Review of Effluents and Health Effects of Cooking and the Performance of Kitchen Ventilation

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ABSTRACT

Cooking effluents are one of the most important sources of pollution in the indoor and outdoor environment. Exposure to cooking oil fumes (COFs) can increase the risk of many diseases. A healthy indoor environment and an energy-efficient ventilation system in kitchens are urgently demanded. This review is concerned with the current knowledge of the physical and chemical compositions of aerosols generated from typical cooking processes as reported in the literature. It is focused on the effects of cooking fuel, cooking oil, cooking temperature, cooking method, cooking style and other factors on the characteristics of cooking particles. The improvement measures in kitchen ventilation, supply air strategy and evaluation index for the kitchen environmental protection are also reviewed. It was found that the cooking process emits high concentrations of particulate matter (PM), and inhalable particles account for a high proportion, which may cause serious harm to human body. Coupled with various factors affecting the particle concentrations and particle size distribution, as well as the main chemical components groups used to characterize the cooking particles, include PAHs, fatty acids, dicarboxylic acids, n-alkanes, sterols, monosaccharide anhydrides, metals and ions. Using an appropriate ventilation system and some auxiliary measures can effectively reduce cooking oil fumes pollution.

Keywords: Cooking particles; Indoor air quality; Health effect; Kitchen ventilation.

INTRODUCTION

According to World Health Organization (WHO), each year, approximately 4.3 million people die from indoor air pollutants (WHO, 2014). Cooking oil fumes have been recognized as a significant source of indoor and outdoor pollutants in urban and rural areas (He *et al.*, 2004; See and Balasubramanian, 2008; Xiao *et al.*, 2015; Ni *et al.*, 2016). COFs are aerosols comprising particles, droplets (oil droplets and moisture), and gaseous companion products. In the indoor environment of residential buildings, the main source of fine particulate matter (PM_{2.5}, diameter less than or equal to 2.5 μm) with nonsmokers in buildings is cooking (Abt *et al.*, 2000). It was reported that 43.2% of the

microparticles and 52.5% of microparticle exposure were from the cooking process (Chowdhury *et al.*, 2012). COFs are also regarded as one of the most important sources of urban atmospheric fine particles (Wallace and Ott, 2011; Wheeler *et al.*, 2011). It has been found that cooking contributes to approximately 7% of the total particle mass and 10–30% of organic aerosol in China (He *et al.*, 2004; Wang *et al.*, 2009). In the city of Los Angeles, 20% of PM_{2.5} in the atmosphere comes from COFs (Schauer *et al.*, 2000).

Cooking particles have been associated with cardiac, pulmonary, dermal and renal toxic effects (Sjaastad *et al.*, 2008). Many airborne substances that are released from cooking are potentially harmful (Shields *et al.*, 1995). The hazards of cooking particles increase with the rise in the concentration and reduction in the particle size (Chowdhury *et al.*, 2012; Sharma and Balasubramanian, 2018). Ultrafine particles (UFPs, diameter less than or equal to 0.1 μm) have a large specific surface area and are prone to attaching to large numbers of viruses, bacteria, and organic matter (Zhao *et al.*, 2015). UFPs emitted during cooking are thought to cause oxidative stress in lung cells (Beck-Speier *et al.*, 2005) and enhance lung inflammation and allergic

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reactions (Alessandrini *et al.*, 2006). There is a consistent positive correlation between the particulate pollutants released from cooking and risk of lung cancer. This explains why nonsmoking women have a high chance of developing lung cancer in China, the West, and Southeast countries (Seow *et al.*, 2000; Wang *et al.*, 2017; Wang *et al.*, 2019). Previous studies have shown that respiratory diseases, such as rhinitis, emphysema, asthma, abnormal lung function, and increased lung cancer mortality among hotel and restaurant staff, are associated with exposure to COFs (Ko *et al.*, 2000; Svendsen *et al.*, 2002). The poor lung function of chefs can be attributed to a single or a combination of the indoor air pollutants, such as polycyclic aromatic hydrocarbons (PAHs) and carbonyl compounds (Singh *et al.*, 2006; Wong *et al.*, 2011). The International Agency for Research on Cancer classifies COFs from high-temperature frying as "possible human carcinogens" (IARC, 2010).

The potential hazard of COFs depends on exposure, which is a function of concentration and time. Exposure to cooking-related pollutants occur within commercial spaces such as restaurants, commercial kitchens, residences, neighborhoods, and urban areas from the aggregation of cooking emissions. Emissions result from fuel combustion and from food preparation. For fuel, there are large differences among solid, liquid and gaseous fuels and electricity. For food preparation, the cooking activity (cooking method, cooking temperature, and edible oil) and cooking style (Chinese or Western) are important. In this review, we explore information regarding the contamination level of cooking-generated PM and techniques using ventilation to control cooking pollution. To this end, we analyze the physicochemical properties of the cooking particles and summarize the potential effects of those pollutants in relation to their adverse impacts on human health. Moreover, comparative analysis of the factors that influence concentration, chemical composition and propagation of cooking particles is conducted. Finally, the effect of kitchen ventilation on pollution removal is evaluated, involving exhaust hood performance, supply air strategy, and capture efficiency. Thus, this review will help us gain a better understanding of pollutants emitted from cooking, influencing factors, and control strategies.

HEALTH EFFECT OF COOKING

Cooking Particles

Cooking process emits high concentrations of particulate matter. Buonanno *et al.* (2010) sampled particles in 15 pizzerias without a ventilation system. The number of particles produced during the cooking process in the test restaurant ranged from $3\text{E}+4$ to $6\text{E}+5$ particles cm^{-3} , and the average concentration was $1.7\text{E}+5$ particles cm^{-3} . Torkmahalleh *et al.* (2013) conducted an experiment in a 0.81 m^3 laboratory hood operating at $65\text{ m}^3\text{ h}^{-1}$ to study the particulates produced during the heating of seven edible oils. The particle number concentration of 10–500 nm at 197°C was $2.5\text{E}+5$ to $2.3\text{E}+6$ particles cm^{-3} . The chamber (with a fan) study conducted by Wang *et al.* (2018)

investigated particle emission characteristics originated from using different types of oil and food materials drew a similar conclusion. In the study of mass concentration, the $\text{PM}_{2.5}$ emitted from five restaurants in China were sampled in the exhaust pipe on the rooftop of the building (Wang *et al.*, 2009). The mass concentration of $\text{PM}_{2.5}$ ranged from 331.3 to $1841.9\text{ }\mu\text{g m}^{-3}$, which was 4.3–20.2 times that of the $\text{PM}_{2.5}$ concentration in the surrounding environment. Pei *et al.* (2016) conducted the test in three commercial restaurants, including those serving Shanghai cuisine, Sichuan cuisine, and Italian cuisine. The test results showed that the $\text{PM}_{2.5}$ concentration at the exit of restaurants' organized emissions purification systems ranged from 325 to $693\text{ }\mu\text{g m}^{-3}$, which was one order of magnitude higher than the background environmental concentration. Gao *et al.* (2013) sampled the particles in a laboratory kitchen with an exhaust hood. They found that the mass concentration of particles during a 2-min heating process of six edible oils was 2–3 orders of magnitude higher than the background concentration. Chiang *et al.* (1999) tested particles produced from six edible oils. In the experiment, when 200 mL of edible oil was heated to $250 \pm 10^\circ\text{C}$, the range of the released particle concentration was $20.3\text{--}24.2\text{ mg m}^{-3}$. Zhao *et al.* (2015) conducted a test in the exhaust pipe of a 9-story apartment building kitchen. During dinner, the average total suspended particles (TSPs) concentration was $138\text{ }\mu\text{g m}^{-3}$.

All of the research results showed that smaller particles occupied a high proportion both in terms of the particle mass concentration and particle number concentration. For the particle mass, Zhao *et al.* (2007a) conducted tests on four commercial restaurants and found that the ratio of $\text{PM}_{2.5}$ to PM_{10} (PM with the diameter less than or equal to $10\text{ }\mu\text{m}$) was approximately 80%. In the test conducted by Lee *et al.* (2001) $\text{PM}_{2.5}$ in barbecue shops, hot pot restaurants, and pastry shops accounted for 80–93% of PM_{10} , while the ratio in Western restaurants was lower (less than 60%). In the test of university cafeterias, particles with a diameter in the ranges of $0.160\text{--}0.268\text{ }\mu\text{m}$ and $0.390\text{--}0.626\text{ }\mu\text{m}$ accounted for the largest proportion of the total mass of PM_{10} (See *et al.*, 2006). Zhao *et al.* (2007b) tested Western-style fast food restaurants and found that the mass concentration of $\text{PM}_{2.5}$ exceeded 90% in the mass concentration of PM_{10} . In Gao *et al.* (2013) test for heating edible oils, the mass of particles in the range of $1.0\text{--}5.0\text{ }\mu\text{m}$ accounted for almost 100% of PM_{10} . In the test conducted by Buonanno *et al.* (2009) when bacon was roasted, the proportions of UPFs, submicron particles (PM with the diameter less than or equal to $1.0\text{ }\mu\text{m}$), and particles with sizes in the range of $1\text{--}2.5\text{ }\mu\text{m}$ were 5%, 67%, and 27%, respectively, among the total mass of PM_{10} . When fries were fried, the above proportion was 9%, 67% and 24%, respectively, indicating that the proportion of PM_1 in PM_{10} was approximately 72–76%. The mass ratios of the particle sizes are shown in Table 1.

Regarding the particle number, Sjaastad *et al.* (2008) measured the number of particles in the range of $0.3\text{--}1.0\text{ }\mu\text{m}$. The results showed that the particles were mainly concentrated in the range of $0.3\text{--}0.5\text{ }\mu\text{m}$, which is consistent

Table 1. The mass ratio of fine particle and total particles during cooking process.

