Original paper

Simulation of UV-C Dose Distribution and Inactivation of Mold Spore on Strawberries in a Conveyor System

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In order to examine microbial decontamination by UV-C treatment of strawberries on a continuously moving conveyor, we developed a three-dimensional irradiation model based on a discrete ordinates (DO) method to evaluate UV-C dose distribution on strawberries. The sliding mesh method was employed to describe the motion of strawberries placed on a UV-C-transparent film tray on a conveyor through a UV-C treatment system. We also estimated total UV-C radiation dose distribution on the surface of strawberries for four different configurations. The models with four lamps installed in parallel to the direction of movement provided uniform dose distribution. The time required for three-log inactivation of *Penicillium digitatum* on the surface of strawberries was also calculated. For the optimal model (Model D), 131 s was required for three-log inactivation of *P. digitatum*. The proposed radiation model was shown to be a useful tool for the optimization of UV-C treatment for strawberry.

Keywords: DO model, sliding mesh method, UV-C, surface decontamination, strawberry

Introduction

Studies on the effect of UV-C treatment of strawberries have been performed previously by numerous researchers (Allende *et al.*, 2007; Erkan *et al.*, 2008; Marquenie *et al.*, 2003; Pombo *et al.*, 2009, 2011). Marquenie *et al.* (2002) demonstrated that fungal growth on strawberries was significantly retarded using UV-C doses of $\geq 0.5 \text{ kJ m}^{-2}$. On the other hand, Nigro *et al.* (2000) found that UV-C pre-treatment at 4.0 kJ m^{-2} induced phytotoxic effects in strawberries, including loss of color brightness and surface dehydration. From these studies, it was concluded that the optimal doses for achieving microbial inactivation or reducing bacterial activity without loss of quality ranged from 0.5 to 4.0 kJ m^{-2} . The uniformity of the UV-C dose distribution is also an important

factor for the successful implementation of UV-C treatment. Many researchers ensured the uniformity of the dose distribution by employing manual rotation of fruits. However, this method is not suitable for strawberries, which have a soft surface, because it may cause bruising. In our previous study (Trivittayasil, 2016), a stationary UV-C radiation model was proposed to achieve uniform irradiation of the surface of strawberries on a UV-C-transparent film, with radiation sources above and below the fruit. The model was combined with a microbial inactivation model, and the UV-C inactivation process was optimized by investigation of the effects of various parameters, i.e., sample orientation, the number of UV-C lamps and the lamp position, on UV-C dose distribution on strawberries; however, the target sample was fixed in a UV-C

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treatment device. Because UV-C treatment of the surface of fruits for microbial inactivation should be carried out continuously in a packing house, using a conveyor system with a speed control device, a model with a moving sample system needs to be developed.

The objectives of this study were to develop a three-dimensional irradiation model based on the discrete ordinates (DO) and sliding mesh methods for describing the motion of strawberries placed on a UV-C-transparent film tray during movement through the UV-C treatment system, achieve uniform irradiation treatment of strawberries and estimate the microbial inactivation time using the proposed models. The proposed models will assist in the optimization of various decontamination treatment conditions.

Materials and Methods

(1) Modeling of UV-C treatment of strawberries

a) UV radiation model The changes in intensity at a point along a radiation ray due to emission, absorption and scattering in a fluid is governed by the following equation (Modest, 2003):

$$\frac{dI(\mathbf{r}, \mathbf{s})}{ds} = \kappa I_b(\mathbf{r}) - \kappa I(\mathbf{r}, \mathbf{s}) - \sigma_s I(\mathbf{r}, \mathbf{s}) + \frac{\sigma_s}{4\pi} \int_{4\pi} I_-(\mathbf{s}_i) \Phi(\mathbf{s}_i, \mathbf{s}) d\Omega_i \quad \dots \text{Eq. 1}$$

where $I(\mathbf{r}, \mathbf{s})$ is the radiation intensity in W m^{-2} at a given location indicated by position vector $\mathbf{r}$, in the direction $\mathbf{s}$ within a small bundle of rays, travelling in a fluid medium. As for the terms on the right-hand side of Eq. 1, $\kappa I_b(\mathbf{r})$, $\kappa I(\mathbf{r}, \mathbf{s})$ and $\sigma_s I(\mathbf{r}, \mathbf{s})$ indicate the emitted, absorbed, and out-scattered intensity in W m^{-3} , respectively. The last term indicates the integrated in-scattered intensity at $\mathbf{r}$ from the surroundings. $d\Omega$ is the finite solid angle and $\Phi(\mathbf{s}_i, \mathbf{s})$ is the phase function. Generally, the absorbed and out-scattered intensity can be drawn together by defining the extinction coefficient $\beta (= \kappa + \sigma_s)$.

