The Impact of Water on Particle Emissions from Heated Cooking Oil

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ABSTRACT

Four edible oils, and five mixtures consisting of oil and water in different ratios were heated to investigate the effect of water on the emission characteristics of particles generated by heating cooking oil. The $PM_{2.5}$ and 0.01–10 µm particles emitted during the oil-water heating were monitored with a DustTrak, a condensation particle counter and an Aerodynamic Particle Sizer. The results showed that the $PM_{2.5}$ mass concentrations and particle number concentrations when heating corn and peanut oil-water emulsions were up to 6 and 50 times higher, respectively, than when heating soybean and canola oil-water emulsions. Emulsions with an oil-water ratio of 6:1 all generated total particle concentrations that exceeded those of mixtures with other ratios. The promoting factors (normalized by the corresponding oil volume to the total volume) for the concentrations of the ultrafine particles, PM_1 and $PM_{2.5}$ ranged from 1.20 to 3.32, 1.14 to 2.50 and 0.71 to 2.14, respectively. In addition, the ratio between the ultrafine particles (10–100 nm) and the total particles, and the particle number mode and median diameters changed with the oil-water ratio, but no clear trend was observed. Regression analysis revealed that the effect of water on particle emissions is not statistically significant.

Keywords: Oil-water ratio; Cooking; Emission characteristics; $PM_{2.5}$; Ultrafine particles; Supermicron particles.

INTRODUCTION

People are indoors approximately 90% of the time (Nazaroff and Goldstein, 2015), especially in their dwelling. Hence, it is important to maintain good indoor air quality. However, indoor air quality in some areas is poor, caused by both outdoor and indoor sources. The World Health Organization (WHO) (2015) reported that indoor air pollution is 5–10 times higher than outdoor air pollution. Indoor sources are more dominant (Bekö *et al.*, 2015; Acciai *et al.*, 2017; Xu *et al.*, 2018), and several indoor activities that contribute to indoor pollution have been studied, including cooking, smoking, candle burning, etc. (Bekö *et al.*, 2013; Tan *et al.*, 2013; Yu *et al.*, 2015). Among these activities, cooking is one of the most important sources of indoor particulate matter (Amouei Torkmahalleh *et al.*, 2017; Jodeh *et al.*, 2017; Tong *et al.*, 2018), including coarse (PM_{10}; aerodynamic diameter < 10 µm), fine ($PM_{2.5}$; aerodynamic diameter < 2.5 µm) (Gao *et al.*, 2013a; Amouei Torkmahalleh *et al.*, 2017b; Admasie *et al.*, 2019) and ultrafine particles (UFP; aerodynamic diameter < 0.1 µm) (Wang *et al.*, 2015; Amouei Torkmahalleh *et al.*, 2017). Zhao *et al.* (2019) and

Wang *et al.* (2018) reviewed some severe health problems that could be due to cooking-related emissions, such as respiratory symptoms (Huboyo *et al.*, 2011; Chang *et al.*, 2019), lung cancer (Buonanno *et al.*, 2015; Vu *et al.*, 2017), brain response (Naseri *et al.*, 2019), etc. Therefore, it is essential to take certain measures to remove such cooking pollutants. Domestic kitchen range hoods or canopy hoods are the most common household appliances implemented to reduce exposure in residential kitchens. The BS-EN-61591 standard (IEC, 2011) gave an odor reduction factor to test the ability to extract odors for kitchen range hoods. However, the capture efficiency for particles cannot be represented by the results from the tracer gas test since particles are more difficult to sequester (Lunden *et al.*, 2015). Therefore, to evaluate/improve the particle capture efficiency of domestic kitchens or canopy hoods and reduce the indoor exposure of individuals to cooking pollution, determining the particle emission characteristics from cooking activities is an essential prerequisite.

Table 1 summarizes previous studies of the past two decades regarding the generation of cooking particles from different methods. These studies show that cooking particle generation methods can be divided into four types: water boiling (Yik and Au, 2002; Rim *et al.*, 2012; Lai and Chen, 2015), oil heating (Welch and Kuehn, 2003; Amouei Torkmahalleh *et al.*, 2012; Gao *et al.*, 2013; Tseng and Chen, 2013; Amouei Torkmahalleh *et al.*, 2017a; Zhao *et al.*, 2019),

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Table 1. Summary of previous work regarding the generation of cooking particles.

References	Method	Pan (mm)	T (°C)	Comment
Yik and Au (2002)	Water boiling	380	100	2 L water
Phase *et al.* (2003)	Oil heating	None	246–260	0.5–3 mL min⁻¹ oleic acid
Sjaastad *et al.* (2010)	Dish cooking	None	> 230	Frying beefsteak
IEC (2011)	Oil-water heating	200	250	48 mL corn oil + 69 mL water
GB/T 17713-2011 (2011)	Oil-water heating	200	290	400 mL corn oil + 69 mL water
Amouei Torkmahalleh *et al.* (2012)	Oil heating	100	205–131	0.2 L oil (olive, peanut, safflower, soybean, canola, corn, coconut)
Rim *et al.* (2012)	Water boiling	None	100	0.75 L water
Tseng *et al.* (2013)	Oil heating	185	180–210	300 mL oil (soybean, olive, sunflower)
Gao *et al.* (2013)	Oil heating	200	113.7–212.3	100 g oil (rapeseed, soybean, peanut, sunflower, olive, blend)
Lai *et al.* (2015)	Water boiling Oil heating	275	100, None	1 L water, 60 mL of oil
Li *et al.* (2017)	Oil-water Heating	None	265	5 mL water + 300 mL oil (rapeseed, sunflower, soybean and corn)
Amouei Torkmahalleh *et al.* (2017)	Oil heating	200	250	150 mL corn oil
Zhao *et al.* (2018)	Dish cooking	None	50–215	15 typical Chinese dishes
Zhao *et al.* (2019)	Oil heating	None	240	50 mL oil (olive, soybean, rapeseed, peanut, corn and sunflower)
Zhai and Albritton (2020)	Oil heating	250	30–270	120 mL oil (olive, canola, vegetable, corn, peanut, coconut)