Cooking style	Items	Mass ratio	References
Chinese commercial	PM _{2.5} /PM ₁₀	~0.8	Zhao <i>et al.</i> , 2007a
Chinese commercial	PM _{2.5} /PM ₁₀	0.56–0.84	Lee <i>et al.</i> , 2001
Chinese commercial	PM _{2.5} /PM ₁₀	> 0.9	Zhao <i>et al.</i> , 2007b
Laboratory kitchen (oil-heating)	PM _{1.0-5.0} /PM ₁₀	~1.0	Gao <i>et al.</i> , 2013
Laboratory kitchen (grilling bacon)	PM _{0.1} /PM ₁₀	0.05	Buonanno <i>et al.</i> , 2009
	PM _{0.1-1} /PM ₁₀	0.67	
	PM _{1-2.5} /PM ₁₀	0.27	
Laboratory kitchen (frying chips)	PM _{0.1} /PM ₁₀	0.09	
	PM _{0.1-1} /PM ₁₀	0.67	
	PM _{1-2.5} /PM ₁₀	0.24	

with the previous study of Abt *et al.* (2000). They found that the particles were mainly concentrated in the range of 0.02–0.5 μm during frying. Wallace *et al.* (2008) conducted an intensive measurement and recognized that most of the particles emitted from cooking were less than 10 nm. The peak concentration was approximately 5 nm to 6 nm. Torkmahalleh *et al.* (2012) used MSP (Shoreview, MN, USA) to monitor the concentration and particle size distribution of cooking particles. The mode diameters of peanut oil, soybean oil, safflower oil, corn oil, olive oil, coconut oil, and canola oil tested were 16–30 nm, 24–82 nm, 20–54 nm, 40–61 nm, 25–88 nm, 16–44 nm and 19–51 nm, respectively. Among them, the number of UPFs accounted for 76–99% of the total number of particles (10–500 nm). This is consistent with the previous studies of Wallace *et al.* (2004), See *et al.* (2006), Glytso *et al.* (2010) and Zhao *et al.* (2019). The ratio of the number of fine particles and total particles is presented in Table 2.

Chemical Property of Cooking Particles

COFs contains over 200 chemical components, mainly elemental carbon (EC), organic carbon (OC), and inorganic elements. OC accounts for a larger proportion of cooking particles, which mainly include PAHs, carbonyl compounds and n-alkanes (Wallace *et al.*, 2004; Abdullahi *et al.*, 2013; Pei *et al.*, 2016; Liu *et al.*, 2017; Zhao *et al.*, 2019). Other ingredients make up less of the cooking particle concentration (Ng *et al.*, 2001). The adverse health effects caused by cooking particle is not only related to its physical properties (e.g., particle number, particle size, and total surface area) but also related to the chemical compositions of PM (Rajasekar and Balasubramanian, 2001; Oeder *et al.*, 2012).

PAHs refer to organic compounds containing two or more benzene rings. During cooking, PAHs are mainly derived from pyrolysis products of unsaturated fatty acids

under high temperature (Chiang *et al.*, 1999; Chen *et al.*, 2019). PAHs occupies only a very small part of cooking particles, and their proportions in quantified organic matter does not exceed 2.07% (Schauer *et al.*, 2002; Zhao *et al.*, 2007a, b). However, because the human body is often exposed to PAHs by direct inhalation into the lungs, the skin, or feeding, and some of the PAHs are carcinogenic, PAHs have received more attention.

One of the major sources of carbonyl compounds is the incomplete combustion of carbonaceous materials. In cooking activities, both combustion of fuel and heating of cooking oil produce carbonyl compounds. For example, different types of fuels, such as natural gas, liquefied petroleum gas, kerosene, and carbon, produce formaldehyde (gaseous) and acetaldehyde (Zhang *et al.*, 1999). Some of these carbonyl compounds (such as formaldehyde, acetaldehyde, and acrolein) pose a threat to human health. Formaldehyde (gaseous), acetaldehyde, acrolein and pelargonic aldehyde are the most common carbonyl compounds produced during cooking (Schauer *et al.*, 2002; Katragadda *et al.*, 2010).

Fatty acids have been found to be a main component of cooking particles in all previous studies. Table 3 lists the proportion of fatty acids in quantified organics and the highest concentrations of saturated and unsaturated fatty acids in each test. The table shows that the proportion of fatty acids in quantified organics ranges from 73.4% to 95.7%. During cooking, glycerides release free fatty acids by hydrolysis and thermal oxidation (Rogge *et al.*, 1991). Particularly, vegetable fats contain more unsaturated fatty acids than animal fat.

Dicarboxylic acids come from the oxidative decomposition of dialdehydes during the auto-oxidation of unsaturated fats (Rogge *et al.*, 1991; Schauer *et al.*, 1999). In general, the concentration of dicarboxylic acid produced during cooking is one to two orders of magnitude lower than the

Table 2. The ratio of number of fine particles and total particles during cooking process.

Cooking style	Items	Amount ratio	References
Laboratory kitchen (Pan-frying of beefsteak)	PM _{0.3-0.5} /PM ₁	0.77–0.82	Sjaastad <i>et al.</i> , 2008
Laboratory kitchen (oil-heating)	PM _{0.01-0.1} /PM _{0.01-0.5}	0.76–0.99	Torkmahalleh <i>et al.</i> , 2012
Laboratory kitchen (oil-heating)	PM _{0.3} /PM ₁	0.84–0.90	Zhao <i>et al.</i> , 2019
Laboratory kitchen (frying onion)	PM _{0.1} /PM ₁	~0.8	Glytsos <i>et al.</i> , 2010
Singapore commercial	PM _{0.1} /PM ₁₀	> 0.9	See <i>et al.</i> , 2006
American residential	PM _{0.1} /PM ₁₀	~0.9	Wallace <i>et al.</i> , 2004

Table 3. Summary of the test fatty acid.

Cooking style	Highest concentration of saturated fatty acids	Highest concentration of unsaturated fatty acids	Proportion of fatty acids in the quantified organic matter/%	References
Shanghai-style	Hexadecanoic acid	Linoleic acid	90.9	Pei <i>et al.</i> , 2016
Sichuan-style	Hexadecanoic acid	Oleic acid	95.3	
Italian-style	Hexadecanoic acid	Oleic acid	93.2	
Guangdong-style	Hexadecanoic acid	Oleic acid	75.5	
Sichuan-style	Hexadecanoic acid	Oleic acid	81.8	Zhao <i>et al.</i> , 2007a
Dongbei-style	Hexadecanoic acid	Oleic acid	73.4	
Hunan-style	Hexadecanoic acid	Oleic acid	81.5	
Chinese mixed cooking	Hexadecanoic acid	Linoleic acid	75.7	
Hunan-style	Hexadecanoic acid	Linoleic acid	95.7	Zhao <i>et al.</i> , 2015 He <i>et al.</i> , 2004
Guangdong-style	Hexadecanoic acid	Linoleic acid	92.0	
Western fast food	Hexadecanoic acid	Oleic acid	78.0	Zhao <i>et al.</i> , 2007b Schauer <i>et al.</i> , 1999
Barbecue-style	Hexadecanoic acid	Oleic acid	83.0	

concentration of fatty acids (He *et al.*, 2004; Zhao *et al.*, 2007a, b; Zhao *et al.*, 2015; Pei *et al.*, 2016).

n-alkanes account for only a small fraction of cooking particles. According to previous studies, the proportion of n-alkanes in quantified organics is 0.32–5.97% (Rogge *et al.*, 1991; Oros *et al.*, 2001a; Schauer *et al.*, 2002; He *et al.*, 2004; Zhao *et al.*, 2007a, b; Zhao *et al.*, 2015; Pei *et al.*, 2016).

Cooking has an effect on the concentration of inorganic elements. There are many sources of metals from food additives, foods, edible oils and biomass burning (Anwar *et al.*, 2004; Acciai *et al.*, 2017; Zhao *et al.*, 2019). For example, Kawashima *et al.* (2003) found Cu, Fe, Mn, and Zn in vegetables, Lombardi-Boccia *et al.* (2004) found Cu, Fe, and Zn in meat, and Atta *et al.* (1997) found Cu, Zn, and Cd in fish. Mn could also be contained in the mushrooms. Na is likely derived from the salt used and K is associated with oil-based meat cooking and bio-related cooking (Tiner *et al.*, 2013; Acciai *et al.*, 2017). Certain elements, such as Cr, Fe, Cu and Ni, may also come from cooking appliances (such as stainless-steel pans, and spatulas). Additionally, burning of fuel also releases inorganic elements. The toxins contained in heavy metals are absorbed onto the surface area of particles, which may cause heart and lung disease, inflammation or DNA damage (Senlin *et al.*, 2008).

The main water-soluble ions in cooking particles are Na^+ , NH_4^+ , SO_4^{2-} , NO_3^- , K^+ , Ca^{2+} and Cl^- . Wang *et al.* (2015) research on commercial restaurants showed that water-soluble ions accounted for 9.1–17.5% of the total mass of $\text{PM}_{2.5}$, with Na^+ , SO_4^{2-} , K^+ , Cl^- , and Ca^{2+} accounting for 62.9–85.7% of the total mass of water-soluble ions. In Schauer *et al.* (2002) study, the identified ions included Na^+ , NH_4^+ , SO_4^{2-} , NO_3^- , K^+ , and Cl^- . The proportion of NO_3^- was approximately 2.2%, the proportion of Na^+ , NH_4^+ , and SO_4^{2-} was approximately 1.0%, and the proportion of K^+ and Cl^- was approximately 0.27%. According to previous research, SO_4^{2-} might come from drinking water used in cooking (PUB, 2007), NO_3^- came from nitrogen oxides produced when fuel was burned, and Na^+ and Cl^- might come from salt (Wang *et al.*, 2015).

