Measurements of the Size and Composition of Volatile Particles Generated from a Heated Tobacco Product with Aerosol Fixation Agents

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ABSTRACT

Accurate measurements of the particle size distribution and chemical composition of particles are important to understanding their influence on human health and the indoor environment. In this research, volatile particles generated from a pod-type Heated Tobacco Product (HTP) were measured with an Aerodyne Aerosol Mass Spectrometer (AMS) and Scanning Mobility Particle Sizer (SMPS) using various aerosol fixation agents to reduce the volatility of the particles. A simple method of aerosol fixation was applied, and the effective fixation agents and the primary factor of fixation were elucidated. The effectiveness of a fixation agent was determined based on the solubility between the aerosol substrates and the agent. Although nonadecanoic acid did not work for aerosol substrates with a low polarity, we found that it achieved greater success in fixing propylene glycol and glycerin. For particles that remained unfixed, the organic mass concentration (derived by AMS) was significantly reduced due to volatilization in the measurement apparatus. By contrast, the fixed volatile particles showed a higher organic mass concentration due to the suppression of volatilization. The peak number diameter of the unfixed volatile particles derived by SMPS was observed to be below 100 nm, whereas that of the fixed volatile particles was about 200 nm. The particle concentration of SMPS with fixation was in agreement with that of a light scattering method (welas®). The elemental and surface compositions of the fixed volatile particles were analyzed by Scanning Electron Microscope-Energy Dispersive X-ray spectrometry (SEM-EDX) and Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) under vacuum conditions. The results revealed that the fixation agent was localized on the surface of the particles, reducing the volatility of the particles.

Keywords: Aerosol fixation; Aerosol mass spectrometer; Tobacco smoke; Volatile particles; Heated tobacco product.

INTRODUCTION

Various measurements related to the particle size distribution and size-resolved composition have been carried out by several on-line apparatuses and the filter collection-gas chromatography method. In general, atmospheric aerosols are targeted in the measurements. Since atmospheric aerosols are composed of numerous compounds including inorganic elements sprayed from the sea, fatty acid from biomass burning, and others (TerVAhAttu et al., 2005; DeceSari et al., 2014; Tsai et al., 2015), the volatility of particles is relatively low. Several apparatuses with a low pressure condition such as Low Pressure Impactor (LPI) and Micro Orifice Uniform Deposit Impactor (MOUDI) are frequently used to collect atmospheric aerosols. Although volatilization of compounds from ultrafine particles (less than 100 nm) related to low pressure conditions has been reported (Sekiguchi et al., 2008), the collection of particles is performed giving due consideration to the influence of volatilization. As for particle size distribution, Scanning Mobility Particle Sizer (SMPS), Differential Mobility Spectrometer (DMS), and Aerodyne Aerosol Mass Spectrometer (AMS) are widely used among researchers. The influence of volatilization on the particle size distribution was also reported (Suresh and Johnson, 2001), as internal dilution and/or low pressure conditions are critical factors to make precise measurement possible for these apparatuses. The influence of either dilution or low pressure conditions has been a concern; however, such influence can be relatively low for atmospheric aerosols.

Recently, particles consisting of mostly volatile compounds have attracted a great deal of attention; these are particles such as tobacco smoke generated from heated tobacco products (heat-not-burn products; tobacco leaves are heated with some aerosol substrates) and Electronic-cigarettes (e-cigarettes). Since the particles are mainly composed of propylene glycol and/or glycerin, the volatility of such particles was higher than that of tobacco smoke from...
conventional cigarettes (Ishikawa and Sekiguchi, 2017). Therefore, the influence of volatilization on the particle size distribution and size-resolved composition is significant, and the applicability of previous methods for these volatile particles still remains an open research problem. Comprehending the influence of volatilization on the particle size and the compositions are important to understand the influence of human health and indoor environment. However, measurement of the particle size distribution in the tobacco smoke generated by the heated tobacco products and e-cigarettes is difficult due to the liquid nature and high coagulation rate of aerosols. Several studies have started reporting on the results of particle size distribution and size-resolved composition using previously described apparatuses (Bertholon et al., 2013; Ji et al., 2016; Mikheev et al., 2016; Baassiri et al., 2017). Those studies utilized SMPS, Fast Mobility Particle Sizer (FMPS), DMS, MOUDI, and LPI. Earlier studies also discussed the influence of volatilization from particles in a diluted state (Ingebrethsen et al., 2012; Alderman et al., 2014; Fuoco, 2014). Ingebrethsen et al. (2012) carried out a comparison study between DMS and the spectral transmission method and reported a large gap between them. Alderman et al. (2014) used MOUDI under a non-diluted condition to eliminate the influence of volatilization. Since a low pressure condition is absolutely necessary for cascade impactors, the influence of volatilization must be significant with nanoparticles. The validity of results and the influence of volatilization have been discussed in a few papers; however, measurement methods under dilution and low pressure conditions have not been proposed. A method without dilution and low pressure conditions could eliminate the influence of volatilization; however, avoiding the low pressure condition lowers the resolution of the particle diameter. Although real-time measurement apparatuses are widely used to examine time-dependent changes of aerosols as they have advantages of usability, saving time, and time resolution, most of these apparatuses are operated under dilution and/or low pressure conditions. Nanosampler (Kanomax Japan Incorporation, Tokyo) has been known as a classification sampler under atmospheric pressure condition; however, it might not be applicable to laboratory-scale experiments due to the high air flow volume (40 L min⁻¹) and low time resolution. We think the methods without dilution and low pressure conditions may be a temporary option. If the measurements of volatile particles could be implemented under dilution and low pressure/vacuum conditions, further investigation using elemental and surface analyzers under the vacuum condition would be possible. Therefore, a technique capable of implementing measurements of volatile particles under dilution and low pressure conditions should be developed.