dish cooking (2010; Zhao *et al.*, 2018) and oil-water heating (See and Balasubramanian, 2006; GB/T 17713-2011, 2011; IEC, 2011; Li *et al.*, 2017). Water boiling can stably generate vapor (Yik and Au, 2002), but the physical characteristics of vapor are different when they contain grease particles (Lai and Chen, 2015), especially in Chinese cooking (See and Balasubramanian, 2006). Therefore, it is still controversial to use vapor to evaluate cooking emissions instead of airborne fine particles. Dish cooking methods can simulate the particles emitted in practical cooking processes. However, the emission processes are unstable and uncontrollable. For example, Wan *et al.* (2011) found that the PM$_1$ concentrations from cooking for 40 min can be up to 8 times higher than that for a cooking time of 10 min. In addition, the particle emission characteristics from dish cooking change with many factors (Amouei Torkmahalleh *et al.*, 2017c; Zhao *et al.*, 2019), including oil type, ingredients, heating temperature, cooking style, indoor air temperature/humidity (Amouei Torkmahalleh *et al.*, 2016), cooking pan (Wallace *et al.*, 2015; Amouei Torkmahalleh *et al.*, 2018; Broomandi *et al.*, 2019) etc.

It was found that oil-based cooking produces more particles than water-based cooking (See and Balasubramanian, 2006; Zhao *et al.*, 2018), and the composition and strengths of cooking fumes generated by dish cooking are highly related to oil type, but temperature has no effect (Zhao *et al.*, 2018). Previous studies (Welch and Kuehn, 2003; Amouei Torkmahalleh *et al.*, 2012; Gao *et al.*, 2013; Tseng and Chen, 2013; Amouei Torkmahalleh *et al.*, 2017a; Zhao *et al.*, 2019) have conducted additional research on oil heating activities. The results in these studies (Amouei Torkmahalleh *et al.*, 2012; Gao *et al.*, 2013a, b) indicated that the particle emission strengths of pure heated oil depended on both oil

type and heating temperature. Moreover, a few studies (Welch and Kuehn, 2003; Amouei Torkmahalleh *et al.*, 2013) investigate the influence of additives on particle emission from heated oil. Amouei Torkmahalleh *et al.* (2013, 2016) found that sea salt, table salt and black pepper reduced the particle number emission rates, but the effect of turmeric and garlic powder was not significant. ASHRAE 1151 (Welch and Kuehn, 2003) provided a cooking simulator that sprayed a mixture of oleic acid and isopropyl alcohol (in a 2:1 ratio) into a hot plate to generate particles. The particle size distribution was similar to that of cooking hamburger (Schrock *et al.*, 2006) but was different from that of general cooking (See and Balasubramanian, 2006; Lunden *et al.*, 2015). Unlike ASHRAE 1151, the approach to a cooking simulator in mainstream standards (GB/T 17713-2011, 2011; IEC, 2011) is oil-water heating, but this method does not provide information about the particle distribution. Li *et al.* (2015) measured the particle emission from four heated edible oils (rapeseed, sunflower, soybean and corn oils) with auto-dripping water and found that the thermal cracking products and the cooking fumes were related to both oil type and the presence of water. However, these mainstream standards (GB/T 17713-2011, 2011; IEC, 2011) and study (Li *et al.*, 2017) only considered one oil-water ratio. Our previous study (Zhang *et al.*, 2019) found that the total concentrations of VOCs emitted from vegetable oils significantly increased with an increasing oil-water ratio, but the effect of the amount of water on particle emissions from heated oil has not yet been determined.

Therefore, the present research aimed to identify the impact of water on the particle emission characteristics from oil-water heating. To systematically study particles ranging

from 0.01–10 µm emitted during oil-water heating, four edible oils (corn, canola, peanut and soybean) with five oil-water ratios were measured by a condensation particle counter (CPC) and an Aerodynamic Particle Sizer (APS). The PM$_{2.5}$ concentration levels were also acquired by using the DustTrak aerosol monitor. The results of the present study are expected to provide full-size (0.01–10 µm) characteristics.

METHODOLOGY

Experimental Apparatus

The experiment was carried out in a fume hood with a constant flow rate of 360 m^3 h^{-1}. The fume hood was composed of a canopy hood and a cuboid enclosure, as shown in Fig. 1. The size of the cuboid enclosure was 600 mm × 600 mm × 1000 mm. A HEPA filter was installed under the fume hood to minimize the background particle concentrations and the turbulent fluctuations induced from the makeup air. The experimental apparatus was placed in an air-conditioned room with an air temperature of 24 ± 1°C.

As shown in Fig. 1, this cooking simulator consisted of an electric stove, a nonstick pot, a thermostat, a liquid feed system, etc. The electric stove with the nonstick pot was placed on the center of the HEPA filter. The diameter of the nonstick pot and the effective heating area of the electric stove were both 240 mm. The thickness of the nonstick pot was 5 mm, and a thermocouple was mounted in the pot to measure the heating temperature. The heating temperature

of the pan was maintained at 260 ± 1°C by the thermostat. In addition to ASHRAE 1151, the liquid feed system consisted of an air compressor, a conical-tip ejector nozzle, an agitator, a liquid peristaltic pump, etc., and an agitator emulsified the water and oil in a container.

Four edible oils (corn, canola, peanut and soybean) and five oil-water ratios (V$_{oil}$:V$_{water}$ = 1:0 [pure oil], 6:1, 2:1, 1:1 and 1:2) were chosen for measurements; the fatty acid content of these oils is provided in our previous work (Zhang *et al.*, 2019). The oil-water ratio 1:1 and 6:1 was referred to the standard IEC (2011) and GB/T 17713-2011 (2011), respectively. The oil-water mixture was made by an agitator; the stability and repeatability of the oil-water mixture is ensured by using a viscosimeter to monitor the viscosity. The oil-water mixture was fed to the ejector nozzle via the liquid peristaltic pump, and the liquid feed rate was 1.5 mL min^{-1}. The air compressor was used to atomize the spray from the nozzle, and the flow rate was 3 L min^{-1}. The ejector nozzle was fixed at 130 mm above the pan, so the droplets could uniformly cover the heating surface. Each case repeated 5 times.