The molecular biomarkers produced by the cooking

process include two types: sterols and monosaccharide anhydrides. Sterols mainly include cholesterol, campesterol, stigmasterol and β -sitosterol. Monosaccharide anhydrides mainly include galactan, mannan, and levoglucan. Sterols are widely found in plant and animal tissues. The vegetable lipid membranes are mainly composed of phytosterols, such as β -sitosterol, campesterol, and stigmasterol. Cholesterol is widely present in animal tissues, such as animal fat (Oros *et al.*, 2001a, b). The main products of cellulose decomposition are levoglucosan, galactan and mannan. Levoglucan is also considered a tracer for biofuel combustion (Radzi bin Abas *et al.*, 2004).

Health Risk Assessment Indicators

The potential hazard of COFs depends on exposure, which is a function of the concentration and time. It can be evaluated by two risk evaluation indexes: excess lifetime cancer risk (ELCR) and hazard quotient (HQ). ELCR is used to evaluate the harm of carcinogens to the human body. A higher ELCR value indicates a greater risk of human cancer. The reference value for ELCR is E-6 (i.e., the ELCR value should not exceed E-6). HQ is used to evaluate the harm of noncarcinogenic effects of carbonyl compounds. A higher value of HQ is linked to greater damage to the human body. The reference value for HQ is 1.0 (i.e., the HQ value should not exceed 1.0). Their calculation method is as follows:

ELCR is calculated as follows (U.S. EPA, 1994):

$$\text{ELCR} = \text{CDI} \times \text{SF} \quad (1)$$

where CDI is the level of chronic intake ($\text{mg kg}^{-1} \text{d}^{-1}$) and SF is the cancer slope factor ($\text{kg d}^{-1} \text{mg}^{-1}$).

HQ is calculated as follows (BJC/OR-271, 1999):

$$\text{HQ} = \frac{\text{CDI}}{\text{RfD}} \quad (2)$$

where RfD is the contaminant reference dose ($\text{mg kg}^{-1} \text{d}^{-1}$).

In previous studies, it was fully demonstrated that COFs

show great harm to the human body. In two residential kitchens of Hong Kong where town gas (Residence A) and liquefied petroleum gas (Residence B) were used as the fuels, the cooking emission samples were collected and evaluated for the carcinogenic risks on the chronic exposure to benzene, formaldehyde and acetaldehyde in housewives (Huang *et al.*, 2011). The results showed that, in residence A, formaldehyde accounted for 68% of the lifetime cancer risk, while the value was close to 100% in residence B. The occupational exposure to cooking emissions was evaluated by ELCR analysis (See *et al.*, 2006) in three commercial kitchens. The ELCRs was estimated to be $1.07\text{E-}3$, $1.21\text{E-}2$ and $4.08\text{E-}3$ in Indian, Malay and Chinese kitchens, respectively. In Turkey, Taner *et al.* (2013) collected PM from 14 restaurants that was fueled with charcoal. The total HQ for $\text{PM}_{2.5}$ was 4.09, and the total ELCR was $1.57\text{E-}4$. In Singapore, the physical and chemical properties of a typical Chinese food stall using a gas stove were investigated (See and Balasubramanian, 2006). The assessed value of total ELCR and HQ was $1.11\text{E-}4$ and 1.54, respectively. In Taipei, four night markets that have high visitor densities were studied by Zhao *et al.* (2011), and sixteen PAHs were analyzed. The excess ELCR of cooks in almost all typical food stalls in the night markets ranged from E-6 to E-4. A health risk assessment in five household kitchens in northern Taiwan was conducted by Yu *et al.* (2015). The ELCR resulting from 2-h daily exposure to PAHs in these sampling sites ranged from $2.46\text{E-}6$ to $1.40\text{E-}5$. Carcinogenic risks of PAHs and heavy metals generated during domestic Chinese cooking were assessed by Zhang *et al.* (2017). The risk of PAHs and heavy metals was $5.8\text{E-}6$ and $2.7\text{E-}3$, respectively, without kitchen ventilation. All the above values were high above the recommended acceptable limit of ELCR and HQ.

FACTORS AFFECTING THE RELEASE OF COOKING PARTICLES

Many factors such as fuel, edible oil, cooking temperature, cooking method and cooking style (Karimatu *et al.*, 2013) could influence the concentration, chemical composition and diffusion of cooking particles. In actual cooking process, the coupling effects of sampling position, food consumption and ventilation conditions would also result in changes in the characteristics of cooking particles. In the following, analysis will be conducted for each influencing factor.

Cooking Fuels

Most fire-based cooking that increases human health risks is based on the combustion of different fuel types (Kima *et al.*, 2011). Cooking fuel has a significant effect on the contribution of particles in environment (To and Yeung, 2011). Several fuels are used for cooking, including biomass fuel (e.g., charcoal or wood), kerosene, coal, liquefied petroleum gas (LPG), natural gas and electrical energy.

In developing countries, traditional solid fuels — e.g., wood, dung, coal or agricultural residues — are used quite frequently, especially in unvented or flueless stoves, leading to solid fuels becoming the largest source of indoor pollution

(WHO, 2010; Tiwari *et al.*, 2015; Shahid *et al.*, 2019). Currently, 50–75% of people in some areas of southern Africa and South America, as well as more than 75% of people in China, and nearby countries, use solid fuels for cooking. In rural areas in Mexico, Brauer *et al.* (1996) monitored 22 kitchens and found that the average $\text{PM}_{2.5}$ in the kitchen using LPG for cooking was $69\text{ }\mu\text{g m}^{-3}$, which was much lower than that in the kitchen using biomass ($555\text{ }\mu\text{g m}^{-3}$) for cooking. Siddiqui *et al.* (2009) investigated 44 and 51 kitchens using LPG and wood for cooking, respectively. The results showed that, in the kitchen using LPG, the daily average concentration of $\text{PM}_{2.5}$ ($380\text{ }\mu\text{g m}^{-3}$) was significantly lower than that using wood ($2740\text{ }\mu\text{g m}^{-3}$). Li *et al.* (2016) compared 107 households that used coal for cooking in the urban area of China with households using gas or electricity for cooking. The results showed that much higher inhalation exposure levels and indoor concentrations were in the households using coal for fuel. Changing from coal to electricity or gas, wood to LPG, and biomass to LPG for cooking reduced the $\text{PM}_{2.5}$ in kitchen by 40–70%, 86.1% and 87.6%, respectively. Xu *et al.* (2018) observed a similar conclusion that households using electrical power for cooking and heating could at least reduce by half personal exposure to $\text{PM}_{2.5}$ as compared to solid fuel.

The above studies further confirmed that using clean fuels like, gas and electricity could reduce the indoor air pollution significantly. However, cooking with electric toaster ovens and gas or electric stoves was still an important source of UFPs (Du *et al.*, 2018). The estimated emission rate of UFPs in the neighborhood was approximately $\text{E+}12$ particles min^{-1} , and the peak personal exposure typically exceeded $\text{E+}5$ particles cm^{-3} (Wang *et al.*, 2015). Gas cooking produced higher concentration of particles than electric cooking. The study of 393 kitchen workers from 53 Chinese restaurants indicated (Wong *et al.*, 2011) that, compared with electricity-fueled kitchens, gas-powered kitchens had a higher prevalence of respiratory symptoms and poorer lung function among the workers. Regarding the two relatively clean fuels that are commonly used in Hong Kong, electricity and town gas, the measurement results showed that, in domestic kitchens, electric cooking produced lower concentrations of PM_{10} than gas cooking for deep frying, stir frying and pan frying (To and Yeung, 2011). Zhang *et al.* (2010) observed a similar conclusion. When frying chips, the TSPs produced by cooking with natural gas was $118\text{ }\mu\text{g m}^{-3}$, while the electric cooking produced TSPs of only $27\text{ }\mu\text{g m}^{-3}$ (Buonanno *et al.*, 2009). The concentration of the particle emissions from different cooking fuels is shown in Table 4.

Principal component analysis indicates that the main sources of indoor PAHs are combustion emissions from biomass, coal, diesel and gasoline. The 2-ring and some 3- and 4-ring PAHs were mainly produced indoors due to cooking activities (Li *et al.*, 2017). The samples of indoor burning of bio-fuels, such as corn cobs, from 8 sampling sites across the Beijing-Tianjin-Hebei region were dominated by 2, 3-ring PAHs (Li *et al.*, 2018). Incomplete combustion of carbon-based fuels is also a major source of aldehydes. Zhang *et al.* (1999) measured a discharge coefficient of

Table 4. Summary of the concentrations of particle emissions from different cooking fuels.

Cooking style	Fuel	Particle size	Concentration ($\mu\text{g m}^{-3}$)	References
Chinese commercial	Gas	PM _{2.5}	404.8–494.9	Wang <i>et al.</i> , 2015
Chinese residential			65–184	Li <i>et al.</i> , 2016
Chinese residential			4–2731	Lu <i>et al.</i> , 2019
Chinese residential			160	Wan <i>et al.</i> , 2011
Singapore residential (Chinese style)			65.7–190	See and Balasubramanian, 2008
American residential			12.4–98.1	Zhang <i>et al.</i> , 2010
Japan residential			22.3–101.6	Huboyo <i>et al.</i> , 2011
Chinese commercial		PM ₁₀	890–4720	To and Yeung, 2011
Chinese residential		TSPs	138	Zhao <i>et al.</i> , 2015
Italy laboratory			60–398	Buonanno <i>et al.</i> , 2009
Indian residential	Electricity	PM _{2.5}	34.5–143.7	Zhang <i>et al.</i> , 2010
Chinese residential			230.9	
Italian residential			36.5	
American student dorm			20.4–78.3	
American residential			10.0–22.2	
Chinese residential			55–153	Li <i>et al.</i> , 2016
Chinese residential		PM ₁₀	520–3980	To and Yeung, 2011
Italy laboratory		TSPs	12–27	Buonanno <i>et al.</i> , 2009
Italy laboratory			1000–11600	Sjaastad <i>et al.</i> , 2008
Singapore commercial				See <i>et al.</i> , 2006
Chinese commercial	Liquefied petroleum gas	PM _{2.5}	201.8–312.4	Wang <i>et al.</i> , 2015
African residential		PM _{2.5}	331.3	Giwa <i>et al.</i> , 2019
		PM _{2.5}	328	
		PM _{2.5}	345	
Chinese commercial		Charcoal	1841.9	Wang <i>et al.</i> , 2015
Chinese residential		Coal	107–213	Li <i>et al.</i> , 2016
Chinese residential		Yak dung	56.6–1280	Xiao <i>et al.</i> , 2015
Chinese residential		Wood or crop residues	111 $\pm$ 63	Qi <i>et al.</i> , 2018
Chinese residential		Wood or coal	310.8 $\pm$ 90.4	Xu <i>et al.</i> , 2018
Western commercial		Wood	12–369	Buonanno <i>et al.</i> , 2010
		PM ₁₀	15–482	

aldehyde materials in common cooking fuels. The results showed that all the carbon-based cook stoves produced aldehydes. LPG and kerosene stoves generated fewer carbonyl compounds than biomass stoves but more than coal gas, coal and natural gas stoves.

