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Study on the real-time size distribution of smoke particles for each fire stage by using a steady-state tube furnace method

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ABSTRACT

For the analysis of the adverse effects of smoke on health, it is essential to determine the amount and location of smoke particles deposited in the respiratory tract. However, the deposition characteristics of the particles are influenced by their morphology and size distribution. Moreover, the real-time particle size distribution during inhalation is important for determining smoke particle deposition in the lungs. Smoke particles generated under different fire conditions differ in their physical and chemical characteristics. Thus, there is a need to adopt international standard methods for characterizing the particles generated in fire. In the present study, the size distributions together with morphology of smoke particles were measured for each fire stage by using the steady-state tube furnace method given in ISO/TS 19700. The size distributions of smoke particles from wood and polypropylene (PP) were measured in real time by using an electric low-pressure impactor ($ELPI^+$), and their morphologies were analyzed using transmission electron microscopy (TEM).

1. Introduction

Smoke inhalation can cause adverse effects on health, such as asthma, allergies, chronic obstructive pulmonary disease (COPD), pulmonary fibrosis, and lung cancer. A prerequisite for determining smoke hazards and conducting a risk analysis is to determine smoke behavior in the respiratory tract. The characteristics of inhalation, which include the absorption and adsorption of toxic gases and the penetration and deposition of smoke particles in the lungs, are related to the morphology and size distribution of smoke particles. Smoke from fire is a mixture of combustion gases and particles that include microdroplets formed from condensed organic vapors and carbonaceous agglomerates [1,2].

Smoke particles generated from different fire conditions differ from each other in their physical and chemical characteristics. A number of studies have been carried out to measure the size of smoke particles generated during fire [3]. However, these studies were carried out under different fire conditions (e.g., temperature, method of air and fuel supply, and dimension of enclosure). Thus, there is a need for adopting international standard methods for characterizing the particles generated in fire. As an international standard to determine the yields of fire under defined combustion conditions, the steady-state tube furnace method becomes important [4]. Recently, in order to establish the repeatability and reproducibility of the method, a round-robin interlaboratory study was carried out [5].

Numerous experiments have been conducted for determining the toxic potency of fire effluents using the steady-state tube furnace. However, a limited number of experiments have been conducted for particle-phase products compared with gas-phase products. Some researchers have measured the size distribution of smoke particles by using the steady-state tube furnace method, by which they could obtain the particle size distribution for each fire stage [6–10]. In these studies, smoke density methods or gravimetric methods using impactors were used for measuring the particle size. For an impactor, the lower particle size limit can be reduced by using a smaller orifice or a lower operating pressure. The major drawbacks of the gravimetric method are the need for a long sampling time (to acquire enough particle mass to be weighed by a microbalance) and the disassembling of collection substrates. An important point to note here is that particle characteristics change with time owing to many factors [1]. Thus, particle size distributions after a long time could be different from real-time particle size distributions during particle inhalation into the respiratory tract.

In the present study, the size distributions and morphologies of smoke particles generated by the combustion of wood and polypropylene (PP) were investigated. The aerodynamic size distributions of the particles were measured using an electrical low-pressure impactor to obtain them in real time. The steady-state (equivalent ratio) tube furnace method given in ISO/TS 19700 [11] was used to generate smoke particles for each fire stage: oxidative

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pyrolysis as no flaming (S1b), well-ventilated flaming (S2), small localized fire as under-ventilated flaming (S3a), and post-flashover fire as under-ventilated flaming (S3b). The fire stages were controlled by varying the furnace temperature and equivalent ratio. In this study, experiments were focused on the size distribution of smoke particles. Particle morphologies were used for gaining a better understanding of the characteristics of particle size distributions. The morphology of the smoke particles was measured using transmission electron microscopy (TEM) by following the method used by Goo [12].

2. Experimental methods

The steady-state tube furnace method, known as the controlled equivalence ratio method given in ISO/TS 19700 [11], was employed in this study. Fig. 1 shows a diagram of the experimental setup used for measuring the size and morphology of the smoke particles by using a steady-state tube furnace. The main body of the steady-state tube furnace had a maximum temperature of 1100 °C, a 600-mm-long heating zone, and a total length of 700 mm. The quartz tube penetrating the main body of the furnace had inlet and outlet lengths of 900 and 85 mm, respectively. The outer diameter of the quartz tube was 48.0 mm, and the wall thickness was 1.5 mm. A sample boat was placed inside the quartz tube to carry combustible materials into the furnace. Fragments or pellets of specimens were spread uniformly in the quartz sample boat over a length of 800 mm at a loading density of 25 mg/mm. An induction motor (DKM, 9IDG3-200FP) was used to introduce the sample boat into the furnace with a typical advancing velocity of 40 mm/min, corresponding to a feeding rate of 1 g/min. The primary air used for combustion was introduced from the right side of the quartz tube, as shown in Fig. 1, at a maximum flow rate of 20 L/min by using a mass flow controller (MFC: KOFLOC, 3660) and a readout (MJT, MR300).