$$\frac{dI(\mathbf{r}, \mathbf{s})}{ds} = \kappa I_b(\mathbf{r}) - \beta I(\mathbf{r}, \mathbf{s}) + \frac{\sigma_s}{4\pi} \int_{4\pi} I_-(\mathbf{s}_i) \Phi(\mathbf{s}_i, \mathbf{s}) d\Omega_i \quad \dots \text{Eq. 2}$$

Boundary conditions need to be defined to obtain the solution of Eq. 2. At the diffuse surface located at position vector $\mathbf{r}_w$, the emitted and reflected intensity are defined by:

$$I(\mathbf{r}_w, \mathbf{s}) = \varepsilon I_b(\mathbf{r}_w) + \frac{1-\varepsilon}{2\pi} \int_{2\pi} I_-(\mathbf{r}_w, \mathbf{s}_i) \mathbf{n} \cdot \mathbf{s}_i d\Omega_i \quad \dots \text{Eq. 3}$$

where ε is the emissivity in decimal values and $\mathbf{n}$ is the direction of the outward surface normal vector. The emission intensity $I_b(\mathbf{r}_w)$ of the UV-C lamp was determined experimentally in our previous study (Trivittayasil, 2016). The generated UV-C ray travels through a participating medium, and Eq. 1 or 2 govern the changes in its intensity. In complicated systems, numerical methods are useful for solving the governing equation with an adequate margin and initial conditions. The DO method is a useful numerical technique for solving radiation problems in such complicated systems. The DO method was employed for discretizing the radiation transfer equation into a finite number of discrete solid angles associated with individual vector direction $\mathbf{s}$, and the integrals over directions are replaced by numerical quadrature.

Table 1. Model parameters

Parameter	Value
Absorption coefficient of LLDPE [m^{-1}] ^a	274
UV power of lamp [W] ^b	1.7
Emissivity of lamp ^c	0.89
Emissivity of lamp cover ^d	0.04
Emissivity of strawberry ^e	0.95
Refraction index of LLDPE ^f	1.525

^a measured value

^b reported by manufacturer

^c Coussirat *et al.* (2008)

^d Incropera (2011)

^e Tanaka *et al.* (2007)

^f Japan Society of Thermophysical Properties Handbook (1990)

Basically, the employed DO model was validated theoretically as shown in our previous study (Trivittayasil, 2016).

b) Geometry and numerical aspects The geometries were created and meshed using ANSYS Workbench 14.0 (ANSYS Inc., PA, USA). The simulation of UV-C irradiation was carried out using Fluent 14.0 (ANSYS Inc.), employing the DO radiation model with polar and azimuthal angles to divide the hemisphere into 10×10 divisions with 3×3 pixels for solving the radiative transfer equation in the computational domain. As for the fluid phase, the continuity, momentum and energy equations were solved by assuming non-compressible laminar flow. In order to complete the mathematical description, a set of boundary conditions was defined for the diffuse surfaces within the model parameters, and their adopted values are listed in Table 1. Some physical properties are also listed in Table 1. To minimize the effect of thermal radiation from temperature differences between the fluid and the lamps, which have power being applied to them, the temperature of the fluid was reduced to 10 K in accordance with Ho *et al.* (2009). The volume of all solid domains, except the sample tray, was intentionally left blank because their internal heat transfer was not relevant to this simulation.

The governing equation was solved with appropriate boundaries and initial conditions using the SIMPLE algorithm, and spatial discretization was solved using the second-order upwind method for the continuity, momentum and energy equations, and the first-order upwind for the DO model.