Instrumentation

In this study, particle mass and number concentration measurements were collected by implementation of three instruments in real time. A condensation particle counter (AMG1500) was applied to obtain the number concentration and particle size distribution in a nanometer size range from 13 to 550 nm over 96 channels. The sampling flow rate was
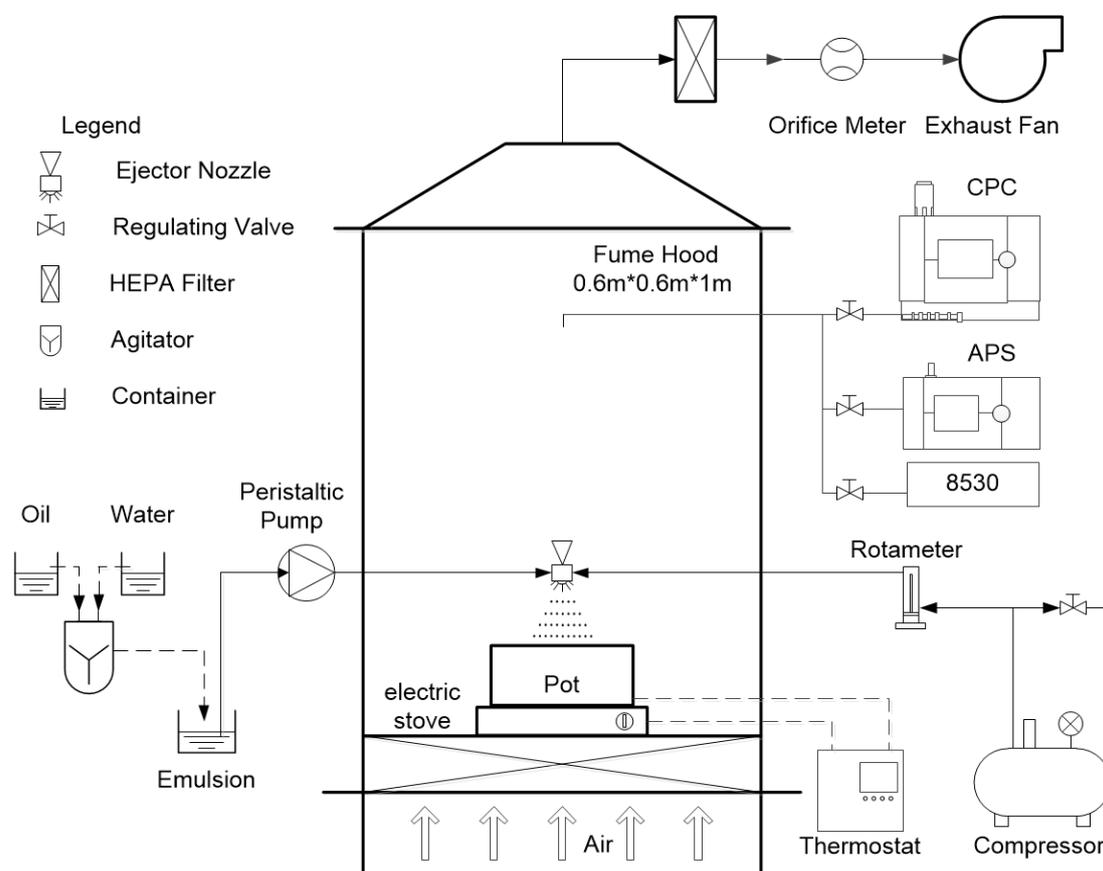

Fig. 1. Schematic of experimental apparatus in fume hood.

set to 6.0 L min^{-1}. The sample scan time was 5 min (Wallace *et al.*, 2004). A better understanding of the different particle emission characteristics between oil types or oil-water ratios is still needed; since CPC only monitored the particles with diameters between 0.013 and 0.550 µm, the TSI Model 3321 Aerodynamic Particle Sizer (APS; St. Paul, MN, USA), which measures particle size distribution and number concentration in the range from 0.542 to 20 µm over 50 channels, was utilized. Approximation of fine particle (PM$_{2.5}$) mass concentration was measured at 1-min intervals via the TSI Model 8530 DustTrak aerosol monitor fitted with 2.5 µm size-selective inlets. The sampling flow rate and time were set as 3.0 L min^{-1} and 1 min, respectively. DustTrak measuring techniques are based on light scattering. The three instruments were connected through a sample diluter with a dilution ratio of 1:50. The sampling probe was placed at a height of 70 cm above the pan. The emission and sampling period were 30 min.