Previous studies proposed a technique suppressing particle volatility by coating techniques with cyanoacrylate. This technique was termed “aerosol fixation” in aerosol science. Previous research utilized the method for tobacco smoke (Carter and Hasegawa, 1975; Keith, 1982), snow crystals and raindrops (Smith-Johannsen, 1965; Kasahara et al., 2003), and salt (Abraham et al., 1979). Studies of particle size measurements by SEM (Scanning Electron Microscope) and elemental analysis were performed. However, this method was problematic for fixing particles under dry conditions as the anionic polymerization initiator of cyanoacrylate is water. In addition, the vapor of cyanoacrylate has a low versatility for experiments due to the toxicity to human health. The method of using cyanoacrylate has been the only alternative to fix particles, and there has been no report of aerosol fixation using any other substances.Coincidentally, we noticed the stability of Sea Spray Aerosol (SSA) in atmospheric environment. SSA is attractive from the perspective of optical properties, reactivity, and volatility on the surface of particles (Gilman et al., 2004; Donaldson and Vaida, 2006; Ault et al., 2013; Nguyen et al., 2017). In particular, fatty acids have received wide attention due to their effect on the surface property of particles. It is a well-known fact that fatty acids are included in SSA, and palmitic acid (C16) is a primary component (Mochida et al., 2002). Several recent studies have shown that the fatty acids are localized on the surface of particles (Peterson and Tyler, 2002; Tervahattu et al., 2002; Ault et al., 2013; Lovric et al., 2016), and the structure is related to molecular structure and surface-active energy (Tervahattu et al., 2002). Wu et al. (2016) performed an experiment with NaCl solution and trans-4-[4-(dibutylamino) styryl]-1-methylpyridinium to simulate SSA and reported that trans-4-[4-(dibutylamino) styryl]-1-methylpyridinium was dominantly localized on the surface of particles. When targeted particles have a hydrophilic core, the same as SSA, fatty acids must be applicable to fixation of volatile particles. Previous studies only reported particles having a brine core; few studies on the surface of particles have reported other substances as the particle core.

In this research, measurements of particle size distribution and composition were demonstrated by AMS and SMPS under dilution and low pressure conditions with a simple method of aerosol fixation. Fixation agents with a low polarity were selected for this research. Aerosol substrates ranging from glycerin with a high polarity to triacetin with a low polarity were employed so as to examine the effect of the particle core on the effectiveness of fixation from the viewpoint of solubility. One of the aims of this paper was to determine a useful fixation agent against propylene glycol and glycerin which are widely used in heated tobacco products and e-cigarettes. We also checked the effect of fixation on the influence of dilution by a comparison between SMPS, as the most common apparatus, and the light scattering method. Since the fixation technique enabled measurements under vacuum conditions, SEM-EDX and Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) analyses were performed to examine the surface and internal composition of fixed particles. These research findings can be applied to the fixation of volatile particles regardless of the means of generation, contributing to the further understanding of particle surface state. Moreover, the size dependence of the fixation agent, which has not been reported, was studied by using AMS through the size-resolved mass spectrum analysis. AMS is typically used for the measurement of atmospheric aerosols and exhaust
aerosols, and it can obtain size-resolved mass spectrum of particles with an aerodynamic lens as proposed by Liu et al. (1995a, b). Since particles with a high volatility must be volatilized in AMS owing to the internal low pressure (2 Torr), the volatile particles are difficult to measure. In this research, AMS was selected as a particle measurement apparatus with the most stringent condition. Previous research carried out the measurement of tobacco smoke from cigarettes using AMS. Yadav et al. (2004) first reported the results of main-stream tobacco smoke. Sleiman et al. (2010) investigated the effect of ozone and humidity on organic mass spectrum in environmental tobacco smoke, and Li et al. (2012) examined the aging effect on side-stream tobacco smoke. However, reports of tobacco smoke from heated tobacco products and e-cigarettes have not been reported; hence, this research appears to be the first attempt. Zelenyuk et al. (2006) reported the evaporation of water from particles in aerodynamic lens. Collier and Zhang (2013) and Pieber et al. (2016) investigated the influence of gas-phase CO2 and inorganic salts on the organic mass concentration. In our experiments, particles were generated from a pod-type heated tobacco product (HTP) at a low temperature; hence, the concentrations of CO2 and sulfate, which affect the organic mass concentration, were not detectable. A small amount of ammonium salt and nitrate were detected; however, the concentrations were lower than those of organics by one to two orders of magnitude. The water in aerosol particles generated from HTP was significantly reduced with respect to the number of puffs because the water is preferentially released. The water in aerosol particles generated from HTP was significantly reduced with respect to the number of puffs because the water is preferentially released. The influence of water would be negligible in our experiments as we did not measure the particles at initial puffs (see the details of smoking condition in the experimental session).

