CFD model development and validation of a thermonebulisation fungicide fogging system for postharvest storage of fruit

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A B S T R A C T
Postharvest treatments of fruits in storage rooms using a fogging system is a recent development that offer a promising means to reduce the use of fungicides in the orchards, where ecological and environmental risks are higher than in the closed environment of the storage room. To investigate the effectiveness of postharvest storage fungicide fogging systems, a computational fluid dynamics (CFD) model was developed and validated. A discrete element (DE) method was applied to generate a random stacking of spherical fruits in a typical bin. The CFD model was then employed to study explicitly the air and fungicide particle flow through the bin vent holes and through the voids of the stack, and to predict the deposition behaviour of the fungicide particle on the products. For model validation purposes, a standardized set-up was used with a single fruit bin positioned in a cold store that was operated at different air flow rates. Good agreement was found between measured and predicted results of deposition profiles of fungicide particles. The deposition on the top layer of the fruit stack was higher than the bottom one, and higher deposition was observed on the top sides than on the bottom sides of the fruit.

The effect of air flow rates and different bin handling parameters on fungicide particles flow and deposition were investigated. Air circulation rates of 0 m³ h⁻¹ (no air circulation), 4080 m³ h⁻¹ and 6800 m³ h⁻¹ and 9520 m³ h⁻¹ were used. The highest fungicide deposition on the fruit was observed during fogging without air circulation while the lowest deposition corresponded to fogging with the highest air circulation rate. Covering the top of the bin with foil and removing the bottom plastic foam that is usually placed on the bottom floor of the bin improves the uniformity of fungicide deposition throughout the bin. Removing the bottom plastic liner increased the average deposition of the fungicide particles, while covering the top of the bin decreased the average deposition.

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1. Introduction
The abundant availability of nutrients and water and the appropriate pH of most horticultural products are favourable conditions for the growth of microorganisms (Tripathi et al., 2008). As a consequence, fungal growth is the cause of most postharvest decays (Amiri and Bompeix, 2005; Bertolini et al., 1995; Morales et al., 2007). To suppress fungal growth, several measures have been developed, including the application of fungicides. Inefficient fungicide treatment of fruits could result in lower biological efficacy, environmental contamination, loss of fungicide, fungicide residue above the allowable limit and decay due to fruit injury.

Fungicide treatments can be applied either at preharvest or postharvest stages. During preharvest application, fungicides are applied in the orchard before the fruit is picked; such application requires large volumes of fungicide solution and could cause environmental contamination and excessive residues on the fruit. During harvest and postharvest handling fruit injuries occur, and these injuries usually initiate decay (Amiri and Bompeix, 2005; Sugar and Basile, 2008). The effectiveness of preharvest fungicide applications to prevent such decays is questionable. Thereto, postharvest treatments have been proposed to control fungal storage decay of fruits (Droby, 2006; Korsten, 2006; Jijakli and Lepoivre, 2003; Bompeix and Clolodowski-Faivre, 2000; Vorstermans et al., 2005). Since this method directly targets the fruit rather than the whole orchard, it has been claimed to be cheaper than the corresponding preharvest application (Berrie, 1993).

Postharvest fungicides are usually applied using dipping or drenching of the fruit in a fungicide solution. This treatment
method has some drawbacks. A suboptimal treatment could aggravate the fungal diseases, the dirt and dust in the fungicide solution can reduce the effectiveness of the fungicide treatment, disposal of the fungicide solution to the environment is a challenge, and it is labour intensive (Moggia et al., 2003; Bertolini et al., 1995; Sugar and Basile, 2008). To overcome these drawbacks, there is an interest in the use of fungicide application systems directly in the cold storage room, thereby excluding a separate postharvest treatment operation. Thermonebulisation is one such method that generates a fog of fine fungicide particles by an aerosol electrical generator at operation. Thermonebulisation is one such method that generates storage room, thereby excluding a separate postharvest treatment and Basile, 2008). To overcome these drawbacks, there is an inter-

labor intensive (Moggia et al., 2003; Bertolini et al., 1995; Sugar and Basile, 2008). To overcome these drawbacks, there is an interest in the use of fungicide application systems directly in the cold storage room, thereby excluding a separate postharvest treatment operation. Thermonebulisation is one such method that generates a fog of fine fungicide particles by an aerosol electrical generator at ±190 °C and it uses air to transport and blow the aerosol particles to the storage room (Bompeix and Clolodowski-Faivre, 2000). In this system, the fungicide is directly applied to the stacked fruits and distributed by a forced airflow in the storage room. In addition, this method allows the reaplication of fungicide while the fruit is in the storage if needed, whereas there is only one opportunity to drench/dip the fruit. The effectiveness of this treatment is highly dependent on the amount and uniformity of fungicide distribution on the stacked product, and achieving the required uniformity is very challenging (Bertolini et al., 1995). Moreover, the losses to non-target materials such as bins should be known.

