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Experimental and numerical analysis of airflow in fruit and vegetable cold stores

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The fan operation for air circulation in cold stores of fruit and vegetables requires high energy use. An important energy saving potential is given by the optimization of the storage bins, the stacking layout in the cold stores as well as a fan control which is based on the airflow next to the product. In order to investigate these questions, the airflow patterns in two commercial storage rooms for apples and cabbage with common ventilation rate and dense bin stacking were analyzed with a CFD model and experimental measurements. The numerical results showed qualitatively high accordance with the airflow profile measurements. In both rooms the air circulated around the produce stack and areas of high and low air velocity were identified. Furthermore, it was shown that too dense stowing of the rooms and unfavorable positioning of the fans leads to inhomogeneous airflow distribution in the stacks.

Keywords
Cold store, fruit and vegetable storage, CFD simulation, airflow pattern, airflow sensor

Horticultural products are stored in refrigerated rooms worldwide. The operation of the cold stores requires high energy use. For example, a common apple CA storage room needs about 80–100 kWh electrical energy per ton and storage season. 30–40 % of this energy consumption is used for the ventilation (Kittemann et al. 2015). Air circulation in the storage rooms is necessary for removal of the field heat and respiration heat of the products. The air coolers in the cold stores operate with oppressive or sucking air duct through the evaporator. The technique of the sucking air duct effects higher throw distance of the air over the stacked product bins than the oppressive air duct technique (Duncan und Kizlauskas 2012).

During the last 15 years the interest has risen in analyzing of cooling and airflow conditions in precooling facilities, cold stores and transport units for horticultural products. (Ambaw et al. 2013, Duret et al. 2014, Moureh et al. 2009). Numerical fluid mechanics models are used for investigations of airflow patterns in cold stores (Nahor et al. 2005, Xie et al. 2006). Nahor et al. (2005) used CFD simulation (CFD: Computational Fluid Dynamics) for analyzing the airflow in a storage room which was partially filled with 8 pear bins (43 m^3). They showed that a vortex is formed in the empty zone in front of the bins. The formation of eddy flows was inhibited by rounding of the edges in a small storage chamber (37 m^3) (Xie et al. 2006). In a storage chamber (29 m^3), which was filled with 2 pallet loads of apple bins, punctual air velocities in a range of 0.22 to 1.2 m s^{-1} were measured in gaps between the bins and the room wall (Duret et al. 2014). Ambaw et al. (2015) used a CFD model in order to quantify the influence of the cooling regime on product cooling and the energy use during storage. Airflow patterns in practical storage conditions in industrial cold stores are widely unknown.

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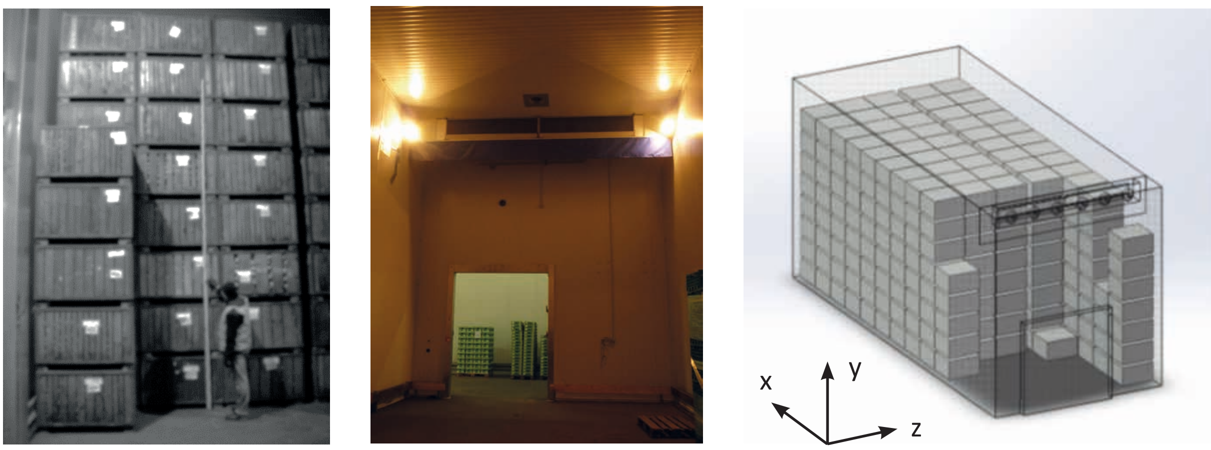
The research project named ‘COOL’ aims to modify the room layout and the ventilation regime in order to minimize the energy consumption by reducing the fan revolution without impact on produce quality.