### METHODS

**A Heated Tobacco Product, Aerosol Substrates, and Aerosol Fixation Agents**

HTP, which was launched by Japan Tobacco Inc., was used to generate volatile particles as an atomizer. HTP has a small pod, which includes tobacco powders (sieve size < 0.5 mm) and 100 mg of aerosol substrates. The pod was continuously heated from the bottom and side at about 170°C (details are shown in Fig. S1 [in supplementary material] and in the paper of Suzuki et al. (2016)). The pod-type HTP enables various ingredients to be added to the tobacco powders as carriers. In the case of e-cigarettes, the ingredients must be uniformly dispersed within the liquid.

In this research, various ingredients were experimentally added, and some ingredients seemed to take time and effort to disperse in the liquid. Therefore, the pod-type heated tobacco product was selected as a generation method with high versatility. The flue-cured leaves grown in Japan were milled and sieved; the aerosol substrates listed in Table 1 were used in the experiments. The difference in volatility was investigated by changing aerosol substrates from propylene glycol with the highest volatility (b.p.: 188°C) to glycerin with the lowest volatility (b.p.: 290°C). In this research, the Hansen Solubility Parameter (HSP) was used as an indicator of polarity and solubility. HSP was referred by Hansen (2007) and calculated from a 2D molecular file using Molecular Modeling Pro (ChemSW Inc., Fairfield, CA).

In our samples, the aerosol substrate with the highest polarity was glycerin, and the secondary was propylene glycol.

The previous method of aerosol fixation utilized the vapor of a fixation agent under a supersaturated atmosphere; volatile particles are needed to pass through the atmosphere.

### Table 1. Sample specs of the tobacco powders, aerosol substrates, and fixation agents in the HTP pod.

<table>
<thead>
<tr>
<th>Tobacco powders</th>
<th>Agent information</th>
</tr>
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<tbody>
<tr>
<td>Name</td>
<td>Amount (mg/pod)</td>
</tr>
<tr>
<td>Flue cured</td>
<td>100</td>
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<td></td>
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<tr>
<td>Fixation agents</td>
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Note: W: Wako Pure Chemical Industries Ltd. and T: Tokyo Chemical Industry Corporation. S: Shin-Etsu Chemical Corporation. ^aThe solubility parameter was calculated according to the method in Hansen (2007) using the values of dispersion, polarity, and hydrogen bonding. ^bThe solubility parameter was calculated by the software of Molecular Modeling Pro (ChemSW Inc., Fairfield, CA) with 2D molecular files. ^cThe solubility parameter refers to that Rozicka et al. (2012). ^dThe boiling point refers the internet site [ChemNet.com (www.chemnet.com)] for nonadecanoic acid.
in order to condense the vapor onto the surface of particles in the method. However, an excess concentration of vapor causes particle generation, and separate experimental systems are required. In our method, the fixation agent was added in the pod (5% on weight basis) in advance and generated in parallel with aerosol substrates for the sake of resolving the previous problems. We confirmed in advance by changing the addition weight of the fixation agent (0.5–40%) that 5% was a sufficient concentration for the fixation under our experimental conditions (heating temperature: 170°C) because the organic mass concentration and particle size distribution, as derived by AMS and SMPS, were not significantly changed in the range of more than 5%. The fixation agent localized on the surface of volatile particles seems to be an ideal state to elicit the effect of aerosol fixation. Since the fixation agent is condensed with aerosol substrates to form particles, the difference in solubility between the fixation agent and aerosol substrates and their stable structure is important for localization just as in two-layer separation of water and oil. We assumed that the fixation agent must have a low solubility for aerosol substrates and it is dominantly localized on the surface of particles in contact with air because air has a low polarity compared to the aerosol substrates. When the aerosol substrate is a hydrophilic solution with a polar OH group, oily substances can be effective as a fixation agent. Therefore, saturated and unsaturated fatty acids were selected in this research. Palmitic acid (C16), stearic acid (C18), which are generally used as the standard particle, and nonadecanoic acid (C19) were chosen. Linoleic acid was used as an unsaturated fatty acid. Dimethyl silicone oil (DMPS), which is a polymer composed of numerous siloxane bonds (a molecular weight of 740 g mol⁻¹) was selected. There was a possibility that DMPS decomposes into low-molecular siloxanes by heating. We confirmed in advance that detected DMPS in particles generated from HTP were mainly those of the molecular weight 740 g mol⁻¹. Dioctyl phthalate that has been used as a standard particle was also selected. The fixation agents can be detectable by Gas Chromatograph-Flame Ionization Detector (GC-FID), and we confirmed that smoke contains a tiny amount (e.g., nonadecanoic acid: 0.005–0.015 mg puff⁻¹). This amount was extremely small as a percentage of Total Particulate Matter (TPM) (e.g., nonadecanoic acid: 0.2–2.0%), and the percentage of all of the fixation agent was the same level because the boiling point of fixation agents is close to each other.

