYS Fluent library (2015).



**Figure 2:** Geometry of the experimental cold store

Thermophysical properties of Chinese cabbage were considered as temperature dependent in order to prepare the model to be used in transient simulations. Defining functions were determined from composition data for cabbage found in ASHRAE Guide (2006) and porosity of a cabbage head taken from Bohojlo-Wisniewska (2015). The bed of the cabbage was modelled as a porous medium. Pressure losses coefficients due to viscosity and inertia were calculated by the use of Ergun equation for non-spherical particles according to Verboven (2004). The flow resistance through the cabbage bed was taken into considerations as an added momentum sink in the governing momentum equation. Since heads of Chinese cabbage are fairly large, thermal non-equilibrium model of heat and mass transfer in porous medium was applied, so conservation equations of energy were solved separately for solid and fluid zones. They were connected by the heat exchanged through the fluid/solid interface and required the heat transfer coefficients to be determined.

Respiration and transpiration are the most important postharvest life processes affecting heat and mass balance in a cold room. The model of evaporation and condensation processes applied in the paper consists in the spatial distribution of volume water vapor sources or sinks in the regions modelled as porous medium (cabbage bed and heat exchanger) and consequently thermal effects of transpiration, condensation and respiration were also represented by volume sources.

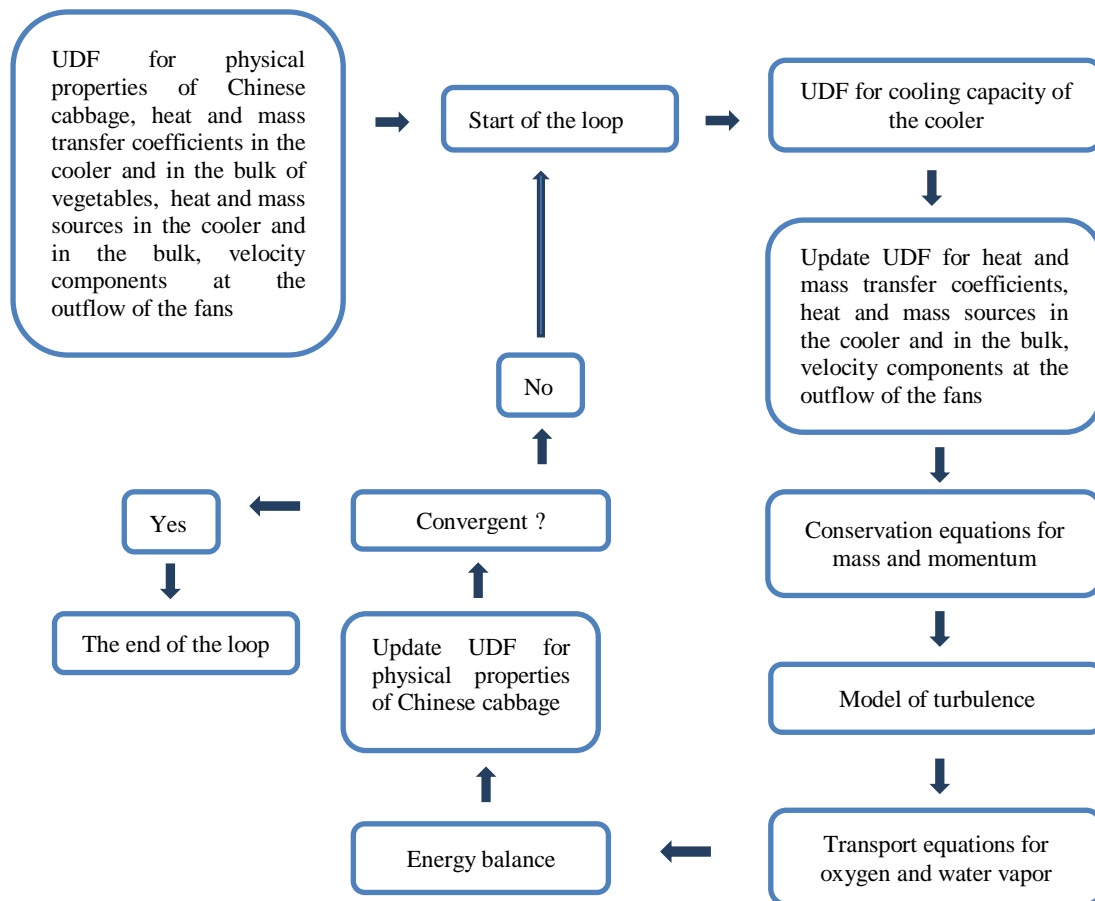
Transpiration was driven by vapor pressure deficit ( $p_s - p_v$ ) between the surface of a vegetable at pressure  $p_s$  and the surrounding air at  $p_v$  (Becker and Fricke, 1996). The mass of moisture transpired per unit area of cabbage surface per unit time in  $\text{kg}/(\text{m}^2 \text{ s})$  can be described by the following formula:

$$\dot{m} = k_t (p_s - p_v), \quad (1)$$

where  $k_t$  is the transpiration coefficient. The water vapor pressure on the vegetable surface  $p_s$  is lower than the water vapor saturation pressure  $p_{sat}$  at the commodity surface temperature due to dissolved substances and can be expressed as  $p_s = \text{VPL } p_{sat}$ . The vapor pressure lowering coefficient VPL was evaluated after Becker and Fricke (1996) at 0.99.

The transpiration coefficient  $k_t$  is composed of the air film mass transfer coefficient  $k_a$  and the skin mass transfer coefficient  $k_s$  as:

$$k_t = \frac{1}{\frac{1}{k_a} + \frac{1}{k_s}}. \quad (2)$$



**Figure 3:** The schematic diagram of UDFs usage

Skin mass transfer coefficient describes diffusional resistance to moisture migration through the skin of a cabbage head and is equal to  $2.5 \cdot 10^{-9} \text{ s/m}$  (ASHRAE, 2006). The convective mass transfer coefficient  $k_a$  is related to the mass transfer coefficient  $k'_a$ , for which the driving force is concentration, through the perfect gas law:

$$k_a = \frac{k'_a}{R_v T}, \quad (3)$$

where  $R_v$  stands for water vapor gas constant,  $T$  is the absolute mean temperature of the boundary layer. The coefficient  $k'_a$  was obtained from Sherwood-Reynolds-Schmidt correlation:

$$\text{Sh} = 0.374 \text{Re}^{0.934} \text{Sc}^{0.33}, \quad (4)$$

obtained on the base of heat and mass transfer analogy and experiments concerning determination of heat transfer coefficient for the Chinese cabbage bed described in Butrymowicz *et al.* (2015). The geometric scale in the Sherwood number was the mean effective diameter of the cabbage head evaluated at 0.146m.

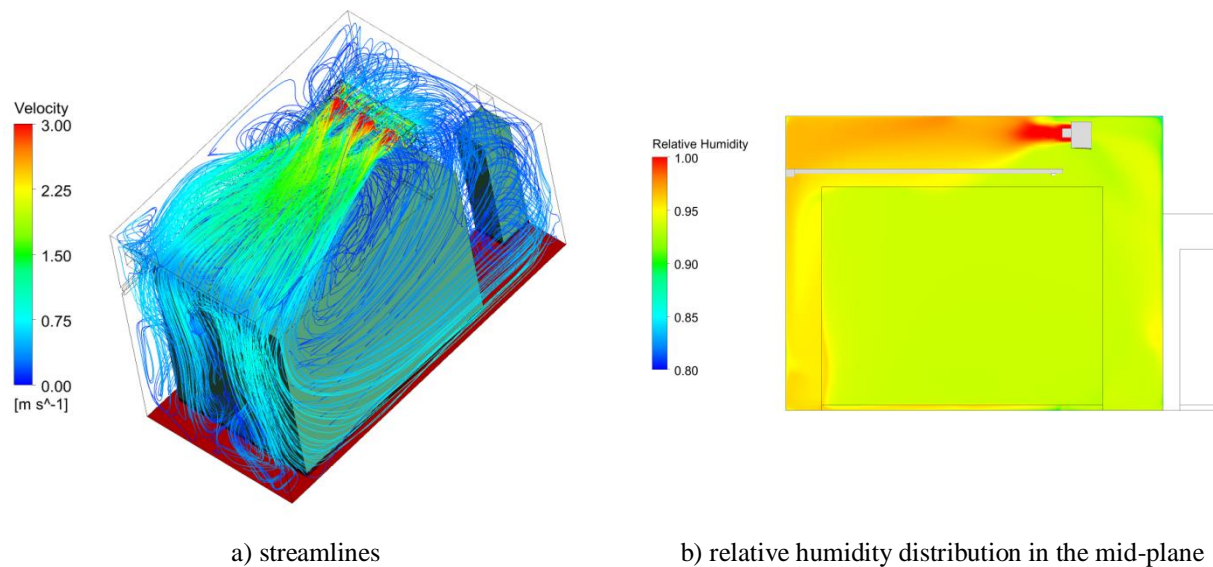
The convective heat transfer coefficient  $h$  was determined from Lewis correlation:

$$h = k_a \rho c_p \text{Le}^{2/3}. \quad (5)$$

In the above formula symbol  $\rho$  denotes humid air density and  $c_p$  stands for specific heat of air. The respiratory heat generation rate, in W/kg, was calculated from the formula (ASHRAE, 2006):

$$W = \frac{10.7 f}{3600} \left( \frac{9t}{5} + 32 \right)^g, \quad (6)$$

where  $t$  stands for temperature in °C. The respiration coefficients  $f$  and  $g$  for cabbage are equal to  $f = 6.0803 \cdot 10^{-04}$  and  $g = 2.6183$  (ASHRAE, 2006).



**Figure 4:** Graphical results of the simulations

The convective airside heat transfer coefficient  $h_x$  for heat exchanger in the cooling unit was derived from the cooling capacity  $\dot{Q}$  containing sensible and latent heat transfer rates:

$$h_x = \frac{\dot{Q}}{A \eta \left[ (T_a - T_{sat}) + \frac{L}{R_v T_a \rho c_p \text{Le}^{2/3}} (p_v - p_{sat}) \right]}. \quad (7)$$

The heat exchange surface area  $A$  was taken from manufacturer data of the cooler;  $\eta$  stands for averaged overall surface efficiency equal to 0.81 under wet conditions (Ma *et al.*, 2007); latent heat of water vapor condensation  $L$  was a function of temperature. Temperature  $T_a$  and vapor pressure of surrounding air  $p_v$ , temperature  $T_{sat}$  and

pressure in the boundary layer under saturation  $p_{sat}$  were taken at each iteration from Fluent solver. The coefficient of condensation in the heat exchanger was calculated by the use of Lewis correlation and the same procedure as in the case of the coefficient of transpiration for cabbage assuming that  $k_s = 0$ .

According to Kondjoyan (2006), heat transfer coefficients in the vegetables bed should be defined based upon the local parameters of the flow. This approach was applied in the present paper in order to compute Sherwood Sh, Reynolds Re and Schmidt Sc numbers. They were calculated for the mean interstitial quantities for humid air in the bulk taken at each iteration from Fluent solver. In consequence, all the heat transfer coefficients in the cabbage bed and in the heat exchanger as well as heat of respiration rate were the field variables and required communication with solver in order to acquire the actual quantities of the flow. The communication with solver completed via specialized User Defined Functions (UDF) and User Defined Memories (UDM) enabled us, moreover, to relate cooling capacity  $\dot{Q}$  to the processes occurring in the bulk and in the rest of the chamber. The whole procedure of data transfer is presented in Fig. 3 as a flowchart of UDF's calls in the course of one iteration. 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 and respiration of vegetables computed based upon the flow quantities taken from the previous iteration. The heat gains/losses through boundaries of the store also were taken into account. Before solving the governing equations heat and mass transfer coefficients, heat and mass sources in the cooler and in the bulk, and velocity components at the outflow of the fans had to be updated. At the end of each iteration the physical properties of Chinese cabbage were renewed.