In the presented study the actual conditions of airflow distribution in practical cold stores were analyzed by measurements of air velocity and CFD simulations. The objectives of the study were the identification of areas with particular low and high air velocity and the deduction of measures in order to achieve homogeneous airflow in the store if applicable.

Material and Methods

Cold stores

During the storage season 2015/2016 the airflow patterns in two industrial stores (apples and white cabbage) were studied with a numerical and an experimental analysis. The measurements were performed in an apple CA-storage room (Figure 1) at Havelfrucht GmbH, situated near Werder (Havel), Germany. The storage room (width 6.6 m, deep 15.2 m, height 7.0 m) had a capacity of 520 wooden bins (1.2 × 1.0 × 0.8 m), corresponding to 170 t apples. At the time of the measurements the room was partly filled beginning from the opposite side of the air cooler with 9 complete bin rows (360 bins) and several single stacks. The bins were stacked closely to each other with their long side (1.2 m) in the direction of the airflow except of leaving one gap of 20 cm width between the third and fourth bin row from the left side. The distances between the right and left room wall and the bin stack were 20 cm, respectively.

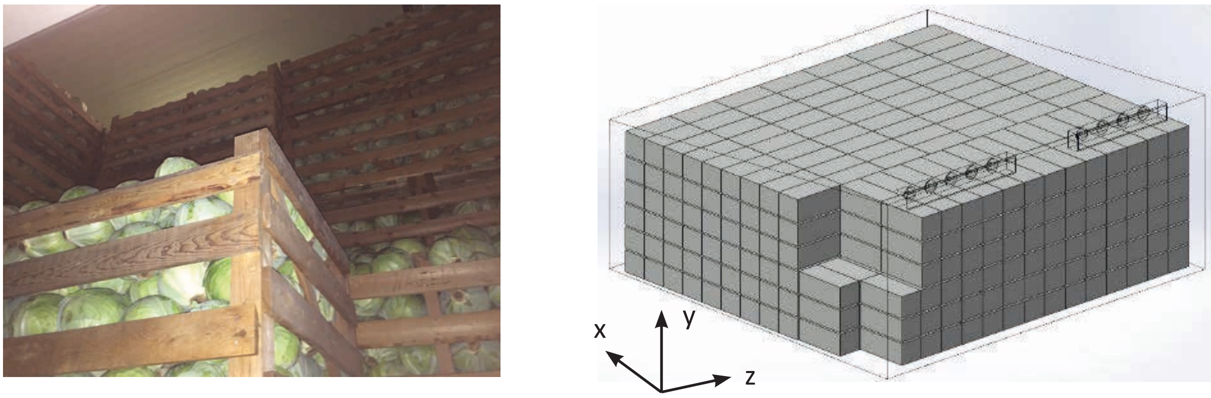


a) b) c)

Figure 1: a) bin stacking, b) air cooler (Photos: ATB) and c) schematic view of the apple storage room

The air cooler (type Helpmann THOR 268-7, Alfa Laval, Glinde, Germany, air flow rate 30,480 $m^3\,h^{-1}$, 6 fans) was attached at the wall above the door and fitted with a baffle plate and a film as sealing-off (Figure 1 b) and was running with oppressive air duct. The room was cooled to < 3 °C before the tests. The air temperature in the room increased to 3–6 °C due to frequent opening of the room and the interruptions of the ventilation between the measurements.

The cabbage storage room at Marne (Dithmarschen, Germany) had a capacity of 393 t of cabbage (524 bins). The bin size was 2.15 × 1.0 × 0.9 m corresponding to a volume of 1.94 m^3 and filled with 750 kg of cabbage. The bins were stacked closely without gaps between the bin rows. The first two bin rows were stacked along the cooling airflow direction placed below the two air coolers which were situated at one side wall. The other boxes were arranged in nine rows transverse to the direction of airflow streaming from the fans. Directly behind the door, the bins were stacked upward until the third bin (Figure 2), because the height of the door did not allow higher vertical stacking in this area. The room was equipped with two air coolers (GEA Küba, KÖ SG 104, Baierbrunn, Germany), which run in sucking air duct condition. The air cooler near by the door was equipped with 5 fans, the cooler at the rear had only 4 fans producing an air volume flow of 17,200 $m^3\ h^{-1}$. The room was constructed with a inclined ceiling. The wall side, where the air coolers were situated, was 0.7 m higher than the opposite side (Figure 2 b). The temperature set point was 1 °C. The air temperature increased temporarily up to 3 °C because the room was opened frequently between the measurements and the fan operation was interrupted several times.



