An Overview of Particulate Matter and its Cost-efficient Evaluation

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Abstract: Ambient particulate matter (PM) is a complex mixture of sizes and types of particles. Exposure to airborne particulate matter adversely affects human health. In this paper, sources of particles are summarized, and epidemiological and toxicological studies on health effects of particulate matter are introduced. Control strategies and cost-effectiveness evaluation of PM are also introduced. Developing optimum control strategies, which likely include a variety of control options and cost-effective preventive measures, is urgent. The purpose of this paper is to provide guidance and suggestions for future researchers.

Key words: particulate matter; cost-efficient; air pollution; health effect; control strategies

1. INTRODUCTION

In the last 30 years, numerous health problems related to the presence of air contaminants have occurred. Until recently, we have found about 100 kinds of air contaminants which are harmful to people and environment. The main air pollutants include particulate matter (PM), sulphide, oxides of nitrogen (NO_x), volatile organic compounds (VOCs), halogen compounds, radioactive material and so on[1]. The researches of air pollutions mainly focus on the source of aerosol, composition and distribution of total suspended particles (TSP) and inhaled particles (IP) and its pathogenic mechanics. With the research of PM, people realize that the main factor of inducing increasing morbidity and mortality is the concentration of IP.

Particles are often categorized according to their ability to penetrate into the human respiratory system. Inhalable dust is a term used to describe dust that is hazardous when deposited anywhere in the respiratory tree including the nose and the mouth (50% cut-point of 100 μm). Particles in the regions of 7 μm ~ 20 μm will penetrate to the bronchioles and are called inspirable or thoracic (50% cut-point of 10 μm). Particles in the size range 0.5 μm~7 μm, which can penetrate to the nonciliated portion of the gas exchange region of the lungs (the alveolar region), are called respirable (50% cut-point of 4 μm). (In these definitions "cut point" describes the performance of particle size selective sampling devices. For personal sampling, the 50% cut point is the size of the dust that the device collects with 50% efficiency.) [2].

Particles greater than around 10 μm in diameter are large enough to settle quite quickly from the atmosphere under the influence of gravity and can cause nuisance through their ability to deposit out on horizontal surfaces, creating dust soiling, whilst the smaller particles are most notable for the health hazard which they present.

Because particulate air pollution is among the top preventable causes of morbidity and mortality in many countries, developing better ways to manage population exposure to particulates should be high on the agenda of the public health community. The problem of managing particulate air pollution is complex, not only because it involves many different pollutant emitters, but also because management options involve many institutions that cut across domains of environment, energy, natural resource, public health, and economic policy. The cost-effectiveness of prevention and control technologies for PM has not been well researched and documented. Optimum control strategies will likely include a variety of control options [3].

2. THE SOURCE OF PARTICLES

Atmospheric particulates are one of the main air pollutants in urban areas. Particulate matter is usually generated from many sources such as automobile exhaust, industrial combustion processes and secondary conversion from gaseous pollutants. ent in commercial district in Dom Pedro and in residential district in Lbirapuera [4]. The generation rate of motor tail gas in commercial district is obviously greater than that in residential district.

Particles in the coarse mode include coarse windblown and road dust, pollens and spores, and some industrial particles. Particles in the fine mode include primary particles from high-temperature metallurgical and combustion processes, secondary particles from atmospheric reactions, and an unknown but theoretically small amount of fine

Pollution sources of suspended particles in the air are showed in table 1. The sources and generation of airborne particles are relevant with economic development, energy structure, technique and control level in different countries and areas, e.g. table 2 shows that the mass distributions of PM_{10} are differ-

particles that have been deposited and resuspended by wind or human activities [3, 5]. Since the epidemiological studies of PM health effects are based on geographically dispersed (but mostly urban) locations with numerous and varied emission sources, the major sources of the particles are difficult to ascertain. Researchers most familiar with these studies have speculated that two types of sources may be particularly important: primary emissions from combustion sources, and secondary particles formed in the atmosphere.

