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Original Article

Influence of smoking rate on ultrafine particle emission of cigarette smoke

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Abstract

Ultrafine particles have been attached the attention for researchers due to their impacts on human health. Ultrafine particles can be emitted from burning process, such as forest burning, agriculture waste burning, cigarette, etc. In this study, ultrafine particles produced by cigarette smokes has been investigated as a function of smoking rate. The samples consisted of different types of Indonesia cigarette called Kretek cigarette. The quantification of emission factors was conducted by the burning of the cigarette samples, then the smoke that was sucked with a different flow rate using an adjustable pump. The flow rate was chosen to correspond as close as the variation of the rate that people smoke. The measurements of ultrafine concentrations were carried out using an ultrafine particle counter P-Trak TSI 8525 capable of measuring particles with the diameter in the range of 20 to 1000 nm. The results showed that the emission factor of ultrafine particles significantly depended on the smoking rate. A higher smoking rate produced higher average ultrafine particle emission factor.

Keywords: Cigarette smoke, emission factor, smoking rate, ultrafine particle

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Introduction

Cigarette smoke has been identified thousands of chemical compounds in a complex mixture of gases and particles (Bi, Sheng, Feng, Fu, & Xie, 2005; Morrical & Zenobi, 2002; Pappas, Polzin, Watson, & Ashley, 2007; Smith & Fischer, 2001). Smoke particles contain of chemical compounds such as: polycycle aromatic hydrocarbons (PAHs) (Kalaitzoglou & Samara, 2006; Lee, Hsieh, & Li, 2011; Thielen, Klus, & Müller, 2008), volatile organic compounds (VOCs) (Charles, Batterman, & Jia, 2007), and heavy metals (Pappas et al., 2007; Slezakova, Pereira, & Alvim-Ferraz, 2009). Cigarette smoke particles have been measured in different sizes of diameter (Klepeis, Apte, Gundel, Sextro, & Nazaroff, 2003; McGrath, Warren, Biggs, & McAughey, 2009) with varies of concentration depending on a classification of the smoke (mainstream and sidestream) (Charles et al., 2007) and smoke environment (Slezakova et al., 2009). Inhaled and exhaled smoke particles were found in the different size of 160 nm and 239 nm (McGrath et al., 2009). The concentrations of particles with the diameter less than 10 μm (PM_{10}) were measured of 107 - 156 mg/m^3 and particles having the diameter less than 2.5 μm ($PM_{2.5}$) of 103-132 mg/m^3 (Slezakova et al., 2009).

The concentration measurement of particles having a diameter less than 0.1 μm or ultrafine particles from cigarette smoke have a limitation in quantity. Moreover, the ultrafine particle emission factor has been unknown, and the influenced factors are still unclear. This study was conducted to measure ultrafine particle emission factor and the influencing factors. One of the factors investigated in this study was the smoking rate based on the reality shows that people smoke with a different rate of smoking. The main purpose of the study was to get a better understanding of the cigarette particle emission and to predict the impacts on health.

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Methods

Experiment Methods

The quantification of emission factors was conducted by the burning of the cigarette samples, then the smoke that was sucked with a different flow rate using an adjustable pump. The flow rate was chosen to correspond as close as the variation of the rate that people smoke. The sample smokes were introduced to a glass chamber with dimensions of 66 x 74.5 x 55 cm^3. A fan was placed to mix the smoke homogeneously in the chamber. The ultrafine particle emission factors were qualified by measuring the total particle concentration during the smoking activities (Fig. 1). The measurements of ultrafine concentrations were carried out using an ultrafine particle counter P-Trak TSI 8525 capable of measuring ultrafine particles as small as 20 nm in diameter. The sampling interval was on 10 seconds (Wardoyo et al., 2007; Wardoyo, Morawska, Ristovski, & Marsh, 2006). The emission factor was calculated using the developed formula as belows:

$$EF = v.A.\int_0^t C(t)\,dt \qquad (1)$$

where *EF* is the emission factor (particles/cigarette bar), *v* is the flow rate of the smokes; and *A* is the area of the outlet of the chamber.