RESULTS AND DISCUSSION

PM$_{2.5}$ Concentrations and Emission Rates

Fig. 2 shows the PM$_{2.5}$ mass concentrations and standard deviation (SD) during oil-water heating at 260°C for four edible oils and five oil-water ratios. The corresponding background concentration of PM$_{2.5}$ for each case has been subtracted from the result in Fig. 2. The averaged background PM$_{2.5}$ concentration for all cases is 0.076 ± 0.033 mg m^{-3}; the background PM$_{2.5}$ is generated by heating the empty pan since the particles in the outdoor air are trapped by the HEPA filter. It can be seen that similar levels and change characteristics of PM$_{2.5}$ concentrations have been exhibited between corn oil and peanut oil. In addition, canola oil and soybean oil also share similar levels and change characteristics with each other. However, corn oil and peanut oil generated higher PM$_{2.5}$ concentrations compared to that of canola oil and soybean oil, exhibiting concentrations up to 6 times higher. This might be due to canola oil and soybean oil having higher smoke point temperatures than corn oil and peanut oil (Zhang *et al.*, 2019). This phenomenon was in agreement with a previously published oil cooling experiment (Amouei Torkmahalleh *et al.*, 2012). Fig. 2 also shows that the PM$_{2.5}$ concentration decreases with a reducing oil-water ratio for corn oil and peanut oil. However, there is a marked increase in PM$_{2.5}$ concentration when the oil-water ratio is 1:1, especially for corn oil and peanut oil. The reason might be that the strong thermal cracking products were larger
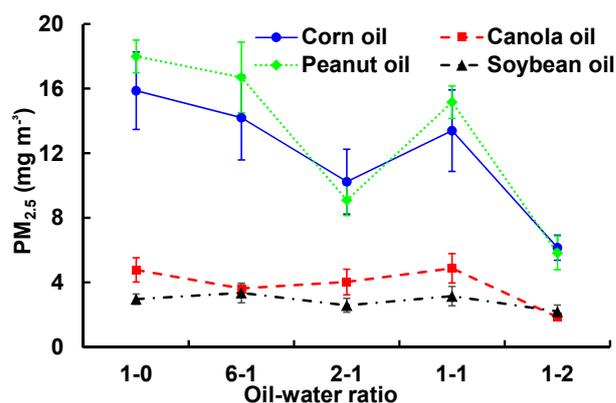

Fig. 2. Mean and standard deviation of PM$_{2.5}$ concentrations during oil-water heating at 260°C (N = 5).

particles when the oil-water ratio was 1:1. The PM$_{2.5}$ concentrations of the four types of oils were the smallest when the oil-water ratio was 1:2.

A regression (Wallace *et al.*, 2015) was performed on the oil-water ratio (Table 2) for four oils; the results demonstrate that the effect of the oil-water ratio on the change of PM$_{2.5}$ concentrations is not statistically significant (P > 0.05).

Particle Concentration and Size Distribution

Fig. 3 shows the number distribution frequency of particles (0.01–10 µm) from heating different oil-water ratios at 260°C, with particle sizes almost below 1 µm based on the number distribution. The measurement data were averaged from the 30-min heating episodes, with the background concentration subtracted. Background measurements were also conducted in the sampling location, showing that all background concentrations were below 2 × 10^2 cm^{-3}. In Fig. 3, averaged number distribution frequency of particles emitted from the heating of different oils are quite different, the similar result was found in the previous study (Amouei Torkmahalleh *et al.*, 2012). It might due to different smoke temperature and chemical compositions of five types of oils, detailed information listed in our previous study (Zhang *et al.*, 2019). As depicted in Fig. 3, the oil-water ratio had a significant effect on the particle size distributions, especially for that of ultrafine particles (10–100 nm). The particle number mode diameter was changed with different oil-water ratios for the four edible oils, but the frequency did not change significantly with the oil-water ratios. Single-modal distributions are observed in Fig. 3 for the corn, peanut and

Table 2. Regression of PM$_{2.5}$ concentrations on oil-water ratio.

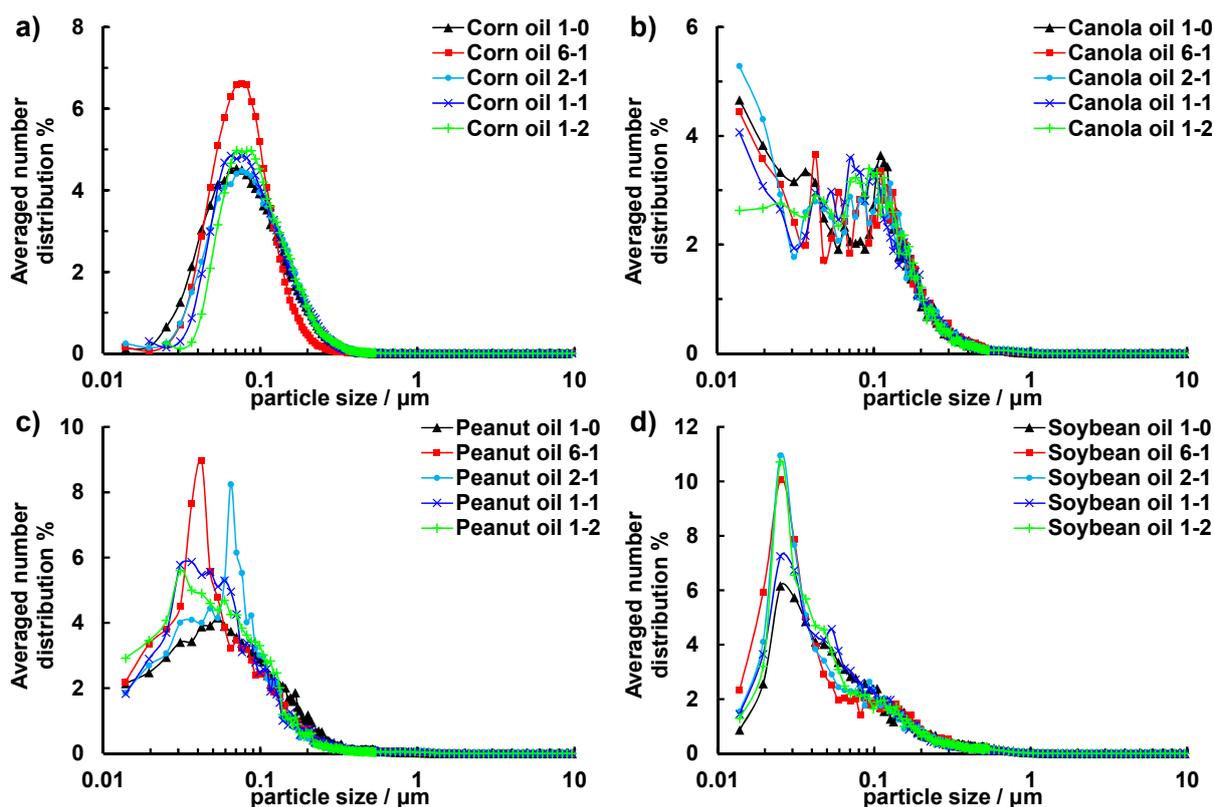|		B (slope)	Standard error	t-Stat	P-value
Corn oil	Intercept	3.94	3.26	1.20	0.31
	Oil-water ratio	11.97	4.58	2.61	0.07
Canola oil	Intercept	2.04	1.53	1.33	0.27
	Oil-water ratio	2.66	2.15	1.23	0.30
Peanut oil	Intercept	2.64	5.00	0.52	0.63
	Oil-water ratio	15.37	7.01	2.19	0.11
Soybean oil	Intercept	2.15	0.56	3.83	0.03
	Oil-water ratio	1.05	0.79	1.33	0.27