Table 1 Pollution sources of suspended particles in indoor and outdoor

Particles mostly coming from outdoor	Non-biological sources	Man-made pollutants	Coal burning boilers of industry and power plant
			Tail-gas of vehicles (diesel oil)
			fuel boilers
			Manufacturing procedure of industrial materials
			Building dust
			Transportation and handling procedure of industrial materials
			Combustion of rubbish
			Combustion of organism
			Agricultural production process
			Asbestos
		Natural chemical sources	Marine salt
			Dust by wind
			Forest fire
			Secondary particles (sulphate smog et al.)
			Pozzolana
			Meteoric dust
The shared sources	Biological source		Algology
			Protozoan
			Fungal (saccharomyces, Penicillium notatum, et al.)
			Bacteria
			Viruses
			Biological allergic sources (cockroaches et al.)
			Pollen
			Spore
			plant fiber
Par ticl	No n-b iol	Ma n-	Tobacco Smoke

			Cooking
			Combustion of wood
			Combustion of gas fuel (liquefied gas included)
			Combustion of coal
			Combustion of organism
			Resuspension of deposited particles
			Combustion of spice
			Combustion of candles
			Combustion of coal oil
			kinds of consumable and makeup
		Natural chemical sources	Particles from building and decorated material (asbestos et al.)
			Secondary particles (reacting product of ozone and toluene,et al)
	Biological sources		Animal dander

Table 2 Generation rate of different sources of PM_{10} [4]

site	bay salt	fuel oil	dust	Motor tail gas	Secondary pollutants	else
Dompedro	1.42	3.62	22.37	50.27	20.34	1.989
Lbirapuera	1.41	3.95	23.41	34.91	32.95	3.37

3. HEALTH EFFECT OF PARTICLES

It has generally been established that exposure to urban airborne particulate matter (PM) with PM_{10} and especially $PM_{2.5}$, adversely affects human health with increased respiratory and cardiovascular diseases and observed mortality in exposed populations [6~8]. However, it is still not clearly understood which particles are responsible for these adverse effects or the mechanisms involved. This is due to the complexity of urban PM which can originate from a multitude of sources and may also undergo physical and chemical transformations in the atmosphere. Low levels of exposure to urban PM can result in the onset of adverse health effects which are not observed for much higher levels of exposure in industrial workplaces [9].

There is increasing evidence that exposure to fine particulate air pollution is an important risk factor, especially for cardiopulmonary mortality but also for lung cancer mortality. Links are generally accepted to exist between airborne particles and morbidity / mortality. At present, the size class most commonly considered is $PM_{2.5}$. The effect process of airborne toxicant to human is showed in Fig. 1.

Table 3 lists the key causal factors that are the basis for current hypotheses on what aspects of particulate matter are responsible for observed health effects. Hypotheses regarding acidic particles, particles containing sulfates, ultrafine particles (smaller than about 0.1 μm), and particles containing transition metals would implicate combustion sources [3].

3.1 Epidemiologic Studies

The epidemiologists mainly use two methods to study the effect of the particles on body health, which are population studies and time series. Now the widely adopted statistic method is poisson regression method based on general additive model. Long-term and short-term studies are widely adopted by researchers to investigate the particle effect.

3.1.1 Long-term Studies

There is sufficient evidence that long term exposure to particulate matter implies serious health risks. Multiple western researchers have found significant links of morbidity with particulate air pollution, e.g. an increase of the prevalence of cough, wheeze and bronchitis [10~17], an impairment of lung function [18~19], an increase of lymphocytes and IgE in the peripheral blood [20]and a decrease in lung growth of children[21~22]

3.1.2 Short-term Studies

Consistent associations are also found between short-term exposure to particles and hospital admissions, or consultations of physicians. The associations are observed for asthma, chronic obstructive pulmonary disease, pneumonia and other respiratory causes, as well as for cardiovascular causes. In asthmatics, small impairment of lung function as well as an increase of respiratory symptoms (cough, phlegm, shortness of breath, use of bronchodilators) is found in association with particle exposure [23].

Due to statistical problems using GAM software in a large American study, the most short-term studies which also had used this software have been reanalyzed. The reanalysis confirmed the most of the conclusions with moderate corrections to the effect estimators [24].