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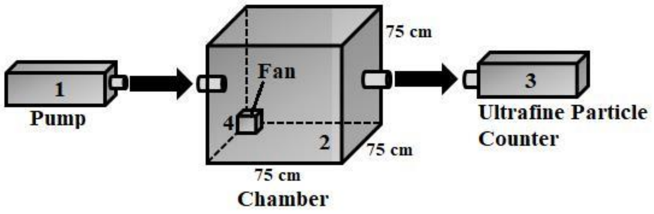

Figure 1. An experimental setup consisting of a smoking pump (1), a chamber (2), ultrafine particle counter (3), and fan (4).

Experiment Setup

The experiment setup was designed to capture the real condition of people smoking. The previous observation found that the sucking rate is varying between 1 m/s to 15 m/s when somebody smokes. The experiments were set up to simulate smoking conditions by withdrawing the cigarette smokes at a different rate using an adjustable pump. The smoking rate of the experiment was conditioned at a slow rate, a medium rate, and a high rate of smoking. The rate was varied of 1.4 m/s, 9.8 m/s, and 13.9 m/s respectively.

The cigarette was burnt on a holder connected to the inlet of the smoking pump. The smoke samples were withdrawn by the pump with the variation of the rate. The samples were then introduced into the chamber. The samples were mixed with a fan in order to distribute the concentration homogeneously. The ultrafine particles concentration was measured using a P-Trak Ultrafine Particle Counter (TSI, Model 8525). The sampling rate of the ultrafine particle counter was 0.6 l/m. The concentration measurements took time about 6 h. This procedure was repeated 3 times in order to confirm the producibility of the results for the same cigarettes.

Smoking Pump

A smoking pump was designed to simulate the rate that people smoke varying between 1 m/s and 15 m/s. The stove was set up in different conditions that are low, medium, and high rate condition. The measurements of the rate for the condition are presented in Figure 2. The result shows that the low condition with the rate of 1.4 ± 0.2 m/s, the medium condition with the rate of 9.8 ± 0.5 m/s, and the high condition with the rate of 13.9 ± 0.4 m/s respectively.

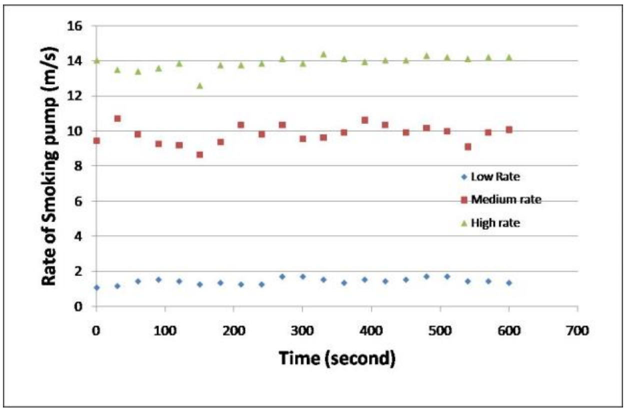

Figure 2. The rate of the smoking pump operating on low, medium, and high rate.

Sample Material

The samples consisted of different types of Indonesia cigarette called Kretek cigarette (Tab. 1). The cigarette made of using Temanggung tobacco, Sampang tobacco, and Jember tobacco mixed with clove and additional amino acids. Tobaccos originating from Temanggung, Sampang, and Jember are commonly used for Kretek cigarette. The cigarette samples were numbered from 1 to 10. The average weight, length, and diameter of the cigarettes was 0.2 gr, 8.1 cm, and 0.6 cm. The samples were placed in an open area of the laboratory for few months to obtain homogeneous moisture contents within the optimum range for burning (Wardoyo et al., 2006; 2007). The moisture content of the cigarettes was measured from the difference between the cigarette weight before and after drying in an oven at a temperature of 110 °C. The moisture content of the leaves varied from 5-10%.

Table 1. List of amino acids as an additive matter to the cigarette.