Although the above advantages of thermonebulisation treat-
ments have been claimed, it is hard to find experimental studies that demonstrate the effectiveness (uniformity) of this system. CFD modelling is an alternative to the expensive, difficult and sometimes dangerous experimental studies. CFD has been used in modelling transfer processes during storage, transport and han-
dling of horticultural products. It is reported that the cooling airflow inside the fruit stack is non-uniform and this caused uneven cooling and product quality (Verboven et al., 2004–2006; Alvarez and Flick, 1999a,b, 2007; Delele et al., 2008; Ferrua and Singh, 2009a–c). This non-homogenous airflow distribution inside the stack could also cause a non-uniform distribution of the fungicide particles. A number of studies also modelled the airflow, temperature and humidity distributions in cold storage rooms (Delele et al., 2009a,b; Chourasia and Goswami, 2007; Hoang et al., 2000, 2003; Nahor et al., 2005; Tassou and Xiang, 1998; Xu and Burfoot, 1999).

The objective of this study was to develop and validate a CFD model of a thermonebulisation fungicide fogging system for fruit postharvest treatments that predicts the fate of the fungicide par-
ticles. In particular, this study aimed to:

- experimentally determine the difference in fungicide deposition on different horizontal layers of fruit inside a bin as a function of the applied air flow rate in a cold store;
- experimentally determine the difference in fungicide deposition between top and bottom sides of the fruits on the different layers;
- verify whether CFD can predict these differences in fungicide deposition on fruits inside the fruit bin;
- use the model to investigate the effect of bin handling parame-
ters (top cover and bottom air circulation gaps) on the amount and uniformity of fungicide deposition in the fruit bin.

2. Materials and methods

2.1. Cold storage room and thermonebulisation system

A small scale storage room (Proefcentrum Fruitesseelt v.z.w., Sint-
Truiden, Belgium) with 4.75 m depth, 4.2 m width and 4.0 m height was used (Fig. 1). The cooling unit was centrally located near the ceiling at the back of the room. For the air circulation of the cooling air in the room, four axial flow fans with a diameter of 33 cm and adjustable flow rate (maximum flow rate of 6800 m3 h−1 or maximum air exchange rate of 85.2 h−1) were attached to the cooling unit. The room configuration is symmetric about the middle line from door to the back of the room.

The thermonebulisation treatment was performed by using an electrofog application system (Xeda International, St.-Andiol, France). The system was installed in the door of the room; an access hole was made for this purpose in the control window (Fig. 1). The nebulisation was achieved using a flow of air over a heated surface at temperature of 190 °C. As the fungicide solution (Xedathane-A containing 160 g L−1 pyrimethanil) passed over the hot surfaces, it quickly nebulises into small aerosol particles that were carried away by the airflow and blown into the room. The velocity of the nebulisation air assistance was measured using an ultrasonic anemometer (METEK USA-1, Elmshorn, Germany) and found to be 0.92 ± 0.06 m s−1.

The particle size distribution of the fungicide particle and the average velocity of the nebulising fog at the exit of the nebulizer were determined. The measured particle size distribution was provided by Xeda International (St.-Andiol, France) and was described

