

Influence of relative humidity on the behavior of aerosols generated from heated tobacco products

by

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Abstract

Heated tobacco products are devices that deliver nicotine into the body via inhalation of the mainstream aerosols generated during direct and/or indirect heating of tobacco leaf material. These aerosols consist primarily of “water droplets” that contain glycerin and/or propylene glycol as an aerosol former, and thus these hygroscopic aerosols will gain or lose water until reaching an equilibrium with the moisture content in the surrounding atmosphere. In this study, we sought to determine the influence of relative humidity (RH) on the behavior of the aerosols generated from a “low-temperature type” device in a test chamber (0.57 m³). Concentrations of PM_{2.5} and PM₁₀ after puffing were measured using a smartphone air quality monitor, based on a laser light scattering method, under low RH (29%) and high RH (82%) conditions. The results revealed that the levels of PM_{2.5} and PM₁₀ in air, along with size distribution and decay rates, were highly dependent on test chamber RH.

Keywords: Aerosol, Relative humidity, Glycerin, Propylene glycol, Heated tobacco products

1 Introduction

Heated tobacco products, also referred to as heat-not-burn tobacco products, are battery-operated devices that deliver nicotine into the body via inhalation of the mainstream aerosol gen-

erated during the direct and/or indirect heating of tobacco leaf material [1–4]. This novel medium is being promoted as a less hazardous alternative to conventional cigarettes for both smokers and non-smokers, given that the tobacco leaf is heated without burning to generate nicotine-containing aerosols, and thus eliminates the emission of side-stream smoke [1–4]. However, considering the chemical and physical properties of aerosols, the potential adverse health effects of these products should be carefully investigated.

The mainstream aerosol generated by these devices consists primarily of “water droplets,” which contain glycerin and/or propylene glycol that functions as an aerosol former [5], and thus is fundamentally different in origin and chemical and physical composition when compared with conventional cigarette smoke [5, 6]. Given that glycerin and propylene glycol are hygroscopic in nature, owing to the presence of hydroxyl groups in their molecules, the generated aerosol gains or loses water until reaching an equilibrium with the moisture content in the surrounding atmosphere [7]. Consequently, it is necessary to gain a better understanding of aerosol deposition in the respiratory system and indoor environments for assessing the potential health effects on both active and passive smokers.

The mainstream aerosol exhaled by smokers can be a source of particulate matter (PM) in air. To assess the PM produced by heated tobacco products, Nakai et al. [8] generated a mainstream aerosol from commercially available heated tobacco products in the laboratory and measured the concentrations of $\text{PM}_{2.5}$ (fine particulate matter with a size of $2.5\text{ }\mu\text{m}$ or less) in indoor air using an optical $\text{PM}_{2.5}$ monitor in responses to changing the temperature of the sensor unit from 21°C to 45°C . They found that the measured $\text{PM}_{2.5}$ concentrations decreased with an increase in the temperature of the sensor unit, owing to an accelerated evaporation of the hygroscopic aerosol by heat. To date, however, the influence of relative humidity (RH) on PM concentrations in indoor air has not been investigated. Accordingly, in this study, we sought to determine the influence of RH on the behavior of hygroscopic aerosols in air contained within a test chamber.

2 Methods

2.1 Heated tobacco product

The Ploom TECH (JT Inc., Tokyo, Japan) device used for the purposes of this study was purchased from a retail tobacco store in Japan. The device consists of a rechargeable battery, cartridge, and consumable tobacco capsule. A “Mevius regular” was used as the tobacco capsule in this study. The aerosol is generated by heating liquid in the cartridge containing aerosol formers and passing this through the tailor-made tobacco capsule at approximately 30°C . This device is thus categorized as a “low-temperature-type” device, in contrast to other brands, such as IQOS (PMI Inc., USA) and glo (BAT, UK), which are classed as “high-temperature-type” devices.

