

Airborne Particulate Matter from Sparkling Fireworks

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Received: January 9, 2017

Accepted: March 7, 2017

Online Published: March 31, 2017

doi:10.5539/ep.v6n1p19

URL: <https://doi.org/10.5539/ep.v6n1p19>

Abstract

The present study examines the emission levels of particulate matters (PM) from sparkling fireworks and to know the emission characteristics of PM. Particulate matter <2.5 microns (PM_{2.5}) and suspended particulate matter (SPM) were determined while burning six brands of sparkling fireworks. The average PM concentrations before burning were levels of 10 $\mu\text{g}/\text{m}^3$, but the average concentrations after burning were 741 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 810 $\mu\text{g}/\text{m}^3$ for SPM. The mean ratio of the concentrations of PM_{2.5} and SPM after burning in all of the sparkling fireworks was 0.890. The emissions per firework ranged from 6.5 mg to 151 mg for PM_{2.5}, and from 7.1 mg to 160 mg for SPM. The means of the emissions per combustible amount of the firework ranged from 0.017 to 0.066 mg/mg for PM_{2.5}, and from 0.018 to 0.071 mg/mg for SPM. The influences of the burning time, burning rate and combustible amount of the fireworks on the PM emissions were investigated. As a result, PM_{2.5} and SPM emissions tend to increase with the burning rates. This suggests that the burning rate of firework have an influence on the PM emissions.

Keywords: particulate matter <2.5 microns (PM_{2.5}), suspended particulate matter (SPM), sparkling fireworks

1. Introduction

Air pollution and its human health effects are of great concern to the general public. In particular, the problem of airborne particulate matter (PM) has received much recent attention. PM with a size of less than about 10 μm can settle in the bronchi and other parts of the lungs. These particles also contain toxic heavy metals and hazardous organic pollutants (Bi, Sheng, Peng, Chen, & Fu, 2005; Vasilakos et al. 2007). Several epidemiological studies have shown that an increase in airborne PM is associated with respiratory symptoms, lung cancer, cardiovascular diseases and mortality (Ackermann-Lieblich et al. 1997; Pope et al. 2002; Du, Xu, Chu, Guo, & Wang, 2016). International Agency for Research on Cancer (IARC) designates PM a Group 1 carcinogen (IARC, 2016).

Owing to its high toxicity, PM is regulated by most governments. The US Environmental Protection Agency sets National Ambient Air Quality Standards (NAAQS) for PM_{2.5} and PM₁₀ under the Clean Air Act (EPA, 2013). PM_{2.5} is defined as particles that pass through a size-selective inlet with a 50% efficiency cut-off at 2.5 μm aerodynamic diameter, and PM₁₀ is defined as those that pass through a size-selective inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter. The daily average guideline values for PM_{2.5} and PM₁₀ in the current NAAQS are 35 and 150 $\mu\text{g}/\text{m}^3$, respectively. The European Union has also established European emission standards, which include limits for particulates in the air (EC, 2016). The annual average guideline values for PM_{2.5} and PM₁₀ in the current European air quality standards are 25 and 40 $\mu\text{g}/\text{m}^3$, respectively. Other governments, including those of Japan, China, Australia and Canada, also set air quality standards regarding PM. PM originates from a variety of natural sources, such as volcanoes, forest fires, dust storms and sea spray. Human activities, such as the burning of fossil fuels in vehicles, power plants and industrial processes, also generate considerable amounts of PM (Gertler 2005; Srimuruganandam & Shiva Nagendra, 2012; Karagulian et al. 2015). Many studies have shown that PM concentrations are high in urbanized areas, where the majority of these man-made sources are concentrated (Roosli et al. 2001; Gomiscek et al. 2004; Yin & Harrison, 2008; Mues et al. 2013).