In total, the short-term studies demonstrate ass-

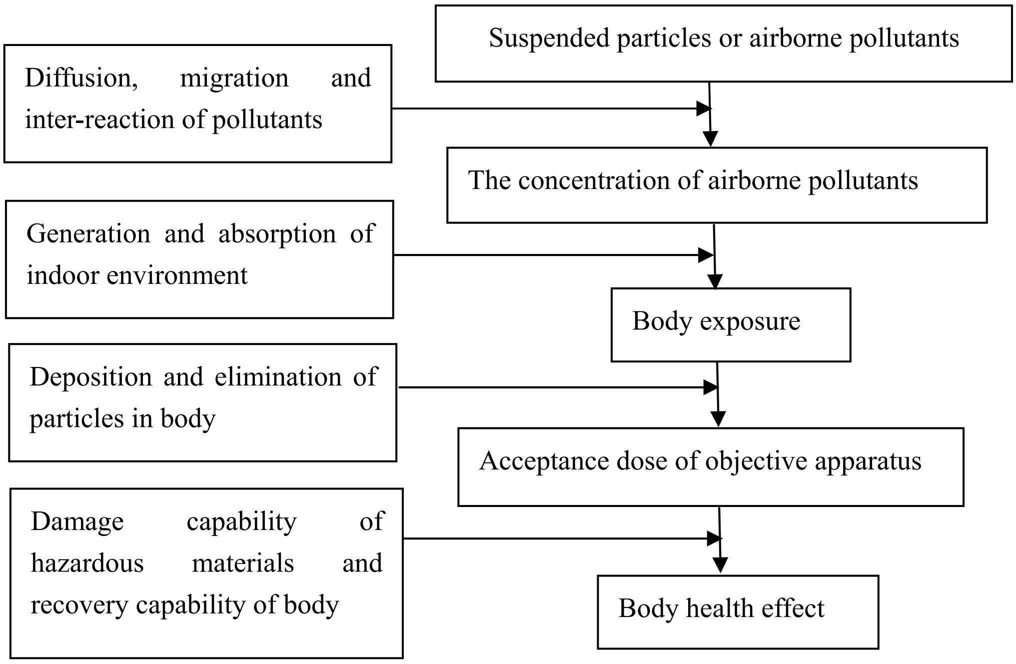

Fig. 1 The effect process of airborne PM to human

Table 3 Factors or constituents that are currently hypothesizes to be significant in fine PM toxicity [2]

PM mass concentration	Metals
Particle size / surface area	Acids
Ultrafine PM	Biogenic particles
Organic compounds	Peroxides
Sulfate and nitrate salts	Soot
Cofactors(e.g., other pollutants, weather)	

ociations of particulate matter concentrations and human health down to the lowest concentrations observed. A no-effect concentration or a threshold can not be derived from previous literatures [25]

Many epidemiological studies provide evidence of an association between airborne particles, measured as PM_{10}, and daily morbidity and mortality. A 10 mg/m^3 change in daily PM_{10} was associated with an approximately 1% increase in mortality, which is of similar magnitude to particle associated impacts identified in urban areas [26]. Gordian et al. [27] found a 3% to 6% increase in outpatient visits for asthma and a 1% to 3% increase for sinusitis visits associated with a 10 μg/m^3 increase in ambient PM_{10}. The study by Hefflin et al. [28] found increases in ER visits for bronchitis and sinusitis (both less than 1 % / 10 μg /m^3), and none at all for asthma. Seaton et al. [29]have proposed that exposure to ultrafine particles (mass median aerodynamic diameter (MMAD) 5100 nm) could provoke alveolar inflammation, causing exacerbations of existing lung disease and increased blood coagulability, leading in turn to cardiovascular deaths through direct effects on either the lungs or the heart. Using concentrated ambient particles, Godleski et al. [30] produced airway inflammation and pulmonary vascular congestion in rats with chronic bronchitis. Alterations in cardiac electrophysiological function were observed in dogs exposed to concentrated ambient air particles [31]. However, the mechanisms that underlie the associations between exposure to PM and mortality in elderly people are unknown.

3.2 Toxicological Studies

Considering the epidemiological evidence of particulate matter on the health effects, the main purpose of the toxicological studies was to prove the plausibility of the statistical associations, to elicit the components of particulate matter responsible for the health effects and to analyze the mechanisms of action and the dose-effect relationship.