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>surface area, m²</td>
</tr>
<tr>
<td>c_a</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>d</td>
<td>particle diameter, m</td>
</tr>
<tr>
<td>g</td>
<td>gravitational acceleration, m s⁻²</td>
</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient, W m⁻² °C⁻¹</td>
</tr>
<tr>
<td>K</td>
<td>Darcy permeability, m²</td>
</tr>
<tr>
<td>k</td>
<td>turbulence kinetic energy, m² s⁻²</td>
</tr>
<tr>
<td>m_p</td>
<td>mass of discrete particle, kg</td>
</tr>
<tr>
<td>p</td>
<td>pressure, Pa</td>
</tr>
<tr>
<td>S_u</td>
<td>momentum source term, kg m⁻² s⁻²</td>
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<tr>
<td>S_v</td>
<td>heat source term, W m⁻³</td>
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<td>time, s</td>
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<tr>
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<td>temperature, °C</td>
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<tr>
<td>T'</td>
<td>fluctuating temperature, °C</td>
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<tr>
<td>u_x, u_y</td>
<td>mean velocity components in X, Y, and Z directions, m s⁻¹</td>
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<tr>
<td>u'_x, u'_y</td>
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<td>u_i</td>
<td>superficial velocity, m s⁻¹</td>
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<tr>
<td>h_i</td>
<td>velocity, m s⁻¹</td>
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<tr>
<td>V</td>
<td>volume, m³</td>
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<td>Cartesian coordinates, m</td>
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<td>β</td>
<td>Forchheimer drag coefficient, m⁻¹</td>
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<td>α</td>
<td>thermal diffusivity, m² s⁻¹</td>
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<tr>
<td>ε</td>
<td>dissipation rate of turbulence kinetic energy, m² s⁻³</td>
</tr>
<tr>
<td>μ</td>
<td>dynamic viscosity, kg m⁻¹ s⁻¹</td>
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<tr>
<td>μ_e</td>
<td>turbulent viscosity, kg m⁻¹ s⁻¹</td>
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<tr>
<td>ω</td>
<td>specific dissipation rate, s⁻¹</td>
</tr>
<tr>
<td>φ</td>
<td>porosity</td>
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<tr>
<td>γ</td>
<td>thermal expansion coefficient, °C⁻¹</td>
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</table>

Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>a</td>
<td>continuous air phase</td>
</tr>
<tr>
<td>c</td>
<td>cooler</td>
</tr>
<tr>
<td>o</td>
<td>reference condition</td>
</tr>
<tr>
<td>p</td>
<td>discrete particle</td>
</tr>
<tr>
<td>f</td>
<td>fruit</td>
</tr>
<tr>
<td>i, j</td>
<td>Cartesian coordinate index</td>
</tr>
</tbody>
</table>
in the form of a Rosin–Rammler distribution \( F = \exp \left( -\left( \frac{d}{d_c} \right)^\gamma \right) \).

The measured \( D_{V10} \), \( D_{V50} \) and \( D_{V90} \) values (diameter at which a volume fraction of 10%, 50%, and 90% is made up of particles with diameters smaller than this value) were 1.09 \( \mu \)m, 1.72 \( \mu \)m and 2.59 \( \mu \)m, respectively. The calculated values of \( d_c \) and \( \gamma \) were 2.01 \( \mu \)m and 3.57 \( \mu \)m, respectively.

2.2. Experiments

The distribution of fungicide particles inside the stack of loaded wooden bin was studied by measuring the amount deposited on the surface of the fruits. A single wooden bin loaded with apple fruit was placed at the backside centre of the room (Fig. 1). The dimensions of the bin were 1.24 m deep, 1.24 m wide and 0.74 m high (Fig. 2). The width of horizontal ventilation slots in the sides and bottom was 1.2 cm. The bin was filled with 380 ± 30 kg of apple (cv. Jonagold) fruit. On the bottom of the bin, a plastic liner was placed to prevent damage to the fruit when filling.

The room was fogged using 19 g of Xedathane-A solution (pyrimethanil 160 g L\(^{-1}\)). This weight of the fungicide solution was calculated based on the specification of the manufacturer by taking the actual weight of the fruit into account (50 g ton\(^{-1}\) of fruit with a target dose of 8 g ton\(^{-1}\) pyrimethanil). The total fogging period for the room with a single bin was 10 min 40 s. Afterwards, a deposition period of 3 h was respected for the suspended fungicide particles to properly settle on the surfaces and fruit.