Edible Oil

The composition and emission of cooking fumes are also related to edible oil. Various edible oils used in cooking are closely connected to people's eating habits. When the type of edible oil is modified, thermal cracking products are different. Researchers have conducted extensive studies on the smoke point and volatile products emitted from cooking with different edible oils. During frying with margarine, significantly higher particle numbers in all size fractions are observed than frying with rapeseed, soybean and olive oils (Sjaastad *et al.*, 2008). In Chiang *et al.* (1999) study, the amount of cooking particles was higher (but not significant) in vegetable oil than sunflower and refined-lard oils. The emission factors determined in Buonanno *et al.* (2009) study revealed the following order of emissions: olive oil (118 mg m⁻³) > peanut oil (68 mg m⁻³) > sunflower oil (60 mg m⁻³). This is consistent with the conclusions of

Torkmahalleh *et al.* (2012) that olive, corn oils and coconut generated higher PM_{2.5} concentrations than peanut, safflower, soybean and canola oils. At the highest monitored temperature (197°C), the PM_{2.5} concentration during cooking olive oil is approximately 10 fold higher than that of safflower oil. Differences in the composition of the oils will affect their fume temperature. The semivolatile compounds emitted from oil condense and form an aerosol phase; consequently, the particle emissions occur (Buonanno *et al.*, 2011). Therefore, the composition of the oil further affects the particle emission rate (Torkmahalleh *et al.*, 2012). For example, soybean oil, safflower oil, canola oil and peanut oil are known to be quite low-particle emitters compared with corn, coconut and olive oils due to the higher smoke point temperature.

The impact of oil choice on carbonyl emissions for barbecue and stir-frying cooking was investigated by Xiang *et al.* (2017). Generally, carbonyl emissions produced from soybean oil were higher than from corn oil. The significantly high amount of carbonyls was possibly due to the presence of large amounts of water in materials. The types of edible oil may affect the generation of aldehydes. According to the results of previous studies, acetaldehyde

and amyl aldehyde can be obtained from linoleic acid, hexanal, 2-heptene aldehyde, 2-octene aldehyde, 2-nonene aldehyde and 2, 4-sebacic olefin aldehyde. Therefore, if cooking oil contains linoleic acid, it is easier to produce more oleic acid decomposition, which can produce caprylic aldehyde, nonyl aldehyde, decanal, and 2-decyl olefin aldehyde (Subramanian and Nakajima, 1997). Katragadda *et al.* (2010) confirmed the same conclusion. They measured the aldehyde-producing conditions of 4 kinds of cooking oil. The content of linoleic acid among the four kinds of cooking oil was in the following order, from highest to lowest: safflower oil, canola oil, olive oil and coconut oil. The results showed that 2-heptene aldehyde substances produced by safflower oil was far more abundant than the other three kinds of edible oil. However, the emission rates of decyl olefin aldehyde and nonyl aldehyde in olive oil were higher than those of other cooking oils. In addition, the type of cooking oil will also affect the distribution of fatty acids. Schauer *et al.* (2002) found that the distribution of C18 fatty acids (including stearic, oleic, linoleic and linolenic acids) in the cooking particles was consistent with the distribution in edible oils. In their tests, the highest proportion of oleic acid was found in canola oil. Canola oil cooking also produced a large amount of oleic acid. The results showed that all cooking oils produced only a very small amount of linolenic acid.

Cooking Temperature

Many particles are generated during high-temperature cooking process. A high cooking temperature increases the particle number, mass concentration, mode diameter (geometric mean diameter) and emission factor. In Buonanno *et al.* (2009), an increase of 29-fold in the case of mass concentration and a 70% increase in the number concentration can be observed with an elevated cooking temperature. However, the influence of oil temperature on emission rates of PM_{2.5} and UFPs was not significant in the experiment conducted by Zhao *et al.* (2018), because practical peak oil temperatures (112–177°C) were mostly below the oil smoke point (107–234°C). Temperature is also found to have a significant impact on the mode diameter. At high temperature, the particles intercoagulate easily and, eventually, the diameter mode of particles increased. This effect was also observed by Yeung and To (2008). When the cooking temperature changed from 200°C to 220°C during frying chicken, the mode diameter of the particles increased from 103 nm to 160 nm. A similar situation occurred in the process of frying steaks and pork chops. Yeung and To (2008) also drew a conclusion that the size distribution of particles followed a lognormal distribution. However, some researchers found that the particle size appeared to show a bimodal distribution based on particle number (Glytsos *et al.*, 2010; Torkmahalleh *et al.*, 2012). When cooking temperature was low, the bimodal distribution was nonexistent. At a high cooking temperature, the smaller sized particles could condense into a larger size, leading to a size distribution of particles followed by a lognormal distribution or bimodal distribution based on the particle number. It was also observed that the particle

emission factor is a function of the increased cooking temperature. When the carbon combustion temperature rose from 450°C to 550°C, the released PM_{2.5} increased from 19.8 mg kg⁻¹ to 241.3 mg kg⁻¹. The total PM₁₀ emissions increased from 31.1 mg kg⁻¹ to 292.8 mg kg⁻¹ (Huang *et al.*, 2016).

With the rising temperature, the emissions of most PAHs, aldehydes, inorganic and unsaturated fatty acids pyrolysis increase. Chiang *et al.* (1999) indicated that PAHs were mainly formed by unsaturated fatty acids, which were oxidized at high temperature. Most PAHs increase with temperature. BaP showed a notable increase, while Acl rapidly increased. Besides, some 3-ring PAHs, such as PHEN, hardly increase at elevated temperatures (Zhu and Wang, 2003; Hao *et al.*, 2016). Katragadda *et al.* (2010) found that, during the heating process, the generation rate of aldehydes increased with the oil temperature. When the oil temperature exceeds the smoke point, the generation rate of aldehydes increased dramatically. With safflower oil (smoke point 217 ± 2°C), when the oil temperature increased from 210°C to 240°C, the generation rate of aldehydes increased to 1971 mg h⁻¹ L⁻³. Additionally, high cooking temperatures would lead to a higher concentration of inorganic elements. Therefore, high-temperature cooking should be avoided. In cooking process, oil temperature should not be higher than the smoke point.

Cooking Method

Cooking method has been known as one of the important factors affecting the emission of some essential pollutants (Abdullahi *et al.*, 2013). Current research has shown that heavy-load cooking method, such as deep-frying, barbecue (pan-frying), and stir-frying produces more PM, PAHs and inorganic elements than others.

The PM_{2.5} mass concentration determined in See and Balasubramanian (2008) study revealed the following order of emissions: deep frying (209 µg m⁻³) > pan frying (130 µg m⁻³) > stir frying (120 µg m⁻³) > boiling (91.6 µg m⁻³) > steaming (72.3 µg m⁻³) > background (15.4 µg m⁻³). The observation also agrees with the research results reported by Lee *et al.* (2001), Wang *et al.* (2015), Giwa *et al.* (2019) and Lu *et al.* (2019). Wang *et al.* (2015) conducted a measurement of PM_{2.5} emitted from different cooking styles, mainly including mixed cooking, stir frying (in home, Shandong cuisine restaurants and Hunan cuisine restaurants) and barbecue. They found that barbecue (pan frying) restaurants had the highest PM_{2.5} concentration, 3.7 to 5.6 times higher than others. The observation was consistent with McDonald *et al.* (2003) who reported that charbroiling produced higher concentrations of PM than stir frying. Lee (2001) found the PM_{2.5} concentration was the highest in Korean barbecue restaurants (pan frying), following by Chinese hot pot restaurants (boiling) and Chinese dim sum restaurants (steaming). The same conclusion was also made by See *et al.* (2006) who compared the PM_{2.5} emitted from three commercial kitchens with different cooking methods (Indian (boiling), Chinese (stir frying), and Malay (deep frying)). In three residence measurements conducted by Zhang *et al.* (2010), it was also found that, during

boiling, lower UFPs concentrations were observed, while the UFPs levels were higher during frying. Many researches have reported similar results (Rogge *et al.*, 1991; Buonanno *et al.*, 2010; Taner *et al.*, 2013; Sofuoglu *et al.*, 2015). A summary of the particle concentrations generated from different cooking methods are presented in Table 5. The concentrations of PM varied considerably, even with the same cooking method, indicating the sensitivity of the measurement conditions where small details and measurement location can have a significant effect on the results.

