Spatial profiling of airflow conditions in cold storage warehouses by wireless anemometers

Reiner Jedermann[1], Nico Hartgenbusch[1], Mykhailo Borysov[1], Chanaka Lloyd[1,2], Ulrike Praeger[3], Marc Spuler[4], Walter Lang[1,2,5]

[1]Institute for Microsensors, -actuators and –systems (IMSAS), University of Bremen, Otto-Hahn-Allee NW1, 28359 Bremen, Germany, +49 (0)421 218 - 62 603, rjedermann@imsas.uni-bremen.de
[2]International Graduate School for Dynamics in Logistics (IGS) LogDynamics, University of Bremen, Germany, clloyd@imsas.uni-bremen.de
[3]Leibniz-Institut für Agrartechnik Potsdam-Bornim e.V. (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany, upraeger@atb-potsdam.de
[4]Kompetenzzentrum Obstbau-Bodensee (KOB), Schuhmacherhof 6, 88213 Ravensburg, Germany, marc.spuhler@kob-bavendorf.de
[5]Microsystems Center Bremen (MCB), University of Bremen, Germany, wlang@imsas.uni-bremen.de

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Abstract: *A set of 23 wireless anemometers (WAMs) was deployed to capture the spatial airflow profile in a vertical gap between bins in a cold-storage warehouse filled with apples. Horizontal and vertical air velocity were measured separately and combined to magnitude and angle. The measurements showed large variations in velocity from 0.34 m/s to 1.5 m/s depending on the location. The results were verified by computational fluid dynamics simulation. As one pre-requisite for automated fan revolution (FR) control, the effect of reduced FR on the velocity between the boxes was measured. Especially for low FR, the accuracy of the WAMs has to be improved, before automated fan control can be put into practice.*

1 Motivation

Reducing the energy consumption of cold storage warehouses and thus their CO_2 footprint is an important challenge. About 40% of the total electrical energy is required for ventilation of a controlled atmosphere (CA) apple storage room [Kit13]. Adaptive ventilation control can largely contribute to energy reduction by setting ventilation speed to the minimal level that is required to achieve the necessary air velocity directly at the fruits. The COOL project, running from 2015 to 2017, aims to install such a *“Flow sensor based air management in fruit and vegetable storage”.*

The first step is to profile the airflow conditions in the warehouse with regard to spatial deviations and zones with low airflow. Secondly, a reduced number of sensor positions has to be selected, which best represent zones of maximal, minimal and average air speed. Finally, sensors have to be installed at selected positions for real-time monitoring of changes of velocity at the fruits as a reaction to the adjustment of fan revolution (**FR**).

Typical loading processes and forklift operation make it hard to apply wired probes. Wireless sensors are the method of choice for the analyses of the airflow profile as well as for the final implementation. In this article we present our wireless anemometer (**WAM**), calibration procedures and first tests in a cold storage warehouse with 163 bins containing approx. 300 kg apples each. Measurement results were compared with a computational fluid dynamics (**CFD**) simulation.

2 Wireless sensor hardware

The WAMs of the first generation were only capable of one-dimensional measurements, i.e., velocity value and sign. Their hardware contained 3 printed circuit board (PCB) layers [Llo13]. The sensor element on the top PCB consisted of a heater in the center between 2 thermopiles. Depending on the direction of the airflow, a temperature difference was created. The second PCB amplified the thermopile signals and controlled the heater voltage to operate at constant power. The TelosB [Cro05] radio module was used as the third PCB to transmit the measurements over 2.4 GHz band.

Our new design contains 2 crossed sensor chips for two-dimensional measurements, combined with amplifiers and a microcontroller on the same PCB (Figure 1a). The energy consumption of the circuit was further reduced by switching to constant energy control. For each measurement cycle, a capacitor is discharged over the heater to create a temperature pulse, which is independent of the internal resistance of the heater. For the future it is planned to integrate a two-dimensional sensor element on a single chip. Radio communication will be handled by a WizziMode module [Wiz13] according to the dash7 standard at 433 MHz, which offers a better penetration of water-containing products [Llo16].

Calibration was initially done in a 62 mm diameter tube, which caused two problems. Firstly, the airflow in the tube showed large turbulences and resulting variations over time. Measurements could only be retrieved by averaging the measured values over periods of at least 1 minute. Secondly, the WAMs obstructed 51% of the cross section of the tube, thus distorting the air flow significantly and giving higher sensor readings than in free air-space. An initial test in an external wind-tunnel with a cross section of 45 cm by 55 cm resulted in a correction factor of 0.46.

For further detailed tests and improved calibration, we set up a new wind tunnel consisting of a laminator (array of small tubes with 5 cm length) and a funnel to reduce turbulences (Figure 1b). The air speed in the measurement chamber can be controlled by the voltage of the ventilator at the outlet. Variations over time of the measured airflow were largely reduced. After smoothing with a moving average filter with a time constant of 1 second, the standard deviations of the measured velocity was reduced to less than 0.003 m/s (example value calculated for a velocity of 0.6 m/s).