The fogging was performed using continuous room air circulation at the rate of 6800 m\(^3\) h\(^{-1}\) and without room air circulation (other cases were considered using the CFD model only). The average room temperature was 13.3 °C. The thermophysical properties of the apple at this temperature were: density of 837 kg m\(^{-3}\), thermal conductivity of 0.558 W (m °C\(^{-1}\)) and specific heat capacity of 3665.6 J kg\(^{-1}\) °C\(^{-1}\) (Lisowa et al., 2002). The circulation air had a density of 1.253 kg m\(^{-3}\), thermal conductivity of 0.0249 W (m °C\(^{-1}\)) and specific heat capacity of 1005 J kg\(^{-1}\) °C\(^{-1}\). Fruit samples were taken from the top, centre and bottom layers of the bin. Ten fruits from each of these 3 layers were taken. The total amount of fungicide deposited was determined for the whole intact fruit, as well as for the top and bottom surfaces of the fruit. The measurement was conducted by FYTOLAB cvba (Zwijnaarde, Belgium) using liquid chromatography tandem mass spectrometry. For the analysis, the sample was completely chopped and homogenized as required by EU directive 396/2005. An analysis portion was weighed out and extracted in a two step extraction: first with acetone and then with a mixture of petroleum ether and dichloromethane. After salting out, the extract was evaporated and redissolved in methanol/water for analysis with liquid chromatography tandem mass spectrometry.

2.3. CFD model formulation

2.3.1. Governing equations

The CFD code used for this work was Ansys 12.1 (ANSYS, Inc., Canonsburg, Pennsylvania, USA). The continuous airflow was solved using the Reynolds-averaged fluid flow equations. In Cartesian coordinates, for an air flow with two-way coupling with the discrete phase, the Reynolds-averaged fluid flow equations are as follows:

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = 0
\]

\[
\frac{\partial (\rho u^2)}{\partial t} + \nabla \cdot (\rho u u u) = -\nabla p + \frac{\partial}{\partial x} \left( \mu \left( \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right) \right) - \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) - \rho g + S_u
\]
The heat transfer equation reads:

\[
\frac{\partial(T)}{\partial t} + \frac{\partial(u_i T)}{\partial x_i} = \alpha \frac{\partial (\partial T)}{\partial x_i} + \frac{\partial (-u_i T)}{\partial x_i} + S_r
\]  

(3)

The momentum source term \(S_r\) contained the momentum exchange with the discrete particles. In the case of the cooler, since it was considered as porous media, the resistance to airflow of the porous medium was added to \(S_r\). The loss coefficients of the flow through the cooling system was calculated using the Darcy–Forchheimer equation (\(S_r = -\frac{q}{\rho} \frac{u}{u} - \frac{1}{2} \frac{\mu}{\rho} \mid u \mid u \)) (Forchheimer, 1901); the first term (Darcy term) was neglected at high flow rate and the parameter \(\beta\) was calculated by taking into account the losses due to wall friction, entrance and exit and acceleration/deceleration effects (Tso et al., 2006). The average superficial velocity at the entrance of the cooler was 4.12 m s\(^{-1}\), this corresponds to the Reynolds number \(\text{Re} = \frac{\rho u D_c}{\mu}\) of 4394.7; where \(D_c\) is the collar diameter of the heat exchanger tube. When the Reynolds number is much greater than 1, the quadratic term dominates the pressure drop (Tso et al., 2006; Zukauskas and Ulinskas, 1990; Verboven et al., 2006). The value of \(\beta\) for the cooling unit was 35.8 m\(^{-1}\). The fourth term in the right side of Eq. (2) represents the buoyancy force, where \(\rho_s = \rho_s(1 - \gamma_s(T - T_0))\), where the reference temperature \(T_0\) was taken as the storage room temperature. The source term \(S_r\) consisted of the heat exchange with the cooler \((S_r = \frac{\text{sensible heat}}{\text{cooling time}}})\) and the heat of respiration from the fruit \((S_{\text{m}} = 1.91T_j + 4.64)\) (Anon, 2000).

The details of the determination of the specific Reynolds stress term \(\frac{\partial\langle u_i u_j \rangle}{\partial x_j}\) and specific Reynolds flux term \(\frac{\partial \langle u_i T \rangle}{\partial x_j}\) by means of turbulence closure models can be found in Wilcox (2000) and Versteeg and Malalasekera (1995). In this study, the accuracy and the convergence of the solutions for different two-equation Eddy-viscosity turbulence models (standard \(k-\varepsilon\), RNG \(k-\varepsilon\), realizable \(k-\varepsilon\), standard \(k-\varepsilon\) and shear stress transport (SST – \(k-\omega\))) were compared. The lowest relative error (20.6%) of the predicted deposition of the fungicide particles compared to the measured values was obtained in the case of SST – \(k-\omega\) model. As a result, SST – \(k-\omega\) model that employs equations for the turbulence variables \(k\) and \(\omega\) in the near-wall region and equations for \(k\) and \(\varepsilon\) in the bulk flow region (Menter, 1994) was used.