Fig. 3. Averaged number distribution frequency of particles (0.01–10 µm) emitted from the heating of different oil-water ratios at 260°C.

soybean oils at different oil-water ratios. The particle number distribution frequency for canola oil showed a peak location at particles < 0.013 nm. We also compared the particle size distributions determined in this study with those of previous studies (Wallace *et al.*, 2004; Amouei Torkmahalleh *et al.*, 2012; Jorgensen *et al.*, 2013). The number distribution frequency of the four pure oils presented in Fig. 3 agreed well with the shapes of particle size distributions measured by Amouei Torkmahalleh *et al.* (2012). As shown in Fig. 3(a), the series of heated corn oil-water mixtures generated similar particle size distributions as those generated by frying flour tortillas (Wallace *et al.*, 2004) (see Fig. S1(a)) and frying bacon (Jorgensen *et al.*, 2013) (see Fig. S1(b)), which were also monitored by a CPC. Fig. 3(b) shows that the series of heated canola oil-water mixtures generated a particle size distribution close to those of the steaming and boiling methods (See and Balasubramanian, 2006).

A regression (Wallace *et al.*, 2015) was also performed on the oil-water ratio (Table 3) for four oils; the results demonstrate that the effect of the oil-water ratio on the change of particle (0.01–10 µm) concentrations is not statistically significant ($P > 0.05$).
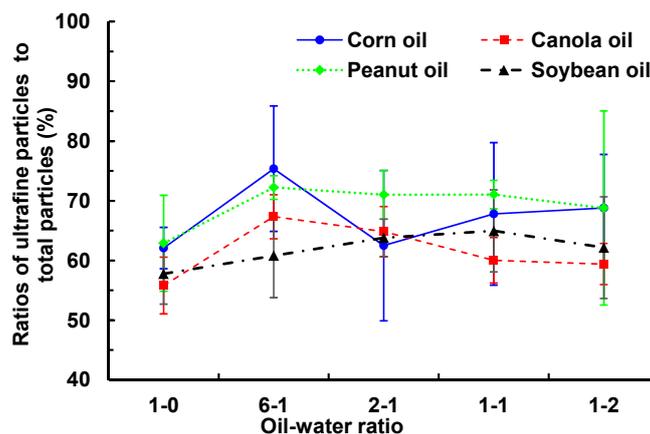
Fig. 4 depicts the ratio of ultrafine particles (10–100 nm) to total particles from the heating of different oil-water ratios at 260°C. The averaged ratios for each case range from 55––75%. The oil-water ratio has an obvious effect on the particle ratio regardless of oil type and oil-water ratio. However, there are no similar trends between the different oils with the change in the oil-water ratio. The highest ratio of ultrafine

particles –to total particles existed at an oil-water ratio of 6:1, except for soybean oil. The reason might be that the small amount of liquid water may vaporize so rapidly that an explosion may occur. These explosions have been termed "vapor explosions," "explosive boiling," or "rapid vapor explosions" (McIntyre, 1978; Manzello *et al.*, 2003), then promotes the production of more ultrafine particles (Fig. 3). The similar result was found in the previous study (Li *et al.*, 2017): Sprayed water into the heated oil promotes the production of ultrafine particles (0.030–0.109 µm). The data depicted in Fig. 4 are also consistent with previous research (See and Balasubramanian, 2006; Jorgensen *et al.*, 2013). The results agree with reported Chinese cooking activities (See and Balasubramanian, 2006), and the ratios of ultrafine particles (10–100 nm) to total particles for stir-frying, steaming and boiling are 69%, 90%, 55% and 62%, respectively. As reported for the frying of bacon (Jorgensen *et al.*, 2013), the ratio of ultrafine particles (10–100 nm) to total particles from three types of bacon ranged from 35—70%. However, the particle ratio for heated oil-water mixtures is smaller than in oil cooling, and the particle ratios for heated corn, peanut, canola and soybean oils ranged from 0.76 to 0.99 with temperature cooling (190–130°C) (Amouei Torkmahalleh *et al.*, 2012).

A regression (Wallace *et al.*, 2015) was also performed on the oil-water ratio (Table 4) for four oils; the results demonstrate that the effect of the oil-water ratio on the ratios of ultrafine particles (10–100 nm) to total particles is not statistically significant ($P > 0.05$).

Table 3. Regression of particle (0.01–10 μm) concentrations on oil-water ratio.

		B (slope)	Standard error	t-Stat	P-value
Corn oil	Intercept	1.57×10^6	3.15×10^6	0.49	0.65
	Oil-water ratio	5.05×10^6	4.42×10^6	1.14	0.33
Canola oil	Intercept	8.85×10^5	9.37×10^5	0.94	0.41
	Oil-water ratio	1.23×10^5	1.31×10^5	0.93	0.41
Peanut oil	Intercept	2.64×10^5	7.04×10^5	0.37	0.73
	Oil-water ratio	1.11×10^6	9.87×10^5	1.12	0.34
Soybean oil	Intercept	3.42×10^5	3.84×10^5	0.09	0.93
	Oil-water ratio	5.99×10^5	5.39×10^5	1.11	0.34

Fig. 4. Ratios of ultrafine particles (10–100 nm) to total particles emitted from the heating of different oil-water ratios at 260°C.