2.2 Experimental setup

Fig. 1 shows the experimental setup used in this study. The mainstream aerosol was generated from the Ploom TECH device using an LM4E Linear Vaping Machine for E-cigarettes (Borgwaldt KC, GmbH, Germany). The outlet port of the vaping machine was connected to a test chamber (0.57 m^3) constructed from acrylic boards with a short silicone tube. Thus, the generated aerosol

was directly introduced with puffing into the test chamber. The dimensions of the chamber were 1.34 m (height) $\times$ 0.85 m (width) $\times$ 0.50 m (depth). Laboratory air was constantly introduced into the chamber using two diaphragm pumps. When changing the RH in the chamber, laboratory air was passed through pure water (Milli-Q, Millipore Corporation, USA, resistivity=18 M Ω ·cm) contained in the impingers. The air within the chamber was thoroughly mixed by a small fan operated continuously at a constant rate. The air exchange rate was determined to be 2.2 h⁻¹, as measured based on the CO₂ tracer gas decay method. The temperature and RH were monitored using a TR-72U thermo recorder (T and D, Tokyo, Japan), and concentrations of PM_{2.5} and PM₁₀ (fine particulate matter with a size of 10 μ m or less) were measured using a smartphone air quality monitor (Pocket PM_{2.5} sensor; Yaguchi Electric Corporation, Miyagi, Japan), which employs a laser light scattering method for the detection of PM_{2.5} and PM₁₀. The monitor consists of a laser light-emitting diode, photodiode sensor, fan, amplifier, and USB encoder connected to an Android-type smartphone [9, 10]. The smartphone displays PM_{2.5} and PM₁₀ concentrations in units of μ g m⁻³, and the background screen color changes from blue to yellow, red, purple, and black with an increase in PM levels. The monitor also generates log data expressed as comma-separated values of the Google Keyhole Markup Language format, including the global positioning system. The calibrated monitors used in this study were purchased from the IDEC Corporation (Tokyo, Japan).

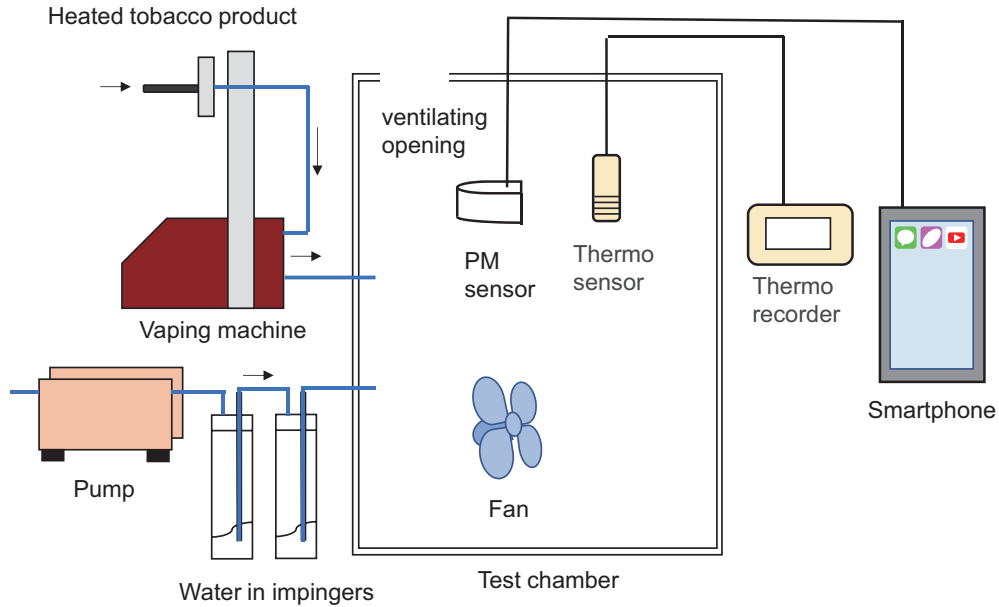


Fig. 1 A schematic representation of the chamber experiment conducted in this study.

