AIRFLOW CONDITIONS IN APPLE BINS AND A COMMERCIAL APPLE COLD STORE

Ulrike Praeger[1], Holger Scaar[1], Reiner Jedermann[2], Daniel Neuwald[3], Marcel König[1], Martin Geyer[1]

[1]Leibniz-Institut für Agrartechnik Potsdam-Bornim e.V., Max-Eyth-Allee 100, 14469 Potsdam, Germany, upraeger@atb-potsdam.de
[2]Institute for Microsensors, -actuators and –systems (IMSAS), University Bremen, Otto-Hahn-Allee NW1, 28359 Bremen, Germany
[3]Kompetenzzentrum Obstbau-Bodensee und Universität Hohenheim, Ertragsphysiologie der Sonderkulturen, Schuhmacherhof 6, 88213 Ravensburg, Germany

Key words: ventilation, cold storage, air velocity, apple bin, wind tunnel

Abstract
In cold stores of fresh fruit and vegetables energy consumption for ventilation and produce losses are important cost factors. The research project COOL targets the development of an airflow sensor based ventilation regime by modifying the fan operation and the layout of cold stores in order to achieve more uniform air movement as low as required. Initial studies were carried out for determination of air velocity in storage bins and a commercial apple cold store. Airflow through single bins was studied in a wind channel. Measurements and simulations showed low air velocity inside the bin filled with produce dummies compared to the oncoming airflow. Similar airflow was measured around an empty bin and a bin filled with produce dummies. In the storage room airflow and temperature measurements were carried out in horizontal gaps between dense stacked bins. Air velocity was 1-1.4 m s^{-1} in the middle rows of the stack similar in different height. Lower air velocity was measured in the lateral bin rows near the side walls, probably due to the centered position of the air cooler in the storage room. The air velocity between the gaps was similar in different heights of the stack. In further tests the effect of modified openings in the bins on airflow will be studied as well as different stacking layouts in a cold store with gaps between the bin rows.

1. Introduction

CA storage of apples during 7 months consumes about 80 kWh/t electrical energy. The fan operation for ventilation needs 30-50 % of the total energy requirement of a cold store (Kittemann et al. 2015; Koca and Hellicson 1993). Air movement is necessary to remove the field and respiration heat of the fruit in order to maintain quality during the storage period. However, increasing air velocity at the fruit surface enhances undesirable mass loss due to transpiration.

Intensive research was done about airflow in bulks or packages of horticultural produces especially in forced-air precooling systems (Alvarez and Flick 1999, Dehghannya et al. 2010, Defraye et al. 2013). During the last decade also the research interest for airflow studies in rooms of produces for long term storage increased (Nahor et al. 2005, Xie et al. 2006, Duret et al. 2014). The effect of storage room layouts on airflow distribution as well as airflow in large storage bins were not studied in detail.

The research project COOL intends to optimize the fan operation and layout of cold stores using a holistic approach in order to achieve more uniform air movement as low as required. Therefore, the potential of an airflow sensor based ventilation regime for fruit and vegetable stores is studied in cooperation of 3 research institutes and 5 industrial partners. The project is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) for 2 ½ years during 2015-2017.

Main objectives are

- development of multi-directional wireless airflow sensors
- optimization of the design of storage bins, storage rooms and the stacking layout for enhanced airflow through the produce stack by airflow measurements and simulations
- fan operation control depending on the airflow next to the produce in the storage room
- development of a planning tool for construction and operation of cold stores with sensor based ventilation control

Initial studies were carried out in order to determine the actual status of airflow conditions through storage bins and in cold stores of apples and cabbage. Exemplary in this paper airflow measurements and simulations are presented in a single common plastic apple bin and a commercial apple CA storage room.

2. Material and methods

2.1 Airflow sensors

Hot film anemometers (Almemo, FVAD TH4, accuracy 0.04 m s^{-1}, directional) were used for air velocity and temperature (accuracy 0.7°C) determination (measuring interval 1 s) in the surrounding of storage bins. A prototype of an airflow velocity measuring device (thermal anemometer) was used for airflow velocity determination between produce dummies in a bin.