Figure 1: (a) Prototype of new PCB design with two crossed sensor elements for two-dimensional measurement. (b) Wind-tunnel for WAM calibration. The measurement chamber has a cross section of 20 cm by 20 cm.

3 Sensor placement

The tests were carried out in October 2015 at the Kompetenzzentrum Obstbau Bodensee (KOB), Bavendorf Germany over two days. 163 bins of apples were stowed in a chamber in 3 rows from left to right wall (R1…R3), 7 columns from door to evaporator side (S1…S7) and 8 bins height from bottom to top (K1…K8). Each bin with size of 1.0 m by 1.18 m by 0.75 m height contained approx. 300 kg of apples. Due to limited space for forklift operation, 5 bin positions at the door side (R2S1K5-8 and R2S2K8) had to be left empty (see Figure 3 in Results section).

The temperature set-point of the chamber was adjusted to 1°C. The apple bins were already precooled before start of the test. The cooling air was blown from 5 fans located above the bins. A sealing-off was installed below the evaporator. The boxes were cooled by airflow through 2 vertical gaps at the left and the right walls, 2 vertical gaps between the rows of approx. 10 cm wide each, airflow though horizontal gaps of 8 cm height between the boxes, and small airflow through slits on the sides of the bins.

During our tests, we focused on one of the central vertical gaps. The WAMs were mounted at the side of the bins of row R1 to measure in the gap between R1 and R2. The revolution speed of the fans was controlled by a frequency converter. Tests were repeated with 4 different levels between 25% and 100%. The horizontal air velocity above the bins was manually measured to 2.03 m/s at 100% FR. The probe was placed in ~1.5 m distance to the fan outlet. The air velocity increased almost linear with the FR.

The airflow in the gap between R1 and R2 was measured with 23 WAMs of the first generation because the new hardware was not available for this initial test. A detailed understanding of the airflow pattern is only possible if not only the magnitude but also the direction of the airflow is measured. For these initial tests, directional measurement was achieved by turning the sensors by 90° between two subsequent tests.

The WAMs were programmed for wireless transmission of the measured air speed every 30 seconds. Three additional WAMs were used to monitor variation of the velocity in time scale below 1 second. These WAMs were directly connected to an oscilloscope, which recorded the sensor voltage with a sampling rate of 1 kHz. Four other WAMs were installed as radio forwarders in the corners of the room.

Figure 2: *Installation of WAMs at the side of the first row of bins. Bins of row R2 removed for installation.*

4 CFD simulation

In order to verify the WAM measurements, a CFD simulation was carried out by the k-ε model for turbulent flow of the conjugate heat transfer module of the software package COMSOL version 5.2. The high mathematical complexity of turbulent airflow simulation made it necessary to simplify the geometrical model in the following points: (a) Symmetry was assumed and only the left half of the room was simulated. The additional free air-space in front of the door at one side of the room was ignored. (b) The outlet of the fans was simulated as a rectangle with even air speed. (c) The bins were modelled as cuboids with feet. Airflow through the bins was ignored. (d) Variations of filling height of the bins were also ignored, instead a free air-space of constant height of 8 cm per bin above the apples was assumed. The simulation required 14 days and 82 GByte of working memory on 16/32 core 2.6 GHz Intel® Xeon® server for the pre-defined mesh resolution ‘coarse’, which is one step below the ‘normal’ mesh size.

5 Results

In the following we present the results from the field test measurements in regard to comparison with the simulated data, dependency on the FR and temporal changes due to turbulences. Interpretation follows in the discussion section.

5.1 Comparison of measured flow magnitude and angle with simulation

The blue arrows in Figure 3a show the air velocity vectors as a combination of the WAM measurements in horizontal and vertical directions. The results of the simulation are displayed in the same figure. The measured velocity magnitude was in the range between 0.34 m/s and 1.49 m/s at 100% FR. The simulation gave values between 0.08 m/s and 1.62 m/s for the same positions. A maximum value of 2.19 m/s was calculated by the simulation for bin S7K8 below the fan, which was not equipped with a WAM.

Simulated and measured velocity magnitude and angle showed a good agreement in the centre of the stack. An exceptionally high deviation was found for the lowest bin at the fan side (S7K1). The measured velocity magnitude by the WAMs was 8 times higher than the simulated value at this position. Further deviations were found in bin S1K1, close to the free airspace at the door, bin S7K5 close to the wall below the fan, and bin S3K7, which was close to the positions left empty during loading. Only for these three outer positions the angle error was >30°.