**Table 1:** Temperature in the bulk of Chinese cabbage

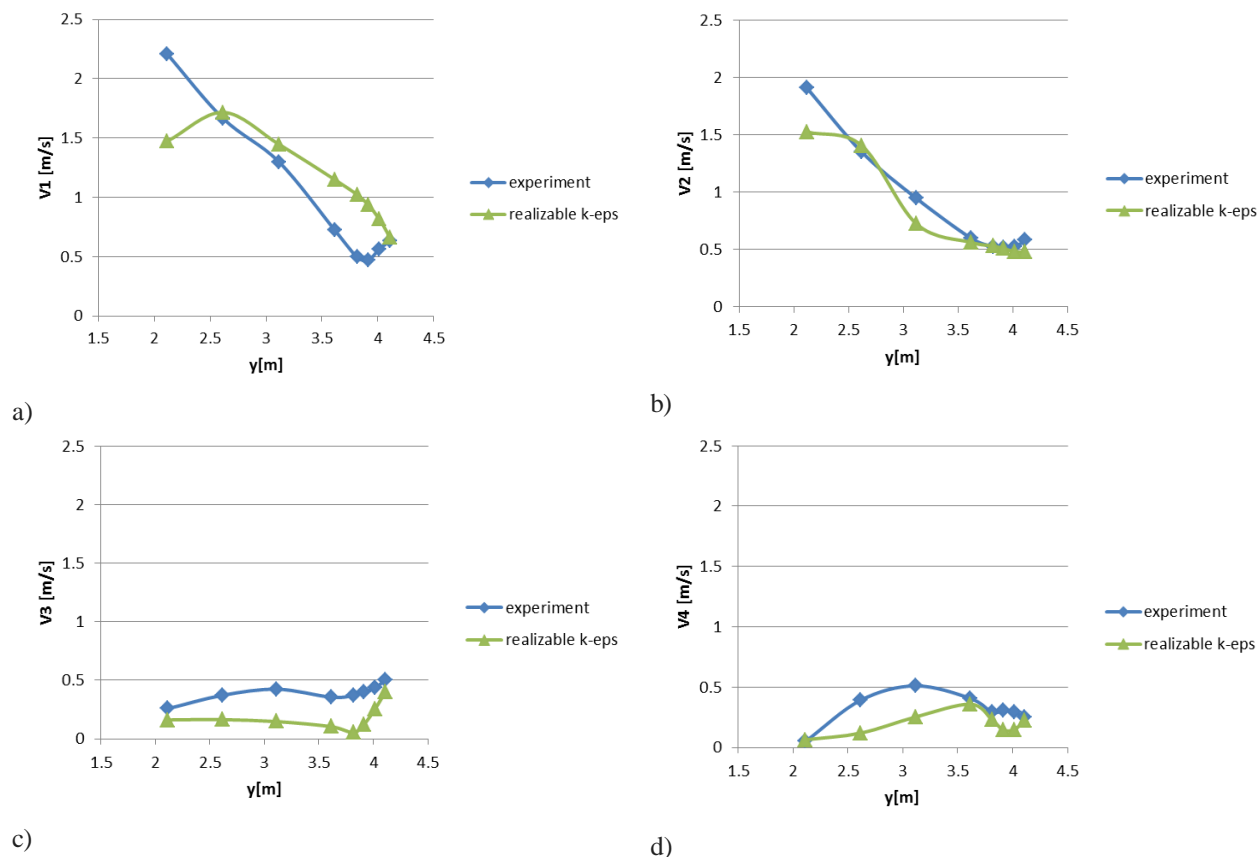
	<b>Tp1</b> [°C]	<b>Tp2</b> [°C]	<b>Tp3</b> [°C]	<b>Tp4</b> [°C]	<b>Tp5</b> [°C]	<b>Tp6</b> [°C]	<b>Tp7</b> [°C]
Experiment	1.21	1.21	0.98	0.78	0.78	0.85	0.79
Simulations	1.19	1.19	1.17	1.17	1.17	1.06	1.05

The governing equations for the airflow in the cold store are the continuity equation for the moist air, the Navier-Stokes momentum equation, two energy equations for fluid and solid zones of porous medium and two species transport equations for oxygen and water vapor. The mass fraction of nitrogen was calculated as a supplement to 1. The Reynolds time-averaging procedure has been applied to transform Navier-Stokes equations into RANS equations, closed by the *realizable*  $k-\varepsilon$  model of turbulence. The lack of space in the text was the reason not to include the conservation equations in detail. They can be easily found in ANSYS Fluent Theory Guide (2015).

ANSYS Mesher with *cut cell* method was used to obtain the computational grid of 22 736 163 control volumes. Calculations were carried out on the computer with processor Intel (R) Xeon (R) 2.7 GHz and 256 GB RAM by the use of SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm in Parallel Fluent with 16 parallel processes. SIMPLE algorithm was selected because of its lower memory requirements.

### 3. RESULTS AND DISSCUSION

A series of test calculations with the following models of turbulence for RANS equations were carried out: with the standard model  $k-\varepsilon$ , RNG  $k-\varepsilon$  and *realizable*  $k-\varepsilon$  (with enhanced wall treatment) and with the model SST  $k-\omega$ . There also was an experimental study performed during post-harvest storage in the investigated cold room with mobile measuring system. Velocity was measured with omni-directional transducers Delta Ohm HD103t at four different levels in the midplane of the chamber at grid points visible in Fig. 2a) (V1 - 5 cm below the ceiling, V2 - 20cm below the ceiling, V3 - 40cm from the ceiling, V4 - just above the bed, 63 cm from the ceiling). Air temperature in the bulk of cabbages was measured with T-type thermocouples Czaki at points marked in Fig. 2a) as Tp. The results of calculations obtained for *realizable*  $k-\varepsilon$  model of turbulence were the best matched to the results of measurements (Fig. 4).



