XVIIth World Congress of the International Commission of Agricultural Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

ENERGY SAVING DURING BULB STORAGE APPLYING MODELING WITH COMPUTATIONAL FLUID DYNAMICS

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CSBE101275 – Presented at Symposium on Nanotechnologies Applied to Biosystems Engineering and the Environment, Section VI: Postharvest Technology and Process Engineering

ABSTRACT Tulip bulbs to plant the next season are stored in containers which are ventilated to a level of 500 or 300 m^3 per m^3 bulbs per hour to avoid high ethylene concentration between the bulbs. In this study a commercial CFD code was used to investigate the distribution of air flow between the containers and the potential energy saving by applying simple solutions concerning the design of the air inlet area and the adjustment of the ventilation rate. By doing so we calculated a variation of container ventilation between 60 and 180%, where 100% is the average flow through the containers. Various measures for improvement were investigated. By smoothing the sharp corners of the entrance channels of the ventilation wall about 7% energy can be saved. The most effective and simple way for improvement, was by covering the open top containers. In this case the variation is between 80 and 120%. By adjusting the overall ventilation to the container with the minimal air flow acceptable in the current situation (67%), energy saving is about 38%.
Keywords: Ventilation rate, one layer storage system, ethylene concentration, tulip bulbs

INTRODUCTION In The Netheralnds, at 1998, the flowerbulb sector had established an energy consumption agreement with the Dutch Government in order to achieve an increase to energy efficiency of 22% in 2005 compared to the level of 1995, together with a contribution of at least 4% sustainable energy, (Van Bruggen 2002). The Dutch flower bulb industry is highly dynamic. From 1990 to 2003 the number of enterprises was reduced by 33% while farm size increased by 50%. Even if the increase of scale reduced production costs per unit, the demand for environmental protection and improved working conditions also affects the production systems (Wildschut et al., 2005).

Tulip bulbs to plant the next season firstly are dried and then stored in containers which are ventilated. During both processes air conditions are controlled by ventilation. Both temperature and humidity should be kept low but the most critical parameter is the ethylene concentration. Ethylene acts as a ripening hormone and high concentrations lead to drastically quality loss, (De Munk 1972; De Wild et al., 2002; Kamerbeek and De Munk 1976). During storage, tulip bulbs are ventilated constantly. Ideally the ventilation rate should be equal through each box. However, differences can be observed pretty easy from the differences in flow through the various slits. The safe ventilation rate has to be adjusted to the crate with minimal ventilation rate; therefore ventilation is set at a high rate to avoid risks. Although this approach is safe regarding the ethylene concentration, is energy consuming, since over ventilation is applied. There are two ways to reduce the energy consumption; by decreasing the resistance of the storage system to the air flow and by improving the uniformity of the ventilation rate between the boxes, which allows a lower ventilation rate to be applied. In this study both solutions are investigated, firstly by changing the design configuration of the storage system and secondly by reducing the ventilation rate. The different solutions were chosen based on simplicity in order to be low cost options for the growers.

SET UP THE CFD MODEL

Air flow through tulip bulbs Definition of resistance of tulip bulbs to the air flow requires an understanding of porous media flow and the equations governing the hydrodynamic and thermodynamic processes. The porosity, ε, of a porous media is defined by Eq. 1; where the total volume of the porous region, V_{total} (m^3), is the sum of the volume of the solid material, V_{solid} (m^3), and the volume of the void space, V_{void} (m^3). As the porosity approaches the unity, the fluid flow becomes less restricted and its physical velocity (actual velocity inside the porous media), v (m/s), is decreased relative to its superficial velocity, u (m/s), (the velocity of the fluid outside of the porous media). The superficial velocity is related to the physical velocity, by the porosity according to Eq. 2.

$$\varepsilon = \frac{V_{void}}{V_{total}} = 1 - \frac{V_{solid}}{V_{total}} \quad (1)$$

$$u = \varepsilon v \quad (2)$$

The pressure drop dp (Pa) of an incompressible fluid across the porous media taking into account both inertia and viscous forces is given by the Ergun equation, Eq. 3, (Wu and Yu 2007).