5.2 Relation between fan revolution and air velocity between bins

Even if the fans were turned off, the WAMs measured an air velocity of 0.218 m/s in average between the bins. Possible explanations are discussed in the next section. For an increase of FR from 25% to 50% only a slight increase of the average measured velocity of 0.021 m/s was observed. Only for the next two steps of increased revolution (50% →75% → 100%) a considerable change in average measured air velocity was observed, 0.161 m/s and 0.354 m/s per 25% step, respectively.

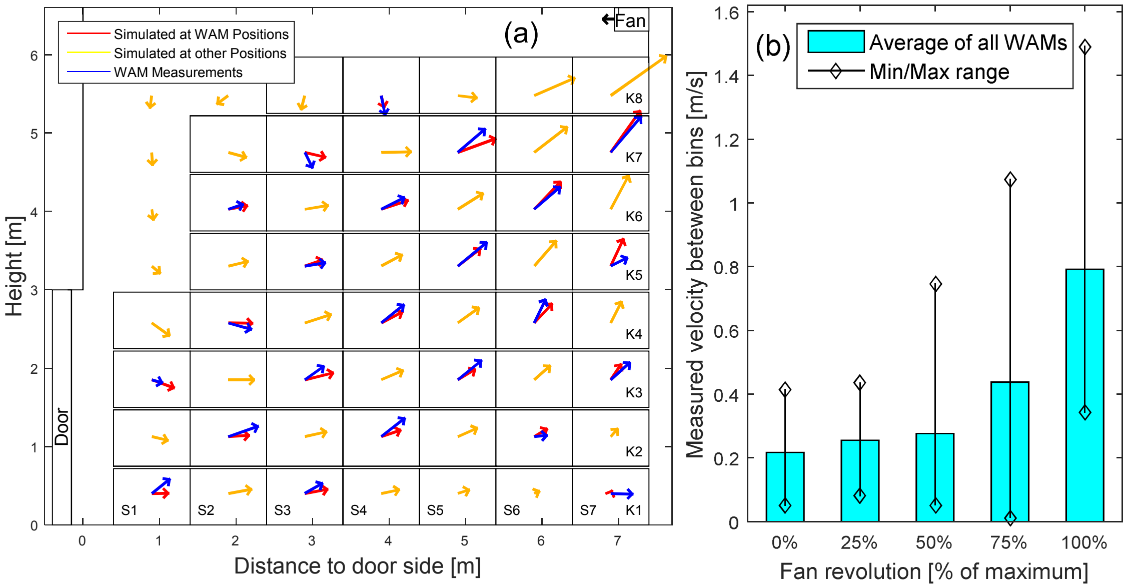

Figure 3: *(a) Air velocity vector according to WAM measurements (blue) and COMSOL simulation (red at WAM positions, orange at other positions) inside vertical gap between R1 and R2. Dimensions of the chamber were 7.7m length, 4.15m width (not shown), and 6.6m height (b) Measured air speed magnitude as function of fan revolution.*

5.3 Turbulences and variation over time

The Reynolds number for the gap geometry was calculated to 11900 for a velocity of 0.8 m/s which is much higher than the threshold of 4000 for spontaneous formation of turbulences. The air gap was assumed as a rectangular duct of 0.1 m width and infinite height.

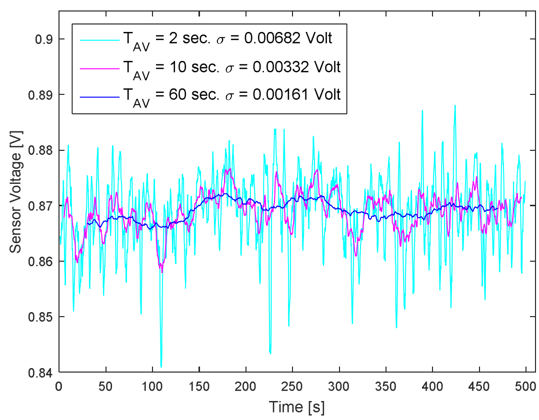

Figure 4: *Signal variation over time and moving average with different widths.*

Turbulences entail not only small eddies but also considerable variations in local velocity over time, which make it difficult to measure an average value. Figure 4 presents the change of sensor voltage over time for one WAM installed at bin S4K8 in vertical direction as an example. The voltage varied between 0.771 V and 0.913 V (Average = 0.869 V ~ 0.59 m/s, σ = 0.011 V) for constant FR of 100% during a time period of 500 seconds. For clarity, Figure 4 gives only smoothed values according to a moving average filter with different widths. A change of the sensor voltage of 0.01 Volt is equivalent to a change of velocity of 0.06 m/s.

5.4 Effects on measurement accuracy

The WAMs were calibrated at room temperature of ~22°C. Offsets of measured air velocity at the warehouse temperature of 1°C were estimated by putting all WAMs into a closed box to prevent any airflow. The offset values were already subtracted in Figure 3. The average offset was 0.089 ± 0.24 m/s.