2.3 Puffing and environmental condition

The Ploom TECH device was consumed by the Linear Vaping Machine following the International Organization for Standardization (ISO) puffing protocol [11] with a minor modification, consisting of puff duration of 2 s, inter-puff interval of 120 s (originally 60 s), puff volume of 35 mL, puff rate of 1.05 L min⁻¹, and a “Bell” puffing profile. Preliminary tests revealed that the range of

PM concentrations in the chamber exceeded the upper limit of the smartphone air quality monitor during repeated puffing, and thus the inter-puff interval was subsequently extended from 60 s to 120 s. The number of puffs in a single run was set to 10, and three repeat runs were conducted under two conditions: low RH (temp. = 26°C, RH = 29%) and high RH (temp. = 26°C, RH = 83%). Given that the target substance in this study was “aerosol,” the vaping device did not incorporate a Cambridge filter that is typically used for the separation of gas and solid phase.

3 Results and Discussion

The time courses of the concentrations of PM_{2.5} and PM₁₀ in the test chamber showed similar patterns in three repeated runs. Fig. 2 presents the results obtained for Run #1 under low and high RH conditions as representative of the three runs. In general, the concentrations of both PM_{2.5} and PM₁₀ peaked within a few minutes after puffing the Ploom TECH device, and subsequently decreased with time. However, we observed differences in the peak maximum concentrations in puff profiles under the two RH conditions. At low RH, the peak concentrations of PM_{2.5} and PM₁₀ were $28 \pm 11 \mu\text{g m}^{-3}$ ($n = 30$) and $38 \pm 19 \mu\text{g m}^{-3}$ ($n = 30$), respectively. Comparatively, the peak concentration of PM_{2.5} and PM₁₀ under high RH conditions were $73 \pm 19 \mu\text{g m}^{-3}$ ($n = 30$) and $84 \pm 23 \mu\text{g m}^{-3}$ ($n = 30$), respectively, both values of which were significantly higher than the corresponding values under low RH ($p < 0.05$, t -test). These findings thus indicate that the generated aerosols immediately lost water to reach equilibrium with the moisture content in the chamber, and that the levels of PM in the aerosol are dependent on the environmental RH.

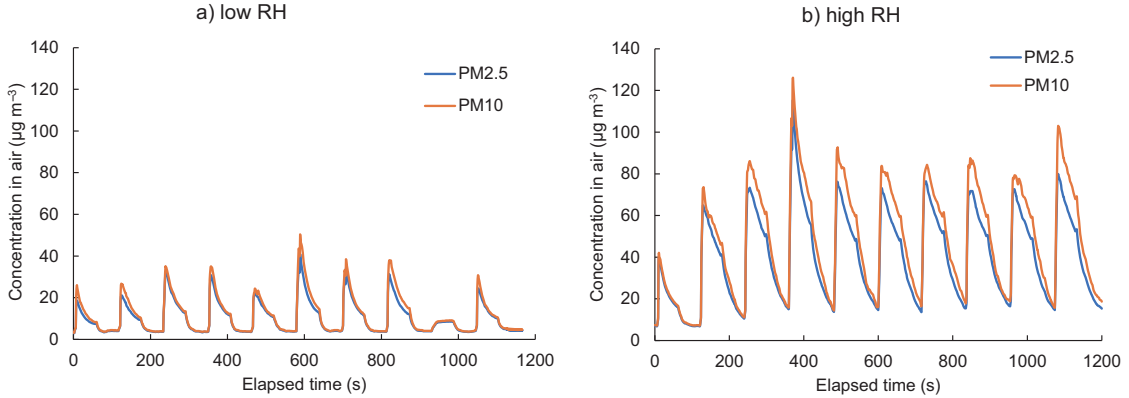


Fig. 2 Typical time-courses of the concentration of PM_{2.5} and PM₁₀ in air within the test chamber during a series of 10 puffs of the Ploom TECH device under low RH (temp. = 26°C, RH = 29%) and high RH (temp. = 26°C, RH = 83%) conditions.