**Experimental Line for the Measurement of Particles**

The dilution system in Fig. 1 was used to lower the particle concentration as SMPS and AMS are technically designed for atmospheric aerosols. The smoke generated by a smoking machine (RM-20, Borgwaldt, Hamburg, Germany) was accumulated in Chamber A (volume: 70 mL) and discharged by a solenoid valve at a flow rate of 350 mL min⁻¹. The flow of 200 mL min⁻¹ was exhausted to reduce the particle concentration; hence, 150 mL min⁻¹ was introduced into Chamber B (volume: 9 L). The chamber was continuously diluted at a flow rate of 10 L min⁻¹ (dilution ratio: 67). The puffing by the smoking machine was set at a volume of 55 mL 2s⁻¹ (bell shaped) and interval of 58 s. The measurements of SMPS, AMS, and welas were performed from the sampling point of Chamber B. Since the concentration of Chamber B fluctuated immediately after the start of smoking, the measurement results were extracted at the timing of set at 12 minutes after commencing the smoking sequence (corresponding to 12th–13th puff). TPM
amount of aerosol substrates generated from HTP gradually decreased with the puff number; however, it tended to be stable after the 10th puff. We confirmed that the influence of fixation agents on TPM was negligible due to the addition of a small amount (TPM amount of each aerosol substrate with and without the fixation agent [nonadecanoic acid] is shown in Fig. S2).

Measurement of AMS, SMPS, welas®, and Spraytec
The measurement conditions of AMS (H-TOF Aerosol Mass Spectrometer, Aerodyne Research Inc., Billerica, MA, USA) were set at 630°C for vaporizer, 140 Hz for chopper, and 1.3 mA for filament emission. MS mode and P-ToF mode were both used every 30 s (one cycle: 60 s), and the analysis was performed only by the P-ToF mode. The calibration of AMS was implemented by using ammonium nitrate particles. Other components including organics are calculated based on the relative ionization efficiency with respect to nitrate ion. As for the mass spectrum, gases (N₂, O₂, and Ar), nitrate ion, sulfate ion, chloride ion, and ammonium ion are identified and quantified. The organic mass concentration is calculated by subtracting these ions from total concentrations. Since the sensitivity of AMS was decreased below 100 nm and the organic mass concentration was calculated to subtract inorganic mass concentration from the total concentration, there can be a case of a negative value of organic mass concentration due to the uncertainty of the calculation. Furthermore, Murphy (2016) reported that the accuracy of correction of ionization efficiency for organics is not sufficient. Therefore, the negative organic mass was treated as a concentration of zero. The correction of ionization efficiency was reflected in the results, and a sensitivity correction with a known concentration of a substance was not considered in our analysis. All measurements were carried out more than twice to check reproducibility.

DMA (Model 3081, TSI, St. Paul, MN, USA) and CPC (Model 3022A, TSI) were used as SMPS under conditions of sheath flow at 2.0 L min⁻¹ and sampling flow at 0.2 L min⁻¹ (dilution ratio: 10). Up-scan, down-scan, and interval time were set at 90 s, 30 s, and 120 s, respectively (one cycle: 240 s). In this research, welas® (digital2000, PALAS, Karlsruhe, Germany) with the light scattering method, which obtains information of the particle number concentration and size distribution in real time, was used to make a comparison with SMPS. Although the principal of measurements is different with SMPS, and the lower limit of particle size is 200 nm due to the light scattering method, the comparison can reveal the influence of dilution inside SMPS on the particle size distribution. The measurements were performed every second at a flow rate of 5 L min⁻¹ with a 2070HP sensor (for high concentration). The results were averaged for one minute so as to compare with that of SMPS. Spraytec (model STP5321, Mulvern, Worcestershire, UK) was used to obtain the particle size distribution at the initial state of the smoke after generation from HTP. In addition, the measurement of Spraytec was considered to be a comparable method as it was performed under the non-dilution condition by the light scattering method. The smoke was temporally accumulated in a small chamber (volume: 70 mL) and measured by He-Ne laser (632.8 nm). The measurements were repeated three times, and the results were determined and averaged within the range of transmitted laser intensity (20–60% at 0.1 s intervals). The mass or number frequency distribution can be obtained by Spraytec, whereas those of concentrations are basically not supported. Accordingly, we cannot discuss the mass or number concentration but rather the frequency size distribution in the results. Since particle diameters were defined by the different detection principles (SMPS: electrical mobility diameter, welas® and Spraytec: optical diameter), the difficulty lies in precisely matching these diameters. There are several reports on the relationship between mobility and optical diameters (Zerrath et al., 2011; Juranvi et al., 2013), and sizing errors could be significant if the refractive index and shape of the aerosol are significantly different from those of PSL (Liu and Daum, 2000; Liu et al., 2010, Pandey et al., 2015). In this research, the particles generated from HTP were liquid droplets and seemed to be spherical shape (the same shape as factory-calibrated standard PSL particles), and the refractive indices were mostly determined by the aerosol substrates (glycerin: 1.47 and propylene glycol: 1.44), which are close to that of PSL (1.59). Accordingly, on the assumption that there is not a significant difference between the mobility and optical diameters, the comparison of particle size distributions was performed.