a) b)

Figure 2: a) Bins of white cabbage (Photo: K. Oelrichs) and b) schematic view of the cabbage storage room

Numerical model

A CFD model was developed using the commercial software Ansys® CFX to analyze the airflow patterns in practical storage rooms. The model describes the flow behavior in the stacked bins and in the free flow volume around the bins. A porous media approach was used to calculate the flow pattern inside the bins. The porosity of the stack was determined using the bulk density (which is defined as the filling volume of the apple bin divided by the filling weight of the bin) and the particle density (Equation 1). The particle density was experimentally determined by measuring the air foundation (water deplacement). A particle density (ρ_P) of 826 kg m^{-3} and a bulk density (ρ_B) of 482 kg m^{-3} were found for the apple variety 'Jonagold'. The porosity (ε) of the apple bulk was 0.42 according to Equation 1.

$$\varepsilon = 1 - \frac{\rho_B}{\rho_P} \qquad \text{(Eq. 1)}$$

The porosity of the cabbage bulk was 0.55. The linear and quadratic pressure drop depends on local air speeds in the bulk. It is calculated with the Ergun equation (VDI 2006) (Equation 2) using the Sauter mean diameter d_s of particles (apple = 70 mm, cabbage = 200 mm).

$$\frac{\partial P}{\partial l_i} = 150\frac{1-\varepsilon^2}{\varepsilon^3}\frac{\mu\, u_i}{d_S} + 1{,}75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho_{air}\, u_i|\vec{u}|}{{d_S}^2} \quad \text{(Eq. 2)}$$

According to Equation 2 to 4 the permeability factors k_{perm} and k_{loss} were calculated for the model. For apples a permeability factor k_{perm} of $6.92 \cdot 10^{-6}$ m² (cabbage $5.65 \cdot 10^{-5}$ m²) and a pressure loss coefficient k_{loss} of 404.62 m^{-1} (cabbage: 141.62 m^{-1}) were found.

The Ergun equation was included in the momentum transport equation for turbulent flows in porous media (Equation 3 and 4).

$$\frac{\partial\varepsilon\rho_{air}\vec{u}}{\delta t} + \nabla\left(\rho_{air}\vec{k}(\vec{u}\times\vec{u})\right) + \varepsilon\nabla P = \nabla\left(\mu_{eff}\vec{k}\left(\nabla\vec{u} + (\nabla\vec{u})^T - \frac{2}{3}\delta\nabla\cdot\vec{u}\right)\right) + \vec{R} \quad \text{(Eq. 3)}$$

with

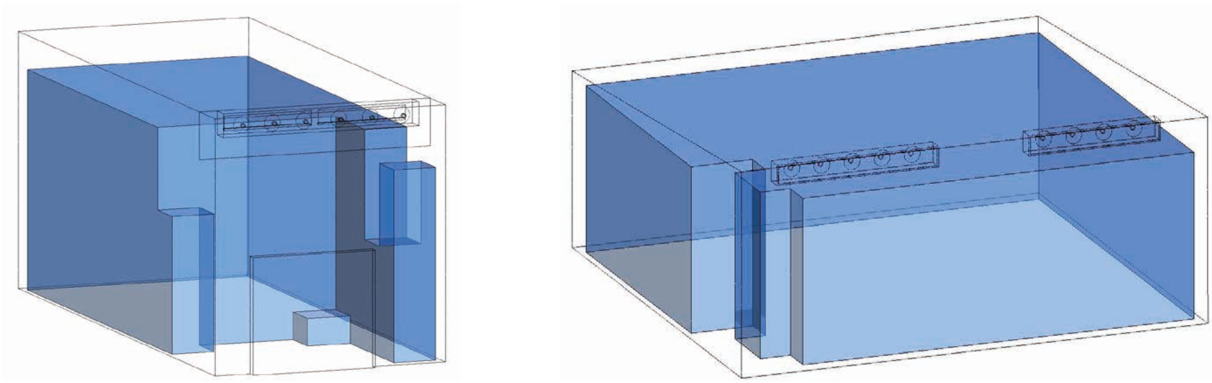
$$R_i = \frac{\mu}{k_{perm}}u_i + k_{loss}\frac{\rho_{air}}{2}u_i|\vec{u}|\ und\ \vec{k}_{ij} = \varepsilon\delta_{ij} \quad \text{(Eq. 4)}$$