Saito *et al.* (2014) found that, regardless of cooking method and food material, the main components of PAHs were 3- and 4-ring PAHs. Naphthalene (Nap) was the most abundant PAHs among the total measured gaseous PAHs (Wang *et al.*, 2015; Hao *et al.*, 2016). The emission rates of Nap were the highest for oil based cooking methods, while Phenanthrene (Phe) and Chrysene (Chr) emissions were the highest for steaming and boiling (Zhao *et al.*, 2019). It is believed during deep frying, the mass concentration of PAHs was the highest, followed by pan frying, stir frying, boiling and steaming (Lee *et al.*, 2001; See and Balasubramanian, 2006, 2008; Wang *et al.*, 2015). However, Zhao *et al.* (2019) found out the concentrations of 16 PAHs in PM_{2.5} followed by stir-frying (58.90–92.14 ng m⁻³), pan-frying (41.23–72.57 ng m⁻³), deep-frying (34.57–50.89 ng m⁻³), steaming (29.54 ng m⁻³), and boiling (8.00 ng m⁻³). During deep frying using edible oils, the levels of PAHs, especially the heavier PAHs (5-ring or above), are increased. The mean concentration of high-ring PAHs (5-ring or above) for deep-frying oils for 45 min was 31.5 times higher than the levels for fresh oils (Hao *et al.*, 2016). During water based cooking or mixed cooking, high-ring (5-ring or above) PAHs were the most abundant compared with oil-based cooking (Zhu and Wang, 2003; Zhao *et al.*, 2019). The most common PAHs with carcinogenic effects are the four- to six-ring compounds. This indicated that lower cooking temperature and less cooking oil consumption does not mean the steaming and boiling processes are less harmful. This is the reason why Chinese-style hot pot restaurant (boiling-based) emitted nearly the same amount of pollutants as barbecue restaurant (Lee *et al.*, 2001). The emission of those two cooking processes all exceed the limits of cancer risk (10 E-6) and the hazard index (= 1) (Ho *et al.*, 2006;

Cheng *et al.*, 2016).

According to the experiment conducted by Xiang *et al.* (2017), the carbonyls (C1–C8) emission factors were in the following order: barbecue (1.596 µg kg⁻¹) > frying (1.530 µg kg⁻¹) > Teppanyaki (1.229 µg kg⁻¹) > stir-frying (0.699 µg kg⁻¹), while C1–C3 carbonyls accounted for over 85% for all cooking types. The primary pollutant produced from cooking was formaldehyde, followed by acetaldehyde and acetone. Barbecue produced higher amount of acetaldehyde and propanal than other carbonyls. Formaldehyde produced from stir-frying was very high while the acetaldehyde produced was negligible.

Regardless of cooking method, Ca, Na, Fe, K, Al, Mg and S are the most abundant elements in the cooking profiles and their mass fractions account for approximately 98% of the measured elements (See and Balasubramanian, 2008; Li, *et al.*, 2015; Wang, *et al.*, 2015; Zhang *et al.*, 2017; Zhao *et al.*, 2019). The concentrations of inorganic elements generated from different cooking methods followed the same order of PM and oil-based cooking generated more elements than water-based cooking (See and Balasubramanian, 2008; Zhao *et al.*, 2019). With the same inorganic elements, ions of cooking particles are also affected by the cooking method. The concentrations of ions emitted during steaming and boiling were higher than those emitted during stir frying even with the same cooking temperature and cooking oil consumption. This might be related to tap water being rich in Cl⁻, F⁻ and SO₄²⁻ concentrations. The concentrations of Cl⁻, F⁻ and SO₄²⁻ in tap water varied in the ranges of 5–100 ppm, 0.4–0.6 ppm and 5–60 ppm, respectively. However, the concentrations of the three ions in cooking oils were only 1–6.5 ppm, 1 ppm and 1 ppm, respectively (Dugo *et al.*, 2007). Therefore, the water-based cooking method releases a large amount of Cl⁻, F⁻, and SO₄²⁻ compared with the oil-based cooking method, likely explaining the ion concentration in the following order: boiling > steaming > stir frying in the test of See and Balasubramanian (2008).

Chinese and Western Cooking Styles

Chinese cuisine emphasizes a balanced diet, mainly vegetables, and the ingredients are reasonable, while Western foods have a higher proportion of fat and meat

Table 5. Summary of the concentrations of particle emissions from different cooking methods.

Cooking style	Features	Particle size	Concentration (µg m ⁻³)	Sampling points	References
Chinese style (commercial)	Mixed cooking	PM _{2.5}	331.3–494.9	Rooftop exhaust	Wang <i>et al.</i> , 2015
	Barbecue	PM _{2.5}	1841.9		
	Mixed cooking	PM _{2.5}	471–693	Rooftop exhaust	Pei <i>et al.</i> , 2016
	Deep-frying	PM _{2.5}	76–158	1.5 m above the ground near	Sofuoglu <i>et al.</i> , 2015
		PM ₁₀	279–1583	(50 cm away) the deep-fryer	
	Deep frying	PM ₁₀	3980–4720	0.2 m from the center of	To and Yeung, 2011
	Griddle frying	PM ₁₀	2260–2600	cooking device and 1.0 m	
	Broiling	PM ₁₀	Out of range (E+5)	above the cooking surface	
	Mixed cooking	PM _{2.5}	312.4	Near the stove and 1.5 m above the ground	See <i>et al.</i> , 2006

Table 5. (continued).

Cooking style	Features	Particle size	Concentration ($\mu\text{g m}^{-3}$)	Sampling points	References
Chinese style (residential)	Mixed cooking	TSP	138	Rooftop exhaust	Zhao <i>et al.</i> , 2015
	Mixed cooking	PM _{2.5}	55–213	Breathing zone (1.0–1.5 m)	Li <i>et al.</i> , 2016
	Mixed cooking	PM _{2.5}	56.6–1280	0.5 m above the ground and 1 m horizontally away from the stove	Xiao <i>et al.</i> , 2015
	Mixed cooking	PM _{2.5}	160	1.7 m above the floor	Wan <i>et al.</i> , 2011
	Frying	PM _{2.5}	230.9	Breathing zone and 1 m from the stove	Zhang <i>et al.</i> , 2010
	Steaming	PM _{2.5}	65.7	0.2 m from the burner and 1.5 m above the ground	See and Balasubramanian, 2008
	Boiling	PM _{2.5}	81.4		
	Stir-frying	PM _{2.5}	120		
	Pan-frying	PM _{2.5}	130		
	Deep-frying	PM _{2.5}	190		
	Steaming	PM _{2.5}	11–88	Breathing zone and 1.4 m above the ground	Lu <i>et al.</i> , 2019
	Boiling	PM _{2.5}	4–247		
	Quick-frying	PM _{2.5}	140–433		
	Stewing	PM _{2.5}	0–573		
	Stir-frying	PM _{2.5}	700–598	0.2 m from the center of cooking device and 1.0 m above the cooking surface	To and Yeung, 2011
	Deep-frying	PM _{2.5}	709–2731		
	Frying	PM ₁₀	1030–1330		
	Pan frying	PM ₁₀	520–1020		
Western style (commercial)	Deep frying	PM ₁₀	680–890	Rooftop exhaust	Pei <i>et al.</i> , 2016
	Mixed cooking	PM _{2.5}	502		
	Mixed cooking	PM _{2.5}	245.3	Near the stove and 1.5 m above the ground	See <i>et al.</i> , 2006
	Grilling	TSP	78–389	2 m from the stove	Buonanno <i>et al.</i> , 2009
	Frying	TSP	12–118	Placed on the left shoulder of the chef	Sjaastad <i>et al.</i> , 2008
	Pan-frying	TSP	1000–11600		
	Baking	PM ₁	10–327	In the center of the restaurants	Buonanno <i>et al.</i> , 2010
		PM _{2.5}	12–369		
		PM ₁₀	15–482		
	Frying	PM _{2.5}	10.0–98.1	Breathing zone and 1 m from the stove	Zhang <i>et al.</i> , 2010
Western style (residential)	Mixed cooking	PM _{2.5}	201.8	Near the stove and 1.5 m above the ground	See <i>et al.</i> , 2006
Other Asian style (commercial)	Pan-frying	PM _{2.5}	34.5–143.7	Breathing zone and 1 m from the stove	Zhang <i>et al.</i> , 2010
	Boiling and stir-frying	PM _{2.5}	36.5		
	Boiling	PM _{2.5}	22.3–30.9	Near the stove and 1.1 m above the floor	Huboyo <i>et al.</i> , 2011
	Frying	PM _{2.5}	41.1–101.6		

TSP: total suspended particle.

Mixed cooking: many cooking techniques are used at the same time.

Barbecue: encompasses four or five distinct types of cooking techniques, like smoking, baking, braising and grilling.

Baking: a method of cooking food that uses prolonged dry heat, normally in an oven, but also in hot ashes, or on hot stones.

Frying: the cooking of food in oil or another fat.

Deep-frying: a cooking method in which food is submerged in hot fat, most commonly oil, rather than the shallow oil used in conventional frying, done in a frying pan.

Stir-frying: a Chinese cooking technique in which ingredients are fried in a small amount of very hot oil while being stirred in a wok.

Pan-frying: a form of frying characterized by the use of minimal cooking oil or fat (compared to shallow frying or deep frying); typically using just enough oil to lubricate the pan.

Grilling: a form of cooking that involves dry heat applied to the surface of food, commonly from above or below.

Steaming: a method of cooking using steam.

Boiling: the method of cooking food in boiling water, or other water-based liquids such as stock or milk.

than vegetables. It is generally believed that Asian-style cooking emits more PM than Western cooking (Lee *et al.*, 2001; Levy *et al.*, 2002; He *et al.*, 2004). For example, grilling Chinese-style food could elevate the concentrations of PM_{2.5} and submicron particles up to 90 and 5 times higher than European-style cooking, respectively (He *et al.*, 2004). Compared with low-fat vegetables, the particle emission factor of high-fat food is much higher. Additionally, the particle size of a high-fat diet may be larger than that of low-fat food even under the same cooking conditions (Torkmahalleh *et al.*, 2013). However, the study concluded by Wang *et al.* (2018) found that the particle concentration released from non-meat ingredients was significantly higher than those from meat, and the decay rate of the particle concentration of cooking meat was significantly lower than that of cooking nonmeat.