$$\frac{dp}{dx} = \frac{150\mu(1-\varepsilon)^2 u}{{D_p}^2 \varepsilon^3} + 1.75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho u^2}{D_p} \quad (3)$$

where dp is the pressure drop, dx (m) is the length the pressure drop is taking place over in porous media, μ (Pa·s or kg/(s·m) is the dynamic viscosity of fluid and D_p (m) is the appropriate characteristic length of the medium or the equivalent mean diameter of particles (in this case of tulip bulbs) and ρ (kg/m^3) is the density of fluid. Ergun's equation combines the Carmen-Korenzy equation (the first term on the right side of Eq. 3) which is valid for $\mathrm{Re} < 10$ (laminar flow) and the Burke-Plummer Equation (second term on the right side of Eq. 3). Burke-Plummer equation denotes the kinetic energy loss primarily in turbulent flow and the kinetic/local energy loss dominates the pressure drop when $\mathrm{Re} > 100$. Ergun equation indicates that the pressure drop across the packing length is dependent upon the flow rate, the viscosity and density of fluid, and the size, shape and surface of packing materials. Eq. 3 can be rewritten as:

$$\frac{dp}{dx} = C_1 \frac{u}{D_p^{\ 2}} + C_2 \frac{u^2}{D_p} \quad (4)$$

where $C_1 = \frac{150\mu(1-\varepsilon)^2}{\varepsilon^3}$ and $C_2 = 1.75\frac{1-\varepsilon}{\varepsilon^3}\rho$. Considering air flow through tulip bulbs the coefficients C_1 and C_2 were experimentally determined, for different tulip bulbs diameter, by van Bruggen (2002) taking the values 0.4 and 28.1 respectively. By setting $C_1 = 0.4$ and $C_2 = 28.1$ in the Eq. 4, the pressure drop dp occurred inside the tulip bulbs was estimated for superficial velocity u ranged from 0.01-0.3 m/s and for three tulip bulbs diameters D_p, 0.04, 0.08 and 0.1 m. By plotting the pressure drop dp against u and by fitting a power law function to the data the pressure drop is expressed as a function of superficial velocity (Figure 1). In this study the pressure drop of air flow due to the presence of tulip bulbs is described according to the power low model (Fluent Inc 1998). For tulip bulbs with diameter D_p=0.4 m, the pressure drop is given by the Eq. 5.