Since the PM_{2.5} and PM₁₀ concentrations cover the different range of particle size respectively, the concentration ratio (PM₁₀/PM_{2.5}) reflects the size distribution of aerosol in the test chamber. Fig. 3 shows typical time-courses of PM₁₀/PM_{2.5} during a series of 10 puffs of Ploom TECH under low RH and high RH conditions (Run#1). Under the low RH condition, the ratio immediately increased just after puffing and decreased within 20 s to the background level. To the contrary, the increase in PM₁₀/PM_{2.5} after puffing was rather moderate under high RH condition. The

$PM_{10}/PM_{2.5}$ at the peaks was observed to range from 1.1 to 2.4, with an average of 1.4 ± 0.38 ($n = 30$) at low RH, whereas at high RH, the ratio ranged from 1.1 to 1.3, with an average of 1.1 ± 0.067 ($n = 30$). The evaporation rate of a water droplet is inversely proportional to its radius [12]; the finer particle has a nature to lose water more easily. The significant difference between these values ($p < 0.01$, t-test) indicates that RH also affects the size distribution of the hygroscopic aerosol at the peaks in the environment.

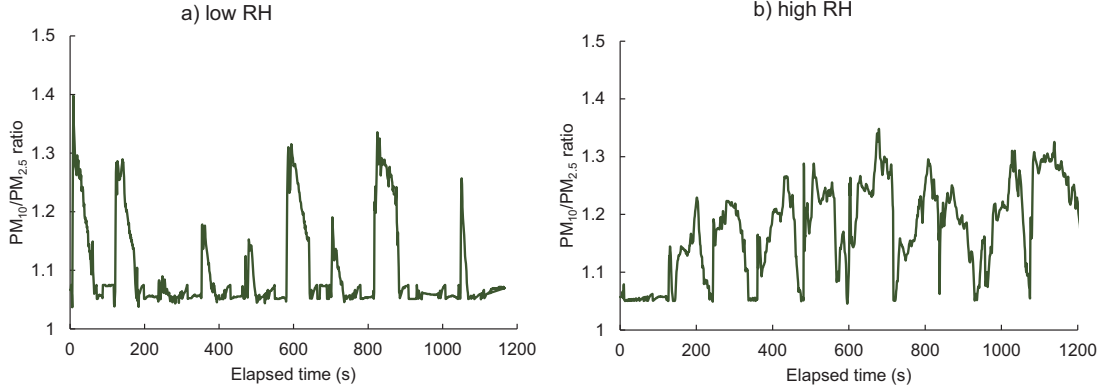


Fig. 3 Typical time-courses of $PM_{10}/PM_{2.5}$ in air of the test chamber during a series of 10 puffs of Ploom TECH under low RH (temp. = 26°C, RH = 29%) and high RH (temp. = 26°C, RH = 83%) conditions.

With regard to the hygroscopic aerosol, we can assume three possible processes whereby the aerosol is removed from the chamber: removal by air exchange, evaporation (loss of water and subsequent volatilization of glycerin and propylene glycol) [7], and deposition on the surface of the chamber. In this context, it should be noted that removal via coagulation was not taken into consideration in the present study, as this process is generally applicable only to finer aerosol of particle size 0.1 μm or less [13]. Accordingly, the change in PM concentration C with time t can be described as follows:

$$\frac{dC}{dt} = -NC - R_{\text{evap}} - R_{\text{dep}}, \quad \dots \textcircled{1}$$

where N is the air exchange rate of the test chamber (2.2 h^{-1}), R_{evap} is the evaporation rate, and R_{dep} is the deposition rate. Fig. 4 shows two linear decay plot generated by log conversion of the time-course PM concentrations. By applying a first-order decay to the first and second phases, the change in PM concentration C with time t can be described using the rate constants k_1 and k_2 .