The effective viscosity μ_{eff} of the model is calculated from the dynamic viscosity of the fluid and the eddy viscosity (determined by the RANS turbulence model) (Ansys 2016).

d_s	Sauter diameter	in m	$\vec{u}$	Velocity vector	in m s^{-1}
i, j	vector component		u_i	Velocity vector component	in m s^{-1}
k	Free flow path length	in m	δ	Porosity tensor	
k_{loss}	Loss coefficient	in m^{-1}	ε	Porosity	
k_{perm}	Permeability	in m^2	μ	Dynamic viscosity	in kg m^{-1}
l_i	Flow path length	in m	μ_{eff}	Effective dynamic viscosity	in kg m^{-1}
P	Pressure	in kg m^{-1} s^{-2}	ρ_{air}	Air density	in kg m^{-3}
R	Pressure loss in bulk	in kg m^{-1} s^{-2}	ρ_B	Bulk density	in kg m^{-3}
t	Time	in s	ρ_P	Particle density	in kg m^{-3}

Figure 3 a shows the model of the apple storage room and Figure 3 b the model of the cabbage storage room. In both models the stack was represented as porous block. The porosity values of the bulks were used as model porosity. The ANSYS® meshing tool was used to construct the grid of the calculation domain. The discrete model of the apple storage consists of 22,935,088 volume elements and the discrete model of the cabbage storage consists of 7,365,957 volume elements, while the smallest node spacing is 0.1 mm in the boundary layer.

For the model of the apple storage room (Figure 3 a), the evaporator outlet was defined as inlet boundary. For the simulation of the cabbage storage room the fan outlet was defined as inlet boundary. The measured flow velocity of the evaporator outlet (apple storage) or fan outlet (cabbage storage) were used to define the inlet velocity for these boundaries. These velocities amounted to 3 m s^{-1} in the apple store and 5 m s^{-1} in the cabbage store. At the fan inlet (apple store) or evaporator inlet (cabbage store), respectively, a relative pressure of 0 Pa was assumed as outlet boundary condition. “No slip” conditions were used to describe the boundary flow along the storage wall. The geometric interface between the porous medium and the free flow volume was defined as “general grid interphase” GGI (Ansys 2016). The ideal gas law was used to describe the physical properties of the air. In the model a constant air temperature of 0 °C was defined. Consequently, all thermal effects affecting the airflow were neglected. The assumed static pressure of the calculation domain was 1.013 bar (standard atmosphere). During the calculation the actual pressure in the domain was calculated as the gravitational corrected static pressure and the dynamic pressure according to the airflow profile.

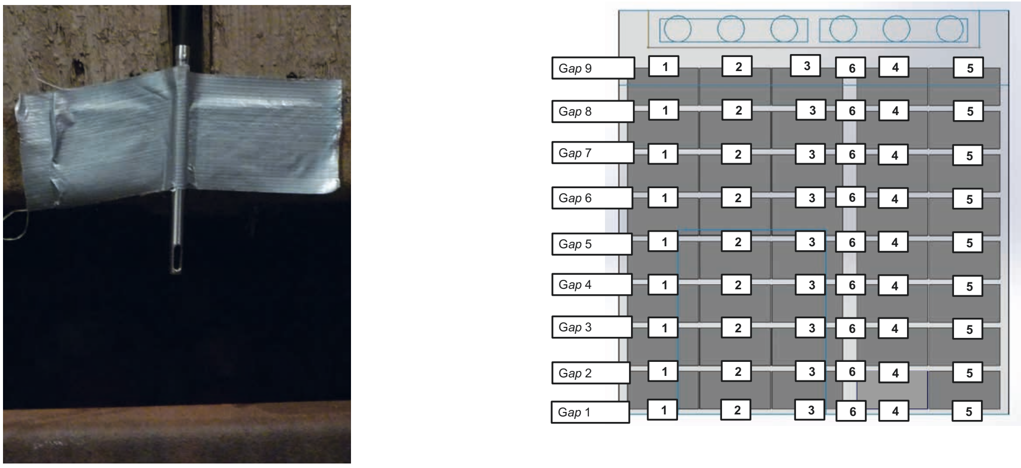


a) b)