Experiments for Solubility by Visual Check and GC-FID
Solubility tests were conducted to assess the solubility of the fixation agents for aerosol substrates. Firstly, the experiments were conducted by checking the solubility of the fixation agents against propylene glycol and glycerin as major aerosol substrates in the market so as to select an effective fixation agent. Secondly, the solubility of the selected fixation agent was checked against each aerosol substrate to determine the requirements of fixation by changing the polarity of aerosol substrate. The aerosol substrates (2000 mg) and fixation agents (10 mg) were added into screw tube bottles (4 mL), and the mixture was shaken by hand and dispersed by an ultrasonic system for 20 minutes. The ratio of fixation agent to each aerosol substrate was nearly the same as that of particles generated from HTP. The solubility was immediately visually checked as to whether the fixation agent was soluble in the aerosol substrates. Since particles from HTP were sufficiently cooled to room temperature (22°C) as a result of the dilution chambers A and B, the experiments were performed under the condition of 22°C to simulate the state of inside particles. The experiments were also conducted under the condition of 90°C to clarify the solubility as the solubility increases with a liquid temperature.

The measurement for the amount of dissolved fixation agents in aerosol substrates was carried out by GC (Agilent, 7890A) coupled with a flame ionization detector. DB-WAX (Agilent, length: 30 m, inner diameter: 0.53 mm, thickness: 1 µm) was equipped with the detector. The carrier gas was helium at the flow volume of 3 mL min⁻¹.
The injector and detector temperatures were set at 250°C; the oven temperature was set at 160°C. In the experiments, an excess amount of the fixation agents was added to aerosol substrates. Subsequently, the mixtures were shaken and allowed to stand for 24 hours to separate into two layers. The amount of dissolved fixation agents in aerosol substrates was measured to determine the solubility.

**SEM-EDX Analysis**

The observation and elemental analysis of fixed volatile particles were carried out by SEM (JSM-7001, JEOL Ltd., Tokyo, Japan) and EDX (Genesis APEX4, AMETEK Inc., Tokyo, Japan) with a silicon drift detector Apollo XV (EDAX Inc., Mahwah, NJ, USA). Since samples were vacuum-deposited with gold, and the observations were implemented under the vacuum condition, we think that these conditions are the most volatile for particles. Particles from HTP were collected with a Cambridge filter (44 mm diameter) at a flow rate of 350 mL min⁻¹ by disconnecting Chamber A (in Fig. 1) were collected on a copper plate (1 cm square) at a flow rate of 350 mL min⁻¹ by disconnecting the tygon tube in the experimental line and spraying the particles from the tube. Detection of the sampling plate instead of the particles is obvious as copper is not used in the HTP pod. The analysis was performed on particles generated from the tobacco powders and nonadecanoic acid, and from the tobacco powders, glycerin, and nonadecanoic acid at 15 keV for accelerating voltage and 30–210 pA for current value. The irradiated primary ion was ⁶⁹Ga⁺ (measurement area: 150 µm square), and the negative ion was analyzed with 0.5–2000 a.m.u. for detection range. If the nonadecanoic acid was localized on the surface of the particles, both samples were thought to be of the same composition, and the glycerin would not be detected on the surface of particles.

**RESULTS AND DISCUSSION**

**Selection of the Most Effective Fixation Agent from the Solubility and AMS Measurements**

Fig. 2 shows the results of the solubility by the visual check and organic mass size distribution of AMS against propylene glycol and glycerin. Table 2 also shows the amount of dissolved fixation agents in aerosol substrates measured by GC-FID. Linoleic acid and diocyl phthalate were dissolved in propylene glycol; palmitic acid, stearic acid, and DMPS were partially dissolved in propylene glycol at 22°C. Palmitic acid and stearic acid in glycerin and nonadecanoic acid in propylene glycol and glycerin captured air as bubbles and become clouded, suggesting a low solubility. As can be seen from Table 2, linoleic acid and dioctyl phthalate also tended to be dissolved in glycerin; however, the solubility was lower than that of propylene glycol. The solubility of all fixation agents in glycerin was apparently lower than that in propylene glycol because all fixation agents were dissolved in propylene glycol at 90°C (see the comparison results in Fig. S3). This indicated that the fixation is expected to be more effective with glycerin.