In order to investigate the surface UV-C dose uniformity for strawberries depending on lamp length (190 or 250 mm with a 15 mm diameter, or 985 mm with a 22.5 mm diameter) and lamp array (installed in parallel or vertically to the direction of movement), four configuration models (Models A to D) with four UV-C lamps and nine strawberries placed on a UV-C-transparent linear low density polyethylene (LLDPE) film tray of 1 mm thickness were constructed (Fig. 1). The molded tray (205 mm $\times$ 205 mm) for fruits has nine cup-shaped depressions for accommodating individual fruits. The area and depth of depression

Fig. 1. A schematic diagram of UV-C treatment configuration models (Models A to D)

Table 2. Model configuration and operating conditions

Model	Operation type	Lamp length[mm]	Lamp direction	Step
Model A	fixed	190	vertical	7
	conveying	190	vertical	7
Model B	conveying	250	vertical	7
Model C	conveying	190	paralell	7
	conveying	190	paralell	71
Model D	conveying	985	paralell	7

Fig. 2. A schematic diagram of UV-C treatment system to show the positions of lamps and strawberries (Model A)

are 50 mm × 50 mm and 20 mm, respectively. These depressions are arranged in 3 rows × 3 columns. As for the conveyor, we disregarded it because the wires used to fix the tray were thin and few in number. The differences in each model are listed in Table 2. The actual power of the UV-C lamps was 99.25 and 94.66 W m⁻² for Models A to C and Model D, respectively. A schematic diagram of the UV-C treatment system showing the positions of lamps and strawberries (Model A) is given in Fig. 2. The vertical distance from the lamp to the tray and the distance between the lamps were fixed as shown in this figure. The distances from the top and bottom lamps were fixed at 150 mm and 131 mm from the top plane surface of the tray, respectively. Each distance was determined by considering the UV-C transmission of the tray. The default automatic meshing method was employed in accordance with the results of our previous study (Trivittayasil, 2016). In Model B, although the lamp arrangement is the same as that of Model A, the length of the lamps is longer. As for Model C, the lamps are rotated around the vertical line through the center of the tray (x-z plane) by 90 degree. In Model D, the length of the lamp is expanded as compared with Model C. Model D is much wider in

Fig. 3. A schematic diagram of the mesh generated for Model A: left: overall view; right: enlarged view

the x direction than the other models; however, we can disregard it because all domain walls were assumed as an open boundary. Mesh inflation and refinement were applied to the major boundaries. According to the default automatic meshing method, the results of 2 303 390, 2 467 714, 2 113 634, and 2 774 786 mesh elements were generated for Models A, B, C, and D, respectively. A schematic diagram of the mesh generated for Model A is illustrated in Fig. 3. The sliding mesh method, which allows a problem to be set up in which separate zones move relative to each other was employed to model UV-C treatment with a conveyor system. The samples travel through the UV-C radiation part on a conveyor system. The computational domain was divided into three cell zones: top, middle, and bottom, as shown in Fig. 4. The top and bottom zones included two UV-C lamps each and the middle zone included nine strawberries on the tray. In this sliding mesh model, three cell zones were used to simulate the motion of nine strawberries placed on the tray. Each cell zone was bounded by the mesh interface. The middle zone was fixed and the other zones were moved to simulate continuous UV-C treatment, because the geometry of the middle zone was too complex. In the unsteady simulation, all the computational domains, set as stationary, were set in one inertial reference frame. The motion of the boundary zones was described using profiles related to the time-dependent position of the moving objects. We also assessed the effects of sliding step and speed of movement on UV-C dose distribution on the surface of strawberries. The total incident UV-C dose distribution was estimated by accumulating incident UV-C dose on the surface of strawberries at six time-dependent positions. The UV-C incident dose data for each position was saved as a 'csv'

Fig. 4. Sliding mesh definition in which the computational domain was divided into three cell zones: top, middle and bottom

formatted file, and the total dose distribution was visualized using freely available Gnuplot 4.4 software.

c) Microbial inactivation model The microbial inactivation effect of UV-C irradiation on the surface of strawberries can be simulated by combining the inactivation kinetic model with the radiation transfer model. For contamination by *Penicillium digitatum*, which causes a common postharvest fungal disease, a first-order kinetic model can be applied to predict the survival curve during UV-C treatment. Since the inactivation model employed in this study was constructed based on an agar surface, one assumption of this work is that the inactivation characteristics of spore mold depend on the intensity regardless of the surface nature.