Some components of ambient particulate matter are more toxic than others. The effects of oil fly ash (EOFA) depend on the content of the transition metals Fe, Ni, V or Zn [32~33]. In the Utah Valley Study, the contamiants diluted and extracted from air filters were applied by instillation to rats and bronchoscopically to human volunteers producing local inflammation. The water soluble components, rich on metals, proved to be specifically toxic [34~35].

The effects of ultra fine particles evoked special interest because of their large surface area per mass. Oberdörster et al. [36] and Li et al. [37~39] compared the effects of fine and ultra fine particles. At equal mass dose, ultra fine particles were more toxic than fine particles producing oxidative stress reactions. The effects depend on the chemical composition of the particles, e.g. ZnO-particles being more toxic than MgO-particles [40]. Ultra fine particles are less frequently phagocytized by alveolar macrophages and are present in the epithelium as well as in the interstitial lung tissue [41~42]. The experimental evidence is insufficient for firm conclusions about the role of ultra fine particles regarding the health effects[23].

However, as with the epidemiological literature, there are few toxicological data examining acute effects of coarse particles other than silica, which produces a prolonged inflammatory response in experimental animals at high exposure concentrations[43~44]. Prior special monitoring studies by the South Coast Air Quality Management District (SCAQMD) indicate that approximately 10% of the annual average PM_{10} mass consists of silicon, a substantial portion of which is in the form of silica[45]. In an experiment examining the relative acute effects of inhalation of nitrates, sulfates, and coarse particles (produced by resuspending road dust) in the lungs of rats, Kleinman et al. [46] found that all three exposures produced some effects consistent with lung injury, though those investigators inferred that the two fine particle exposures were generally more potent in inducing such effects than the resuspended road dust. Both sulfate and road dust exposures caused a significant suppression of alveolar macrophage function, as measured by production of superoxide anion during respiratory burst activity, while increased epithelial permeability (assessed by albumin concentration in postexposure bronchoalveolar lavage fluid) was observed in rats exposed to road dust or to nitrates, but not sulfates [46].

Crustal particles may also contain endotoxin, a potent inflammatory agent derived from gram-negative bacteria. To the extent that inhalable coarse particles are capable of provoking or exacerbating a pulmonary inflammatory response, it is possible that they may, like fine particles, elicit effects on the cardiovascular system remote from the site of particle deposition. Most other toxicological studies of crustal particles have involved extremely high exposure concentrations with exposures generally administered by instillation rather than inhalation or have examined chronic rather than acute effects [47]. Studies of acute exposures to extremely high concentrations of either carbon black alone (10,000 mg/m^3, MMAD= 2.4 mm, 4 h) or carbonyl iron (100,000 mg/m^3, MMAD=3.6 mm. for 6 h or 3/days at 6 h/day) found no inflammatory effect in mice or rats, respectively [43, 48].

In principal, the toxicological in vitro and animal experiments give clear hints as to the mechanisms of the effects observed in the epidemiological studies but the exposures in these experiments are by up to two magnitudes higher than the exposures observed in epidemiology.

4. CONTROL STRATEGIES AND COST-EFFICIENT EVALUATION FOR PM

4.1 Control Strategies

In order to achieve better indoor air quality, some control measures must be implemented. In general, we can classify them as (1) suppression of the generation rate, or source control; (2) reduction of indoor air contaminant concentration by outdoor air exchange, or dilution control; and (3) removal of indoor air contaminant by air cleaners, or removal control. For multizone environments, additional measures can be implemented to restrict the transport of contaminants to non-contaminated zones, or local segregation. Increased ventilation and indoor air filtration are two commonly used engineering techniques to reduce occupant exposure in residential homes [49].

Control of the coarse particle fraction is far more problematic. Whilst limiting concentrations of marine aerosol is implausible, it is reasonable to think that controls on concentrations of resuspended particles are feasible. Current knowledge of the extent to which these particles arise from wind-blown soils as opposed to street dusts resuspended by traffic action is poor. Whilst control of the former may prove difficult, it is possible to envisage controls on the latter either through limiting the volume of traffic or by the regular washing of road surfaces to remove accumulated surface dusts. The overview of current knowledge on control of fine particles is listed in table 4.