$$dp = 535u^{1.2} \quad (5)$$

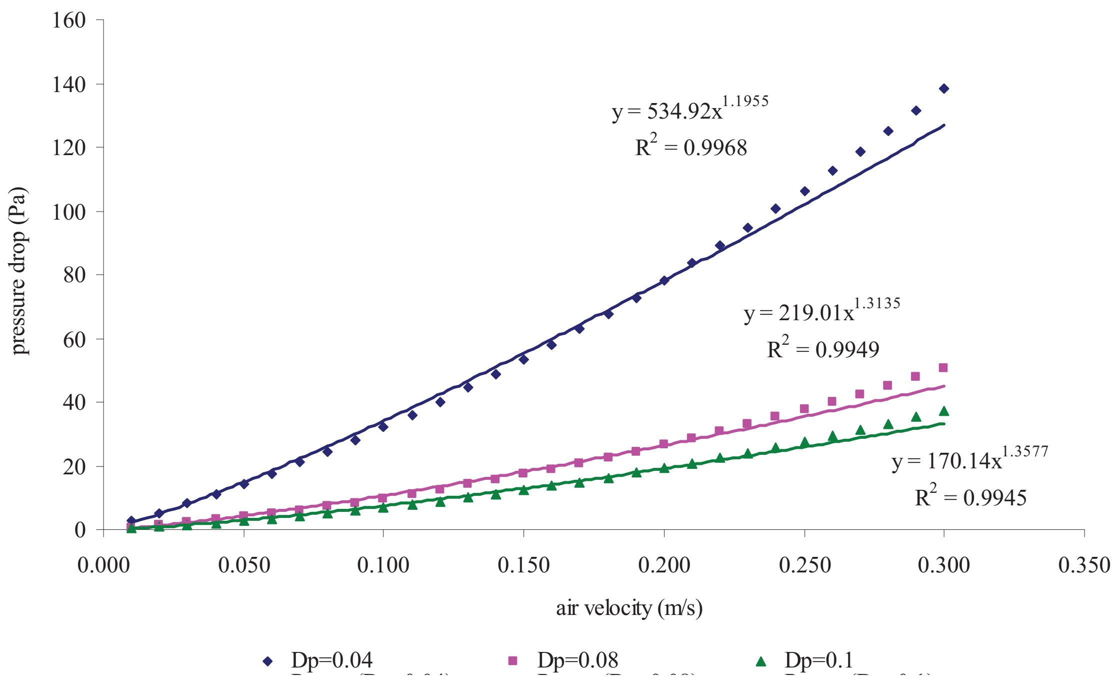


Figure 1. Pressure drop as function of superficial velocity for different tulip bulb diameters.

Air flow through perforated iron bottom Boxes or crates which are used for tulip bulbs storage have a perforated iron bottom which can be simulated as porous surface (Figure 2). In the commercial CFD code Fluent used in the present study, the pressure drop due to the presence of a porous surface is modeled by a porous jump boundary condition (Fluent Inc 1998). The pressure drop is described by the Forchheimer equation (similar to Eq. 3).

$$\frac{dp}{dx} = \frac{\mu}{K}u + \frac{1}{2}\rho C u^2 \qquad (6)$$

where C is the pressure-jump coefficient and K (m^2) is the permeability of the porous medium which is independent of the nature of the flow. The permeability and pressure loss coefficient for a perforated iron bottom, with opening area 40%, were calculated by simulating the perforated plate as a porous surface in a virtual wind tunnel. By solving the simulation model for different boundary conditions, regarding the superficial velocity, a set of results, as pairs of velocity applied and pressure drop occurred in the porous zone, is obtained. As it is known that the pressure drop per unit of thickness of the material is given by the Eq. 6, a second order polynomial without intercept was applied to the calculated data using the non-linear regression tool of the Matlab software, (Depypere et al., 2004). By this approach the permeability was calculated to $K = 1.2 \cdot 10^{-8}$ and the pressure loss coefficient to $C = 3220$.

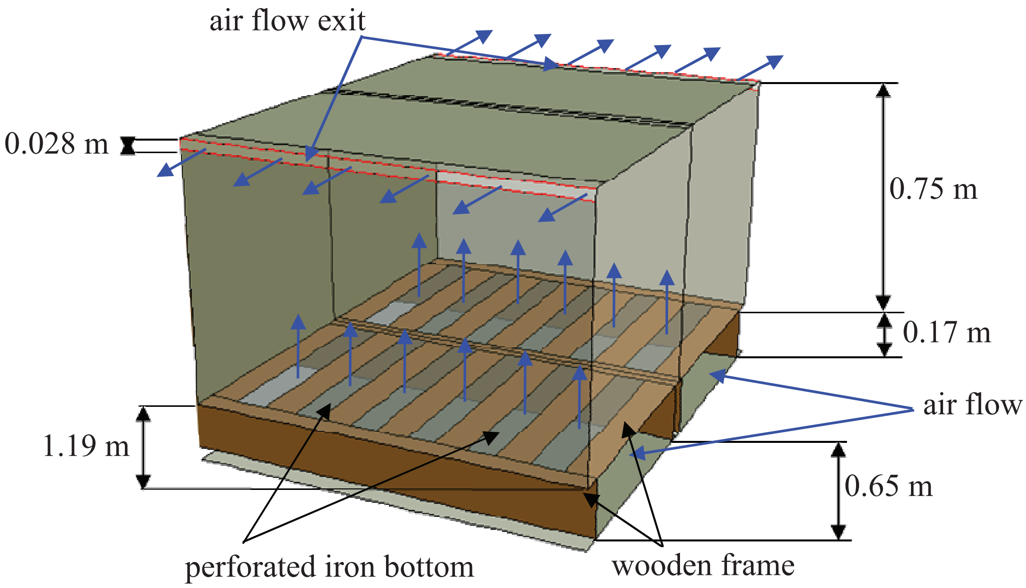


Figure 2. Typical box used for tulip bulbs storage as it was simulated in CFD model.