Sample	Amino Acids
1	Tryptophan
2	Serine
3	Histidine
4	Glutamine acid
5	Proline
6	Asparagine
7	Cysteine
8	Serine+ proline + glisin
9	Folic acid
10	Cortisone

Results

Ultrafine Particles Concentration

In order to obtain the optimum performance of the measurement system, The data collection of ultrafine particles were conducted three times for every cigarette sample. Figure 3 shows the ultrafine particle concentrations of the smokes emitted by a cigarette sample that was sucked with a different smoking rate of 1.4 m/s, 9.8 m/s, and 13.9 m/s. The average particle concentration was calculated by integrating the total concentration during one run and dividing by the burning time. The standard deviation was derived from 3 repeated runs for every rate burning.

Figure 3 above shows that the smoking rate of 1.4 m/s (slow rate) generates the lowest initial concentrations of ultrafine particles. The higher concentrations are no more than 200.000 particles/cm^3. Meanwhile, the highest smoking rate (13.9 m/s, high rate) generates up to 400.000 particles/cm^3 of ultrafine particles in the initial measurement time. In the medium rate (9.8 m/s), the initial concentrations of ultrafine particles are up to 350.000 particles/cm^3. In general, the results show that a higher smoking rate produces higher ultrafine particle concentration (as seen in Fig. 3).

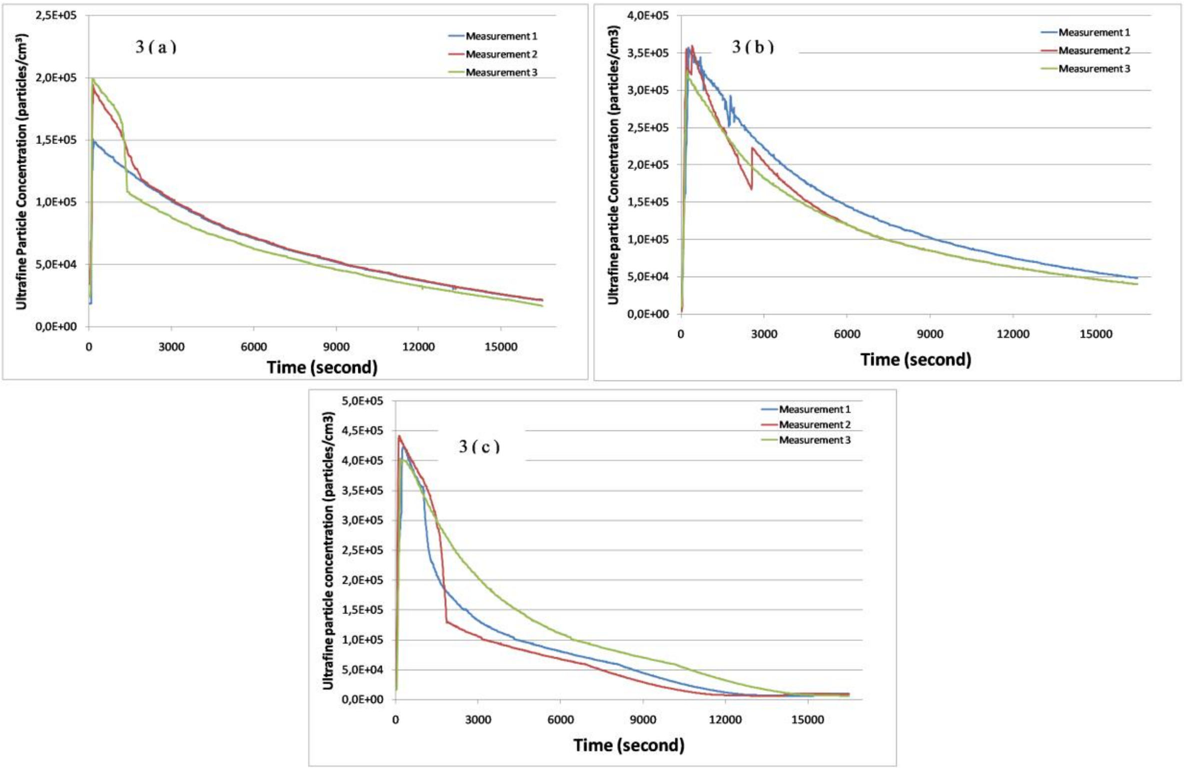

Figure 3. Measured ultrafine concentrations for a sample withdrawn with the smoking rate of (a) 1.4 m/s; (b) 9.8 m/s; and (c) 13.9 m/s.