With respect to particulate matter as a whole, the greatest gains have been made through controls over the combustion of coal. Whilst emissions from road traffic threatened at one time to reverse the declining trend, substantial tightening of vehicle emissions standards is having a highly beneficial effect and the prognosis for the future is very bright with respect to this source category. Similarly, emission controls on sulphur dioxide are having a beneficial influence on sulphate aerosol, whilst the control of nitrate through NO_x controls is considerably more problematic, although progress is being made. As these sources of fine particles decline, so does the contribution of coarse particles become more marked, and attention will focus on those parts of the coarse particle mass that can be influenced by legislative intervention, as opposed to those (such as Saharan dust) that are unlikely to benefit from human intervention on any practicable timescale[50].

While any particular area that is in non-attainment status will have its own distribution of these sources, it is likely that control strategies will address one or more of these source types. Two general approaches will be taken to estimate which sources are contributing most to ambient monitoring stations in the non-attainment area: source inventories and source-oriented (dispersion) modeling to estimate impacts on the ambient stations, and chemical characterization of particles collected at the ambient sites coupled with receptor-oriented modeling to calculate contributions of various source types.

4.2 Remedial Action to Avoid Exposure

People with cardiac or respiratory illnesses have often been advised to avoid going outdoors during periods of high air pollution and smog. How efficient a home is in protecting from particulates of outdoor origin will depend on the tightness of the home and the nature, if any, of filtration of intake air. New building technologies (e.g. air-sealing insulation and energy recovery ventilators) are enabling the design and construction of tight buildings with filtered air intake which are much more protective from smog exposures than previous types of buildings. Indoor air particles can be reduced by aggressive dust control programs, which may include removing curtains and carpeting, which can harbour small particles easily. Use of high-performance vacuum cleaners or central vacuums can also reduce dust accumulation without adding to the fine particle fraction in the air. Air cleaners can be helpful, depending on what size particles they are designed to capture, how efficient their capture rate is, and how much air flows through the unit. However, they may not address heavier particles which settle out of the air readily but become airborne easily when a carpet or piece of furniture is disturbed. Some households also maintain a “no shoes” policy to ensure that outdoor particulates from soil and road dust do not get tracked throughout a home [51].

4.3 Cost-efficient Evaluation

Comparing typical exposures from coal-fired cook stoves and power plants, Roumasset and Smith[52] estimate that the marginal cost of exposure control for a cook stove is only about 11% that for a power plant. So a system that could substitute exposure reductions in the household sector for exposure reductions in the industrial sector could greatly improve the economic efficiency of particulate management [53]. By using a model to quantify the impact of particulate matter on population exposure, Joshua T. Cohen [54] found that that emission controlled diesel (ECD) and compressed natural gas (CNG) produce very similar reductions in health damages compared to conventional diesel (CD). However, ECD is far more cost effective ($400,000 ~ $900,000 cost per quality adjusted life years (QALY) saved) than CNG (around $4 million per QALY saved).

As Table 4 implies, there are few data on the effectiveness and costs of emissions prevention, emissions reduction, or exposure reduction technologies for fine particles (i.e., $PM_{2.5}$). Research related to fine PM control strategies is being conducted by EPA in two areas: Source Characterization, where the focus is on new knowledge about the emission rates, chemical and physical compositions, and toxicities of particles from various sources; and Risk Management Evaluation, where the emphasis is on developing new information about the effectiveness and costs of prevention and control technologies for emissions of PM [3].

The overall objective of the risk management evaluation research is to evaluate the cost and effectiveness of currently available options for reducing emissions of primary particles and gaseous precursors of secondary particles, and exposures to ambient and indoor fine particles. Current focus is on pilot-scale field evaluation of devices for industrial and utility boilers. A paper study is also underway to develop a framework for evaluating fine PM control strategies for all types of sources. Laboratory- and house-scale studies are being cond-

Table 4 Overview of current knowledge on control of fine particles (values for efficiencies and costs are estimates or judgments by the author) [3]

Source Type	Primary control options, efficiencies for PM_{10}	Approximate costs of PM_{10} controls
Roads	Vacuum sweeping (0~50%), Water flushing and sweeping (0~96%), Paving and roadside improvements, Covering trucks Speed and traffic reduction	Dependent on type of control, time of event, frequency of event / year, and volume of traffic. Very limited published data
Agricultural production (including erosion)	Low tillage, punch planting, crop strips, vegetative cover, windbreaks; Chemical stabilizers, irrigation	Dependent on crop type and regional weather conditions. Little data
Construction activities	Wet suppression of unpaved areas, material storage, handling and transfer operations;	Dependent on type of control, time of event, land area of event, and activity

