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Particle Size Distribution of New Type Nanomist Humidifier

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This study was designed to investigate the particle size distribution of a new type nanomist humidifier. The measurement of particle size was performed inside storage chamber at 5°C and 15°C by means of using a scanning mobility particle sizer and a light–scattering spectrometer. The nanomist generator was set to operate at frequencies of 3500, 4000, 4500 and 4750 rpm. Size distributions were measured at different points along a straight line extending from the outlet of nanomist generator. The results showed that the number mode of the particle size produced by the new type nanomist humidifier at 4500 rpm and distance of 500 mm was 24 nm and the mode diameter changed slightly with modification in frequency. The particle concentration increased with a rise in frequency of generator. The arithmetic mean diameter (AMD) and Sauter mean diameter (SMD) of the new type nanomists were much smaller than those generated by the old type. This finding indicates that new type nanomists would have benefits for postharvest storage of fresh fruit and vegetables. Moreover, the Nukiyama–Tanasawa equation could be used to estimate the particle size distribution by nanomists.

Key words: nanomist, particle concentration, size distribution, relative humidity

INTRODUCTION

Humidification systems have been used to minimize the water loss of fresh produce by increasing relative humidity (RH) of the storage environment, thereby diminishing the water vapour pressure deficit. Traditional humidifiers often produce mists with average particle diameters varying between 2.9 μm (Rodes *et al*., 1990) and 210 nm (Hung *et al*., 2010b). It is true that the large size mists can easily drop on the produce surface before evaporation and be responsible for generating environment favourable to microbial growth (Dieckmann *et al*., 1993; Brown *et al*., 2004). As the major cause of this problem is the size of water droplets, the use of ultra–fine water mists called nanomists is expected to be an effective technique for the postharvest storage of fresh produce. Previous study showed that nanomists, generated by a nanomist humidifier (Mayekawa Co., Ltd, Tokyo, Japan), have average particle diameters less than 100 nm (Hung *et al*., 2009). Due to being ultrafine particle, it is assumed that generated mists become vapour before settling on the produce surface. The utilization of nanomists for storage of fresh produce was shown to be effective in maintaining the strength of corrugated cardboard (Hung *et al*., 2010a), controlling the weight loss and keeping the quality of produce (Hung *et al*., 2011a; Hung *et al*., 2011b).

Particle size distribution is the most important physical characteristic of mists. This property influences the evaporation process of water. Issa (2008) reported that the size of mists has a great effect on the heat transfer enhancement. The smaller the droplet size, the easier it is for the droplet to evaporate on its surface, thereby leading to higher heat transfer. Thus, smaller size droplets would help to prevent the occurrence of wetness on the produce surface. In addition, Hung *et al*. (2010b) demonstrated that mean diameter of nanomists decreased with an increase in frequency of generator. Therefore, by the means of improving the revolutions of nanomist generator, the size of mists is expected to be much finer.

The aims of this research were (a) to characterise the particle size distribution of nanomists discharged by the new type nanomist humidifier inside storage chamber at 5°C and 15°C and (b) to use mathematical expression to determine suitable distribution and density functions for describing the experimental data.

MATERIALS AND METHODS

Nanomist humidifier

A new type nanomist humidifier (405 mm in length, 355 mm in width, 325 mm in height) manufactured by Mayekawa Co., Ltd., Tokyo Japan was used to produce nanomists. The device consists of a nanomist generator as shown in Fig. 1 and a system controller. The nanomist humidifier was placed inside the storage chamber (2600 mm in length, 1700 mm in width, 2400 mm in height) in which temperature could be controlled. The details of nanomist generator operation were described in the previous study by Hung *et al*. (2010b).

Experimental setup

The measurements of particle size distribution were performed inside the storage chamber under two conditions; one at temperature of 5°C and 65% RH and the other at 15°C and 52% RH. Sampling points were per-

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formed at height of 640 mm and distances of 300 mm (A), 500 mm (B), 150 mm apart from B (C) and 700 mm (D) along a straight line extending from the outlet of nanomist generator as shown in Fig. 1. The temperature and RH were measured using a humidity and temperature transmitter (model HMT337; Vaisala, Helsinki, Finland). To understand the relationship between particle number concentration, size distribution and generator frequency, the nanomist humidifier was allowed to operate at 3500, 4000, 4500 and 4750 rpm. The aerosol sample flow was drawn via a conductive tube 4.5 mm internal diameter and 2100 mm in length. Air velocity was measured at the sampling points using data logger digital wind speed meter (Custom WS–02, China).