One of the many man-made sources of PM is burning fireworks. Wehner, Wiedensohler, and Heintzenberg (2000) determined the aerosol size distribution and mass concentration during the Millennium fireworks in Leipzig, Germany. The range of the size distribution and mass concentration of the aerosol was higher during than before and after the fireworks. Several studies have shown that fireworks contribute to increased PM concentrations and

increased contents of Ba and Sr in the airborne particles (Wang, Zhuang, Xu, & An, 2007; Vecchi et al. 2008; Barman, Singh, Negi, & Bhargava, 2009; Camilleri & Vella, 2010). Seidel and Birnbaum (2015) also studied PM_{2.5} observations at 315 sites across the US between 1999 and 2013 to estimate the effects of Independence Day fireworks. They showed that hourly PM_{2.5} concentrations during the fireworks were higher than those on control days, and that sites adjacent to firework displays showed a 48 $\mu\text{g}/\text{m}^3$ (370%) increase in the 24-h-average PM_{2.5} concentration. However, little is known about the PM emission characteristics of burning fireworks. This study therefore examined the PM emission characteristics of six brands of sparkling fireworks. The primary objective of this work was to determine the amount of PM emitted from the fireworks. The secondary objective was to understand the influence of the burning time, burning rate and combustible amount of the fireworks on the PM emissions.

2. Materials and Methods

Six brands of sparkling fireworks were investigated in this study. The weights of each brand of firework before and after burning and their burning times were measured five times. The results are shown in Table 1. The mean weights of the fireworks ranged from 203 to 7920 mg before burning and from 83 to 5280 mg after burning. The concentrations of PM_{2.5} and suspended particulate matter (SPM) in air samples before and after burning each brand of firework were measured six times. SPM is defined as particles that pass through a size-selective inlet with a 100% efficiency cut-off at 10 μm aerodynamic diameter. SPM is an air quality standard peculiar to Japan, and corresponds to PM_{6.5-7.0}.

Table 1. Sparkling firework weights before and after burning, and their burning times

	Firework weights (mg)			Burning times (s)
	Before burning	After burning	Difference	
Brand A	203 \pm 36	83 \pm 10	121 \pm 43	30.8 \pm 3.7
Brand B	2154 \pm 28	1799 \pm 16	354 \pm 13	68.6 \pm 1.6
Brand C	4540 \pm 49	2460 \pm 162	2080 \pm 160	59.2 \pm 11.6
Brand D	4940 \pm 242	2620 \pm 147	2320 \pm 98	32.4 \pm 1.0
Brand E	7920 \pm 160	5280 \pm 214	2640 \pm 301	78.4 \pm 10.3
Brand F	7780 \pm 232	5020 \pm 75	2760 \pm 162	43.8 \pm 1.9

Note. The values show arithmetic means \pm SD ($n = 5$). The difference means the firework weight difference between before and after burning.

A high-volume air sampler (HV-500R; Sibata Scientific Technology Ltd., Souka, Japan) was used to collect PM_{2.5} and SPM in air. This instrument is a compact and transportable sampler used for industrial hygiene purposes, and collects suspended airborne particles at a suction flow rate of 100–800 L/min. It can be used for various measurement types by combining options, inertial-impact distributors or shuttle tubes. Two air samplers were used in this study; one was fitted with a PM_{2.5} distributor and the other with an SPM distributor.

Sampling room 1 was used for the experiments with Brands A, B and E. The sampling room was 2.5 m high, 5.3 m long and 5.0 m wide (approximately 66 m³). Sampling room 2 was used for the experiments with Brands C, D and F, and was 2.7 m high, 6.9 m long and 6.8 m wide (approximately 126 m³). Each firework was burned in the center of the room. The numbers of burned fireworks were two for the experiments in sampling room 1 and one for sampling room 2. The two high-volume air samplers were set at a height of 60 cm above the floor on the diagonal line of the room about 1 m from the center. The larger sampling room 2 was used for Brands C, D and F because the maximum PM_{2.5} concentration is estimated to reach levels of 10000 $\mu\text{g}/\text{m}^3$, and the experimental environment is not good for our health.

To remove PM_{2.5} and SPM from the sampling rooms before burning the fireworks, the air was purified by suction using the two high-volume air samplers. The suction rates and times were 500 L/min for 2.0 h for the experiments in sampling room 1, and 400 L/min for 2.0 h for the experiments in sampling room 2. The maximum concentrations of PM immediately after burning the fireworks in sampling room 2 were expected to be high. A lower suction rate was used in sampling room 2 than in sampling room 1 because the air samplers stopped during Brand E experiments in sampling room 1 owing to high (7000 $\mu\text{g}/\text{m}^3$) PM levels. After the initial air purification, one sparkling firework was burned in the sampling room. For the experiments in sampling room

1, about 60 m³ air was collected with each air sampler at an initial rate of 500 L/min. For the experiments in sampling room 2, about 110 m³ of air was collected with each air sampler at an initial rate of 400 L/min.