For a discrete particle moving in a continuous fluid medium, the equation of motion for the fungicide particle can be written as:

\[
m_x \frac{d v_p}{dt} = \frac{1}{8} \pi \rho c_p d^3 v_i - 1. \left( v_i - v_p \right) + \frac{1}{6} \pi d^3 \left( \rho_p - \rho \right) g_i + F_i
\]  

(4)

The first and the second terms in the right hand side represent the drag and buoyancy forces, respectively. The drag coefficient \(c_d\) was calculated using an empirical correlation for spherical particles developed by Morsi and Alexander (1972). \(F_i\) represents the additional forces that include the lift, thermophoretic and Brownian forces. Flow shear causes a lift force, this lift force was calculated based on Saffman expression (Saffman, 1965). The thermophoretic force is a force experienced by a small particle suspended by a gas that has a temperature gradient and acts opposite to the gradient. The details of the equations used in this study can be found in Talbot et al. (1980). Brownian motion is a common phenomenon of suspended submicron particles. The Brownian force was determined by a model that was developed by Li and Ahmadi (1992). Due to the low concentration of the dispersed fungicide particles inside the room, the coalescence was neglected. Since the fungicide particle has a very low vapour pressure (2.2 mPa at 25 °C) (product data sheet, Xeda international, St. Andol, France), the effect vaporization on deposition and secondary volatilisation of the particles after deposition were also neglected. To take into account the interaction between the two phases, two-way coupling with turbulent dispersion was considered. For the turbulent dispersion of the fungicide particles, the model developed by Gosman and Ioannides (1981) was used. The detailed equations for the calculation \(c_d\) and turbulent dispersion of particles can be found in Delele et al. (2009a, 2007).

2.3.2. Product stacking

A random stack of products in the bin was generated using the discrete element (DE) method (Delele et al., 2008). The DE method is a numerical method that solves Newton's equations of motion for an assembly of interacting particles. The forces that were considered include gravity and contact forces due to collision with other spheres or walls. The details of the working principle of the
DE model and the contact force model can be found in Tijskens et al. (2003). The vented bin was filled with 1620 spheres that represent 380 kg of apples with a normally distributed size of 70–85 mm in diameter (Fig. 3). By assuming symmetry only half of the bulk was taken for simulation.

2.3.3. Boundary conditions

The simulation domain considered one side of the refrigerated room (assuming symmetry) including the cooling battery with the fan and the heat exchanger (Fig. 1). The fan was modelled as a fan boundary with a given pressure rise, this was a lumped parameter model that predicted the amount of flow through the fan. The pressure rise was defined as $\Delta p_i = \sum_{n=1}^{N} f_n r^{n-1}$, where $f_n$ are the pressure jump polynomial coefficients and $V$ is the local fluid velocity normal to the fan. The cooler was treated as a porous medium with a corresponding pressure loss coefficient. All the solid surfaces in the room were treated as a no slip wall boundary condition. For the walls that were exposed to the outside atmosphere, the heat flux through the wall was calculated using, $q_w = \frac{k}{tw} (Tw - T)$. The wall temperature $(Tw)$ was taken as the outside temperature $(13.4^\circC)$, the thermal conductivity $(\lambda_w)$ of the insulation wall and the concrete floor were 0.02 and 2.6 W m$^{-1}$ K$^{-1}$ and the thickness $(tw)$ was 0.11 m. The exit of the nebuliser was also assumed laminar. Buoyancy induced turbulence was also checked using the flow Rayleigh number $(Ra = \frac{D_n \alpha \Delta T D}{\nu \beta_0})$; where $\Delta T$ is the difference between the nebuliser outlet and the room air temperatures and $D_n$ is the characteristics length (diameter of the nebuliser exit). The calculated $Ra$ number of the room was $1.86 \times 10^4$. This value is in the range of buoyancy induced laminar flow. For the study on indoor airflow Sinha et al. (2000) observed buoyancy induced turbulence when the $Ra$ value was higher than $1.7 \times 10^7$. The assumption was checked by comparing the accuracy and the convergence of the solution between the laminar and turbulent cases. A time step of 10 s and 50 iterations per time step was used. The calculation was done using 64-bit, Intel® Core™2 Quad CPU, 3 GHz, 8 GB RAM, Windows Vista computer. The CPU time of calculation was more than 17 h.