Table 4. Regression of ratios of ultrafine particles (10–100 nm) to total particles on oil-water ratio.

		B (slope)	Standard error	t-Stat	P-value
Corn oil	Intercept	74.92	9.67	7.74	0.004
	Oil-water ratio	−14.91	13.57	−1.09	0.35
Canola oil	Intercept	61.11	7.05	8.67	0.003
	Oil-water ratio	0.53	9.88	0.05	0.96
Peanut oil	Intercept	73.15	5.20	14.06	0.001
	Oil-water ratio	−5.92	7.29	−0.81	0.47
Soybean oil	Intercept	67.00	2.93	22.81	0.0001
	Oil-water ratio	−7.61	4.12	−1.84	0.16

Fig. 5 presents the variations of particle number mode diameter and mean diameter from the heating of different oil-water ratios at 260°C. As shown in Fig. 5(a), the effect of oil type on the particle number mode diameter is more significant than that of the oil-water ratio. The influence of oil-water ratio on particle number mode diameter is less visible, it might be due to the particle number mode diameter is more dependent on the oil type. The particle number mode diameter for the series of corn oil-water emulsions ranged from 59–87 nm, the particle number mode diameter for the series of peanut oil-water emulsions ranged from 31–54 nm, the particle number mode diameter for the series of canola oil-water emulsions ranged from 93–127 nm, and the particle number mode diameter for the series of soybean oil-water emulsions ranged from 26–32 nm. The results are in agreement with the previous research summarized by Abdullahi *et al.* (2013), where different cooking activities generated particle

number mode diameters ranging from 20 to 150 nm. Besides, it can be found that the particle number mode diameter for the four series of oil-water emulsions almost greater than the test of emitted during heating oil at 197°C (Amouei Torkmahalleh *et al.*, 2012). The heating oil generated particle number mode diameters ranging from 11 to 50 nm (Amouei Torkmahalleh *et al.*, 2012). The difference may be attributed to two reasons; one is the heating temperature, two is most of particles emitted during heating oil is produced by the evaporation without the effect of water.

As shown in Fig. 5(b), the highest number median diameter (NMD) existed for pure heated oil because the water was beneficial for producing larger-diameter particles. The particle number median diameter for the series of corn oil-water emulsions ranged from 87–110 nm, the particle number median diameter for the series of peanut oil-water emulsions ranged from 70–81 nm, the particle number
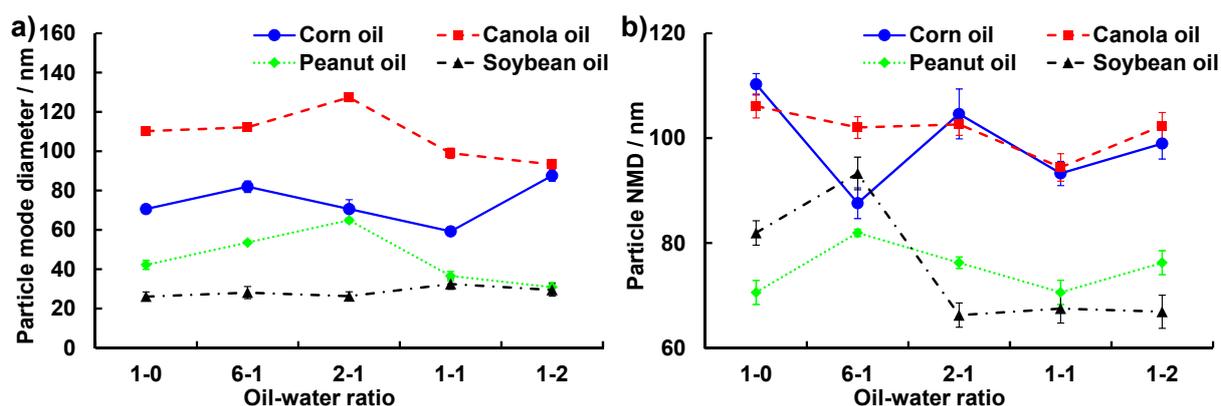
Fig. 5. (a) Particle number mode diameter distribution and (b) particle number median diameter (NMD) distribution of particles emitted from the heating of different oil-water ratios at 260°C.

median diameter for the series of canola oil-water emulsions ranged from 94–106 nm, and the particle number median diameter for the series of soybean oil-water emulsions ranged from 67–91 nm.

Fig. 6 shows the calculated cumulative volume distribution frequency of particles (0.01–10 µm) from the heating of different oil-water ratios at 260°C. The effects of oil type and oil-water ratio on the cumulative volume distribution frequency were both significant. The thermal cracking products are different between oil types and when the oil-water ratio is modified. The largest volume median diameter (VMD; Dv0.5) in Fig. 6 indicates that the mixture of oil and water produced a larger particle diameter, especially for the oil-water ratio of 6:1. Two sharp increases in the cumulative frequency are presented in the ranges of 0.01–1 µm (PM_1) and 5–10 µm. The volume ratio of PM_1 to total particles ranged from 20—60% for the four oil types. This result is in agreement with the oil heating experiment conducted by Gao *et al.* (2013b). However, Gao *et al.* (2013b) did not detect particles > 5 µm. This discrepancy might be that larger particle sizes cannot be detected at a long distance from the instrument due to gravitational deposition. Another reason might be due to the use of different emission methods.

Fig. 6 also presents the volume median diameter for the different cases; the VMD changed with the changing oil-water ratio. Fig. 7(a) further shows the VMD distribution from the heating of different oil-water ratios. The largest VMDs within all four oil types was at an oil-water ratio of 6:1, while the smallest VMDs for the four types of oil all existed in the pure heated oil. To investigate the volume distribution width, a span index is defined as (Dv0.9 – Dv0.1)/Dv0.5 (Gao *et al.*, 2013). As shown in Fig. 7(b), the span index ranges from 3–20, which represents a very wide width of size distribution. The smallest space index for all four oil types existed at oil-water ratios of 6:1.