The PAHs, nonyl aldehyde, fatty acid, dicarboxylic acid and n-alkanes released during the cooking process in Chinese and Western cooking processes are also quite different. Previous studies have shown a similar distribution of PAH components from different cooking cuisines in Guangzhou China. Its main components were naphthalene, phenanthrene, fluoranthene, pyrene and fluorene, constituting 77.1%–84.1% of the total quantified PAHs (Zhao *et al.*, 2015). Many studies have indicated that pyrene was the highest in typical Chinese cooking emissions (He *et al.*, 2004; Zhao *et al.*, 2007a). However, chrysene contributed to the highest mass fraction in seed oil cooking and meat cooking (Rogge *et al.*, 1991; Schauer *et al.*, 1999, 2002) and the phenanthrene concentration was the highest in beef or chicken grilling and charbroiling (McDonald *et al.*, 2003). More 5-ring PAHs than other PAHs were found in restaurant cooking in Hong Kong (Hu *et al.*, 2012). It should be noted that the mass concentrations of benzo[a]pyrene in Chinese restaurant emissions were always above the threshold value according to the 2nd-level air quality in China (GB 3095-2012). This may be related to the very hot oil and strong stirring in a wok during the Chinese cooking process, leading to a high incidence of lung cancer in Chinese women who smoke little (Zhao *et al.*, 2007b; Zhao *et al.*, 2015; Pei *et al.*, 2016). Different from Chinese style cooking, benzo(b+k) fluorescein was the main PAH compound found in Western-style fast food cooking, and fluorene was the main PAH emitted from the Western style restaurants (Zhao *et al.*, 2007b; Pei *et al.*, 2016).

Generally, Carbonyl emissions from non-meat dishes were smaller than for meat dishes (Xiang *et al.*, 2017). In Chinese-style and Western-style cooking, the aldehyde concentration was approximately the same as the distribution of carbon atoms. Only nonyl aldehyde showed an obvious difference: the nonyl aldehyde concentration in Western cooking was an order of magnitude higher than that in Chinese cooking (Schauer *et al.*, 2002; Ho *et al.*, 2006; Zhao *et al.*, 2007b; Cheng *et al.*, 2016). Nonyl aldehyde is from the decomposition of oleic acid (a fatty acid produced by cooking oil) (Schauer *et al.*, 2002). Compared with Chinese-style cooking, Western cooking uses more cooking oil. This may be one of the reasons for the high concentration of nonyl aldehyde in Western cooking. Other researches

also support this explanation. In the field test study in 15 restaurants, Western-style fast food restaurants had the highest concentration of nonyl aldehydes (Ho *et al.*, 2006).

Fatty acids were found to be the most important constituents of cooking particles. Western-style cooking processes produce a higher concentration of fatty acids than Chinese cooking. Pei *et al.* (2016) analyzed the emissions from three restaurants. They found that the total concentration of fatty acids in Italian restaurant cooking was 2–3 times higher than that of Shanghai restaurant and Sichuan restaurant. Zhao *et al.* (2007b) measured a Western-style fast food restaurant and compared the results with Chinese-style cooking. It was found that the fatty acids in fast food restaurants was 13 times higher than in Chinese restaurant. Similar to the results of Zhao *et al.*, (2015), the total concentration of the fatty acids in Western-style fast food restaurants was approximately 10 times higher than that in Chinese-style cooking. Higher fatty acid concentrations in Western cooking are associated with a greater use of high-fat food ingredients and high cooking temperature. High-fat foods release more fatty acids during the cooking process than lower-fat foods, and high cooking temperatures make grease and vegetable fat more easily release free fatty acids. Chinese cooking has a higher proportion of unsaturated fatty acids than Western cooking. In Chinese cooking, the ratio of unsaturated fatty acids and saturated fatty acids was generally 1.2–4.4 and that in Western cooking was only 0.3–1.1 (He *et al.*, 2004; Zhao *et al.*, 2007b; Pei *et al.*, 2016). In both Western and Chinese cooking, the highest concentration of saturated fatty acids was palmitic acid, while the highest level of unsaturated fatty acids in Western and Chinese cooking were oleic acid and oleic acid or linoleic acid, respectively.

Regarding dicarboxylic acids, Western cooking and Chinese cooking have two major differences: the mass concentration and composition. Zhao *et al.* (2007b) found that the mass concentration of dicarboxylic acid in Western-style cooking was almost 30 times higher than that in Chinese-style cooking. Western cooking with high cooking temperature resulted in a large number of unsaturated fatty acid pyrolysis, explaining the high concentration of dicarboxylic acid. Another reason is the higher consumption of meat than in Chinese cooking. Regarding the composition, the main components of dicarboxylic acid in Chinese cooking was azelaic acid. In Western-style cooking, adipic acid, octyl diacid and azelaic acid were the most common components (Table 6). In addition, the ratio between adipic acid and azelaic acid in Western cooking was greater than 1, while the ratio was less than 1 in Chinese cooking (Zhao *et al.*, 2007b).

The proportion of n-alkanes in the quantified organic compounds was 0.32–5.97%. There were three main differences in cooking particles between Chinese and Western cooking. First, C29 and C31 were generally of the highest concentration in n-alkanes produced in Chinese cooking. This reflected the high proportion of vegetables used in Chinese cooking (Simoneit *et al.*, 1986; Rogge *et al.*, 1993). In Western cooking, the concentration of C25 was generally the highest, while the process of cooking

Table 6. Summary of the test dicarboxylic acid.

Cooking style	Dicarboxylic acid ingredient	Main component proportion in the dicarboxylic acid/%	References
Shanghai-style	Azelaic acid	55.1	Pei <i>et al.</i> , 2016
Sichuan-style	Azelaic acid	58.3	
Italian-style	Azelaic acid, Suberic acid	76.3	
Guangdong-style	Azelaic acid	63.1	Zhao <i>et al.</i> , 2007a
Sichuan-style	Azelaic acid	58.3	
Dongbei-style	Azelaic acid	49.5	
Hunan-style	Azelaic acid	54.8	Zhao <i>et al.</i> , 2015
Chinese mixed cooking	Azelaic acid	72.3	
Hunan-style	Azelaic acid	50.8	
Guangdong-style	Azelaic acid	58.1	He <i>et al.</i> , 2004
Western fast food	Adipic acid, Azelaic acid	87.1	
Barbecue-style	Adipic acid, Suberic acid	100.0	

meat increased the production of C25. Second, compared with Chinese cooking, Western cooking produced higher concentration of n-alkanes. This was 2–3 times higher than that in Chinese food (Zhao *et al.*, 2007b). Third, n-alkanes had a significant parity advantage in the study of Chinese cooking (Zhao *et al.*, 2015; Pei *et al.*, 2016). In the study of Western cooking, it was found that n-alkanes also reflected the parity advantage but not as obvious as Chinese cooking (Poon *et al.*, 2016). In the analysis of Zhao *et al.* (2007b) the carbon dominance index (CPI) was 3.02. If food contains only a small amount of vegetables, a high CPI can be achieved. In Western cooking, the CPI value was lower (1.08–1.62).

According to the previous studies, monosaccharide anhydrides were not produced when cooking meat (Rogge *et al.*, 1993; Schauer *et al.*, 1999). As Chinese cuisine uses more vegetables and Western cooking uses more meat, it can be inferred from the above research results that the concentration of monosaccharide anhydrides and phytosterols in the particles produced in Chinese cooking should be higher. Additionally, the concentration of the above two types of substances in Western cooking should be lower but with higher concentrations of cholesterol. In the site testing of Western-style fast food restaurants, β -sitosterol was not found, while β -sitosterol was the most common phytosterol in Chinese cooking. Additionally, the concentration of β -sitosterol was lower than that in normal Chinese cooking, while cholesterol was higher than that in Chinese cooking (Zhao *et al.*, 2007b). These test results are consistent with previous research results. In all tests, levoglucan had the highest concentration among monosaccharide anhydrides, and β -sitosterol had the highest concentration among sterols (He *et al.*, 2004; Zhao *et al.*, 2007b; Pei *et al.*, 2016).

Others

Due to the combined effects of many factors, significant differences were observed among the different cooking conditions. This created challenges for sampling conditions (Zhao *et al.*, 2015; Cheng 2018; Huan *et al.*, 2019). For most pollutants, the emission factors from the controlled tests in experiments were much lower than those from uncontrolled burning tests in real-world (Du *et al.*, 2018b).

The studies conducted by Sjaastad *et al.* (2008) and Svendsen *et al.* (2002) showed that exposure to the cooking fumes of frying pan in the residential kitchen may be similar or even higher than cooking in commercial kitchen. However, the concentration of particulate matter monitored in rooftop exhaust from Chinese domestic cooking was one order of magnitude lower than that from commercial cooking (He *et al.*, 2004), indicating fewer particle emissions from some domestic cooking and better capture efficiency of the hood in the commercial applications. Zhao *et al.* (2015) also found that the mass concentration of particulates produced in the home kitchen was lower than that in commercial kitchens. The study conducted by Sharma and Jain (2019) concluded that usage of efficient designing of the kitchen structure coupled with improved cook stoves could improve the overall indoor air quality of the household. Food consumption also affects the production of cooking particles. The concentrations of PM_{2.5} and PM₁₀ were elevated with the increase in fried potatoes (1.25 kg–3.75 kg) (Sofuoglu *et al.*, 2015). However, Chen *et al.* (2018) found that, when the ingredient weights were large (for 2–5 persons), the emission rates of PM_{2.5} were significantly lower than those of the weight for 1 person.