Quartz fiber filters (QR-100; Advantec, Tokyo, Japan) were used in the high-volume air samplers to collect PM_{2.5} and SPM. The fiber filter was placed in a dry box (165CDB; Toyo Living Co., Ltd., Yokohama, Japan) for 30 min before use. The initial mass of the filter was measured using an electronic balance (Sartorius TE214S; Data Weighing Systems, Illinois, USA) after removing it from the dry box. Then, the filter was placed into a stainless steel petri dish and brought to the experimental room. After the sampling was complete, the filter was returned to the dry box for 30 min and then weighed to determine its final mass. The amounts of PM_{2.5} and SPM were calculated based on the difference between the filter masses before and after sampling. For the experiments in sampling room 1, one filter was used for Brand A, one for Brand B and four for Brand E. In sampling room 2, five to seven filters were used for Brand C, seven to eight for Brand D and four to five for Brand F.

3. Results and Discussion

PM_{2.5} and SPM were measured in the sampling rooms before and after burning the sparkling fireworks. The results are shown in Table 2. The average PM_{2.5} concentration before burning was 15.8 µg/m³ and the PM_{2.5} concentrations ranged from 2.1 to 45.9 µg/m³. The average SPM concentration before burning was 20.0 µg/m³ and the SPM concentrations ranged from 5.0 to 48.0 µg/m³. The average concentration levels were almost the same as the annual average ambient concentrations in Japan. The mean ratio of the concentrations of PM_{2.5} and SPM before burning was 0.801, and the correlation coefficient between the PM_{2.5} and SPM concentrations before burning was 0.825 ($p < 0.01$), as shown in Fig. 1. The average PM_{2.5} concentration after burning was 741 µg/m³ and the PM_{2.5} concentrations ranged from 217 to 1580 µg/m³. The average SPM concentration after burning was 810 µg/m³ and the SPM concentrations ranged from 249 to 1670 µg/m³. The mean ratio of the concentrations of PM_{2.5} and SPM after burning in all of the sparkling fireworks was 0.890, and the correlation coefficient between the PM_{2.5} and SPM concentrations after burning was 0.984 ($p < 0.01$), as shown in Fig. 2.

The PM_{2.5} and SPM emissions per firework are shown in Fig. 3. The emissions were calculated from the total weight difference of all of the filters used in each experiment. The arithmetic means of the PM_{2.5} emissions per firework were 8.0 mg for Brand A, 8.2 mg for Brand B, 124 mg for Brand C, 115 mg for Brand D, 48.5 mg for Brand E and 47.1 mg for Brand F. The arithmetic means of the SPM emissions per firework were 8.5 mg for Brand A, 11.8 mg for Brand B, 135 mg for Brand C, 125 mg for Brand D, 58.0 mg for Brand E and 50.0 mg for Brand F, respectively. The minimum and maximum PM_{2.5} emissions per firework were 6.5 mg for Brand A and 151 mg for Brand C. The minimum and maximum SPM emissions per firework were 7.1 mg for Brand A and 160 mg for Brand C. The mean ratio of PM_{2.5} emissions to SPM emissions in all sparkling fireworks was 0.878. The mean ratios were 0.947 for Brand A, 0.696 for Brand B, 0.836 for Brand C, 0.920 for Brand D, 0.917 for Brand E and 0.950 for Brand F.

Table 2. PM_{2.5} and SPM concentrations in air samples before and after burning the sparkling fireworks

	Sampling room	PM _{2.5} (µg/m ³)		SPM (µg/m ³)	
		Before burning	After burning	Before burning	After burning
Brand A	1	15.0 ± 7.0	266 ± 34	15.3 ± 6.5	308 ± 72
Brand B	1	12.8 ± 5.7	274 ± 23	15.3 ± 4.9	405 ± 26
Brand C	2	20.2 ± 8.2	1060 ± 160	31.3 ± 10.3	1140 ± 131
Brand D	2	22.3 ± 14.1	1030 ± 136	26.4 ± 12.3	1090 ± 135
Brand E	1	11.4 ± 3.3	1420 ± 92	13.3 ± 4.0	1500 ± 103
Brand F	2	12.9 ± 6.1	394 ± 37	18.4 ± 6.2	419 ± 59
All brands	-	15.8 ± 9.1	741 ± 459	20.0 ± 10.3	810 ± 464

Note. The values show arithmetic means ± SD ($n = 6$ for Brand A-F and $n = 36$ for All brands). The volumes were 66 m³ for sampling room 1 and 126 m³ for sampling room 2. The numbers of burned fireworks were two for the experiments in sampling room 1 and one for sampling room 2.