2.2 Airflow analyses in and around a storage bin

A common apple bin was placed centric in a wind tunnel (length 18 m, height 2.3 m, width 3.0 m) at ambient temperature with oncoming air velocity of 2 m s^{-1}. The bin (dimension 1.20 m x 1.00 m x 0.75 m) was filled with plastic spheres (Ø 70 mm) serving as dummy apples. At the front side towards the oncoming airflow are 120 vents (size 5 mm x 45.5 mm, in total 27300 mm^2). The area of the bin openings at the front side is 4.6 % of the inner side area which is in contact to the produce. In order to measure air velocity in the forklift openings, two parts of the neighboring bins (about 0.3 m height) in a stack were placed above and below the bin (Fig.2).

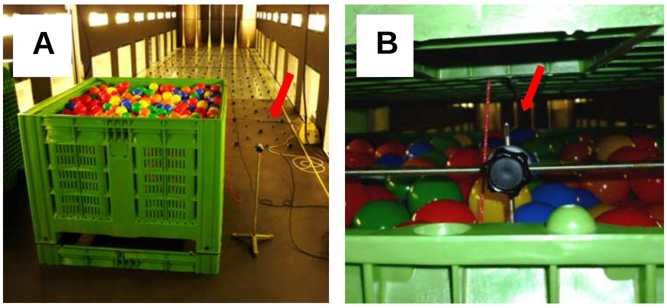


Fig. 2: Storage bin in the wind tunnel (A) and exemplary two positions of the airflow sensor (A, B)

Airflow measurements were done at 18 positions inside the bin between the spheres with minimum 150 mm distance to the bin wall. In the surrounding of the bin 27 positions were chosen at the side, above, in front and behind the bin for measurements in flow direction along the wind tunnel each in a distance of 50 mm from the bin walls (Fig. 5). The airflow measurements outside the bin were repeated with an empty bin in a second test.

CFD simulation was performed to predict air velocity profiles in storage bins by using the commercial Software ANSYS® CFX. Therefore a model was developed and validated by wind tunnel experiments. This model describes the geometry of the storage bin in detail. The apples inside the storage bin were modeled by using a porous media approach. In order to determine the bulk density and the porosity of the apple bulk, a filled and an empty storage bin were weighted. The difference of both values was divided through the inner volume of the empty storage bin.

Table 1: Model Parameters used in CFD

Parameter	Variable	Dimension	Value
Particle density	ρ_P	[kg m^3]	826
Bulk density	ρ_B	[kg m^3]	482
Bed porosity	ε_B	[-]	0.42
Wall porosity	ε_W	[-]	0.29
Inlet velocity	v	[m s^{-1}]	2
Outlet pressure	P	[Pa]	0
Permeability	K_{perm}	[m^2]	81.242
Loss coefficient	K_{loss}	[m^{-1}]	0.0591

The apple density was determined by dividing the weight through the volume which was measured by water displacement of the fruit. Then the porosity was calculated by dividing the bulk density though the particle density. The permeability and the quadratic loss coefficient for the bulk were determined according to Ergun (VDI Wärmeatlas, 2006) by assuming the apples as spherical particles. The slotted surfaces of the bin were also modeled by a porous zone. For these zones no pressure loss was defined. The used values for the Model are shown in Table 1.

2.3 Airflow measurement in a cold store

In November 2015 airflow measurements were done in a commercial CA apple storage room (Havelfrucht GmbH in Glindow) of dimensions 6.6 m x 15.2 m x 7.0 m. The room was at the moment of the measurements partly loaded with 5 rows of 9 stacks each with 8 wooden apple storage bins (dimension of 1.2 x 1.0 x 0.8 m) and 32 additional boxes (in total 130 t apples) with free distance of about 4 m between the bins and the door below the cooling unit. The bins were stacked dense except one vertical gap between the third and fourth row and two gaps between the stack and the walls of 0.2 m width each. The cooling unit (Typ Helpmann THOR 268-7, flow rate 30480 $m^3\ h^{-1}$, 6 fans) is located at the ceiling centric above the door and fitted with a baffle plate and a vertical sealing-off (Fig.3,4). At the fan outlet the air velocity was 2.96 $m\ s^{-1}$.

