Using CFD to optimize the design of one layer storage system for tulip bulbs

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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. The containers are positioned in an arrangement of 5-6 rows with 8-10 containers per row, each one on a pallet (one layer system), with an adjusted large box containing a ventilator. 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. Two different design variations of the one layer system were simulated and two size of tulip bulbs were considered. The results shown that the average energy consumption for different configurations was 1.00 kW and 0.79 kW for the first and the second design respectively, regarding both tulip bulbs sizes. Smaller tulip bulbs result higher energy consumption of 19.4% for the Design-1 and 26.0% for the Design-2. The best variations of both designs can achieve a minimum air flow per box of 79% of the nominal one, which is 300m^3/h per m^3 of tulip bulbs. The Design-2 has proven to be more energy efficient since it needs -22% less energy to achieve the same minimum air flow.

INTRODUCTION

In The Netherlands, at 1998, the flower bulb 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.

The results presented in this study were obtained during the implementation of a research project started in 2007 in collaboration between Wageningen UR (WUR Greenhouse Horticulture and Flower PPO), DLV Plant, bulb companies, installers and manufacturers. The project aimed to demonstrate the performance of the current state of art technology storage systems for tulip bulbs and suggest improvements for energy saving, while maintaining or improving product quality.

SET UP THE CFD MODEL

Air flow through tulip bulbs

The 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.

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

$$u = \varepsilon \cdot v \qquad (2)$$

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).

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

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:

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

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 and by using a simulation model where the tulip bulbs were represented as uniform volume with certain porous characteristics, the pressure drop dp occurred inside the tulip bulbs was estimated for superficial velocity u ranged from 0.01-0.3 m/s, (Sapounas et al., 2010). In this study two tulip bulb sizes were considered, one with bulb perimeter of 12 cm and one with bulb perimeter of 6 cm. In the simulation models the pressure drop was described by the power low model (Fluent Inc 1998) considering $dp = 530u^{1.2}$ and $dp = 1650u^{1.1}$, for tulip bulbs with perimeter of 12cm and 6cm respectively.

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 (Fig. 1(c)). In the commercial CFD code Fluent used in the present study, the pressure drop due to the presence of a porous surface was modelled as porous jump (Fluent Inc 1998). By this approach the permeability, for a perforated iron bottom, with opening area 40%, was calculated to $K = 1.2 \cdot 10^{-8}$ and the pressure loss coefficient to $C = 3220$, (Depypere, et al., 2004; Sapounas, et al., 2010).

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, (Fig. 1(a, b)). The boxes are positioned in an arrangement with an adjusted large box, containing a ventilator (ventilation box). 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 (Fig. 1(c)). In this study two designs (Design-1 and Design-2) of the one layer system were simulated. Both designs consist of 6 rows with 10 boxes per row and both have the same dimensions.

In the Design-1 (Fig. 1(a)) there is a “wall” which drives the air flow to the boxes. In order to improve the performance of the system it was suggested to install a plate just in front of the first air-flow channel, since from measurements in situ it was proven that this channel was over ventilated. Before realizing this idea the question that must be answered was: which will be the dimension and the position of this plate. In Fig 2(a) the different dimensions and positions of this plate considered for the simulations are depicted.

In the Design-2 (Fig. 1(b)) the improvements were suggested to be realized by installing plates in front of each air flow channel in order to uniformly distribute the supplied air. Again the question must be answered was: which is the best plate configuration regarding both size and locations. It is obvious that the suggested improvements for both designs were chosen due to their simplicity. Details about the geometry of the CFD model, the grid quality, the turbulence model and the boundary conditions considered, can be found in the study carried out by Sapounas et al. (2010).

RESULTS AND DISCUSSION

In the present study, after many preliminary calculations for different configurations depicted in Fig 2 (a, b), the results of five simulations models for each design are presented. Each simulation model was solved for both tulip bulb sizes.