Storage system design Tulip bulbs are stored in wooden boxes which are ventilated to a level of 300-500 m^3/h per m^3 tulip bulbs to avoid high ethylene concentration between the bulbs. One of the most common storage systems is the one layer system, (Figure 3). The boxes are positioned in an arrangement with an adjusted large box, containing a ventilator (ventilation wall). The air flows through the bottom canals of the boxes, through each box and then escapes through a small slit at the upper side wall of the box (Figure 2).

The simulation model was designed and meshed with the geometrical processor Gambit as a 3D scale model. Only half of the system was designed since its symmetrical configuration to the z-redirection (Figure 4). The main target in this stage was to combine a grid with the smallest number of cells with acceptable accuracy concerning the simulation results. The structured mesh consist of only tetrahedral elements was characterized as according to EquiAngleSkew criterion as excellent for more than 80% of the mesh elements (Fluent Inc

1998). Design modifications were integrated in the initial design in order to decrease the resistance of the construction to air flow and improve the uniformity of the air flow between the boxes.

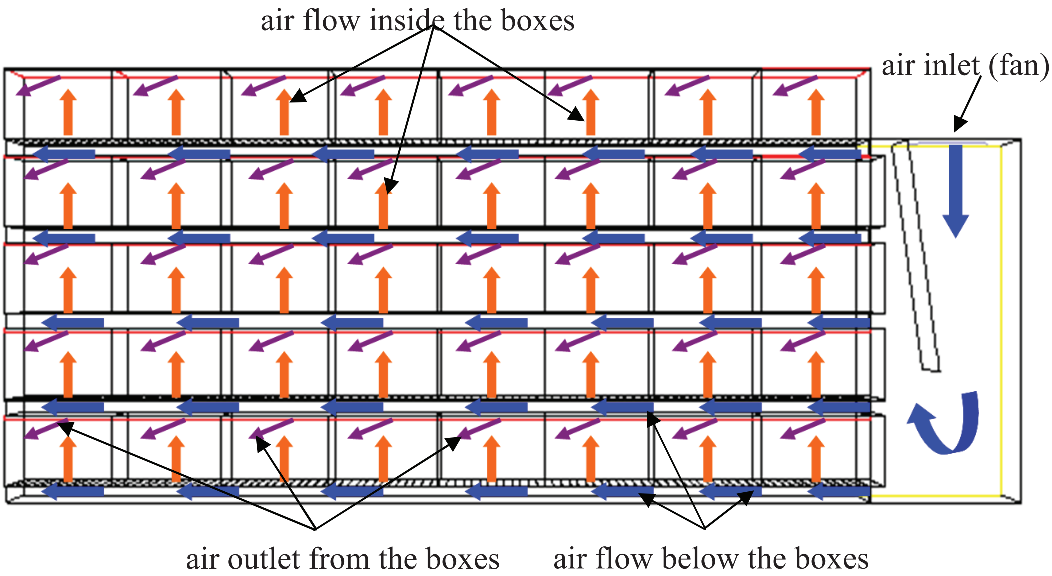


Figure 3. One layer system consists of 5 rows, 8 crates per row and an adjusted box with the ventilator.