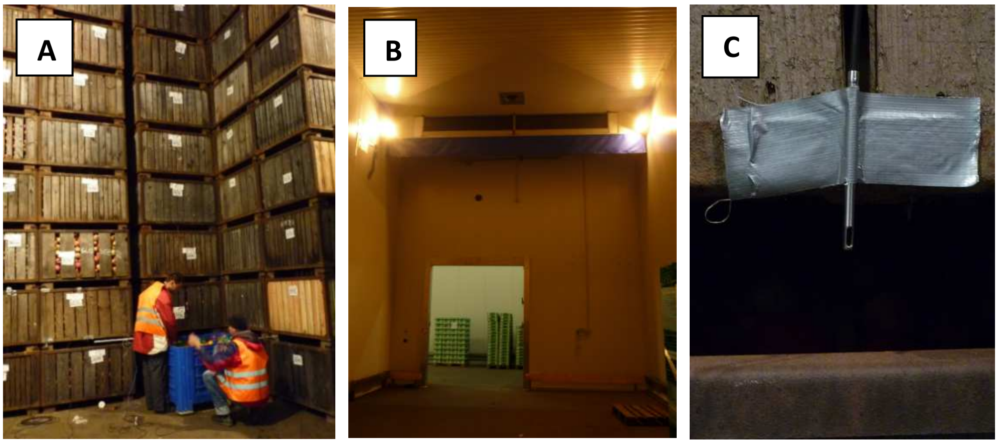


Fig. 3: Stack of apple bins in the cold store (A), cooling unit (B), airflow sensor (C)

The airflow and temperature sensors were placed in the horizontal gaps (Fig. 3,4) between the last accessible bins of each row for air velocity measurements in the flow direction of the fan outlet. Measurements in gap 1 to 9 were done successive over a period of 1 min each (interval 1 s). The cooling unit and fan operation were interrupted for 15 min between the measurements in one row. In the wide vertical gap at level of the horizontal gaps 2,4,6 and 8 between row 3 and 4 the air velocity was measured additionally in the right angle (90°) to the measurement direction along the bin rows. Airflow was measured also inside one additional plastic bin filled with spheres (Ø 70 mm) at 21 measuring points with 120 mm minimum distance to the bin wall. This bin was placed at the ground of the room in front of the 4th bin row (Fig. 4).

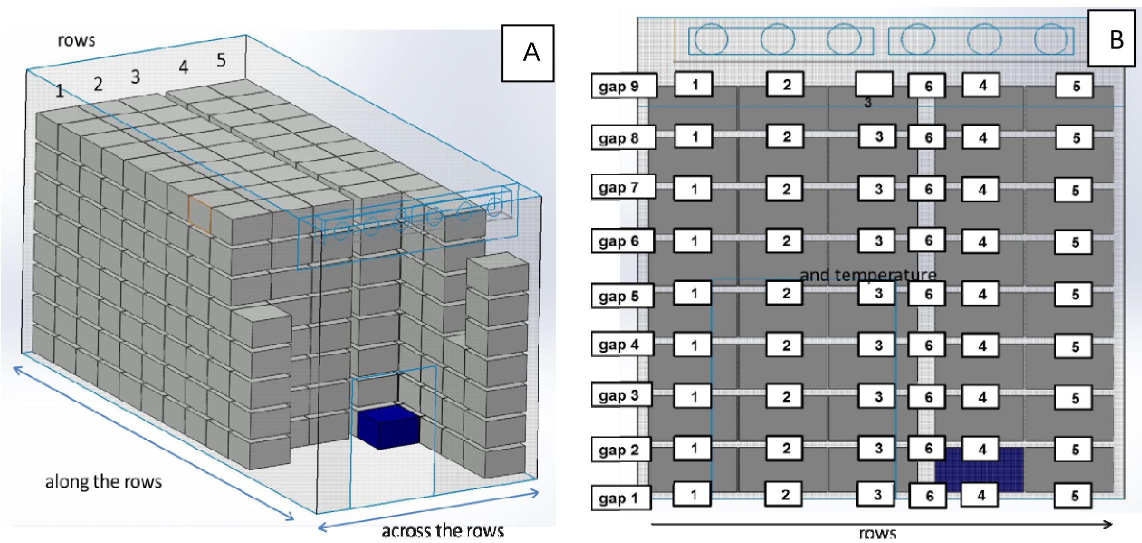


Fig. 4: Schematic array of the bin stack in the cold store (additional bin with plastic spheres dark blue) (A) and measuring positions for airflow and temperature (B)

4. Results and discussion

4.1 Airflow conditions of the storage bin

At 50 mm distance in front and at the side of the bin the oncoming air velocity of 2 m s^{-1} in the wind tunnel was reduced to 0.4-0.7 m s^{-1} due to the air resistance of the bin. Behind the bin velocity is deceased further to 0.1-0.3 m s^{-1}. Highest air velocity of 3 m s^{-1} was measured in the gap above the bin with decreasing average values in flow direction. The air velocity outside the bin filled with spheres was similar compared to the empty bin (Fig. 5).