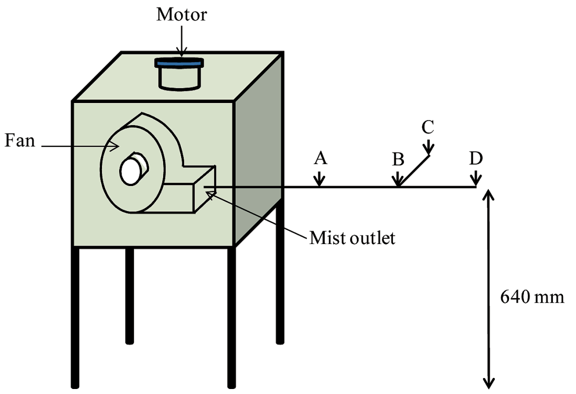

Fig. 1. Diagram of measuring points; A, B, C and D is a sampling point of mist.

Particle size measurement

The mist samples were taken by connecting the sampling tube of the measuring instruments to the sampling points as described in Fig. 1. For particle sizes ranging from 15.1 to 661.2 nm, a scanning mobility particle sizer (SMPS) (SMPS model 3936, TSI Inc, Dylec Corp. Tokyo, Japan) was used to measure particle number concentration and size distribution by separating particles based on their electrical mobility. The particles of a selected size are detected optically, using a detection technology through which the visibility of fine particles is enhanced by "growing" the particles in condensing butyl alcohol vapour. The device used for particle separation is referred to as a differential mobility size analyser (DMA) (DMA 3081, Dylec Corp. Tokyo, Japan). The particle counter is referred to as a condensation particle counter (CPC) (CPC model 3775, Dylec Corp. Tokyo, Japan). The aerosol sample flow rate was 0.3 l min^{-1}, while the sheath airflow was set to 3.0 l min^{-1}, which allowed the measurement of particles as fine as 15.1 nm diameter. The use of sheath airflow also minimises the diffusion losses of ultrafine particle during sampling. Aerosol instrument manager (AIM) software (version 4.0, TSI Inc, Dylec Corp. Tokyo, Japan) was used for data reduction and analysis of the SMPS output. For each measurement, three SMPS samples were taken, with a scanning time of 100 s. In addition, a light scattering aerosol spectrometer (Welas 2000, Dylec Corp. Tokyo, Japan) was used to determine particle concentration and particle size over 661.2 nm. The detailed operation of this instrument was described in the study of Luu *et al.* (2010). It has a wide concentration range from 1 to 10^5 particles ml^{-1} and particle size ranging from 0.2 to 10 μm diameter. Data analysis was performed using PDControl 1.0 software (Dylec Corp. Tokyo, Japan). The particle size distribution was presented according to the method used by Babinsky (2002). In order to compare the particle size distribution generated by the old and new types of nanomist humidifiers, the data from previous study were used in this paper.

Mathematical formulation of droplet size distribution

Distribution functions for particle size distribution

Several mathematical distribution functions have been used to fit particle size experimental data. In this study, the equation of Nukiyama–Tanasawa (Tanasawa 1963; González–Tello *et al.*, 2008) was applied to obtain the size distribution of droplets from the measured data.

Nukiyama–Tanasawa equation can be expressed as

$$f(x) = \frac{1}{N_T}\frac{dN}{dx} = Ax^{\alpha}\exp(-Bx^{\beta}) \qquad (1)$$

where x is the particle diameter, $f(x)$ is the probability density function of the number distribution (nm^{-1}), N_T is total number of particles, N is particle number and A, B, α, and β are adjustable parameters. Li and Tankin (1987) assumed that α=2. The remaining parameters can be calculated via non–linear least square method which is easily obtained by using Microsoft Excel Solver.

Representative diameters

The Sauter mean diameter (x_{vs}) represents the size of a droplet with the same volume surface area ratio of the entire spray and is known to characterise the heat and mass transfer of the droplets better than, for example, the arithmetic mean diameter (Semião *et al.*, 1996). Sauter mean diameter is expressed as

$$x_{vs} = \frac{\int_0^{\infty} x^3 f_N(x)dx}{\int_0^{\infty} x^2 f_N(x)dx} \qquad (2)$$

Arithmetic mean diameter (AMD) indicates droplet diameter (Bhanarkar *et al.*, 2008) and is defined as

$$AMD = \frac{\int_0^{\infty} x f_N(x)dx}{\int_0^{\infty} f_N(x)dx} \qquad (3)$$

where $f_N(x)$ is the particle number distribution (ml^{-1}).