Furthermore, we observed drifts of the measured air speed after installing the WAMs in the warehouse for 14 out of total 23 WAMs, after they had been stored outside the warehouse at ~15°C. Measurements stabilized after 1 hour maximum.

Calibration turned out to be difficult for velocities below 0.2 m/s, due to low sensitivity of the WAMs and difficulties in adjusting the calibration tube for low air velocities. Additionally, the relative air humidity >95% might have caused condensation on the heater element and thermopiles of the flow sensor, distorting the readings.

6 Discussion

Both WAM measurements and simulation confirm a large spatial variation of air velocity. The expected air velocity ranges from less than 0.1 m/s to more than 2 m/s. Multipoint measurement cannot be avoided to evaluate the airflow conditions inside a cold-storage warehouse. The actual airflow in the warehouse was lower than assumed during the design of the WAM hardware and housing. Their resolution has to be improved to cover a velocity range of 0.2 m/s and below with a better accuracy.

The CFD simulation was in general verified by the WAM measurements, although there were deviations in some positions. Most deviations between CFD simulation and measurements can be ascribed to the following factors:

- The CFD simulation assumed an even size of vertical gaps and an even filling height of the bins, which is not the case in real-world applications. Further simplifications, especially the exclusion of airflow through the bins contributed to simulation inaccuracies. Due to an already extensive simulation time of 14 days, it is not feasible to include all physical effects in the simulation.
- Temperature differences in the contents of the warehouse created a convective airflow when the fans were turned off. The effect was increased by the fact that the surface of the bins warmed up when they were taken out of the chamber for a period of ~2 hours to install the WAMs. But convection effects are too small to explain the measured offsets alone.

The following effects have to be considered for improved hard- and software and calibration processes. The goal of the hardware improvements is to provide sufficient accuracy that the effects of changed FR can also be quantified for the range between 0% and 50% FR.

- Although the applied measurements principles of constant power and constant energy are independent of temperature related changes of the heater resistance, we observed a temperature drift during the field tests. Other possible reasons of temperature dependency have to be considered and eliminated, e.g., non-linearity of the thermopiles and temperature dependency of the voltage of the used rechargeable lithium battery.
- Due to the high relative air humidity, condensation on the sensor surface might have affected the measurement results. Condensation can be detected by not only measuring the difference signal between the thermopiles, but capturing the voltage separately to detect an unexpectedly high thermal conductivity by water on the sensor surface. If detected, condensation can be removed by turning on the heater for an extended period of time.

- The setup of the wind-tunnel has to be adapted to cover velocities below 0.2 m/s and to provide accurate reference measurements. Even good standard handheld anemometers (VT200, Kimo instruments) do not provide a sufficient accuracy below 0.2 m/s. A hot wire probe should be directly integrated into the wind tunnel instead.

The effect of turbulences was also larger than expected. Turbulences create a high level of pink noise on the measurement signal with a spectrum almost proportional to the inverted frequency, i.e., the signal has a high share of low frequency noise, which is hard to be removed by filtering. Measurements have to be averaged over a period of one minute or more.

Although CFD cannot replace real-life measurement, it is a useful tool to evaluate the spatial pattern of airflow and for detailed analysis of possible ventilation problems. The first problematic zone is the bottom bin at the fan side (S7K1). The simulation calculated an insufficient velocity of 0.08 m/s. Because the WAM at this position showed a much higher value of 0.7 m/s, further experimental evaluation is necessary. The bottom position at the door side (S1K1) is also a candidate for insufficient airflow, although not as critical as the fan side.

Eddies can cause deficient airflow especially in zones, where the air flow has to change direction due to the warehouse geometry. Above the pallets, the airflow direction is from fan to door side, but reverses inside the stack. Although, according to the simulation the affected bins S3K8 and S4K8 have a sufficient airflow of 0.375 m/s or more with almost downwards vertical direction, a sensor should be placed in S3K8 for detection of possible problems.

Based on the above considerations, we recommend sensor placement at least at the above listed positions S7K1, S1K1, and S3K8, plus additionally one sensor in the middle of the stack to evaluate average airflow, e.g. S4K4, and one sensor below the fan S7K8, were the simulation gave the highest velocity.

A two-dimensional measurement of velocity is necessary because the angle of the airflow can change by modifications in the stacking scheme, e.g. by varying gap diameters. Unexpected changes of the angle of airflow indicate that the airflow pattern is probably distorted by formation of an eddy.

Although their accuracy is not fully satisfying yet, the presented WAMs turned out to be a useful tool to analyze the airflow patterns in cold-storage warehouses, monitor the effects of changed FR, and thus enable a closed-loop FR control, which not only has a high potential to reduce the high share of energy required for ventilation, but also prevents unnecessary high moisture loss in the fruits.

7 References

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