Figure 3: a) Model geometry of the apple storage room and b) the cabbage storage room

Experimental test procedure

Directional hot wire anemometers with a measuring range of 0.08–2 m s^{-1} (FVAD TH4, resolution 0.04 m s^{-1}, accuracy 1 %) and a measuring range of 0.2–20 m s^{-1} (FVAD TH5, resolution 0.2 m s^{-1}, accuracy 2 %) were used for the measurements of airflow velocity. The measurements in the apple store were performed during storage of apples to the room in autumn. The anemometers were fixed at the accessible sites of the bin stacks (at the door side of the room) for measuring the air velocity in the horizontal gaps over the whole height of the stacks. (Figure 1 and 4). The air velocity was measured with the directional sensors in x-direction of the room. The measurements were carried out successively in the horizontal gaps (measurement interval 1 s, time 1 min), each one time. In addition, in the wide gap (20 cm) between the third and fourth bin stack from the left side in the horizontal gaps 2, 4, 6 and 8 airflow was measured in z-direction (horizontal), i.e. in 90° angle to the previous measurements (Figure 1 and 4).



a) b)

Figure 4: a) Sensor arrangement (Photo: ATB) and b) measurement positions in the apple store

Above the bin stack in the cabbage store the air velocity was measured at 12 different positions with the hot wire anemometers (interval 1 s, time 1 min, respectively) at a height of about 25 cm (Figure 9). Owing to the slope of the ceiling it was impossible to do measurements in the rear area of the storage room (Figure 2).

Three anemometers were attached on a stick in order to hang up them at the lateral boards of the bins. Thus, simultaneous measurements in three directions (x, y, z, Figure 5 a) were realized (interval 1 s, time 3 min, the stick was temporary hold in the hand). The values in x- and z-direction were measured about 2–3 cm in front of the boards, in z-direction inside the bin direct behind the boards. Furthermore, the air velocity was measured in the middle of the gap between the room wall and the bin stack at a height of about 1 m at two positions (Figure 5 b, 10 a).

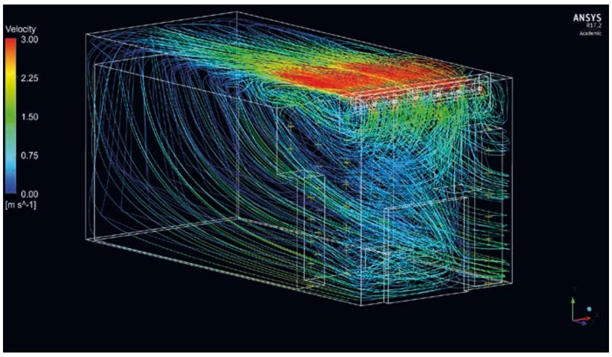
a) b)

Figure 5: a) Air velocity measurement in three directions in front of the bins in the gap between bin stack and room wall, b) gap between bin stack and room wall below the air coolers (Photos: ATB)

Results and discussion

Numerical simulation

The airflow simulation showed in both storage rooms the forming of an air roll (Figure 6 and 7). The airflow range of the fans in the apple storage room was wide enough to overcome the free space in front of the door. Thus, a circulation of process air was ensured. A vortex was formed in the free space near the ground and a light short circuit flow occurred close to the fans. The mean air velocity close to the ceiling is 3 m s^{-1} and the mean air velocity in the stack is 0.1 m s^{-1}, whereat the flow rate in the stack close to the fan is slightly higher than in the rear area of the storage room. In the lateral pile right next to the door, the flow velocities were also slightly lower. The air velocities in the gap between the stack and the wall were 0.8 m s^{-1} up to 1.3 m s^{-1}. The flow vector plots do not indicate any vortexes within the stack.