RESULTS AND DISCUSSION

The particle size distributions measured at distance of 500 mm (B) from the outlet generated by different operating frequencies of the nanomist humidifiers at 5°C (data from 3000 rpm was obtained from the old type

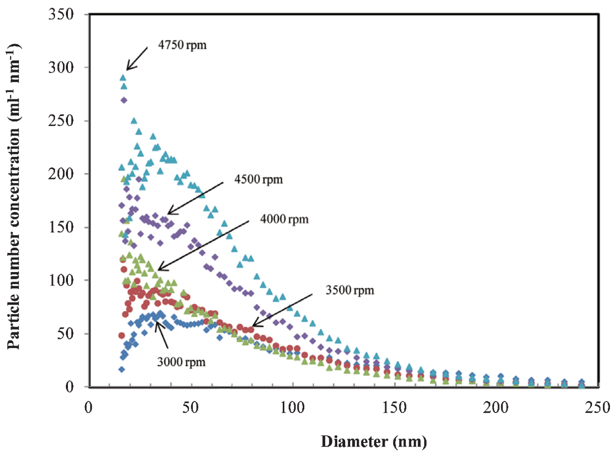

Fig. 2. Changes in particle size distribution generated by different frequencies of nanomist humidifier at point B and 5°C.

nanomist humidifier which was shown in the previous study by Hung *et al.* (2010b)) is presented in Fig. 2. It can be seen that the observed size distributions were unimodal and a peak value occurred at c.a 17 nm irrespective of generator frequency for new type and 35 nm for old type. It is noted that although the measuring instrument of Welas 2000 was able to measure the particle size up to 10 μm, there were no particles with diameter over 661.2 nm observed. There was a clear correlation between the particle number concentration and frequency of the generator. The particle number concentration increased with increasing generator frequency. The peak number concentration generated by nanomist humidifiers at 3000, 3500, 4000, 4500 and 4750 rpm was 70, 120, 196, 270 and 291 (ml^{-1} nm^{-1}), respectively. Adiga (2005) observed that the particle size and particle concentration depended on nanomist generator frequency. In this study, a very small change in mode diameter was observed when the frequency was varied.

Fig. 3 presents the fitting of the Nukiyama–Tanasawa equation to experimental data generated by new type nanomist humidifier at 4500 rpm, 5°C and different positions as a representative and the parameters A, B, α, β are shown in Table 1. It is apparent that the curve of size distribution obtained from the Nukiyama–Tanasawa equation fitted the experimental data well which were shown by very low RMSE and thus the Nukiyama–Tanasawa equation could be used to estimate the particle size distributions produced by new type nanomist humidifier.

The changes in particle size distribution created by new type nanomist generator at 3500 rpm, 5°C and 15°C and at distances of 300 mm (A), 500 mm (B), 150 mm apart from B (C) and 700 mm (D) along a straight line extending from the outlet of nanomist are shown in Fig. 4.