The results shown that the average energy consumption for difference configurations was 1.00 kW and 0.79 kW for the first and the second design respectively regarding both tulip bulbs sizes. Smaller tulip bulbs result a higher energy consumption of 19.4% for the Design-1 (Table 1) and 26.0% for the Design-2 (Table 2). The best variations of both designs can achieve a minimum air flow per box of 79% of the nominal one, which is 300m^3/h per m^3 of tulip bulbs. The second design has proven to be more energy efficient since it needs -22% less energy to achieve the same minimum air flow. The size of the tulip bulbs strongly influences the energy consumption. When the tulip perimeter is 6cm instead of 12 cm, in average terms, 70% and 89% more energy needed for the Desing-1 and Design-2 respectively. The Desing-2 can achieve a better uniformity of the air flow inside the boxes. The average standard deviation for tulip bulbs with diameter of 12 cm was 87 m^3/h per m^3 of tulip bulbs for the Design-1 while 43 m^3/h per m^3 of tulip bulbs for the Design-2. For the tulip bulbs with perimeter of 6 cm the correspondence values are 35 and 21 m^3/h per m^3 of tulip bulbs. For all the calculations the fan motor efficiency was considered 80%.

CONCLUSIONS

The influence of simple design improvements, which can easily been adjusted to the current storage systems for tulip bulbs, to the ventilation performance was studied. Since the current systems are characterised by pure uniformity, all the improvements simulated had positive effect to the air flow distribution, but negative effect to the energy consumption, since the installation of plates, in order to drive the air flow to the right direction, increases the resistance of the overall system. In practice the entrepreneurs over ventilate the tulip bulbs, sometimes even above 500 m^3/h per m^3 of tulip bulbs. Measurements have been made on ten companies indicated that there is 4-5 times much air flow through the most ventilated box than the air flow through the least ventilated box. This indicates a great potential in energy saving. The configurations proven to be the best for both designs must be used simultaneously with the adjustment of the ventilation rate to the minimum air flow can be observed in the boxes. By this approach the resistance of the overall system becomes lower resulting a higher energy saving. If the ventilation rate is adjusted to the air minimum air flow, the Design-2 is more energy efficient than the first one, while the same time provides a better uniformity. As most of the entrepreneurs 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.

Literature Cited

De Munk, W.J. 1972. Bud necrosis, a storage disease of tulips. III. The influence of ethylene and mites. Netherlands Journal of Plant Pathology. 78(4):168-178

De Wild, H.P.J., Gude, H. and Peppelenbos, H.W. 2002. Carbon dioxide and ethylene interactions in tulip bulbs. Physiologia Plantarum. 114(2):320-326

Depypere, F., Pieters, J.G. and Dewettinck, K. 2004. CFD analysis of air distribution in fluidised bed equipment. Powder Technology. 145(3):176-189

Fluent Inc. 1998. Fluent User's Manual, Fluent Inc. Lebanon.

Kamerbeek, G.A. and De Munk, W.J. 1976. A review of ethylene effects in bulbous plants. Scientia Horticulturae. 4(2):101-115

Sapounas, A.A., Campen, J.B., Wildschut, J. and Bot, G.P.A. 2010. Energy Saving During Bulb Storage Applying Modelling with Computational Fluid Dynamics.. Proc. XVIIth World Congress of the International Commission of Agricultural Engineering (CIGR). Québec, Canada p. 1-10

Van Bruggen, H.P. 2002. Het bewaren van tulpen in kuubskisten: Analyse en verbetering van e luchtverdeling. IMAG, Wageningen University. Wageningen, The Netherlands

Wildschut, J., Gude, H. and Krikke, A. (2005). Bulbous Flower Production Systems: State of the Art. In "Acta Horticulturae", Vol. 673, pp. 751-754.

Wu, J. and Yu, B. 2007. A fractal resistance model for flow through porous media. International Journal of Heat and Mass Transfer. 50(19-20):3925-3932

Tables

Table 1. Computational results of different configurations of one layer storage for Design-1

		case-1	case-2	case-3	case-4	case-5
Tulip bulbs with perimeter 12cm	Energy consumption,* [kW]	0.97	0.73	0.67	0.52	0.81
	Min air flow, [m^3/h per m^3 tulip bulbs]**	222	235	199	155	204
	Standard deviation**	25%	17%	49%	73%	45%
	Air flow per energy consumption***, [m^3/W]	13.7	19.4	17.7	18.1	15.0
Tulip bulbs with perimeter 6cm	Energy consumption,* [kW]	1.31	1.12	1.20	1.41	1.27
	Min air flow, [m^3/h per m^3 tulip bulbs]**	230	217	216	208	213
	Standard deviation**	7%	9%	22%	29%	26%
	Air flow per energy consumption***, [m^3/W]	10.6	11.6	10.8	8.9	10.1
Increase of energy consumption due to smaller tulip size		35%	54%	78%	173%	56%