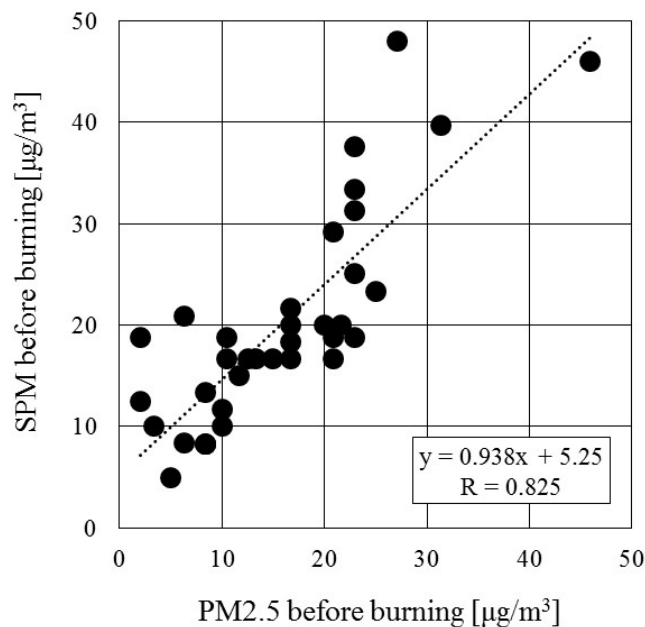


Figure 1. Relationship between PM2.5 and SPM in air samples before burning the sparkling fireworks

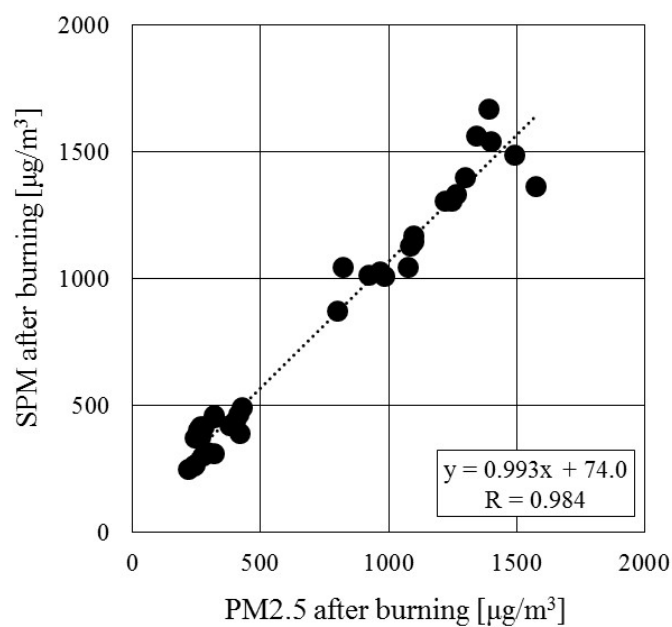


Figure 2. Relationship between PM2.5 and SPM in air samples after burning the sparkling fireworks