**Figure 5:** The comparison of experimental and calculated results: a) velocity at V1 level, b) velocity at V2 level, c) velocity at V3 level, d) velocity at V4 level

The comparison of experimental and calculated temperature in the bulk is presented in Table 1. The highest difference equal to  $0.32^{\circ}\text{C}$  is at a point Tp7, that is in the upper left corner of the bulk looking from the cooler. From the presented comparisons one can conclude that the airflow in the chamber is modelled not sufficiently enough. The flow in the chamber is mostly affected by the swirling currents blown out by the fans (Fig. 4a). The flow at the outlet from the cooler and in the whole chamber is highly turbulent and unsteady. The direction of the velocity at the outlet was visualized by means of yarn tufts and measured, but the results of measurements of the velocity angles at the outflow are subject to high uncertainty arising from the mixing and interference of three air jets from the fans which has a great impact on the results of simulations. From authors' experience modelling of the outflow from the fans is the most important factor affecting the spots of attachment and detachment of the flow to the ceiling and, consequently, the flow in the chamber and in the bed of the vegetables. The second factor which may have the influence on the flow is the model of turbulence. The thermal conditions in the bulk of cabbages were in good agreement with the real ones (Tab. 1) except for the parts of the bulk most vented, as the box Tp7 and Tp6. Apparently, the airflow outside the bulk affected the conditions inside not as much as it is expected.

The relative humidity RH distribution is shown in Fig. 4b). The mean relative humidity in the empty space of the chamber reaches the value of 94.6%. The relative humidity in the bulk of cabbages is approx. equal to 93.5%. The heat transfer coefficient between the cabbage heads and the moist air in the bulk is modelled as a function of position and its mean value is equal to  $85 \text{ W}/(\text{m}^2 \text{ K})$  due to the fact that the water vapour partial pressure in the bulk (621.4 Pa) is much lower than the saturation pressure (664.3 Pa). There is a very intensive transpiration in the cabbage bed. The total vapour production of the bulk is equal to  $1.1 \cdot 10^{-5} \text{ kg/s}$ . The total heat of respiration rate in the bulk was  $48.4 \text{ J/s}$ .



The mean airside heat transfer coefficient in the heat exchanger of the cooler equals  $34.7 \text{ W}/(\text{m}^2 \text{ K})$ . Heat and mass exchange in the cooler was less intensive than in the bulk of vegetables. The total heat transfer rate (capacity of the cooler)  $\dot{Q}$  was  $244.1 \text{ W}$  and the total air flowrate of the cooler  $936.7 \text{ m}^3/\text{h}$ . The operating conditions of cooling unit were much less than nominal capacity and air flow rate.

#### 4. CONCLUSIONS

The numerical model and results of calculations of heat and mass transfer in a Chinese cabbage cold storage chamber are presented in the paper. The transpiration, respiration and heat exchange in the bulk of vegetables were considered in association with heat and mass transfer in the heat exchanger of cooling unit and accomplished through user defined functions UDF in order to relate cooling capacity to the processes occurring in the bed of cabbage. The thermal non-equilibrium model of heat transfer in porous media was applied both to the bed of vegetables and to the heat exchanger of the cooler. All the coefficient of mass and heat transfer were considered as field quantities. The connection between the vapor production in the bulk and condensation in the cooler is the distinctive feature of the model. This relation is very important under conditions close to saturation, which occurs very often in the cold rooms, because the species transport model does not contain any mechanism of condensation, and the relative humidity can easily exceed 100%, when vapor is produced in the bulk.

The results of calculations were compared with the results of experiments. The comparisons prove a good agreement with the experiment in the bulk temperature but the airflow in the chamber requires improvements to the model to be performed. The main difficulty is to deal with real swirling jets coming out from the fans, unpredictably mixing and interfering with each other and strongly affecting the conditions in the chamber. Although, the realizable k- $\epsilon$  model of turbulence was the best from all the tested ones, it seems to be insufficient in this case. Improvements in modelling of the outflow from the fans and turbulence should be performed simultaneously, which is a long and laborious process. Our future works are going to focus on transient simulations, which seem to better model so complex flow and heat transfer in the cold storage chamber. 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 can to be considered as very promising.

#### ACKNOWLEDGMENTS

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