* assuming that the motor efficiency is 80%

** excluding the top row (6th)

*** regarding the box with the minimum air flow

Table 2. Computational results of different configurations of one layer storage for Design-2

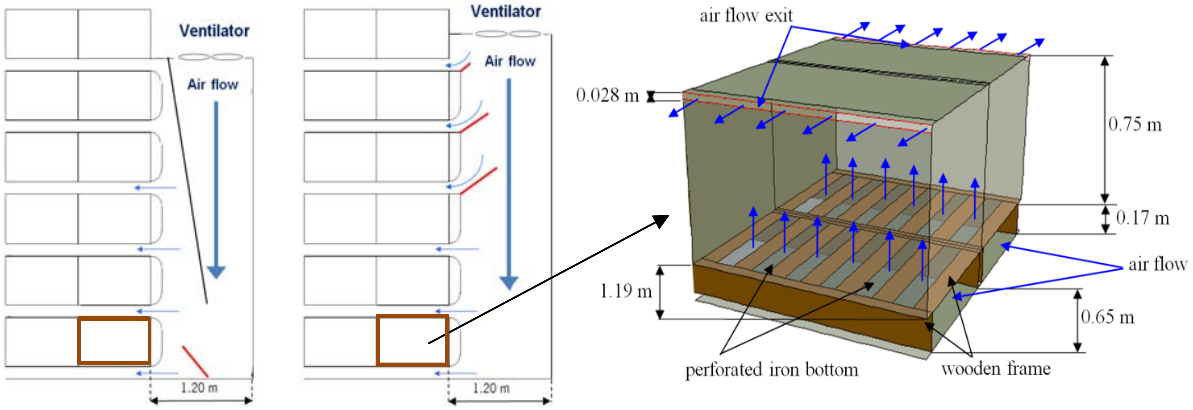
		case-1	case-2	case-3	case-4	case-5
Tulip bulbs with perimeter 12cm	Energy consumption,* [kW]	0.55	0.55	0.55	0.54	0.53
	Min air flow, [m^3/h per m^3 tulip bulbs]**	237	190	206	203	220
	Standard deviation**	18%	27%	26%	24%	21%
	Air flow per energy consumption***, [m^3/W]	26.0	20.9	22.5	22.5	24.9
Tulip bulbs with perimeter 6cm	Energy consumption,* [kW]	1.04	1.03	1.04	1.04	1.00
	Min air flow, [m^3/h per m^3 tulip bulbs]**	241	240	244	241	236
	Standard deviation**	10%	12%	12%	8%	11%
	Air flow per energy consumption***, [m^3/W]	13.9	14.0	14.1	13.9	14.2
Increase of energy consumption due to smaller tulip size		90%	88%	90%	92%	87%

* assuming that the motor efficiency is 80%

** excluding the top row (6th)

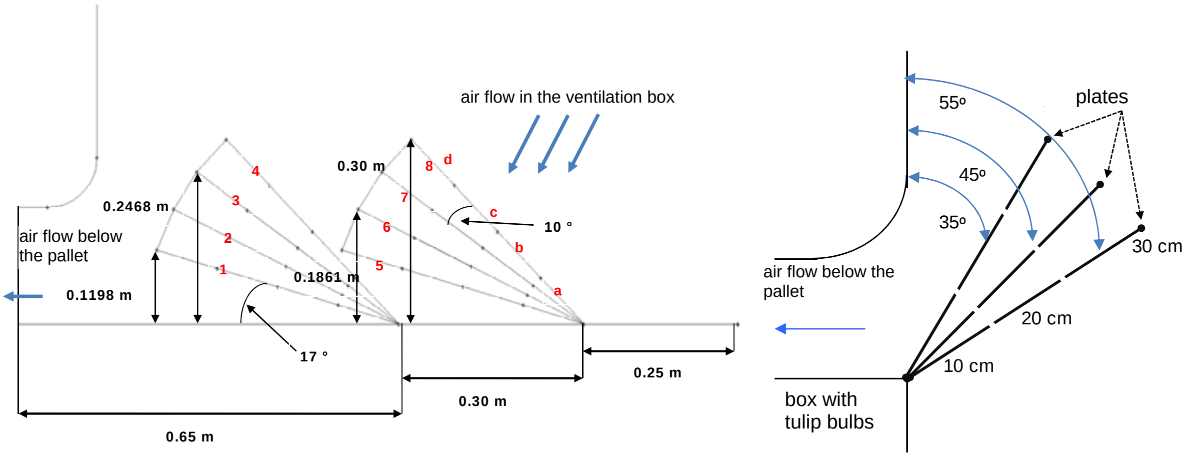
*** regarding the box with the minimum air flow