Smoke exited into the mixing chamber connected to the left side of the quartz tube. The mixing chamber was made of 5-mm-thick polystyrene and 1-mm-thick stainless steel plates; it had inner dimensions of 310 mm (depth) × 310 mm (width) × 340 mm (height). Details on the apparatus and methodology specified in ISO/TS 19700 [11] were adopted for the generation and sampling of smoke from combustion materials. Wood and polypropylene (PP) were used as the combustion materials. Fig. 2 shows a typical fire flame for wood. For wood, birch wood sticks kept under room conditions were used by cutting into cubes with sides about 5 mm in length. For PP, pure PP pellets with a spherical shape and having a diameter of 5 mm were used. Secondary air was introduced into the mixing chamber at a combined primary and secondary air flow rate of 50 L/min achieved using a flow meter (KFM, PA-20).

The classification of fire stages defined in ISO/TS 19700 is given in Table 1 [4,11]. The condition of each fire stage is determined from the furnace temperature and the equivalent ratio (ϕ) which is determined by the primary air flow rate (Q_p). The furnace temperature and primary air flow rate (Q_p) were varied for each fire type, as shown in Table 1. In the table, the data in parentheses are values used in this study. The equivalent ratio is a parameter used to describe ventilation conditions, and is defined as

$$\phi = \frac{\dot{m}_{fuel}/\dot{m}_{oxygen}}{\left(\dot{m}_{fuel}/\dot{m}_{oxygen}\right)_{stoich}}.$$

In the above equation, $\dot{m}_{fuel}$ and $\dot{m}_{oxygen}$ are the mass flow rates of fuel and oxygen, respectively, and "*stoich*" represents the stoichiometric condition. In this experiment, decomposition conditions were selected according to the experimental procedure described in chapter 9 of ISO/TS 19700 [11].

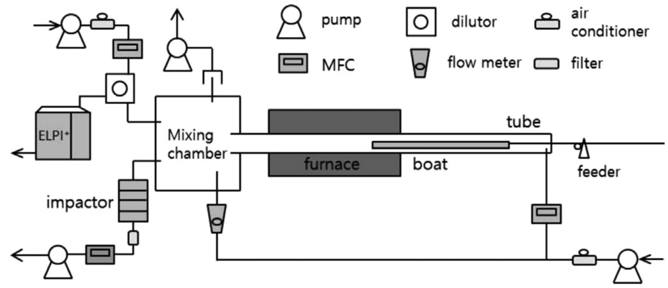

Fig. 1. Diagram of the experimental setup for the steady-state tube furnace method.

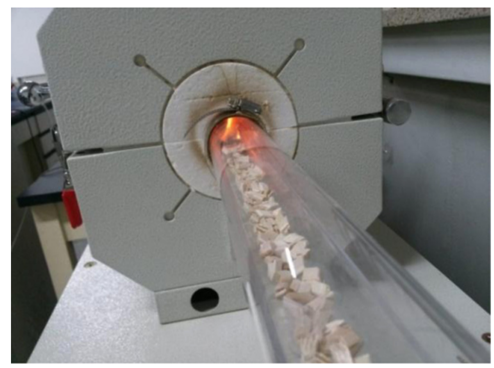

Fig. 2. Typical fire flame for wood pellets.

Table 1
Test conditions.

Fire stage		S1b	S2	S3a	S3b
Fire type		No flaming: oxidative pyrolysis	Well-ventilated flaming	Under-ventilated flaming: small localized fires	Under-ventilated flaming: post-flashover fires
Temperature (°C)		350	650	650	825
Q_p (L/min)	For wood	2	(10)	(2.4)	(2.4)
	For PP	2	(10)	(2.9)	(2.9)
Equivalent ratio (ϕ)		–	< 0.75	2 ± 0.2	2 ± 0.2

For size distribution measurements, an electrical low-pressure impactor (Dekati, ELPI+) with a nominal airflow rate of 10 L/min was used. It consisted of three operating parts that performed the following functions: particle charging, size classification, and electrical detection. These parts enabled the monitoring of the number concentration versus aerodynamic diameter of the particles in real time. The particles were sampled through the hole of the mixing chamber at a flow rate of 1 L/min and the concentration was reduced using a dilutor to a dilution ratio of 10:1. In this study, the midpoint diameters of 13 impactor channels between the 14 impactor stages (excluding the filter stage) were used. For the morphology analysis of the particles, a separate three-stage cascade impactor with a sampling flow rate of 1 L/min was used as a particle sampler. The particles were collected using TEM grids (TedPella, 01800-F) placed on each stage of the sampler. The morphology of the particles deposited on the TEM grids was analyzed using TEM (Hitachi, Bio-TEM, H-7650).