Table 2. Ultrafine particle concentration for different sample and smoking rate.

Cigarette	Ultrafine Particles (particles/cm^3)		
	Speed 1.4 m/s	Speed 9.8 m/s	Speed 13.9 m/s
1	41.800	132.300	147.000
2	25.500	58.200	87.300
3	45.500	65.500	92.300
4	38.200	80.100	119.000
5	54.500	67.200	74.500
6	85.500	87.300	136.400
7	78.200	98.200	147.100
8	60.100	109.100	147.300
9	53.900	101.800	120.000
10	70.900	98.400	115.100

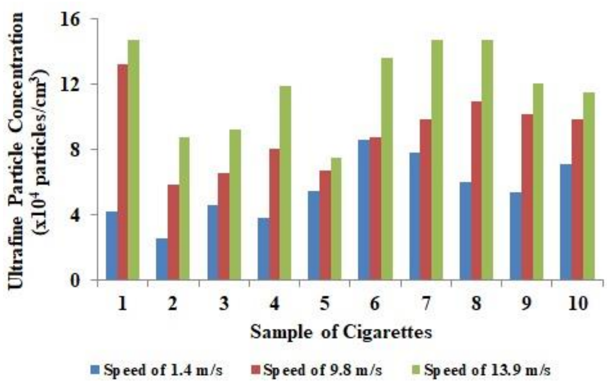

Figure 4. Total concentrations measured in the chamber.

According to the measurement results, the ultrafine particle concentrations are detailly presented in Figure 4 and table 2.

Based on Figure 4, the blue bars interpret the concentrations of ultrafine particles of the slow rate. The red bars and green bars represent the concentrations of ultrafine particles in the medium and high rates, respectively. These results were obtained from ten different cigarette samples. In the low smoking rate, sample 2 produces the smallest concentration of ultrafine particles, and the highest concentration is found in sample 6. This trend is almost similar to the ultrafine particle concentration measured for the medium smoking rate, whereas sample 2 produces ultrafine particles with the smallest concentration, but the highest concentration is for the sample 1. For the high smoking rate, sample 5 produces the lowest concentration of ultrafine particles, and the highest concentration is produced by the sample 8. These findings confirm that a higher smoking rate generates a higher ultrafine particles concentrations. Meanwhile, a lower smoking rate generates a lower ultrafine particles concentration. As expected, these findings suggest the correlation between the smoking rate and the concentration of ultrafine particles.

Emission Factor of Ultrafine Particles

Figure 5 shows the emission factor, measured from 10 different cigarette samples (n = 10) when the smoke rate was varied. The mean values were plotted according to the results obtained in Figure 4, for all measurements.

As the smoke rate increased, the emission factor increased for all cigarette samples. For the same cigarette sample, the emission factor of the low rate was lower than the medium and high rates. It can be seen in Figure 5 and Table 3 that emission factors of ultrafine particles significantly are depended on the smoking rate. For the low rate, the smoking produces a small number of ultrafine particles, and the high smoking rate results in high emission factor.

Table 3 shows that the emission factors of the cigarette samples in the low rate were 0.02 x 10^{12} particles/cigarette to 0.14 x 10^{12} particles/cigarette. In this smoking rate, the average and deviation of emission factor for the cigarette samples are (0.06 ± 0.01) x 10^{12} particles/cigarette. Meanwhile, the average and deviation of emission factors for the smoking rate of 9.8 m/s and 13.9 m/s is (0.82 ± 0.08) x 10^{12} particles/cigarette and (1.46 ± 0.14) x 10^{12} particles/cigarette respectively.