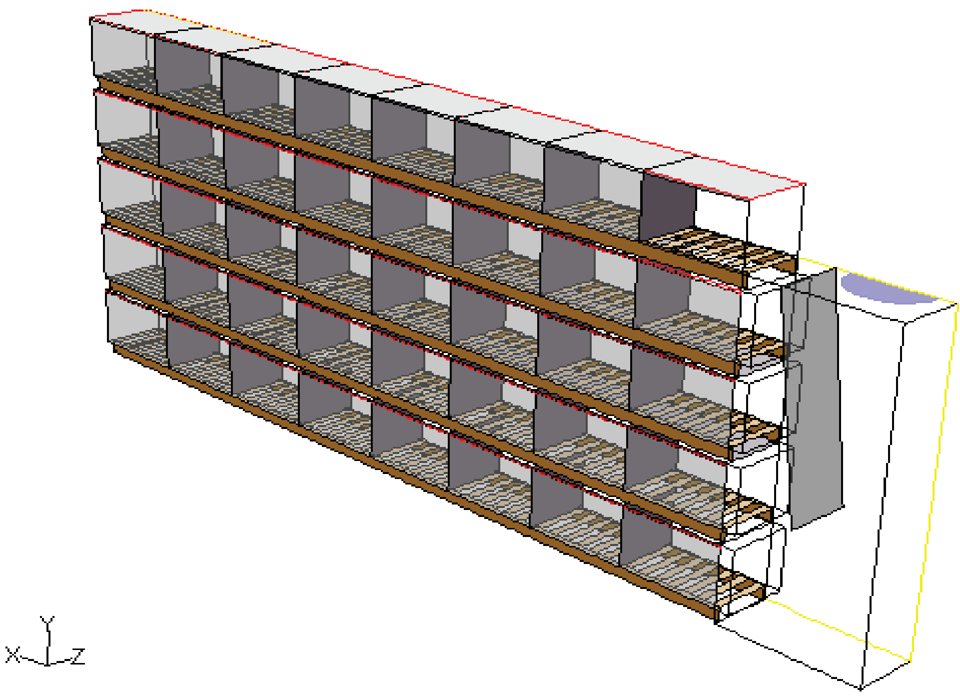


Figure 4. 3D symmetrical model of the one-layer storage system for tulip bulbs as it was designed by the geometrical processor Gambit.

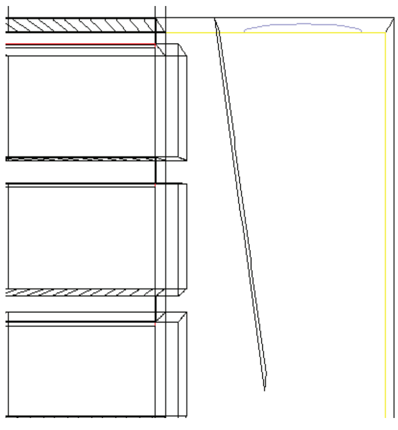
Boundary conditions As CFD models are totally deterministic models, next to grid quality and physical models (i.e. turbulence, wall functions, heat and mass transfer, etc), the results are depended on the boundary conditions. The boundary conditions for both tulip bulbs and perforated iron bottom of the crates are summarized in Table 1. All the calculations were performed assuming adiabatic conditions. The air flow, which was considered fully turbulent, was solved using the control volume numerical method and realizable k-ε turbulence model in conduction with two-layer zonal model, (Fluent Inc 1998).

Table 1. Boundary conditions used in CFD model.

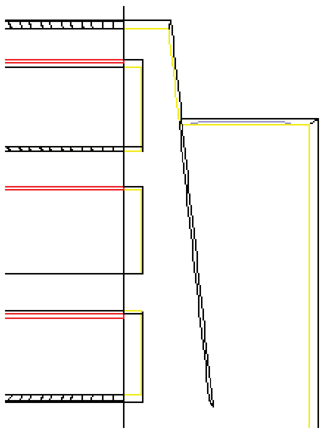
Boundary element	Value	Unit
Ventilator	234 – 300	m^3/s
Turbulence kinetic energy	5	m^2/s^2
Turbulence dissipation rate	5	m^2/s^3
Perforated iron bottom (porous jump)	$K = 1.2 \cdot 10^{-8}$, $C = 3220$	
Tulip bulbs (porous media, power law model)	$dp = 535u^{1.2}$ ($C_0 = 535, C_1 = 1.2$)	

COMPUTATIONAL RESULTS

In the present study six design configurations were investigated, (Figure 5a, 5b, 5c). The first target was to decrease the air flow resistance by applying simple modifications to the current storage system. The second target was to adjust the ventilation rate to the minimum ventilation rate occurred in the boxes. The computational results were evaluated using the standard deviation of the air flow inside the boxes which indicates the air flow uniformity, the minimum air flow occurred in the boxes and the maximum pressure, which is actually the pressure increased as a result of fan operation.