$$\frac{dC}{dt} = -k_1C - k_2C \quad \dots \textcircled{2}$$

As the air in the test chamber was constantly exchanged during the measurement period, the values obtained for k_1 and k_2 must reflect the air change rate ($N = 2.2 \text{ h}^{-1}$). Table 1 shows the k_1 and k_2 values derived from the log C slopes obtained for $PM_{2.5}$ and PM_{10} under low and high RH conditions, excluding some irregular peaks. Given that the values of both k_1 and k_2 are considerably greater than N , evaporation and deposition are presumed be the dominant processes for the

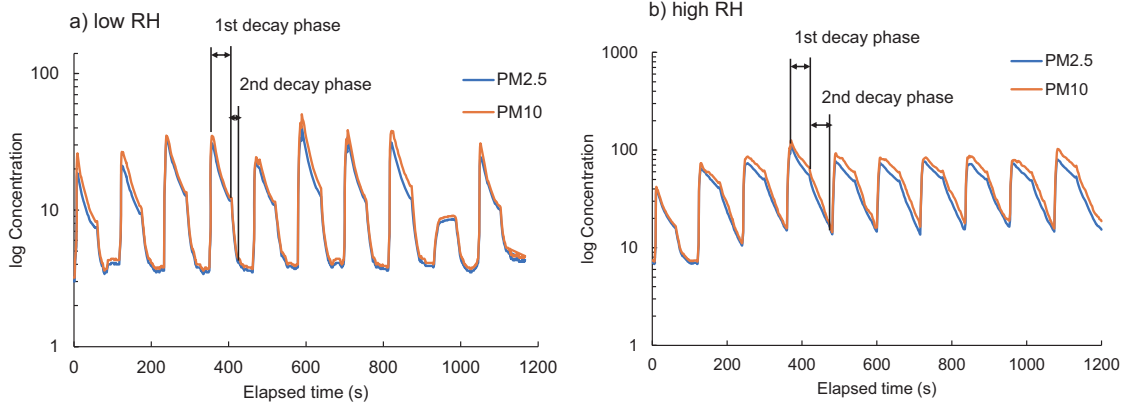


Fig. 4 Typical linear decays plots for the time-courses of $\text{PM}_{2.5}$ and PM_{10} concentrations derived from the curves shown in Fig. 2 converted to a log scale. The first and second phases of the 4th puffs are indicated as examples.

decay of hygroscopic aerosols. For both $\text{PM}_{2.5}$ and PM_{10} , the k_1 values were lower than those of k_2 under both RH conditions, thereby indicating the operation of a rate-determining process in the first phase, presumably evaporation. Furthermore, higher values of k_1 and k_2 were observed under high RH conditions, thus indicating that the rate of hygroscopic aerosol decay is also dependent on environmental RH.

Table 1 Apparent first-order decay rate constants derived from the first and second phase slopes for $\text{PM}_{2.5}$ and PM_{10} in the test chamber. Number of puffs used for this calculation was 27 for low RH and 30 for high RH conditions.

	$\text{PM}_{2.5}$		PM_{10}	
	$k_1 (\text{h}^{-1})$	$k_2 (\text{h}^{-1})$	$k_1 (\text{h}^{-1})$	$k_2 (\text{h}^{-1})$
Low R.H.	97 ± 45	245 ± 144	99 ± 38	229 ± 118
High R.H.	33 ± 9.4	77 ± 16	30 ± 10	76 ± 18

4 Conclusion

In this study, we aimed to determine the influence of relative humidity on the behavior of aerosols generated from heated tobacco products. Given that aerosols consist of water droplets containing glycerin and propylene glycol, the levels of $\text{PM}_{2.5}$ and PM_{10} in air, along with their size distribution and decay rates, were found to be highly dependent on the relative humidity within the test chamber. The findings in this study will also provide a valuable reference for gaining insights into the airborne transmission of novel coronaviruses and other viruses, as such pathogens are potentially present in water droplets in indoor air.

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