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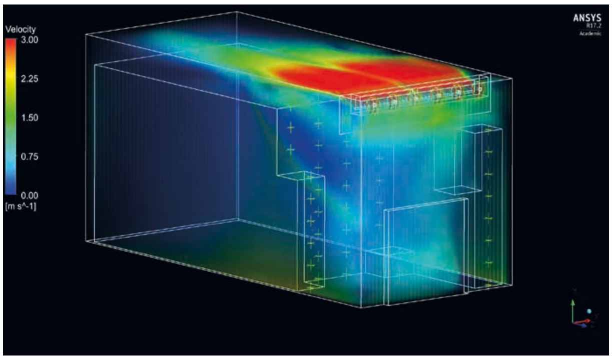

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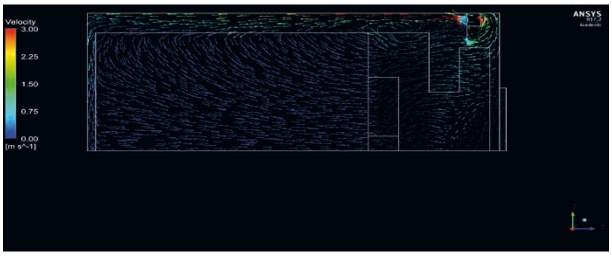
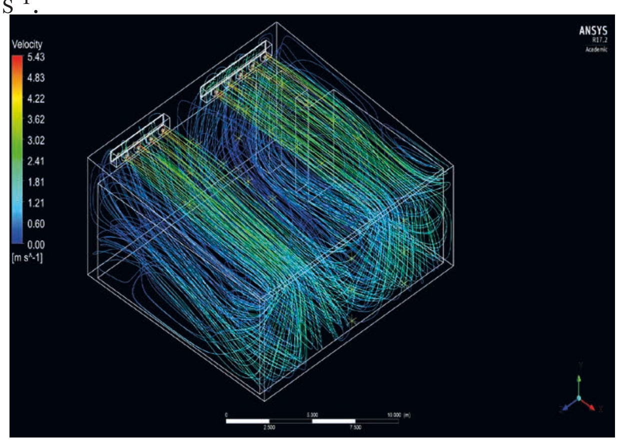


c)

Figure 6: CFD simulation of the apple store: a) 3-D view of the streamlines , b) 3-D view with measuring positions (yellow crosses) and c) cross section of flow distribution

The flow distribution in the cabbage storage (Figure 7) is inhomogeneous compared to the flow distribution in the apple storage due to the arrangement of the two evaporators. Inside of the stack the flow rate is at 0.4 up to 0.8 m s^{-1}. A vortex occurs in the stack which reduces the real air circulation rate. However, the air velocity is higher (approximately 1.3 m s^{-1}) at the bottom of the stack and directed towards the evaporator. The throw distance of the fans of the evaporator is sufficient to bring the air to the rear end of the cold store. The inclined slope of the ceiling of the storage room pressed the air at the rear of the room in the bin stack which leads to high air velocities (up to 2 m s^{-1}) next to the product. In the lateral slit between the stack and the bearing wall the air velocity was in the range of 0.4 up to 0.8 m s^{-1}.



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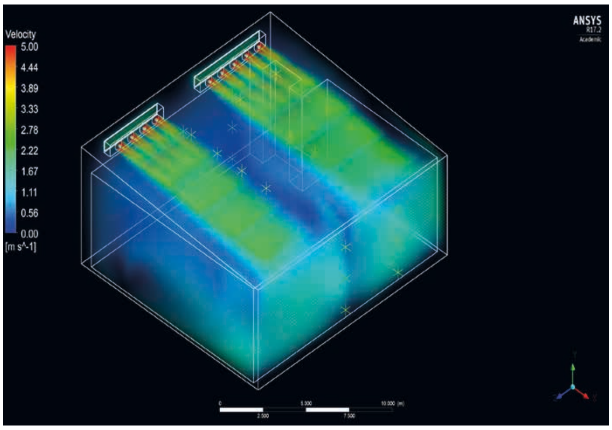