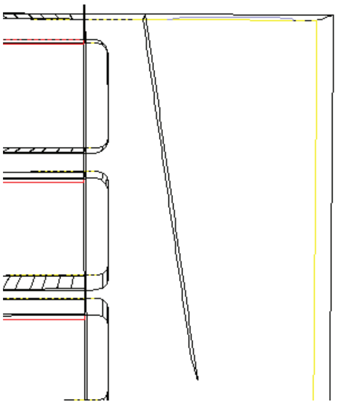


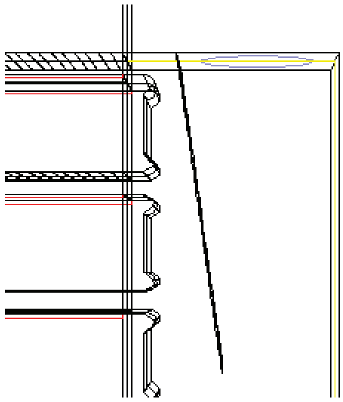
a) Design-1, (case_1-A, case_1-B, case_1-B_a)



b) Design-2, (case_2-A, case_2-B)

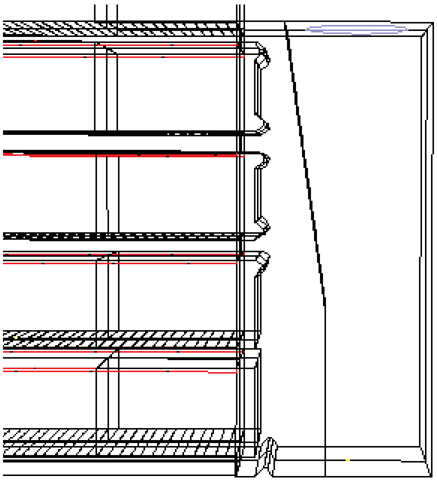
Figure 5a.Design configurations of one layer storage system and simulation cases correspond to them, a) current system with normal height of air flow channel and b) with double height.

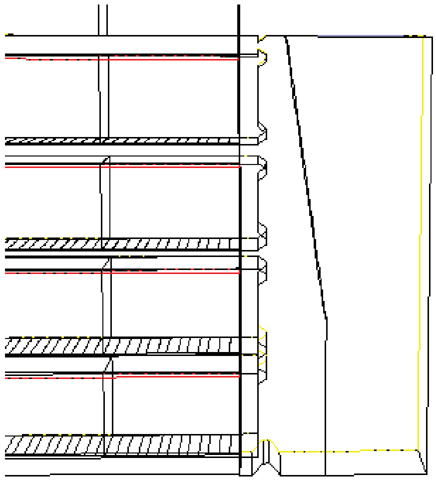




a) Design-3, (case_3-A, case_3-B, case_3-B_a) Design-4, (case_4-A, case_4-B, case_4-D)

Figure 5b.Design configurations of one layer storage system and simulation cases correspond to them, a) air channels with curved corners and b) air channels with droplet corners





a) Design-5, (case_5-A) b) Design-6, (case_5-E)

Figure 5c. Design configurations of one layer storage system and simulation cases correspond to them, a) air channels with droplet corners and obstacle in the first channel and b) air channels with droplet corners, an obstacle in the first channel and smaller inlet of the top channel.

The results regarding the ventilation rate are expressed as percentage of the optimum ventilation rate which is 300 m^3/h per m^3 of tulip bulbs. The current system was characterised by pure uniformity. The min ventilation rate is 66.6% while the max one is 180.2% with standard deviation 32.4%. In average terms, the min and max ventilation rate of all designs are 73.9% and 146.0%. By comparing the results regarding the max pressure it is clear that it is possible to reduce the resistance of the system to the air flow and by doing so to reduce the energy consumption. All the computational results are summarized in Table 2.