KITCHEN VENTILATION

Hood Performance

An efficient ventilation system is quite necessary to provide a comfortable, healthy and energy-efficient working environment (Kotani *et al.*, 2009; Han *et al.*, 2019). One significant element in the creation of a healthy working environment in the kitchen is the exhaust hood, which could significantly reduce the personal PM exposure (Poon *et al.*, 2016; Du *et al.*, 2017). Scholars have conducted much research on measures to improve the efficiency of fume extraction. Tables 7 and 8 present the improvement measures in kitchen ventilation. Possible solutions have been recommended as follows:

1. Positioning the Cooking Appliance

The purpose of positioning the appliance is to make the thermal fume flow within the size of the exhaust hood to

Table 7. Summary of improvement measures on kitchen hood performance.

Kitchen style	Research method	Cooking style	Ventilation mode	Improvement measures	Enhancing effect	References
Residential kitchen	Experiment	Stir-frying	Exhaust hood with natural air supply	Single-slot, twin-slot, and fence-slot exhausts installed close to the pot rim	Reducing the exhaust flow rate by 30.7%	Lai, 2005
Commercial kitchen	Experiment	Boiling water	Exhaust hood with displacement air supply system	Move cooking appliance from end to middle Increase in front overhang associated with pushing appliances toward the back Reducing the gap between wall and the rear of the appliance	Reducing the exhaust flow rate by 27.0%–50.0% Reducing the exhaust flow rate by 9%–27% Reducing the exhaust flow rate by 30%	Swierczyna et al., 2006
Commercial kitchen	CFD analyses	--	Exhaust hood with natural air supply	Side panels installed on both side of hood Baffle plate attachment inside the hood (horizontal)	Improving the hood performance by 25% C&C efficiency increased up to 8%	Kotani et al., 2009
Residential kitchen	CFD simulation	--	Exhaust hood with mechanical air supply	Separate plate installed inside the hood (Vertical)	1.4%–1.9% more efficient at temperature distribution and 9.4%–11.9% more at CO ₂ concentration distribution	Lim and Lee, 2008
Commercial kitchen	CFD simulation	--	Exhaust hood with mechanical air supply	Side panels installed on both side of hood	C & C efficiency can be increased by 20%	Zhao et al., 2013
Residential kitchen	Measurement	Boiling water	Exhaust hood with natural air supply	Change the flat bottom and downdraft exhaust system to actual collection hoods	C & C efficiency can be increased by as high as 60%	Singer et al., 2012

Table 8. Effect of supply air distribution strategy on kitchen ventilation performance.

Kitchen style	Research method	Cooking style	Ventilation style	Ventilation mode	Improvement measures	Enhancing effect	References
Commercial kitchen	Experiment and CFD analyses	--	Ceiling system	Mixing ventilation	Air conditioning ceiling with capture jet	Reducing the average contaminant level in occupied zone by 40%	Kosonen and Mustakallio, 2003b
Commercial kitchen	Experiment and CFD analyses	--	Ceiling system	Displacement ventilation	Reduce the height of the ventilated ceiling from 2.6 m to 2.3 m	Increasing the C & C efficiency by 10.5%	Kosonen 2007
Commercial kitchen	CFD analyses	--	Mixing system	Displacement ventilation	Displacement ventilation	C & C efficiency can be as high as 98%	Kosonen 2007
Commercial kitchen	CFD analyses	--	Mixing system	Displacement ventilation	Displacement ventilation	Cooling the kitchen space more effectively than mixing ventilation system	Livchak et al., 2005
Commercial kitchen	CFD analyses	--	Mixing system	Air curtain ventilation	Air curtain ventilation	Increasing the capture efficiency by 15.2%	Li et al., 2014
Residential kitchen	Experiment and CFD analyses	Frying potato filament and brassica chinensis	Exhaust hood with natural air supply	Push-pull ventilation	Push-pull ventilation	Reducing CO ₂ level by 23%	Zhou et al., 2016, 2019

improve the capture performance as much as possible. The ASHRAE research project RP-1202 (2006) has quantified the effect of the location and combination of cooking appliances on the minimum capture and containment (C & C) efficiency of hood. Based on the research conclusions, some suggestions are given:

- Locating heavy-load cooking appliances near the center of the cooking appliance line.
- Moving the cooking appliance from end to middle.
- Reducing the gap between wall and rear of the appliance.
- Increasing the front overhang of hood associated with pushing appliances toward the back.

2. Installing Attachments

Attachments are not an integral part of exhaust hoods. However, many studies have found that adding diverse attachment components helps to increase the C & C efficiency of the hood (Fig. 1). Project RP-1202 (2006) investigated the effects of rear seals, front overhang and side panels. Side exhaust systems were investigated by Lai (2005) to investigate the effect of different exhaust configurations on hood performance. Lim and Lee (2008) conducted a three-dimensional numerical analysis to study how to use a separation plate to improve the exhaust hood system to more effectively eliminate pollution. An exhaust hood with a high capture efficiency was developed by Kotani *et al.* (2009) using a baffle plate inside the exhaust hood. The results of these studies provide suggestions for HVAC designers to improve the performance of the kitchen ventilation system.

3. Changing the Shape of the Exhaust Hood

There are two ways for hoods to exhaust the COFs: top exhaust and side exhaust. It is popular to use side exhaust hood in residential kitchen because it can save top space. Most commercial kitchens use top exhaust hood, which can also be divided into two types: canopy hood/umbrella-

shape hood (Chinese style) and box hood (American or European style). The grease filter and front edge of the canopy hood constitute a triangle to reduce the flow resistance of exhaust air flow and avoid the captured grease that adheres to the top of hood falling into the wok. Considered from another aspect, to ensure a sufficiently large hood volume, the cross section of the American- or European-style exhaust hood is designed as a rectangle. Fig. 2 shows the common used exhaust hood in commercial kitchens. To fully understand the influence of the hood volume on the C & C efficiency, Zhao *et al.* (2013) studied 21 types of volumes from canopy hood to box hood as shown in Fig. 3. The results showed that the small hood volume of traditional Chinese-style hoods did not reduce the C & C efficiency. Tsai and Hsieh (2006) studied the flow field of the exhaust hood induced by the combination of crosswind and extract flow. The results found that the flow field would be affected by the oblique angle of the hood's set-up. These studies on the shape of hood gave the following suggestions (Swierczyna, 2006):

- Increasing the depth of hood (from front to back) improves the performance of hood. This additional depth of hood should be used as much as possible to increase the size of the front overhang.
- Increasing the height of hood to increase the volume so that the thermal plume is evenly distributed along the filtering device to improve hood C & C efficiency.

4. Positioning the Exhaust Hood

Mounting hood at the lowest practical (or allowable) height, minimizing the distance from cooking surface to hood to improve the hood performance.

- Installing side panels on both sides of the hood;
- Installing baffle plate inside the hood (horizontal);
- Installing separate plate inside the hood (Vertical);
- For side exhaust systems, installing single-slot, twin-slot, and fence-slot exhausts close to the pot rim;
- Mounting shelves or attachments on or behind the oven.

Fig. 1. Schematics of side panels, baffle plate and separate plate (Swierczyna *et al.*, 2006; Lim and Lee 2008; Kotani *et al.*, 2009).

Fig. 2. The types of exhaust hood commonly used in the commercial kitchens.

Fig. 3. Schematic of the volume change from canopy hood to box hood (Zhao *et al.*, 2013).

5. Exhaust Hood Connection

The connection between the exhaust hood and fan or exhaust duct has a nonnegligible impact on the C & C efficiency. Chao and Law (2000) investigated the effect of direct or indirect connection of hood on the efficiency of pollutant removal. Two different arrangements of the exhaust duct whether located on the upper side or rear part of the hood has been studied by Zhao *et al.* (2013). The results of these studies produced the following recommendations:

- A hood directly connected to the exhaust fan is more effective than a hood that is not directly connected or a kitchen with only a window-mounted exhaust fan.
- Compared with the upper side, when the exhaust duct is located at the rear of hood, the hood C & C efficiency is enhanced.

6. Increasing the Exhaust Fan Speed

The exhaust speed is crucial for hood C & C efficiency.

Obviously, the higher the speed of the exhaust hood is, the higher the C & C efficiency is. Singer *et al.* (2012) evaluated the correlation between the C & C efficiency and fan speed in residential field experiments. As expected, higher C & C efficiencies were achieved with higher fan speeds and related higher air flow rates. However, it is worth noting that high exhaust air speeds can lead to huge energy consumption in kitchen ventilation system. In Chinese commercial kitchens, the design exhaust airflow rate reaches 60 h^{-1} , and, in actual projects, it even reaches 80 h^{-1} . The ventilation energy consumption accounts for 30–40% of the total energy consumption of restaurant industry, resulting in unnecessary economic waste. The latest research indicated that extending the running time of the exhaust hood had the same effect as increasing exhaust flow rate to reduce particle exposure. For $\text{PM}_{2.5}$, the effect of running an exhaust fan for 15 min after cooking was similar in magnitude to the impact of a 100-cfm increase in the flow rate used

while cooking (Dobbin *et al.*, 2018). On this basis, it is necessary to further analyze the energy consumption of kitchen ventilation system to determine the best operation scheme.

In addition to the above improvement measures, scholars have also studied the influence of operators on the C & C efficiency of exhaust hoods. Experiments were conducted by Huang *et al.* (2010) to investigate the relative magnitudes and physical mechanisms of hood spillages. The results indicated that COFs would attach to the mannequin's body standing in front of the cooking appliance. Through the front edge of hood where the mannequin was standing, the attached COFs induced room air and created remarkable dispersion of COFs into the environment. Singer *et al.* (2012) also found that the presence and movement of cooks in front of the appliance may interfere with airflow fields and affect C & C efficiency.

Supply Air Distribution Strategy

Many engineers and designers have the misconception that poor indoor air quality and thermal environment in kitchen are only related to exhaust hood itself. They do not realize the negative impact of bad air distribution on the hood performance. Without makeup air system, the exhaust hood was not able to decrease the particle concentration effectively during the cooking period (Kang *et al.*, 2019). The supply air distribution strategy has a significant influence on the pollutant removal effectiveness in a kitchen environment (Pekkinen *et al.*, 1992; Kosonen, 2007; Stabile *et al.*, 2015). The following provides several ways to help increase the efficiency of exhaust hoods.