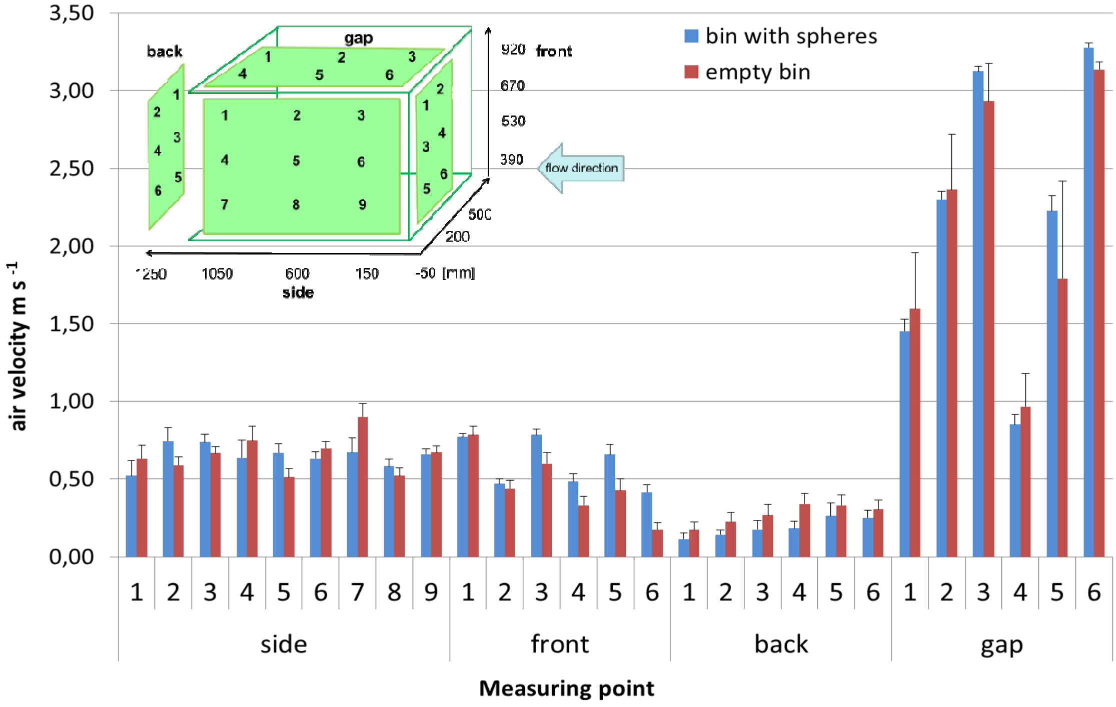


Fig. 5: Air velocity measured at 27 positions around the bin in direction of the oncoming flow of 2 m s^{-1}

Inside the bin between gaps in the sphere bulk at different positions air velocity was in a range of 0.05–0.15 m s^{-1}. Additional measurements with the sensor in a produce stack showed variation of air velocity values of ±0.5 m s^{-1} at one position (unpublished). Therefore, in order to determine the spatial distribution of the air velocity inside the bin, additional measurements with a high number of repetitions at one measuring position are necessary.

Figure 6 shows the simulated isobar distribution and the velocity vectors in vertical slice plane (200 mm depth) through the storage bin. As visualized, the pressure drop of the storage bin is high compared to the pressure drop in the apple bulk due to the low opening area of the storage bin compared to the bulk porosity. Hence, a high eddy flow occurs on the shadow side behind the bins in flow direction. This effect leads to counter eddies and to a low air velocity in the apple bulk in the storage bin. It is recommended to increase the opening area of the storage bin in order to reduce these flow effects.