Impact of Water on Emission Rate

To further determine the influence of water on particle emission, the particle number concentrations of UFP, PM_1 and PM_{10} and the mass of $PM_{2.5}$ in the samples of different oil-water ratios were normalized by the corresponding ratio of oil to total volume. The corresponding pure oils were

defined as the reference value (promoting factor = 1):

$$promoting\ factor = (C_i / oil\text{-}ratio_i) / C_{1\text{-}0} \quad (1)$$

where *i* is the case of corresponding oil at different oil-water ratios, C_i is the concentration of case *i*, $C_{1\text{-}0}$ is the concentration of corresponding pure oil, oil-ratio$_i$ is the oil ratio of corresponding oil at different oil-water ratios (range from 0.33–0.86). And the results are presented in Fig. 8. Fig. 8 shows that water increases the particle number or mass concentration, especially for UFP. The promoting factor for UFP ranges from 1.20 (canola oil-water at 1:2) to 3.32 (corn oil-water at 6:1). The promoting factor for PM_1 ranges from 1.14 (canola oil-water at 1:2) to 2.50 (corn oil-water at 6:1). The promoting factor of $PM_{2.5}$ ranges from 0.71 (peanut oil-water at 1:2) to 2.14 (soybean oil-water at 1:2). The promoting factor for PM_{10} ranges from 1.13 (canola oil-water at 1:2) to 2.49 (corn oil-water at 6:1). Fig. 8 also shows that water has the highest promoting factor for all oil types with an oil-water ratio of 6:1. The reason might be that the small amount of liquid water may vaporize so rapidly that an explosion may occur. These explosions have been termed "vapor explosions," "explosive boiling," or "rapid vapor explosions" (McIntyre, 1978; Manzello *et al.*, 2003), then promotes the production of more ultrafine particles (Li *et al.*, 2017). Besides, it is likely that with the increasing amount of water, the lipid (oil and fat) oxidation rate initially increases and then eventually decreases (Chan, 1987; Binks and Lumsdon, 2000). However, the regression results in Table 2 and Table 3 demonstrate that the effect of the oil-water ratio on the change of $PM_{2.5}$ and particle number concentrations is not statistically significant (P > 0.05). Correlational analyses were further conducted between different cooking oils at the same oil-water ratio (Table 5). The averaged correlation coefficient of particle emissions between different cooking oils at the same oil-water ratio ranges from 0.89–0.98, showing a strong correlation.

CONCLUSIONS

Our results indicate that the mixtures consisting of corn or peanut oil and water produced more particle mass and
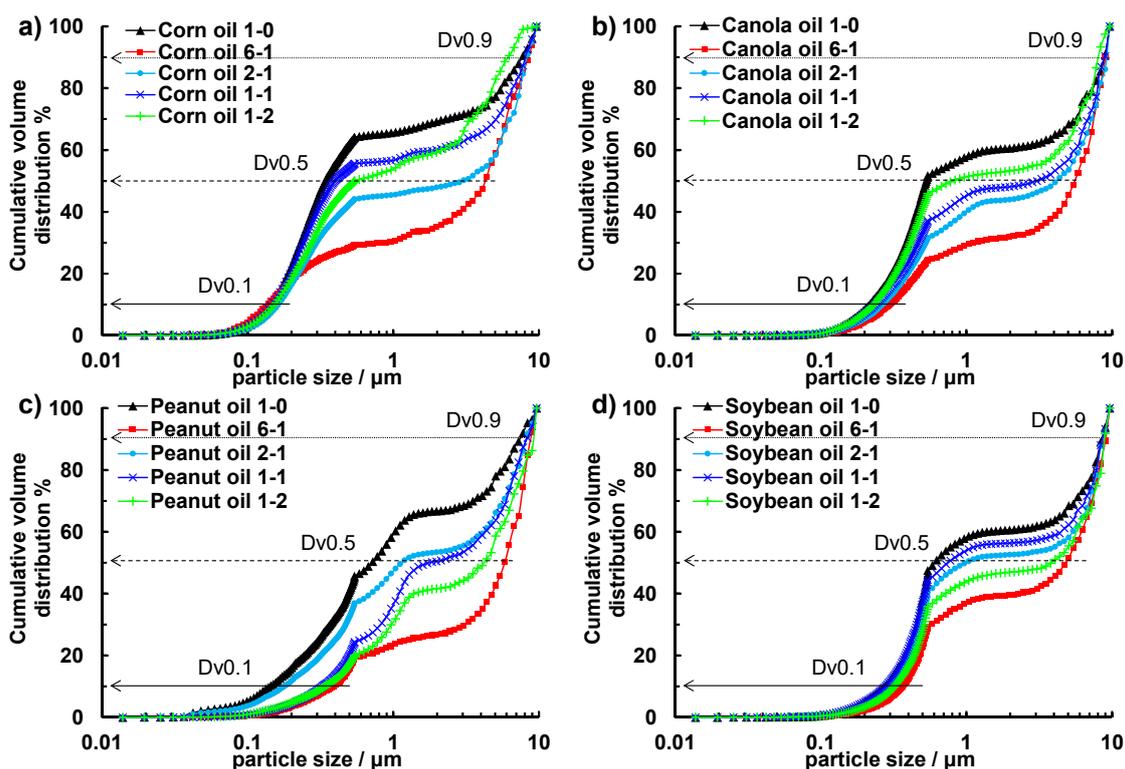
Fig. 6. Cumulative volume distribution frequency of particles (0.01–10 μm) emitted from the heating of different oil-water ratios at 260°C.
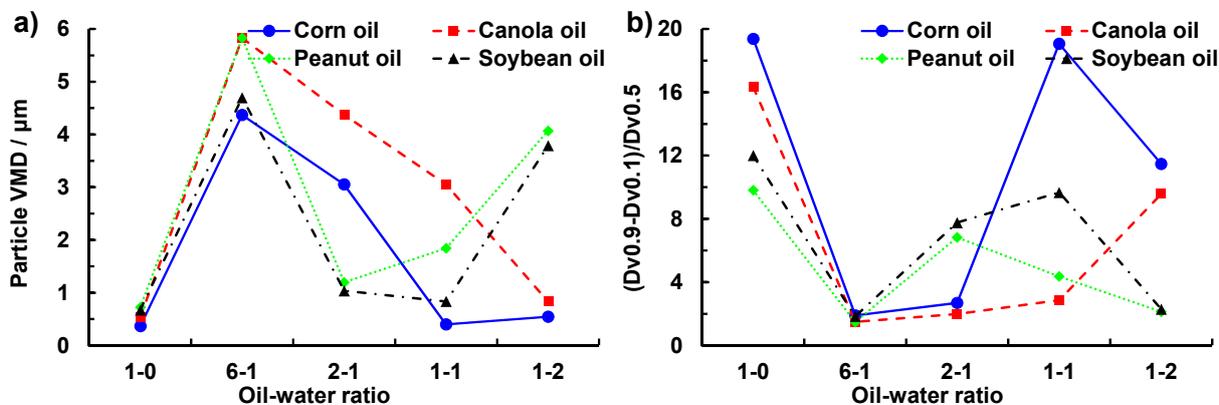