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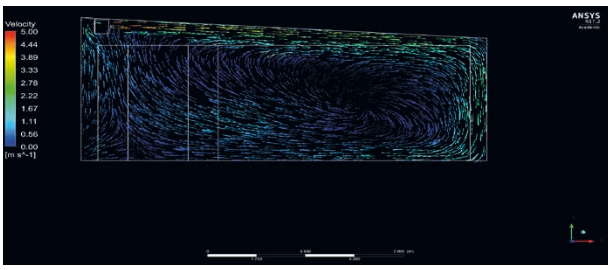
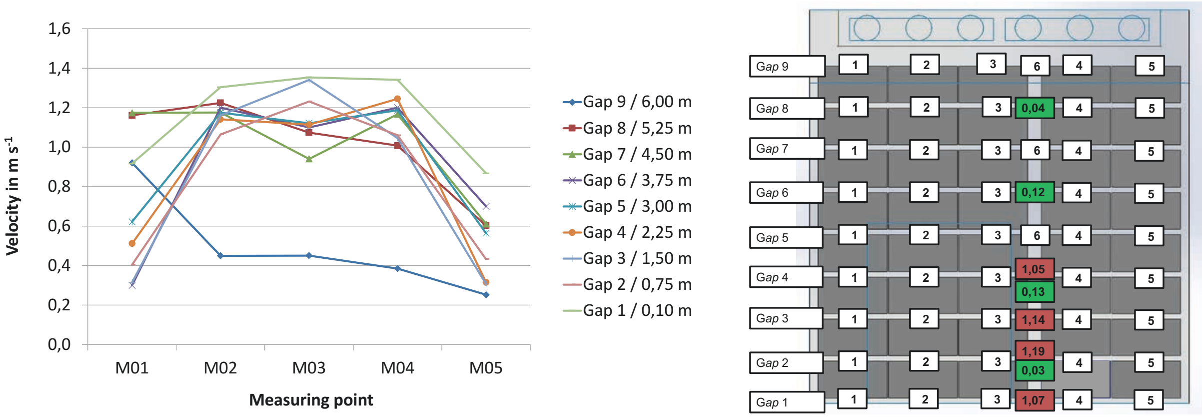


c)

Figure 7: CFD-simulation of the cabbage store: a) 3D-view of the streamlines, b) 3-D view with measuring positions (yellow crosses) and c) cross section of flow distribution

Experiment

In the apple store the inlet air velocity at the air cooler was 3 m s^{-1}. Between the bins in the horizontal gaps of the central three bin rows, the air velocity in x-direction was 0.9–1.35 m s^{-1} and hence about half as low as near the air cooler. The airflow simulation (Figure 6 b and c) shows in the area of the measuring points, and in the bin stack, respectively, dark to light-blue coloration and thus similarly corresponding to slightly lower air velocity of ≤ 1 m s^{-1} as the measured values in the gaps. The reason for the slight difference is the higher air resistance in the apple bulk than in the horizontal gaps, which are not considered in the simulation. In the bin rows at the borders the velocity was about 0.7 m s^{-1} lower as in the middle rows. At the upper margin of the bins (gap 9) the velocity was clearly lower in comparison to the gaps between the bins (Figure 8). Obviously the air is directed from the outlet of the cooler, which is situated above the highest bin and fitted with a baffle plate, over the top edge of the stack and is then sucked through the lower gaps between the bins towards the inlet at the cooler. In this study it was impossible to measure the velocity of the airflow through the stacks at the back of the room.



a) b)

Figure 8: a) Air velocity in the apple store in the horizontal gaps in x-direction and b) in the vertical gap in z- ( ) and x- ( ) direction

In the cabbage store the air velocity was 3–5 m s^{-1} at the measuring positions which were situated in front of the air cooler outlet (row 1 and 2, Figure 9) about 25 cm above the cabbage bins. The air velocity decreased with increasing distance from the cooler similar to the simulated airflow distribution (Figure 7 b and c). This effect is shown in the simulation view by color change from the left to the right side (orange to light green) indicating a velocity reduction in flow direction below the ceiling from 4 to 2 m s^{-1}. At the measuring positions, which are not situated directly in the flow blown from the fans, the air velocity was much lower in the range of 0.8 to 1.7 m s^{-1} (Figure 9).

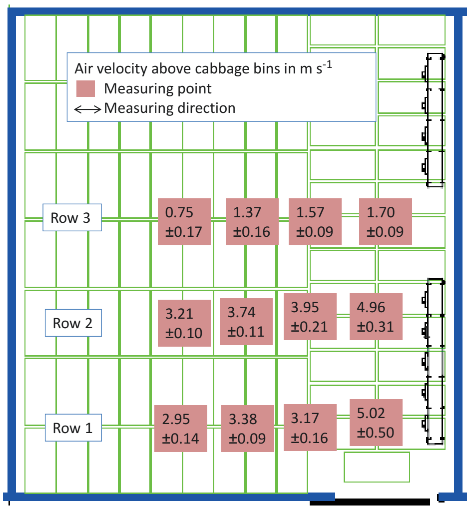


Figure 9: Air velocity (average and standard deviation of each measurement) in the height of 25 cm above the highest cabbage bin level at 12 measuring points