3. Results and discussion

3.1. Airflow and fungicide particle distributions

The predicted airflow and fungicide particle flow profiles inside the fruit storage room that was loaded with a single fruit bin are given in Figs. 4 and 5, respectively. A large portion of the circulating air did not penetrate the stack, rather it was deflected by the bin and returned back to the fan (Fig. 4a). The airflow profile inside the bin was far from uniform (Fig. 4b). The velocity of the air above the product (the top unoccupied portion of the bin) was higher than the interior air velocity. The air that was forced through the slots of the bin flowed to the top of the bin with little penetration into the stack.

The pathways of fogged particles were highly affected by the air velocity profile (Fig. 5a). A significant portion of the fogged fungicide particles was not penetrating the stack; rather they were taken by the return air towards the cooler assembly. The fungicide particles that were taken to the cooler by the return air were more likely to deposit on the surface of the cooling coils and fins. This unwanted deposition will adversely affect the efficiency of the postharvest treatment; moreover, this deposition could cause
corrosion and damage the cooling coils. Most of the fogged particles that passed through the bin slots were dragged to the top portion of the bin (Fig. 5b). However, in the case of fogging without air circulation the fungicide particles did not have a tendency to pass through the cooling coils but deposit on either the fruit or other room surfaces (Fig. 6).

The balance between the forces acting on the particles determines their path through the free air spaces in the room, mainly gravity and drag (Delele et al., 2009a). For the very small particles (<1 μm) in the fog, gravity is less important than the forced drag caused by the cooling airflow and turbulence. For the larger particles, the balance between the two forces will determine where they will deposit. Lift forces due to shear in the flow can also be important due to the presence of many surfaces (cool room walls, bin walls, fruit surfaces) as well as the velocity gradients caused by the jet of the coolers. The lift force is expected to be mainly important very close to the surfaces (McLaughlin, 1989). Buoyant movement due to particle concentration and temperature gradients may also play a role, particularly because the concentrated fog originates from a hot surface. The fog disperses quickly and concentration based buoyancy is small with respect to the forced air flow, from both the room (at high air flow rate) and the nebuliser itself. In the case of fogging without air circulation, the effect of thermal buoyancy on dispersion of the fungicide particles was more pronounced than the case of fogging with air circulation.

3.2. Fungicide particle deposition, CFD vs. experiments

Table 1 presents the experimental fungicide deposition data. For an intact fruit, the predicted deposition for fogging with air circulation were 3.86 ppm, 2.23 ppm and 2.11 ppm at the top, centre and bottom sections of the stack, respectively. Likewise, during fogging without air circulation, the predicted deposition were 22.57 ppm, 10.92 ppm and 7.55 ppm at the top, centre and bottom sections of the stack, respectively. The target dose was 8 ppm, obviously the treatment results in deposition values that are much smaller than the target dose when continuous air circulation is used. Most of the particles will then deposit on the walls and the cooler assembly. In the case without air circulation, the deposition is substantially higher, only in the bottom of the bin the dose could be below the target. This showed that fogging without air circulation could result fungicide deposition higher than the allowable residual limit. Maximum deposition values exceed values of 30 ppm, far above the target dose of 8 ppm.

The deposition of the fungicide particles on the apples in the bin was far from uniform in the case of no air circulation. The highest deposition of the fungicide particles then occurred on the top layer of the stack and decreased from top to bottom layers (Fig. 7). For the case with continuous air circulation; only at the top there is a chance of somewhat higher deposition. During fogging with air circulation, there was no significant difference \( p < 0.05 \) in deposition between the top and bottom surfaces (Table 1). In the case of fogging without air circulation, the deposition on the top side of the surface was larger than the deposition on the bottom side. The largest and smallest deposition differences between the top and bottom surfaces of the fruit were observed at the top and bottom layers of the bin, respectively.

There was a good agreement between measured and predicted deposition profiles (Figs. 7 and 8). Generally, there was a slight over prediction by the model. This shows that there could be a tendency of some particles resuspend from the fruit surface. The model did not take into account such behaviours. As well for the non-ventilation as for the continuous ventilation cases, the trends of the deposition as function of position are clearly predicted.