Fig. 7. (a) Particle volume median diameter distribution of particles emitted from the heating of different oil-water ratios at 260°C and (b) volume span index of different oil-water ratios at 260°C.

higher number concentrations than those observed for the other oils, either pure or mixed with water. By contrast, the mixtures consisting of soybean or canola oil and water generated lower particle concentrations than those measured for the other oils, either pure or mixed with water. The $PM_{2.5}$ mass and particle number concentrations associated with heating the corn and peanut oil-water emulsions exceeded those associated with the soybean and canola oil-water emulsions by up to 6 and 50 times, respectively. Thus, our study provides information on choosing edible oils for real cooking activities that reduce one's exposure to cooking fumes.

Regression analysis revealed that the effect of water on particle emissions is not statistically significant. Heating mixtures with an oil-water ratio of 6:1 generated higher total number concentrations. The shape of the particle number distribution was not obviously affected by the amount of water, but the ratio between the ultrafine particles (10–100 nm) and the total particles, and the particle number mode and median diameters changed with the oil-water ratio, although no clear trend was observed. The promoting factors (normalized by the corresponding oil volume to the total volume) for the UFP number concentration, the PM_1 number concentration and the $PM_{2.5}$ mass concentration ranged from 1.20 to 3.32, 1.14 to 2.50 and 0.71 to 2.14, respectively.
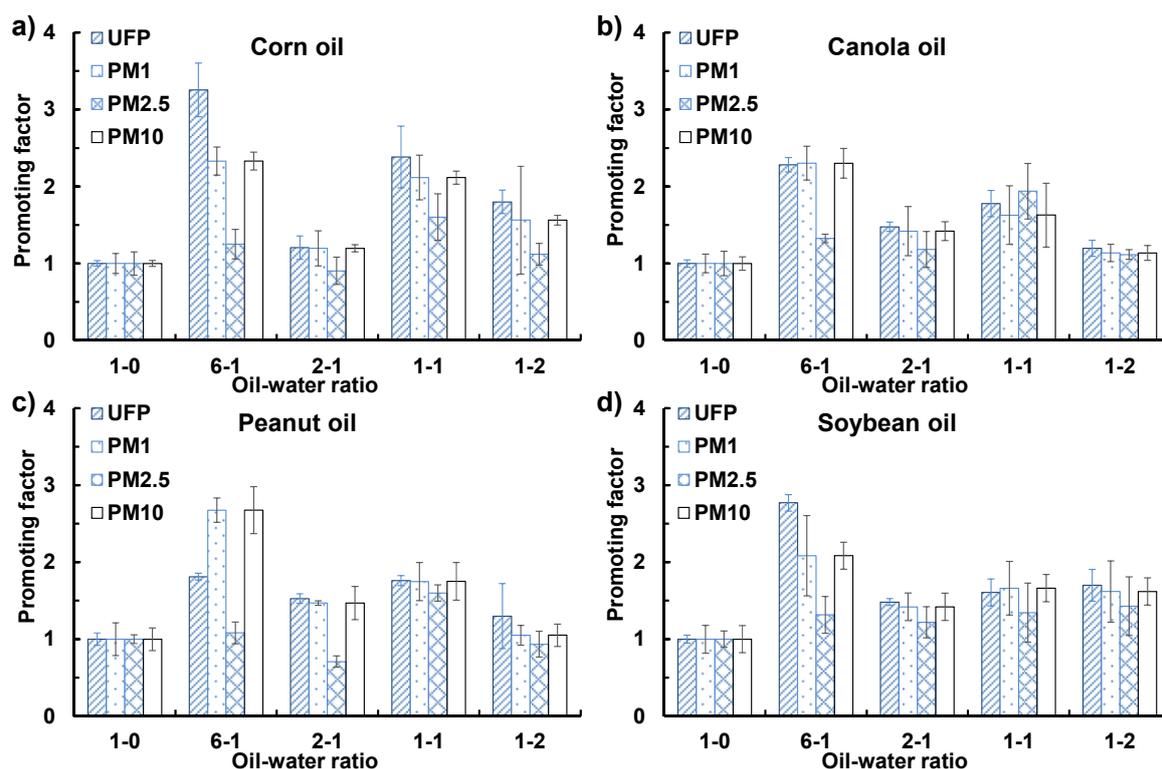
Fig. 8. Influence of water on particle emissions: (a) corn oil, (b) peanut oil, (c) canola oil, (d) soybean oil.

Table 5. Averaged correlation coefficient of particle emissions between different cooking oils at the same oil-water ratio.

	Corn oil	Canola oil	Peanut oil	Soybean oil
Corn oil	1	-	-	-
Canola oil	0.90	1	-	-
Peanut oil	0.95	0.89	1	-
Soybean oil	0.94	0.98	0.91	1

SUPPLEMENTARY MATERIAL

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

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