Lower air velocity was measured in the gap between the bin stack and the wall below the air coolers than in the gap at the wall opposite to the air coolers (Figure 10 a and b). Lower air velocity below the coolers is also visible in the simulation view (Figure 7 b and c). The air velocity in y-direction (vertical direction) was higher at the positions, which were situated in the main flow direction from the fans, than at the central positions in front of the stack which were situated between the air coolers considering the main flow direction (Figure 10 a and b). In general, air velocity values (recorded in 3 directions) were very low in comparison to the measurements above the stack except some values (mainly between 0.1 m s^{-1} and 0.6 m s^{-1}). The highly dense stacking of the bins is supposed to inhibit the airflow. Therefore, the measurements in z- and x-direction are not shown here in detail. In front of the lowest bin level at some positions no airflow was determined (Figure 10 a). The air moving upward and towards the fans is probably sucked mainly from the gaps between bin stack and the lateral walls because only very low airflow (velocity ≤ 0.3 m s^{-1}) was measured streaming out of the bin stack.

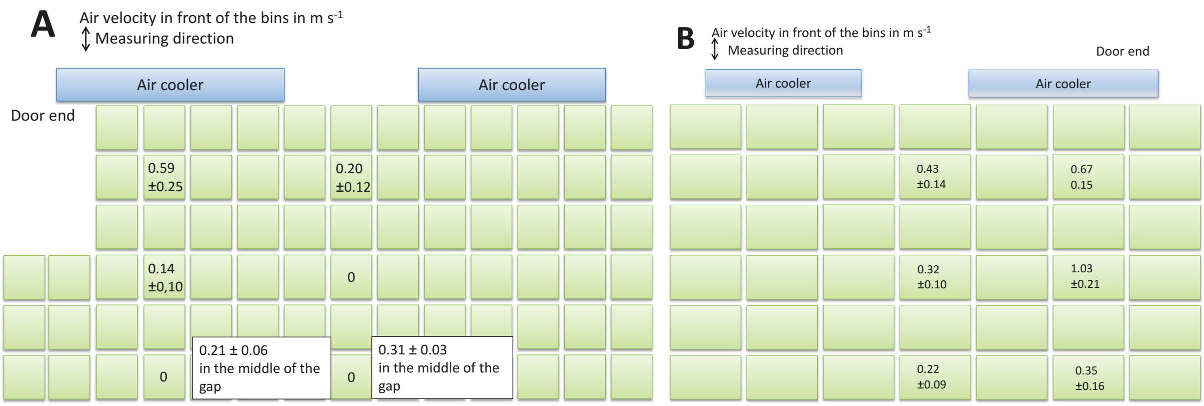


Figure 10: a) Air velocity (average and standard deviation of each measurement) in the gaps between the room wall below the air cooler and b) opposite to the coolers (measurement direction y, Figure 2 and 5)

Conclusions

The qualitative comparison between simulation and experiment shows similar flow conditions in both investigated storage rooms. In the apple storage homogeneous airflow behavior with a mean velocity of 0.1 m s^{-1} was measured in x-direction in the horizontal pile gaps. This indicates that the air is drawn through the horizontal pile gaps in direction of the fans and in the store an air vortex is formed accompanied by a downstream behind the stack. This flow pattern was also confirmed by the simulation. The measurements and simulations for the cabbage store show that the air velocity at the wall in face of the fans is higher compared to the airflow directly below the fans in the gaps between the stack and side walls.

Based on the measurements it has been demonstrated in both storage rooms that higher air velocities occur in the areas of the rooms which are situated directly in the main airflow direction generated by the fans compared to the areas situated beside the main flow direction. These results were confirmed by the simulations which show also in these areas of main airflow higher velocities. The measurement of air velocity between the stacks and the room walls showed as well a good agreement with the simulation results. Hence, the developed CFD model is suitable to simulate air flow patterns in industrial cold stores.

In further studies, a more detailed geometric model will be developed to simulate airflow pattern in gaps between stacked boxes (e.g. horizontal and vertical arrangements of boxes in apple storages by taking the column spacing into account) to provide information about appropriate stacking arrangement. Thermal effects do not play a significant role on airflow patterns in already chilled product stacks, but they should be considered in further simulations to define hot and cold spots inside the stack. Also, the influence of the spacing between stacked bins and the fan revolution on distribution of air velocity and temperature in cold stores should be examined, aiming to reduce energy consumption during the storage period without a negative impact on product quality.

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