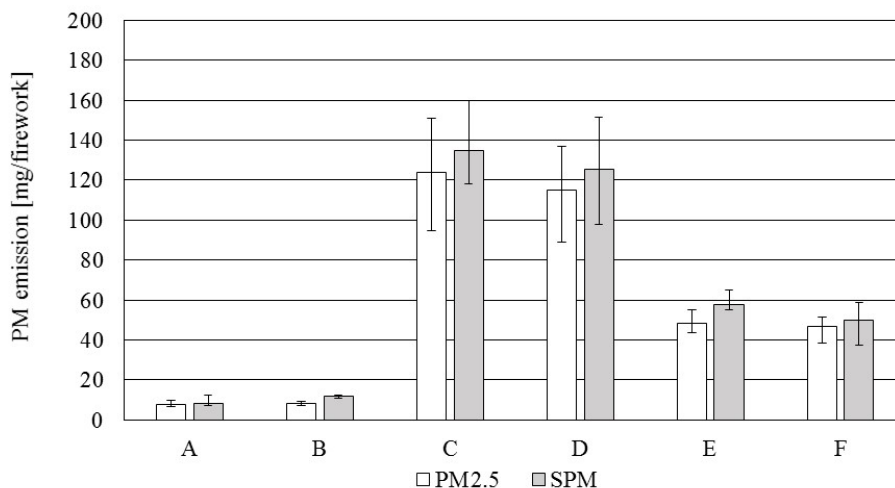


Figure 3. PM2.5 and SPM emissions per firework while burning the sparkling fireworks

Note. The numbers of PM emission data are six for each brand. The bars indicate the arithmetic mean values of the calculated PM emissions per firework. The ranges show that between minimum and maximum values.

To assess the influence of the combustible amount of the fireworks on PM2.5 and SPM emissions, the weights of the sparkling fireworks before and after burning were measured five times, and are shown in Table 1. The arithmetic means of the firework weight differences were 121 mg for Brand A, 354 mg for Brand B, 2080 mg for Brand C, 2320 mg for Brand D, 2640 mg for Brand E and 2760 mg for Brand F. The relationship between the means of the burning times and the means of the PM2.5 and SPM emissions of each firework are shown in Fig. 4. The relationship between the means of the weight differences and the means of the PM2.5 and SPM emissions of each firework are shown in Fig. 5. These correlation coefficients were not significant, which indicate that the burning time and the combustible amount did not influence PM2.5 and SPM emissions. The mean emissions per combustible amount ranged from 0.017 to 0.066 mg/mg for PM2.5, and from 0.018 to 0.071 mg/mg for SPM. The arithmetic means of the burning rates were 3.9 mg/s for Brand A, 5.2 mg/s for Brand B, 35.1 mg/s for Brand C, 71.6 mg/s for Brand D, 33.7 mg/s for Brand E and 63.0 mg/s for Brand F. The burning rates were calculated by dividing the means of the weight differences by the means of the burning times. The relationship between the means of the burning rates and the means of the PM2.5 and SPM emissions per firework are presented in Fig. 6. PM2.5 and SPM emissions tended to increase with increased burning rates, which probably suggests that the burning rates of the fireworks influence these PM emissions.

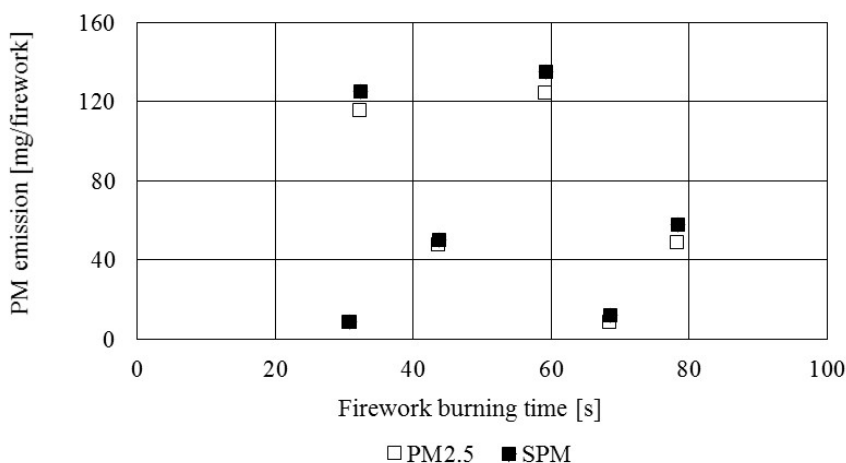


Figure 4. Relationships between firework burning times and PM emissions

Note. The arithmetic mean values of the firework burning times and those of the PM emissions per firework are plotted.