The AMS measurements were implemented to confirm the effect of fixation on particle volatility. Figs. 2(a’) and (2b’) show the particle size distribution of organic mass derived by AMS. Since the mass concentrations increased due to the fixation agents, all fixation agents were effective for glycerin. In contrast, nonadecanoic acid was the only alternative for propylene glycol. Palmitic acid and stearic acid were effective for glycerin; however, they did not sufficiently work for propylene glycol because of the increase of solubility (see in Table 2). Based on the experiments, the most effective fixation agent was revealed to be nonadecanoic acid for propylene glycol and glycerin, and the solubility for fixation agents was an important factor for the effect of fixation. Through mass spectrum analysis, m/z = 45 and 61 were predominantly observed, as derived from the fragmentation of propylene glycol and glycerin; m/z = 297, which shows the molecular ion of nonadecanoic acid, was also detected at a relatively high concentration (see details in Fig. S4). Hence, these results suggest that volatile particles can be detectable due to the effect of the fixation agent.

**The Applicability of Nonadecanoic Acid to Other Aerosol Substrates**

As an additional verification for the requirement of fixation, the fixation effect of nonadecanoic acid on the other aerosol substrates with a low polarity was examined. The mass particle size distributions of various volatile particles by AMS and Spraytec are shown in Fig. 3. It can be seen from the results of Spraytec (Fig. 3(a)) that the mass peak diameter of particles immediately after generation was different for each aerosol substrate. The reason for the
Fig. 2. Results of the solubility check at 22°C (a) between propylene glycol and fixation agents and (b) between glycerin and fixation agents. Mass size distribution derived by AMS (a’) with various fixation agents against propylene glycol ($N = 2$) (12th puff), and (b’) with various fixation agents against glycerin ($N = 3$) (12th puff).

Table 2. The solubility between various fixation agents and aerosol substrates and other fixation agents for propylene glycol and glycerin.

<table>
<thead>
<tr>
<th>Fixation agent</th>
<th>Propylene glycol</th>
<th>Glycerin</th>
<th>1,2-pentanediol</th>
<th>1,3-butanediol</th>
<th>Dipropylene glycol</th>
<th>Triacetin</th>
<th>Triethylene glycol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palmitic acid</td>
<td>5.12</td>
<td>0.218</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stearic acid</td>
<td>2.67</td>
<td>0.166</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nonadecanoic acid</td>
<td>0.544</td>
<td>0.100</td>
<td>17.7</td>
<td>1.36</td>
<td>13.0</td>
<td>0.670</td>
<td>0.720</td>
</tr>
<tr>
<td>Linoleic acid</td>
<td>Mixed</td>
<td>4.31</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dimethyl silicone oil</td>
<td>4.08</td>
<td>1.84</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dioctyl phthalate</td>
<td>15.9</td>
<td>6.18</td>
<td>-</td>
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</table>

larger peak diameter with aerosol substrates such as PG and 1,3-butanediol is related to the difference in volatilization volume. The aerosol substrates with a low boiling point had a supersaturated vapor in the pod, making particles large by particle growth. The amplitude of organic mass size distribution by AMS was extremely low without the fixation agent (Fig. 3(b)). In contrast, Fig. 3(c) reveals that organic mass size distribution with the fixation agent had a higher concentration, in particular, propylene glycol and glycerin showed a significant difference among aerosol substrates. Since the peak diameter of propylene glycol and glycerin with AMS was the same as that with Spraytec, and the organic mass concentrations were higher than those of other aerosol substrates, the effect of fixation on the suppression of volatilization was effective for propylene glycol and glycine. The causes for the difference in size distribution below 300 nm were thought to be the low sensitivity and accuracy of AMS in the range of smaller particles due to the high particle concentration. Accordingly, the difficulty lies in comparing the results of particle size distribution below 300 nm, and only the peak diameter should be discussed in the results.

In our results, the aerosol substrates having the lowest organic mass with the fixation agent by AMS were dipropylene glycol and 1,2-pentanediol. Table 2 and Fig. S5 show the results of solubility experiments for the nonadecanoic acid against various aerosol substrates. The aerosol substrates that can preferably dissolve nonadecanoic acid were dipropylene glycol and 1,2-pentanediol in these experimental conditions. It should be noted that these
findings were in agreement with the aerosol substrates that showed the lowest organic mass concentration by AMS measurements with fixation. As mentioned earlier, when the fixation agent was not able to dissolve the aerosol substrates, the effect of fixation must be sufficiently assessed. In our results, propylene glycol and glycerin were effective for fixation because nonadecanoic acid could not be dissolved with the high polarity aerosol substrates. Peterson and Tyler (2002) and Tervahattu et al. (2002) reported that fatty acids are localized on the surface of SSA having a brine core, which is considered to be of high polarity. The particles of propylene glycol and glycerin seem to be the same state as SSA, and aerosol substrates with high polarity can be applicable to fixation with fatty acids. We think that nonadecanoic acid was not sufficiently effective for aerosol substrates with a low polarity.