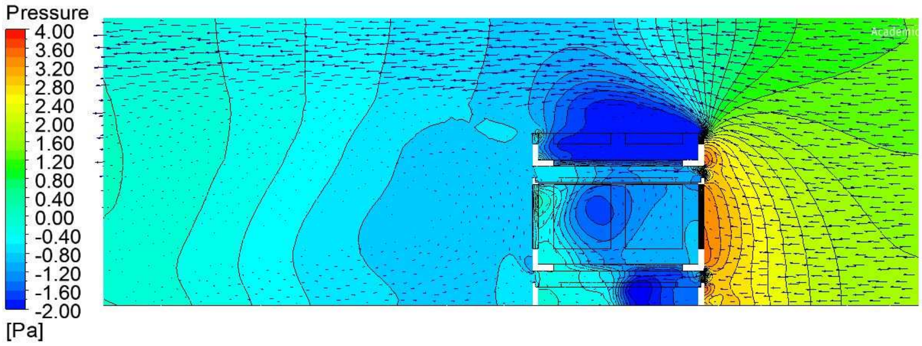


Fig. 6 Simulated flow pattern in apple storage bin (arrows indicate the velocity vectors)

4.2 Airflow in a cold store

In the horizontal gaps between the bins of the 3 middle bin rows air velocity was between 0.9 and 1.4 m s^{-1}. In most horizontal gaps of the side rows next to the room walls air velocity values were about 0.7 m s^{-1} lower than in the middle presumably due to the centric position of the cooling unit. At the border above the highest bins air velocity was much lower than in the horizontal gaps. Airflow might be lower on top than in the gaps between the bins because the baffle plate is conducting the air blown from the fans towards the room ceiling above the bins and back through the horizontal gaps. Accordingly, simultaneous temperature measurements during cooling and fan operation (average of 1 min.) show faster cooling in the middle rows than at the sides. During interruption of the fan operation temperature was uniform (data not shown).

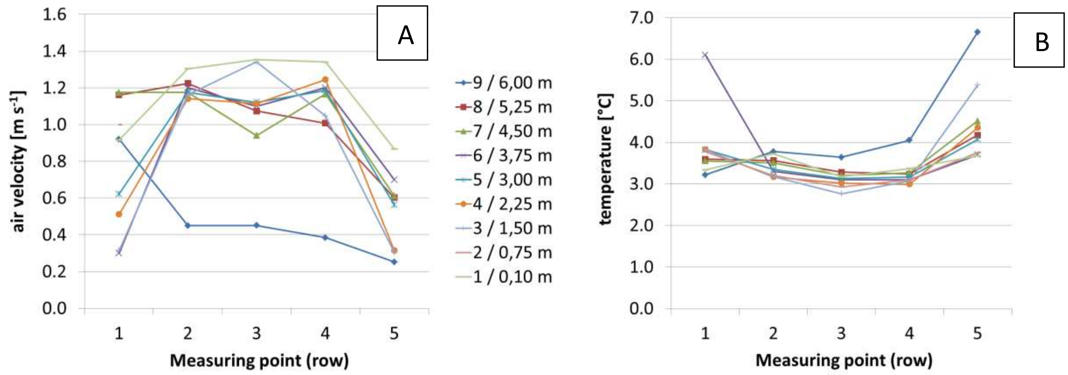
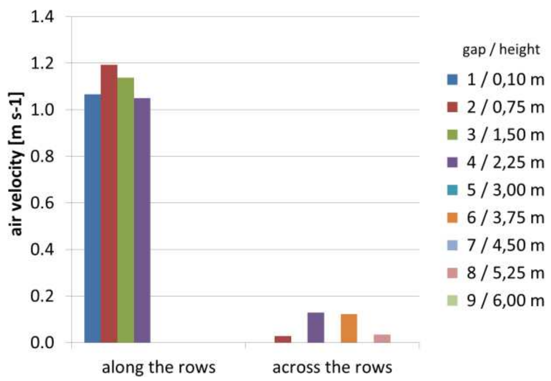


Fig. 7: Air velocity measured along the bin rows (A) and temperature (B) in horizontal gaps between the bins



In the vertical gap air velocity was 1-1.2 m s^{-1} at the level of the low horizontal gaps (1-4) similar to the positions between the bins. The sensors at higher positions in the stack failed. In cross direction (90° angle) only negligible air flow < 0.2 m s^{-1} was measured.