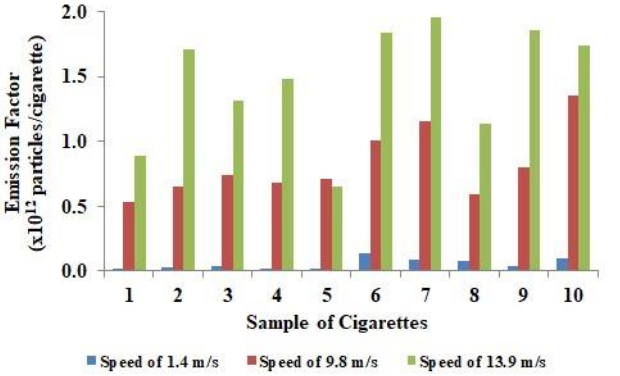

Figure 5. Emission factor of ultrafine particles for the different smoking rate.

Table 3. Emission factor of ultrafine particles for the different smoking rates.

Sample of Cigarette	Emission Factor ($x10^{12}$ particles/cigarette)		
	Speed 1.4 m/s	Speed 9.8 m/s	Speed 13.9 m/s
1	0.02	0.53	0.89
2	0.03	0.65	1.71
3	0.04	0.74	1.31
4	0.02	0.68	1.48
5	0.02	0.71	0.65
6	0.14	1.01	1.84
7	0.09	1.15	1.95
8	0.08	0.59	1.13
9	0.04	0.8	1.86
10	0.1	1.35	1.74

Discussions

According to the results, emission factor depended on the smoking rate (*v*). Interestingly, these results were persistent for all cigarette samples. It would be interested in investigating the relationship between smoking rate and emission factors. Based on the previous study, the relationship of two variables could be analyzed using a linear regression approximation (Klepeis et al., 2003; Wardoyo et al., 2018). As the result, the relationship between smoking rate and emission factors is presented in Figure 6.

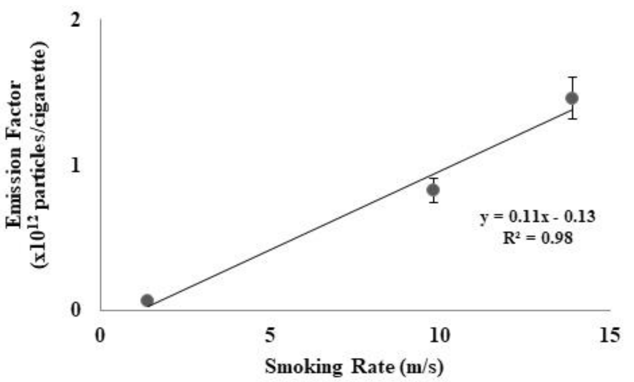

Figure 6. The relationship between smoking rate and emission factor.

The emission factor of ultrafine particles is proportional to smoking rate with the linear equation of $Y = 0.11X - 0.13$ and $R^2 = 0.98$ where Y is emission factor, and X is smoking rate. The resulted determination coefficient R2 indicates that there is a significant relationship between the smoking rate and the emission factor since the value approaches 1. This result was confirmed by Wang et al. (2017), that in a combustion process the emission ratios might depend on the burning conditions. The regression analyzed result also confirms with the Equation (1), where:

$$EF = v.A.\int_0^t C(t)\,dt \qquad (1)$$

According to the Equation (1), the smoking rate *v*, including the ultrafine particle concentrations *C*, were proportional to the emission factor *EF*. On other words, the increase of *v* influenced the increase of *EF* linearly, as approached by the linear regression analysis.

From Equation (1), the influence of *C* was also proportional to the EF, since the radical particles, such as ultrafine particles, were generated when the cigarette was burnt (Novrial et al., 2017). As reported in the previous study, the total particle mass emitted by a cigarette was related to the emission rates and the particle diameter (Klepeis et al., 2003). This emission factor was influenced by the burning rate in different burning phases, including the smoldering phase, flaming phase, and warm start (Fachinger et al., 2017). The burning rate might determine the emissions and size distributions of particulate matter (Shen et al., 2013).

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