1. Air-conditioning Ceiling with Capture Jet

The effect of an air-conditioning ceiling with a capture jet on the containment efficiency was conducted with laboratory measurements and CFD simulations by Kosonen (2007), as shown in Fig. 4 (Kosonen, 2007). When the cooking heat loads are relatively low and the bottom space of the kitchen is limited, the ventilated ceiling, which can help to enhance the efficiency of the kitchen ventilation system, is an available choice for kitchen ventilation. The

capture jet flows horizontally across the ceiling to helping direct the air impurities and convection heat towards the exhaust opening. A combined ventilated ceiling and capture jet can reduce the average contaminant level of the occupied zone by 40%.

2. Push-pull Ventilation

A push-pull ventilation system consisting of a range hood combined with the air supply through a slot air curtain was proposed by Zhou *et al.* (2016, 2019). It can effectively reduce the indoor CO₂ level by 23.0%. The result suggested that utilization of the air curtain can effectively improve the performance of the exhaust hood. The schematic diagram of the push-pull ventilation system is presented in Fig. 5.

3. Thermal Displacement Ventilation and Air Curtain Ventilation

Mixing ventilation is the most widely used system in commercial kitchens. Cold air is supplied through ceiling diffusers at a high discharge velocity. The cross-drafts and unwanted air movement in the kitchen are caused by a high-momentum air jet that makes it difficult to capture the pollutants emitted from the cooking process with range hoods (Livchak *et al.*, 2005). There is a misconception that many designers and engineers believe that they may use the airflow from ceiling diffusers to “cool” the chef. However, they do not realize its negative impact on the exhaust hood performance (Li *et al.*, 2012a). Thermal displacement ventilation (TDV) is an alternative air distribution system that is better suitable for the kitchen environment (Li *et al.*, 2012b). The hood exhaust airflow can be reduced by 12.5% (VDI 2052), when mixed ventilation is replaced with TDV in kitchen. Additionally, the TDV mode with a high ventilation efficiency (98.0%) can cool the kitchen space more effectively (Livchak *et al.*, 2005; Kosonen, 2007). However, in practice, because of the space constraint in kitchen, the utilization of a TDV system may be difficult. A new air distribution pattern named air curtain ventilation (ACV) was proposed by Li *et al.* (2014) as shown in Fig. 6. It is regarded as a combination of the

Fig. 4. Air conditioning ceiling with capture jet system in commercial kitchen (Kosonen, 2007).

Fig. 5. Schematic diagram of push-push ventilation system (Zhou *et al.*, 2016).

Fig. 6. Schematic diagram of air curtain ventilation in kitchen.

displacement flow and mixing flow. Due to Coanda effect, the "air pool" or "air lake" phenomenon created by air curtain ventilation is somewhat similar to displaced air movement. The C & C efficiency could be increased by 15.2%, when the air curtain ventilation system is used in commercial kitchen environment.

Evaluation Index

In practice, the main purpose of kitchen ventilation is to extract the contaminants and convective heat sufficiently from working area with a minimum air flow rate. The capture efficiency is a basic indicator of the local exhaust ventilation performance (Kotani *et al.*, 2009). ASTM 1704 defines the "Hood capture and containment (C & C)" as "the ability of the hood to capture and contain grease laden cooking vapors, convective heat and other products of cooking processes" (Zhou *et al.*, 2016).

The Schlieren visualization system complementing the heat gain testing capabilities were incorporated into the Commercial Kitchen Ventilation (CKV) laboratory for capture and containment testing in the ASTM Standard

F1704-99. Additional laboratory data to improve ASHRAE documentation (ASTM F1704-99) for general hood capture and containment exhaust rates and values for appliance heat gain to the space were conducted by Swierczyna *et al.* (1997) and Fisher (1998) respectively. Different from previous studies, a measurement method for C & C efficiency under practical indoor conditions has been developed by Knappmiller and Schrock (1997). However, one current limitation for ASTM 1704 is that it was designed for mixing air-conditioning systems with exhaust-only hoods.

In Europe, the Verein Deutscher Ingenieure Standard (VDI 2052) was used to determine the C & C requirements for range hoods. In VDI 2502, the main parameters for the airflow calculation are the convective heat load of cooking appliances and distance between the hood and appliance. The engineered procedure is used in some codes (AS 1668.2-2002) for the kitchen hood design. The utilization of suitable technology or solutions is allowed to achieve the designated targets. However, the technology or solutions should be proven with appropriate calculations or reviewed in the field.

In the literature, there is substantial definitions of C & C efficiency and general local exhaust systems for kitchen exhaust hoods (Farnsworth *et al.*, 1989, Geerinckx *et al.*, 1991). They could evaluate the performance of exhaust hoods and could be used for the practical design. The two formulas summarized and proposed by Geerinckx *et al.* (1991) used the perfect mixing situation without a hood as a reference. Jansson (1990) defined the C & C efficiency of the exhaust hood as the ratio of directly captured pollutants to the total amount pollutants of the sources, which is consistent with Geerinckx's theory. The concept of the direct capture efficiency was further studied by Madsen *et al.* (1994). However, it is difficult to separate the directly captured pollutants from the total generated pollutants, not only regarding the measurement but also the numerical simulation. Wolbrink and Sarnosky (1992) derived the C & C efficiency in a confined space, where a two-zone mixing model based on mass conservation was assumed. The method has been widely applied in many studies to evaluate the performance of range hoods. Li and Delsante (1996) further derived the formula, making it suitable for general ventilation systems. Based on Li's study, Kosonen and Mustakallio (2003) derived the deduced C & C efficiency formula for the ceiling ventilation system in a confined space.

Due to the loss of particles deposited in the exhaust hood and pipe, the efficiency of capturing cooking particles is quite different from that of gaseous pollutants. A few studies have reported on the effectiveness of exhaust hoods at reducing the concentrations of cooking particles (Sjaastad and Svendsen, 2010; Delp and Singer, 2012). The C & C efficiency of particles should be achieved indirectly by comparing the concentration of PM in the room when the exhaust hood is used with the concentration under the same cooking condition when the exhaust hood is not used (Lunden *et al.*, 2014).

CONCLUSIONS

In cities and rural areas worldwide, cooking has proven to be an important source of indoor and outdoor PM. The apportionment studies that identified this source primarily used source profiles from the United States, Europe, and Asia because many studies were conducted in these regions.

Further understanding of the physicochemical components associated with cooking sources facilitates the assessment of human exposure, health injury and environmental impact under cooking conditions. This review found that the composition of cooking aerosol particles is highly diverse, depending on the fuel type, cooking oil (if used), cooking temperature, cooking method, cooking style (raw food ingredient) and other factors. This diversity means that prediction and evaluation of the cooking aerosol are very difficult, although the characteristics of the cooking source are well known.

The submicron particles that have a small natural sedimentation rate and follow the movement rule of fluid account for more than 90% of the cooking particles. It is

not only difficult to be captured and purified by the ventilation system but also more easily inhaled by the human body or in contact with the skin surface. In addition, the cooking particles are affected by ventilation and thermal plume at high temperatures, and their growth and diffusion characteristics are significantly different from other indoor particles. Therefore, it is difficult to achieve high C & C efficiency of cooking particles in real situations. Presently, improvement measures and air supply strategy of kitchen ventilation systems have been studied through experiments and numerical simulation methods.

EXPECTATION

Cooking oil fumes are aerosols comprising particles, droplets, and gaseous companion products, which are recognized as a significant pollutants source. Diffusion and transmission of COFs is a complex process involves physical and chemical reactions. Evaluate and control of COFs requires an in-depth understanding of numerous cooking processes, chemistry, fluid mechanics, and thermodynamics.

Most studies on COFs' characteristic currently focused on the particulate matter and mainly consider the particles concentration, chemical composition and human exposure. Cooking particles interact with each other during transport, and their related parameters change and ultimately affect the removal and purification of particles. Theoretical and experimental research is needed on the growth and evolution of cooking particles in order to further study the emission characteristics of each component, including: physical and chemical. Further research on the accurate prediction model of the diffusion of cooking particles is needed.

Furthermore, the existing kitchen (residential or commercial) exhaust hood design method and exhaust flow rate calculation method are all based on the thermal plume generated during cooking process, without considering the entrainment and sliding between particles and ambient air. There are obvious differences between the control of cooking particles and the control of gaseous pollutants. However, the existing kitchen ventilation design specifications has hardly involved in the relevant content, resulting in the low C & C efficiency of cooking particles. Research is needed on the coupling mechanism of particle group and ambient air in order to study the ventilation control of cooking particles. The structure design, flow rate and C & C efficiency of the exhaust hoods in the current literature varies greatly, and further research is needed for exploring the appropriate design method to reduce exhaust air flow rate and exposure to cooking pollutants. In addition, in the future, the energy consumption analysis in kitchens, especially in commercial kitchens, is needed. Exposure to pollutants, kitchen ventilation patterns and system energy consumption are interrelated. The kitchen ventilation should be given more attention because it is the key to solve the problem.

ACKNOWLEDGMENT

This research was supported by the National Natural

Science Foundation of China (No. 51504182, 51674188, 51874229, 51404191), Shaanxi Innovative Talents Cultivate Program-New-star Plan of Science and Technology (2018KJXX-083), Scientific Research Program funded by the Shaanxi Provincial Education Department (No. 19JK0543), Scientific Research Program funded by Xi'an Science and Technology Bureau (Grand No. 201805036YD14CG20(5)) and Outstanding Youth Science Fund of Xi'an University of Science and Technology (No. 2018YQ2-01). This research was also supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIP) (No. CRC-16-38502-KICT).

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Received for review, April 11, 2019

Revised, July 10, 2019

Accepted, July 16, 2019