Fig. 8: Air velocity in the wide vertical gap between row 3 and 4 (measuring point 6, Fig. 4) measured along and across the rows

In the additional bin filled with plastic spheres air velocity was in the range of 0.03-0.13 m s^{-1} similar to the airflow in the storage bin of the wind tunnel experiments (4.1).

5. Conclusions

The measurement and simulation of airflow inside and around the bin show high air resistance of the bin for oncoming velocity of 2 m s^{-1} in the wind tunnel. The porosity of the bin wall of 0.04 is low in comparison to the porosity in the sphere bulk of 0.42. In order to increase low air velocity < 0.2 m s^{-1} inside the bin filled with produce the opening area of the bin wall should be increased as far as requirements for stability, stackability and produce quality maintenance are considered. In further experiments airflow through bin walls with modified openings are studied. In a cold store ventilation maybe reduced in order to decrease energy consumption when airflow through the bins is enhanced.

In an apple cold store at industrial scale the effect of gap width between bin rows on airflow profiles in the room will be studied. The presented experiment in the wind tunnel showed similar airflow of the bin filled with spheres compared to an empty bin. Hence, the experiment in the storage room will be carried out with empty bins assuming that also in the stack the influence of bin filling with apples on airflow around the bin is negligible.

In the cold store the airflow in the gaps of the lateral rows was much lower than in the middle. For evaluation of the effect of varying airflow, the air velocity and average temperature during storage in different room areas should be related to produce quality. As air velocity was similar in the wide vertical gap as between the dense stacked bins, stacking without this gap would increases the space between the wall and the bins. Hence, maybe the boundary rows could be better ventilated because of the centric position of the air cooler. For fruit and vegetable storage stacking with vertical gaps of 50-100 mm is recommended (Belker (in Böttcher 1996, Geyer und Praeger 2012)) in order to achieve 0.8-1.2 m s^{-1} air velocity between bin rows, similarly as it was measured here in the horizontal gaps. The effect of the gap width will be studied in further experiments.

Acknowledgements

The project is supported by the Federal Ministry for Economic Affairs and Energy of Germany on the basis of a decision by the German Bundestag under grant number VP2050828CL4.

References

Alvarez, G. and Flick, D. (1999). Analysis of heterogeneous cooling of agricultural products inside bins, Part I: Aerodynamic study. Journal of Food Engineering 39(3), 227-237.

Böttcher, H. (1996): Frischhaltung und Lagerung von Gemüse. Ulmer Verlag, Stuttgart.

Defraeye, T., Lambrecht, R., Tsige, A.A., Delele, M.A., Opara, U.L., Cronjé, P., Verboven, P., Nicolai, B. (2013). Forced-convective cooling of citrus fruit: Package design. Journal of Food Engineering 118, 8-18.

Dehghannya, J., Ngadi, M., Vigneault, C. (2010). Mathematical Modeling Procedures for Airflow, Heat and Mass Transfer During Forced Convection Cooling of Produce: A Review. Food Engineering Reviews, 2, 227-243.

Duret, S., Hoang, H. M., Flick, D., Laguerre, O. (2014). Experimental characterization of airflow, heat and mass transfer in a cold room filled with food products. International Journal of Refrigeration-Revue Internationale Du Froid 46, 17-25.

Geyer, M.; Praeger, U. (2012). Lagerung gartenbaulicher Produkte. KTBL, Darmstadt.

Kittemann, D., McCormick, R., Neuwald, D. A. (2015). Effect of high temperature and 1-MCP application or dynamic controlled atmosphere on energy savings during apple storage. European Journal of Horticultural Science 80(1), 33-38.

Koca, R. W. Hellickson, M. L. (1993). Energy savings in evaporator fan-cycled apple storages. Applied Engineering in Agriculture 9 (6), 553-560.

Nahor, H. B., Hoang, M. L., Verboven, P., Baelmans, M., Nicolai, B. M. (2005). CFD model of the airflow, heat and mass transfer in cool stores. International Journal of Refrigeration-Revue Internationale Du Froid 28(3), 368-380.

VDI Wärmeatlas (2006). VDI-Gesellschaft für Verfahrenstechnik und Chemieingenieurwesen, Springer Verlag Berlin Heidelberg.

Xie, J., Qu, X. H., Shi, J. Y., Sun, D. W. (2006). Effects of design parameters on flow and temperature fields of a cold store by CFD simulation. Journal of Food Engineering 77(2), 355-363.