The Size-resolved Fraction of Nonadecanoic Acid

The size-resolved fraction of the fixation agent was examined by AMS P-TOF mode. In the experiments, we focused on the particles consisting of propylene glycol or glycerin, which can be fixed by nonadecanoic acid from previous experiments. In the analysis, we used the ratio of the mass intensity of nonadecanoic acid to the total organic mass as an indicator of mass fraction of nonadecanoic acid. As previously stated, there is the case in that the organic mass intensity shows a negative value in the smaller particle range; thus, the particle range of greater than 300 nm was chosen for analysis in the experiments. According to Fig. 4, the composition of nonadecanoic acid was not significantly different in the range of 300–3000 nm. The larger particles had a tendency to show a high fraction with respect to particle size. In contrast, the analysis of variance (ANOVA) shows there was no significant difference at p = 0.05 level. Ellison et al. (1999) proposed the model of SSA with fatty acids on the surface of particles and claimed that the fraction of fatty acids would be larger in the smaller particles in consideration of the surface thickness. The fraction of nonadecanoic acid did not differ regardless of the particle diameter in our results, suggesting that the layer thickness of nonadecanoic acid must be thin in the smaller particles. Assuming that the particle density was that of propylene glycol or glycerin, the layer thickness of nonadecanoic acid can be estimated from the particle mass calculated by particle diameter and the mass fraction of nonadecanoic acid to TPM measured in advance. The thickness was 0.1–10 nm in the particle diameter range of 300–3000 nm, that is to say, the smaller the particle diameter, the thinner the layer. In our experiments, we could not sufficiently investigate the effect of fixation on the small particles due to the sensitivity of apparatuses. It remains a challenge for future research to determine the effectiveness of fixation in the particle range of less than 300 nm.

The Effect of Fixation on the Measurement of Volatile Particles by SMPS

The comparison between SMPS and welas® with and without the fixation agent was made to elucidate the influence of dilution on the volatilization. For the diameter range below 300 nm, the results cannot be compared due to the measurable diameter range of welas®. Propylene glycol and glycerin were also used in the comparison. It is clear from Figs. 5(a) and 5(b) that the peak diameters of propylene glycol and glycerin without fixation derived by SMPS were observed below 100 nm; on the other hand, with fixation those of diameters around 200 nm were observed. The concentration of SMPS was in agreement...
Fig. 5. Comparison of number concentration between SMPS and welas® with volatile particles generated from HTP (a) G ($N = 3$) (12th puff) and (b) PG ($N = 3$) (12th puff) with and without fixation. The comparison is difficult below 300 nm due to the sensitivity of the apparatus (welas®). Number frequencies derived by Spraytec (a representative of a comparable method with light scattering under non-dilution condition) are shown in blue.

with that of welas® with fixation (see the black legends) in the comparable particle range. These results indicate that the particles without fixation were volatilized inside SMPS due to the internal dilution and dilution in the experimental chamber. The number concentrations of welas® were significantly decreased in the case of propylene glycol without fixation (see the red legends in Fig. 5(b)). This shows that most particles of propylene glycol without fixation were volatilized and shrunk in the dilution chamber B, thus particles were nearly undetected by welas®. In the results of glycerin by welas®, in Fig. 5(a), the difference in number concentration between particles with and without fixation was not confirmed to be significant, suggesting that the influence of the dilution chamber for glycerin seemed to be negligible. The volatile particles of propylene glycol and glycerin were not completely volatilized to a gas phase as the number concentrations of SMPS with and without fixation were almost same. The number particle size distribution of SMPS was nearly consistent with those of Spraytec (the light scattering method) under non-dilution condition (see the blue legends). The slight gap in the size distribution seems to be due to the difference in measurement principles. The comparison between the light scattering method (Spraytec) under the non-dilution condition and other methods under dilution or low pressure conditions was also reported by Ingebrethsen et al. (2012). Here, a comparison with previous studies is not possible because on-line measurements of particle size distribution for the pod-type heated tobacco product have not been implemented in the studies. Further work in this area is under way to verify the effect of fixation by using other apparatuses under dilution or low pressure conditions. The results of these experiments revealed that the influence of dilution on the particle size had a great impact; however, particles with fixation were not affected by the dilution inside SMPS and the experimental chamber. There is a possibility that the measurement of volatile particles as it is by the apparatuses with internal dilution can result in misinterpretations regarding the particle size distribution. We would like to emphasize the importance of aerosol fixation for volatile particles in order to measure the appropriate particle size distribution.