$$\log_{10} S = -\frac{kIt}{2.303} \quad \dots\dots\text{Eq. 4}$$

where S is the survival rate, I is the irradiation intensity of UV-C (kW m^{-2}), t is the treatment time (s), and k is the modified inactivation rate constant ($11.98 \text{ m}^2 \text{ kJ}^{-1}$) (Trivittayasil *et al.*, 2015). In this study, we calculated the time required for three-log inactivation of *P. digitatum* on the surface of strawberries (Izumi, 2008).

(2) Uniformity evaluation Uniformity of UV-C dose distribution on the surface of strawberries was evaluated using the coefficient of variation (CV), which was a normalized index of dispersion of a probability distribution.

Results and Discussion

(1) Uniformity evaluation In order to evaluate the uniformity of UV-C dose distribution on the surface of strawberries, the radiation simulations were carried out using four configuration models. The UV-C treatment time was fixed at 7 s, the conveying speed and mesh sliding steps were fixed at 0.1 m s^{-1} and seven, respectively. This meant that the incident UV-C intensity was calculated independently at seven time-dependent positions with 0.1 m sliding distances, and the irradiation time for each position was 1 s. The total irradiated UV-C dose distribution was estimated

by accumulating incident UV-C dose on the surface of strawberries at seven time-dependent positions. The results of the simulation are presented in Fig. 5. The frequency polygons of incident radiation dose on the surface of strawberries can be recognized visually. In Model A, the simulations were conducted with and without movement of the tray to investigate the effect of sample movement on the incident UV-C dose distribution. In an unsteady state, the peak of the UV-C dose distribution shifted towards lower values in comparison with the stationary case. Table 3 shows the maximum, minimum, mean, and CV of the accumulated incident UV-C dose distribution. In Model A, more uniform treatment was achieved without tray movement. In order to improve the uniformity with tray movement in Model A, the lamp length was increased from 190 mm to 250 mm in Model B. This was to provide a larger radiation area for strawberries in order to reduce their under-irradiated area. In this case, the CV became lower than that of Model A without tray movement; however, the distribution still spread widely with CV of 0.406. In Model C, UV-C lamps were installed parallel to the direction of movement to avoid non-uniform distribution. This model improved the uniformity of UV-C dose distribution on the surface of strawberries. Figure 6 shows the contours of the incident radiation dose during UV-C treatment. The area with high radiation dose is represented in red, whereas areas with low radiation dose are in blue. It was shown that the underexposed area was mostly found along the sides of the strawberries. In Model C, uniform radiation dose distribution was achieved with CV of 0.200. The frequency polygons of incident radiation dose in Model C had a sharp distribution, as shown in Fig. 5. We also investigated the effect of the step in time-dependent positions. The sliding distance and irradiation time for each step were changed from 0.1 m to 0.01 m and from 1 s to 0.1 s, respectively. This meant that the total radiation time was fixed at 7 s. This revealed that there was no significant effect of the difference in mesh sliding steps on the solution, as shown in Fig. 5 and Table 3. However, the mean values of UV-C dose were quite low for both simulations of Model C. In the aspects of practical usage, the

Fig. 5. Frequency polygons of incident radiation dose on the surface of strawberries for each model and operation

Table 3. The maximum, minimum, mean and *CV* of the accumulated incident UV-C dose distribution

Model	Operation type	Maximum	Minimum	Mean	CV
Model A	fixed	33.57	0.648	16.41	0.416
	conveying	31.42	0.515	13.96	0.450
Model B	conveying	36.19	1.703	17.27	0.406
Model C	conveying(7)	15.05	4.758	9.34	0.200
	conveying(71)	15.14	5.22	9.27	0.201
Model D	conveying	86.72	30.85	53.85	0.194

mean dose should be higher to allow faster treatment time. In Model D, longer and more-powerful UV-C lamps were installed as radiation sources, parallel to the direction of movement to achieve optimal treatment. The distribution of incident radiation dose became wider, whereas the mean dose increased in comparison with Model C. Therefore, the *CV* decreased slightly to 0.194. It was concluded that Model D was the optimal configuration to achieve the most-uniform UV-C dose distribution.