Figures



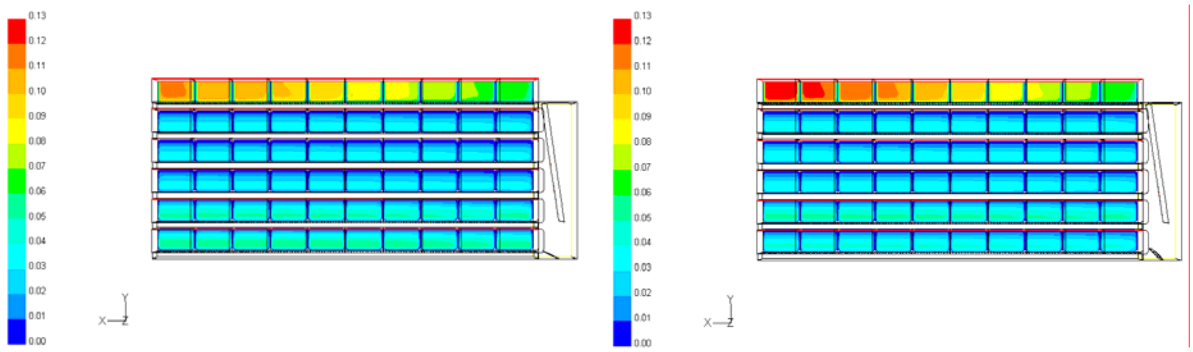
(a) (b) (c)

Figure 1. One layer storage system for tulip bulbs: (a) Design-1, six layers with plates (—) on the bottom of the ventilation box, (b) Design-2 six layers with plates (—) in front of air-flow channels and (c) 3D model of a wooden pallet with storage box considered in the CFD model.



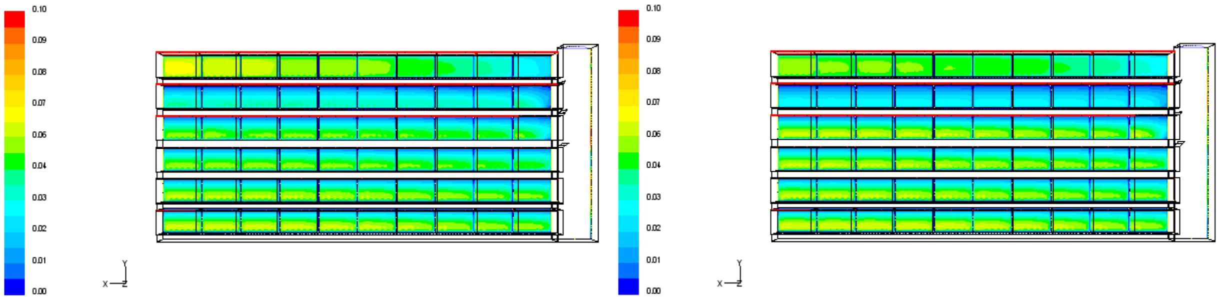
(a) (b)

Figure 2. Position of the different plates considered in the CFD models, (a) Design-1 and (b) Design-2



(a) (b)

Figure 3. Air flow velocity inside the storage boxes filled with tulip bulbs, (range 0-0.13m/s). (a) Design-1, configuration: plate-2 of Fig. 2(a), tulip bulb perimeter 12cm, (b) Design-1, configuration: plate-4 of Fig. 2(a), tulip bulb perimeter 12cm



(a) (b)

Figure 4. Air flow velocity inside the storage boxes (range 0-0.1m/s). (a) Design-2, row-5: plate-5=10cm at 45°, row-4: plate-4=20cm at 35° and row-3: plate-3=20cm at 55°, (Fig. 2(b)), tulip bulb perimeter 12cm, (b) Design-2, row-5: plate-5=10cm at 45°, row-4: plate-4=10cm at 45° and row-3: plate-3=20cm at 55°, (Fig. 2(b)), tulip bulb perimeter 12cm