Table 2. Computational results of different design configurations of one layer storage system for tulip bulbs

Simulation Cases	top surface of boxes	air flow (m^3/h per m^3 of tulips bulbs)	standard deviation	min ventilation rate	max ventilation rate	max pressure (Pa)	Energy consumption
case_1-A	top outflow	300	32.4%	66.6%	180.2%	96.89	0.0%
case_1-B	top wall	300	13.0%	81.7%	122.9%	111.05	14.6%
case_1-B_a	top wall	234	8.6%	66.5%	93.8%	77.27	-37.8%
case_2-A	top outflow	300	45.8%	62.3%	194.5%	82.26	-15.1%
case_2-B	top wall	300	13.9%	85.9%	126.4%	102.23	5.5%
case_3-A	top outflow	300	32.8%	71.3%	183.9%	90.01	-7.1%
case_3-B	top wall	300	11.1%	87.0%	119.4%	107.00	10.4%
case_3-Ba	top wall	285	10.1%	82.7%	113.0%	99.16	-2.8%
case_4-A	top outflow	300	32.1%	65.1%	175.2%	98.81	2.0%
case_4-B	top outflow	300	14.9%	80.6%	124.7%	111.33	14.9%
case_4-D	top outflow	300	31.1%	65.4%	171.4%	95.35	-1.6%
case_5-A	top outflow	300	33.1%	69.7%	185.3%	101.46	4.7%
case_5-E	top outflow	264	8.0%	76.2%	106.9%	97.82	-11.2%

The ideal power consumption of a fan P_i (W) (without losses) can be expressed from Eq. 6.

$$P_i = dp \cdot q \qquad (6)$$

where dp (Pa) is the total pressure as a result of fan operation and q (m^3/s) is the air volume delivered by the fan. By reducing the pressure dp which means the resistance, the air flow q or both, the energy consumption was decreased. The results presented in Table 2 shown that by smoothing the sharp corners of the entrance channels of the ventilation wall, keeping the same ventilation rate (case_3-A, Figure 6), about 7% energy can be saved with almost the same uniformity. Doubling the height of the air flow channels (case_2-A) almost 15% energy can be saved but in this case the uniformity is worst (standard deviation 45.8%). By covering the open top boxes the uniformity is better for all the cases. An effective and simple way for improvement, was by covering the top boxes and simultaneously adjusting the ventilation rate to the minimum air flow (67%), which means providing air flow 234 instead of 300 m^3/h per m^3 of tulip bulbs, (case_1-B_a, Figure 7). In this case the energy consumption is decreased by 38%. Positive results are obtained when a combination of different configuration was applied (smooth corners of the entrance channels, decrease of the inlet area of the top channel and putting a round obstacle in front of the first channel (case_5-E)). In this case the energy consumption is decreased by 11%.