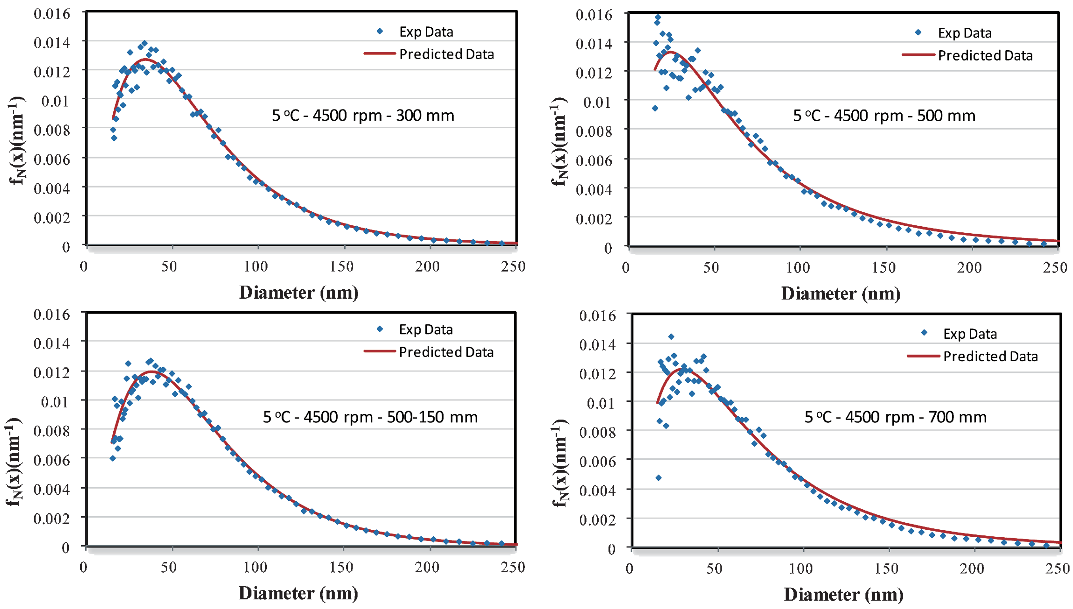

Fig. 3. Fitting of the Nukiyama-Tanasawa equation to experimental data generated by new type nanomist at 4500 rpm, 5°C and different positions.

Table 1. Parameters used in distribution equation at 5°C, 4500 rpm and various positions

Distance (mm)	SMD (nm)	α	β	A	B	RMSE (nm^{-1})
300	134	2	0.69	1.98E–01	2.52E–01	5.22E–04
500	150	2	0.45	1.97E–03	1.07E–00	8.29E–04
500–150	137	2	0.75	1.17E–04	1.72E–01	5.58E–04
700	145	2	0.52	6.68E–04	6.72E–01	8.65E–04

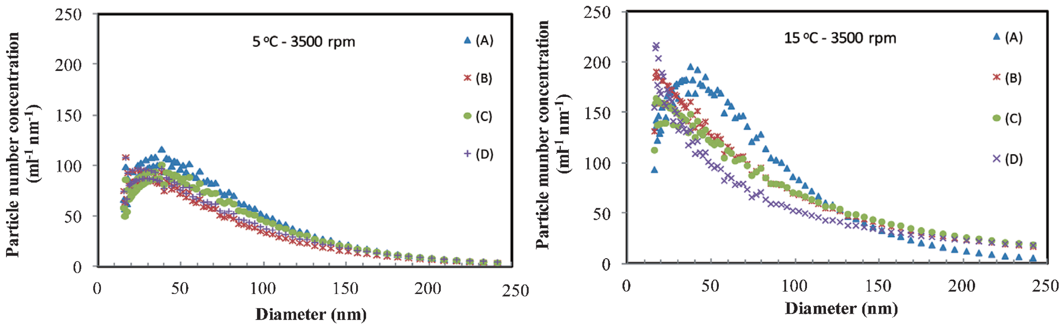

Fig. 4. Particle size distribution at 3500 rpm, 5˚C and 15˚C from different positions.

Again, the nanomist size distribution shown was unimodal regardless of positions. It is obvious that the number concentration reduced with an increase in distance. However, the number concentration measured at point C, which is 150 mm apart from B, was higher than that recorded in point B at 5˚C. This indicates that the mists tend to spread externally. It is also noticed that the particle number concentration sampled at 15˚C was much higher than those measured at 5˚C at the same frequency and position. The RH recorded when sampling at 5˚C and 15˚C was 65.4% and 52%, respectively. It has been reported that there was a correlation between mist concentration and RH. The concentration generated by nanomist increased with the increase of RH from 80% to 90% at the same temperature of 5.5˚C (Hung *et al.*, 2010b). However, the difference in particle concentration between two conditions found in the present study could be attributed to the difference in RH and temperature. Further experiments need to be conducted to clarify this phenomenon.

In the study of particle size distribution, mode diameter is often used to compare the size distribution and can be calculated by differentiating $f(x)$ in Eq. (1) and expressed as

$$\frac{df(x)}{dx} = Ax^{\alpha-1}(\alpha - B\beta x^{\beta})\exp(-Bx^{\beta}) \quad (4)$$

at the maximum value, $\frac{df(x)}{dx} = 0$ (5)

By solving Eq. (4) and (5), a solution is obtained as

Table 2. Prediction of mode diameters at 5˚C and different frequencies and positions