(2) *Model-based investigation of inactivation of Penicillium digitatum* The dose required to inactivate *P. digitatum* can be estimated using equation (4), and the estimated dose (*It*) for one- (90% of survival rate calculated by eq. (4)), two- (99%) and three-log (99.9%) reductions were 192, 385 and 577 J m⁻², respectively. Generally, a three-log reduction is recognized as the target for mold inactivation in the treatment of fruits (Izumi, 2008). The time required to achieve three-log inactivation for *P. digitatum* on the surface of strawberries was calculated for all the proposed models. In section 3.1., we discussed the uniformity of the incident UV-C dose on the surface of strawberries with a treatment time of 7 s. However, the total incident dose was not sufficient to inactivate *P. digitatum* during this UV-C treatment period, because it did not reach 577 J m⁻². In this section, we adjusted the speed of movement

Fig. 6. Contours of the incident radiation dose during UV-C treatment (Models A to D)

Table 4. Adjusted conveying speed, treatment time, and total UV-C incident radiation dose to achieve three-log inactivation for *P. digitatum*, and the maximum total incident dose during UV-C treatment

Model	Operation type	Step	Conveying speed [cm s ⁻¹]	Required time [s]	Maximum dose [kJ m ⁻²]	Minimum dose [kJ m ⁻²]	Mean dose [kJ m ⁻²]
Model A	fixed	-	-	6237	29.91		14.62
	conveying	7	8.90 × 10 ⁻³	7861	35.28		15.68
Model B	conveying	7	2.95 × 10 ⁻²	2373	12.27	0.577	5.85
Model C	conveying	7	8.24 × 10 ⁻²	849	1.83		1.13
Model D	conveying	7	5.35 × 10 ⁻¹	131	1.62		1.01

to yield an adequate dose for mold inactivation by changing the radiation time for each sliding step with a fixed sliding distance. To achieve the three-log reduction in mold density on all surfaces of the strawberries, we regulated the speed of movement as follows:

Conveying speed = 0.1 m s⁻¹ × 7 s / Required time
and,

Required time = 577 J m⁻² × 7 s
/ Minimum dose in Table 3

Table 4 shows the adjusted speed of movement, treatment time, and total UV-C incident radiation dose to inactivate mold for Models A to D. When the lamps were installed in parallel in the models (Models C and D), the maximum incident radiation doses were sufficiently low, whereas in the other models the dose exceeded the quality loss criteria substantially. According to Marquenie *et al.* (2002) and Nigro *et al.* (2000), the adequate radiation dose for strawberries was between 0.5 and 4.0 kJ m⁻² from the view point of antimicrobial safety and retaining sufficient fruit quality. Models C and D completely satisfied this requirement. Our results suggested that the optimal treatment could be achieved using Model D with 131 s of UV-C radiation. If a shorter time is

required, lamps of higher power should be considered to increase the overall radiation dose. For meaningful implementation of UV-C irradiation of fruits, it is recommended that the inactivation characteristics of the target microorganisms on each fruit need to be investigated to determine the required irradiation time. It is expected that the model developed here can be a useful tool for the optimization of UV-C treatment to inactivate microorganisms on the surface of fruits.

Conclusion

A three-dimensional UV-C irradiation model based on the DO method and a sliding mesh technique was developed to evaluate and improve the uniformity of the incident UV-C dose distribution on the surface of strawberries, placed on a tray on a conveyor line irradiated with UV-C lamps, for microbial inactivation. An investigation based on computational modeling and simulation was carried out with various irradiation conditions. The results are summarized as follows:

(1) Models C and D with UV-C lamps installed in parallel with the direction of movement provided more uniform incident dose distribution on the surface of strawberries with *CV* of around 0.2; (2) the usage of a UV-C-transparent film tray helped to irradiate strawberries without the need to rotate them; (3) the best configuration providing the most uniform incident dose distribution was Model D, with longer UV-C lamps installed parallel to the direction of movement; (4) in Models C and D, a three-log reduction in the survival rate of mold was achieved without under- or over-exposing; and (5) for the optimal model (Model D), 131 s was required for a three-log inactivation of *P. digitatum*.

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