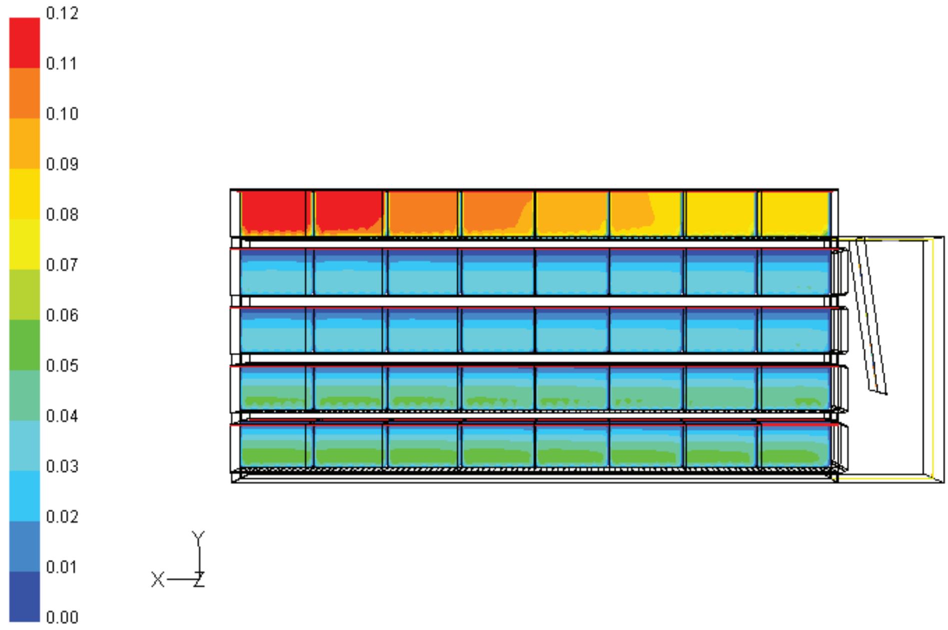


Figure 6. Air velocity magnitude of one layer storage system with smoothed sharp corners of the air flow entrance channels.

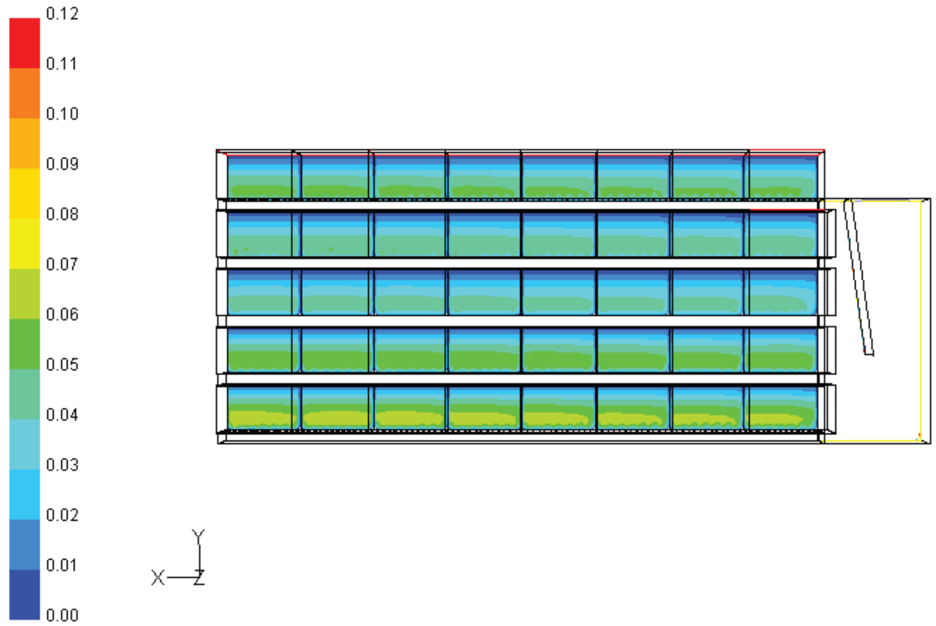


Figure 7. Air velocity magnitude of one layer storage system when the top row of boxes is covered.

CONCLUSIONS The performance of the one layer storage systems was investigated using CFD models. The current system is characterised by pure uniformity and high energy consumption due to over ventilation. Simple modifications of the current system can improve uniformity and save energy as well. This can be achieved by reducing the resistance to the air flow and by adjusting the air supplied by the fan to the box with the minimum ventilation rate. The most effective way of improvement is by smoothing the sharp corners of the entrance channels and simultaneously by covering the top row of boxes and reducing the air flow to a level of 67%. In this case the energy saving is about 45%.

All the calculations were performed considering tulip bulbs diameter 0.04 m and 40% perforation of the iron bottom of the boxes. Since the resistance of the storage system has a key role to the energy consumption, the above results are expected to be changed in the case that different size of tulip bulbs are stored or different boxes are used. In addition, the ventilation rate of 300 m^3/h per m^3 of tulip bulbs is applied for storing tulip bulbs and not for drying. During the drying process of tulip bulbs the ventilation rate is 5-6 times higher. As most of the growers use similar systems for both drying and storing processes, more research is needed in order to design a system which can perform properly for all conditions and for different size of tulip bulbs. CFD has been proven to be a useful tool to this direction.

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