Confirmation of Aerosol Fixation by SEM-EDX

The observation and analyses of fixed particles were performed by SEM-EDX under the vacuum condition. The results of SEM-EDX are shown in Fig. 6. The particles generated from HTP with the tobacco powders and glycerin (Fig. 6(a)) were not observed because of the volatilization of particles under the vacuum condition. In contrast, numerous small particles generated with the tobacco powders and nonadecanoic acid were attached to the filter fibers, revealing that the particles can be observed with low volatile substances such as nonadecanoic acid. When the particles were generated with the tobacco powders, glycerin, and nonadecanoic acid, numerous adhesive particles were observed on the filter fiber (Fig. 6(c)). The form and size of particles were apparently different from those of particles generated with the tobacco powders and nonadecanoic acid. These results demonstrate that fixed particles with nonadecanoic acid must include glycerin inside the particles and can be observed by SEM.

Fig. 6(a') illustrates that the elemental composition of glass fibers was obtained through the analysis of EDX as the particles did not exist. The particles generated with the tobacco powders and nonadecanoic acid showed a large fraction of carbon in Fig. 6(b') owing to the composition of nonadecanoic acid. It can be seen from Fig. 6(c') that the fractions of carbon and oxygen were significantly changed as glycerin has many oxygen atoms. Since the composition of particles with glycerin and nonadecanoic acid was unique and included many carbons and oxygens, we think that glycerin can exist inside particles under the vacuum condition thanks to the effect of fixation.

Confirmation of Aerosol Fixation by TOF-SIMS

The results of composition analysis on the surface of particles by TOF-SIMS are shown in Fig. 7. It can be seen that the surface composition of particles generated with the tobacco powders, glycerin, and nonadecanoic acid was...
Fig. 6. SEM image of the particles generated from HTP with (a) the tobacco powders and glycerin, (b) the tobacco powders and nonadecanoic acid, and (c) the tobacco powders, glycerin, and nonadecanoic acid. EDX elemental analysis of the particles generated from HTP with (a') the tobacco powders and glycerin, (b') the tobacco powders and nonadecanoic acid, and (c') the tobacco powders, glycerin, and nonadecanoic acid. The measured points are indicated by the red circles.

Fig. 7. Comparison of TOF-SIMS results ($N = 2$) for the surface analysis of particles generated from HTP with the tobacco powders and nonadecanoic acid and the tobacco powders, glycerin, and nonadecanoic acid.

The same as particles generated with the tobacco powders and nonadecanoic acid. Several volatile compounds were generated from the tobacco powders; however, the intensity of nonadecanoic acid was sufficiently high (details of mass spectrum are shown in Figs. S6 and S7). On the other hand, the molecular ion ($m/z = 91$) of glycerin was low, and the fragment ion ($m/z = 61$) was not detectable. From SEM-EDX analysis, glycerin seemed to exist inside the particles according to the composition of particles. These results suggest that glycerin did not exist on the surface of particles, and nonadecanoic acid was dominantly localized on the surface. It should be noted that nonadecanoic acid was naturally separated in particles and localized on the surface, even though the aerosol substrates and fixation agent were generated and condensed at the same time. We assume the reason for the separation and localization was the polarity between the particle surface and air. The surface of particles was covered with the fatty acid, and air would show low polarity because of the composition (mostly nitrogen and oxygen). Therefore, the fatty acid was localized on the air side, and glycerin formed the core in particles to become energetically stable. In previous research, aerosol fixation was performed by condensing the fixation agent onto the surface of particles in a separate step. We found that the fixation was possible by the combination of aerosol substrates and fixation agents in the same generation processes.

CONCLUSIONS

We measured the particle size distribution and elemental/surface compositions of volatile particles generated from a pod-type heated tobacco product with and without fixation agents. An effective fixation agent was selected based on the solubility experiments and changes in the particle size distribution as measured by AMS (low pressure condition: 2 Torr). Our hypothesis was that fatty acids as low polarity substances can be applied in aerosol fixation in order to reduce the particle volatility through the knowledge of SSA, which is covered by fatty acids on the surface of the particles. We found that the solubility of
the fixation agent was an important factor in fixation. Based on the experimental results, aerosol fixation was useful in preventing the influence of volatilization and enabling measurements via SMPS and AMS. The particle size distributions with and without fixation that were derived by SMPS differed significantly, and the particle number concentration with fixation was in agreement with that of welas® (light scattering method) for the comparable range of particle size. Furthermore, the peak diameters derived by SMPS and AMS were almost the same as that of Spraytec.

The results of SEM-EDX and TOF-SIMS showed that the fixation agent was localized on the surface of the particles. We reached the conclusion that particles covered by fatty acids can be formed not only with sea water but also with aerosol substrates with a high polarity, such as glycerin and propylene glycol. In this research, the fixation agents with a low polarity were effective for the aerosol substrates with a high polarity; however, the fixation of aerosol substrates with a low polarity remains for future work. Moreover, the challenge for future research will be to confirm the effect of fixation below 100 nm under low pressure or vacuum conditions.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

REFERENCES


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