The uniformity of the fungicide particles deposition was analysed using the coefficient of variation (CV), \( CV = \frac{\sigma}{\mu} \times 100 \), where \( \sigma \) and \( \mu \) are the standard deviation and the mean of the fungicide particles deposition, respectively. Higher CV values correspond to lower uniformity of deposition.

During fogging with air circulation, the predicted and measured CV values were 35.8% and 39.9%, respectively; however, during fogging without air circulation the corresponding CV values were...
57.7% and 77.8%, respectively. From this result, it is obvious that air circulation improves the uniformity of fungicide deposition inside the fruit stack. The large gradient in deposition that was particularly obvious in the case of fogging with no air circulation could result in an excessive dose on the top layers of fruit or an insufficient dose on the bottom layers.

3.3. Sensitivity study

The CFD model was used to explore the effects of air circulation in more detail. A (hypothetical) 40% increase of the air circulation rate from the reference at 6800 m³ h⁻¹, which corresponds to 9520 m³ h⁻¹, resulted in a decrease of 11.03% in average deposition in the bin. A 40% decrease to a level of 4080 m³ h⁻¹, resulted only in an increase of 0.83% in average deposition in the bin. However, the uniformity of deposition increased with an increase in air circulation rate. At 9520 m³ h⁻¹, the CV value decreased to 14.7%, while the decreased air circulation rate resulted in an increase in CV to 43.8%. The advantage that was gained in uniformity due to the increase in air circulation rate was compromised by the decrease in deposition that could have an adverse effect on the efficiency of the treatment. This indicates the need for optimization of the system that gives the required deposition with best possible uniformity.

3.4. Improving uniformity of deposition in the bin

The validated model was used to study effects of covering the top surface of the box and removing the bottom plastic foam liner. Covering the top of the box could minimize the top deposition and thus improve the uniformity. Likewise, removing the bottom liner that is normally used as a shock absorber to avoid fruit injury during handling, could increase the particle flow through vent holes in the bottom of the bin and improve the bottom deposition and uniformity.

Covering the box decreased the fungicide deposition throughout the stack. Particularly the top deposition decreased by 67.6% and 84.5% for the cases of fogging with air circulation and without air circulation, respectively (Fig. 9). The CV of deposition decreased significantly to 12.6% and 24.8% for the cases of fogging with air circulation and without air circulation, respectively. This shows that putting a top cover over the box improves the uniformity of deposition. However, a significant amount of fungicide was lost by depositing over the top cover. This amount was as high as 52.2% of the average deposition within the stack.

Removing the plastic liner that is often placed on the bottom floor of the bin allowed the penetration of the fungicide particles through the bottom slots. The bottom deposition increased by 137.55% and 25.38% for fogging with and without air circulation,
respectively, and the corresponding CV value was decreased to 23.9% and 50.6%. Removing this plastic liner thus increased the uniformity of deposition. The effect of removing the bottom plastic was more pronounced for the case of fogging with air circulation. It may not be necessary to completely remove the plastic liner but it is possible to add vent holes to the liner that could allow the penetration of the air with the fungicide particles. However, further study on the optimum vent parameters is needed.

4. Conclusion

Thermonebulisation of fungicides in storage rooms may become a reliable alternative for postharvest fruit rot control. The distribution of the fungicides in the storage room however needs to be optimized to reduce the spatial variability of the treatment. In the presented study, it was demonstrated that both bin design and air flow rate to a large extent affect the magnitude and uniformity of fungicide deposition on fruits.

The amount and uniformity of deposition were a function of air circulation rate and bin parameters. The amount of fungicide particles deposition inside the stack decreased with an increase in air circulation rate. However, the uniformity of deposition was increased with air circulation rate. Covering the top of the bin decreased the amount of deposition throughout the stack,
particularly on top layer of the stack, but it increased the uniformity of deposition. Removing the plastic liner to improve air penetration from the bottom of the fruit bin increased both the deposition on the bottom layer of the stack and the uniformity of deposition.

Because airflow increases uniformity and still air increases deposition, configuration can be designed where periodic air circulation is used. To maintain the required amount of fungicide deposition with the highest uniformity, the optimal regimes for air circulation rate must be determined for more practical bin stacking patterns in large-scale cold stores. The validated CFD model will be readily applied for this purpose.

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