	Wind fences for windblown dust	level of equipment. Very limited published data
Open burning (including wild-fires agricultural burning	Low wind speed and appropriate wind direction	Unknown
Residential wood combustion	Replace with cleaner burning stoves or furnaces	~US$1000 per replaced stove or furnace
Diesel engine combustion	Combustion modification, improved fuel characteristics, particle traps	very limited published data
Mineral products production	Enclosing crushing, transfer areas; Water spray suppression; Chemical stabilization of unpaved traffic areas	Dependent on type of control and activity level of equipment. Little data
Pulverized coal boilers	ESPs, Fabric Filters	Capital cost US$50~100 per kW, annual cost 2~5 mills / kWh,total installed cost US$ 25~50 per m^3/h
Heavy fuel oil combustion	Cyclones, ESPs	Unknown
Residential fuel oil combustion	Proper maintenance, modern furnaces	Unknown
Waste incineration	Fabric filters, ESPs, venture scrubbers	Total installed cost US$15~30 per m^3/h
Metal smelting and refining	ESPs, cyclones	Total installed cost US$15~30 per m^3/h
Outdoor air introduced into the indoor envir-onment Tracked-in dust	Air cleaners for ventilation air (30~98%)[a];	Capital cost US$3~10 per m^3/h of outdoor air treated
	Whole-building air cleaners (30~98%)[a];	Capital cost US$1~10 per m^3/h of indoor air treated
	In-room air cleaners (30~98%)[a];	US$200~800 per room
	Cleaning (e.g., vacuuming)	No published analyses
	Whole-building air cleaners (30~98%)[a];	Capital cost US$1~10 per m^3/h of indoor air treated
	In-room air cleaners (30~98%)[a];	US$200~800 per room
Indoor activities (that generate or resuspend particles)	Source control, including maintenance;	Highly variable; no published analyses
	Whole-building air cleaners (30~98%)[a];	Capital cost US$1~10 per m^3/h of indoor air treated
	In-room air cleaners (30~98%)[a]	US$200~800 per room

[a] Range of single-pass efficiency for removing particles. The effectiveness of air cleaners in reducing exposures to indoor particles is very dependent on installation and operating conditions, and is generally less than the single-pass efficiency.

ucted to understand how penetration of outdoor particles into buildings is affected by particle size, composition, environmental conditions, and building operational conditions [3].

5. CONCLUSIONS

Long-term exposure against PM for years or decades is associated with elevated total, cardiovascular, and infant mortality. With respect to morbidity, respiratory symptoms, lung growth, and function of the immune system are affected. But the effect mechanisms for particles on health are still unknown. During the past 10 years many new epidemiological and toxicological studies on health effects of particulate matter (PM) have been published, while a few literatures are about the pathogenic mechanisms. Ambient PM is a complex mixture of sizes and types of particles that originate from many sources. The size, chemical composition, and source of particles may all play a role in human exposures, and health effects resulting from those exposures. What are the physical and chemical characteristics of particles which are relative with human health are needed to solve in future. The cost-effectiveness of prevention and control technologies for PM has not been well researched and documented. More research is needed regarding developing the most cost-effective prevention and control options for particles.

Currently, in most countries that regulate air pollution, regulators employ standards that limit the quantity or concentration of particulate emissions. Analysts have noted, however, that standardizing on pollutant emissions is both indirect and inefficient compared to standardizing on pollutant exposure [55]. This is because uniform emissions standards do not reflect source-to-source differences in source-receptor transport of pollutants. Particulates emitted from the tall stack of a power plant in a sparsely populated rural area, for instance, will have a very small chance of being inhaled compared to particulates emitted from the short stack of a small heating boiler in the middle of a densely populated city. In China, given the institutional and legal hurdles that would have to be overcome to integrate exposure management for very diverse types of sources, it might be more realistic to first rationalize exposure management just in those areas of China's State Environmental Protection Administration (SEPA) current authority. This could involve, for instance, abandoning emissions standards in favor of exposure standards (for both the most-exposed individual and populations), or better yet, charging a pollution levy based on exposure rather than on emissions [54].

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