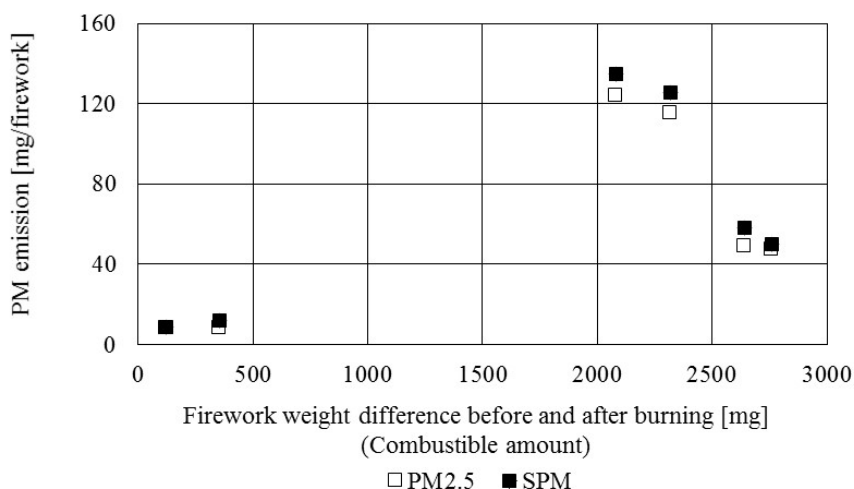


Figure 5. Relationships between firework weight differences before and after burning, and PM emissions

Note. The arithmetic mean values of the firework weight differences before and after burning the fireworks, and those of the PM emissions per firework are plotted.

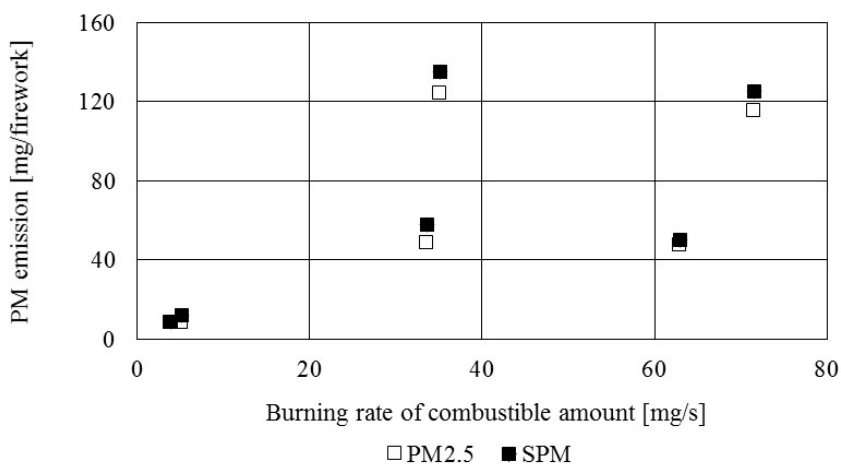


Figure 6. Relationships between burning rates of combustible amount and PM emissions

Note. The arithmetic mean values of the burning rates of combustible amount in the fireworks, and those of the PM emissions per firework are plotted.

4. Conclusion

The PM emissions of six brands of sparkling fireworks and their characteristics were investigated. PM2.5 and SPM were measured in the sampling rooms before and after burning the fireworks. The average concentrations before burning were $15.8 \mu\text{g}/\text{m}^3$ for PM2.5 and $20.0 \mu\text{g}/\text{m}^3$ for SPM. The mean ratio of the concentrations of PM2.5 and SPM was 0.801. The average concentrations after burning were $742 \mu\text{g}/\text{m}^3$ for PM2.5 and $810 \mu\text{g}/\text{m}^3$ for SPM. The mean ratio of the concentrations of PM2.5 and SPM was 0.890. The emissions per firework ranged from 6.5 to 151 mg for PM2.5 and from 7.1 to 160 mg for SPM. The means of the emissions per combustible amount of the firework ranged from 0.017 to 0.066 mg/mg for PM2.5, and from 0.018 to 0.071 mg/mg for SPM. It was investigated how much influence the burning time, burning rate and combustible amount of the fireworks on the PM emissions. The relationships between PM emissions and burning times and combustible amount of the fireworks were not significant. However, PM emissions tend to increase with the burning rates. This probably indicates that firework burning rates influence these PM emissions. Furthermore, studies are needed to investigate emission levels and characteristics of PM for many different kinds of fireworks.

Acknowledgments

The author would like to thank Kindai University for providing the grant to complete this research. The author acknowledge the assistance given by Yusuke Ishiko and Soichiro Takeshita.

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