Distance (mm)	Mode diameter (nm)			
	3500 rpm	4000 rpm	4500 rpm	4750 rpm
300	38	38	34	33
500	28	15	24	24
500–150	38	40	38	33
700	29	30	30	31

$$x = \left(\frac{\alpha}{B\beta}\right)^{\frac{1}{\beta}} \quad (6)$$

Table 2 shows mode diameters generated by the new nanomist humidifier at 5˚C, different frequencies and positions which were predicted by using Eq. (6). In general, mode diameter became slightly finer when frequency was accelerated and when particles were measured at further distances. Fig. 5 presents an illustration of changing mode diameters shown in particle density distribution obtained by Nukiyama–Tanasawa equation at 4500 rpm, 5˚C and 15˚C and different positions. As can be seen from the Fig. 5 that the distributions were almost the same at 5˚C, but distribution at point A was largely different from other points at 15˚C. The representative diameters produced by two types of nanomist humidifiers at 5˚C are demonstrated in Table 3. It can be seen from the table 3 that the AMD of both nanomist humidifiers became finer with increased frequency. Although

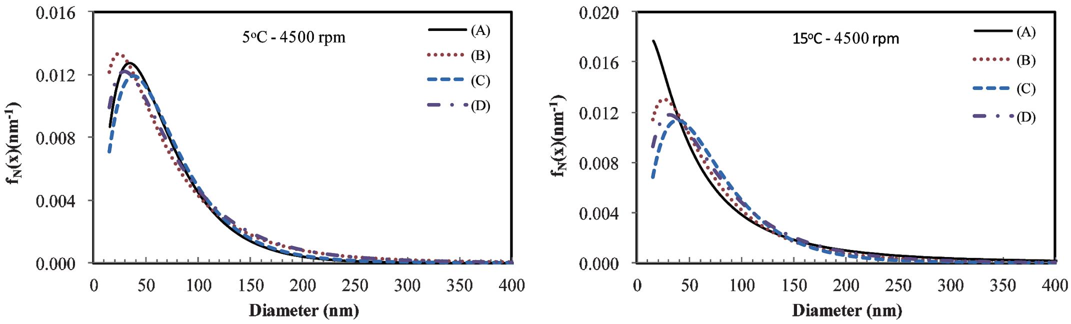

Fig. 5. Particle density distribution predicted by using Nukiyama–Tanasawa equation at 5˚C and 15˚C by frequency of 4500 rpm from different positions.

Table 3. Comparison of representative diameters by two types of nanomist humidifiers at 5˚C

Frequency	old type*			New type			
	2400 rpm	3000 rpm	3600 rpm	3500 rpm	4000 rpm	4500 rpm	4750 rpm
AMD (nm)	104	86	82	80	79	71	69
SMD (nm)	333	235	314	163	159	145	137

AMD is arithmetic mean diameter, SMD is Sauter mean diameter
* Date were extracted from the previous study by Hcug *et al.* (2010b)

the SMD of old type nanomist was not affected by generator frequency, it was really influenced by new type one. The higher the revolutions, the smaller the SMD. As mentioned previously (Hung *et al.*, 2010b), the SMD is known to characterise the heat and mass transfer of water droplets. The evaporation rate is greater with fine droplets because they have greater surface area relative to their volume (surface area to mass ratio) compared with coarse droplets (Barrow and Pope 2007). Therefore, it is noticeable that mists produced by higher frequency of nanomist humidifier are easier to evaporate than those generated by lower revolutions of humidifier.

Table 1 presents SMD and the parameters A, B, α, β obtained at 5˚C and different positions by new type nanomist humidifier at 4500 rpm as an example. There was a connection between parameter B in Nukiyama–Tanasawa equation and SMD. This was in agreement with the finding by Tanasawa (1963) who reported that parameter B is a function of SMD; the smaller the parameter B, the higher the SMD.

In summary, this study characterised the particle size distribution produced by the new type of nanomist humidifier at temperatures of 5˚C and 15˚C. The results showed that the number mode diameter of nanomist humidifier was 24 nm at operation of 4500 rpm and distance of 500 mm and changed slightly with changes in revolutions of generator and distances. The particle number concentration of the nanomist increased with increased frequency of humidifier and decreased with a rise in distance. The AMD and SMD produced by new type nanomist humidifier were much smaller than those produced by the old type. From these findings, it can be concluded that new type nanomists evaporate more easily than those of old type. This feature of nanomists produced by a new humidifier is believed to contribute toward minimising the wetness on produce surface, thereby diminishing microbial growth during the postharvest storage of fresh produce. In addition, the Nukiyama–Tanasawa equation could be used to estimate the particle size distributions by nanomists.

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